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Abstract

This paper provides an overview of the environmental, economical, and policy considerations related to biofuels. While the biofuel production and consumption exhibited significant increase over the first decade of the new millennium, this and further increases in biofuel production are driven primarily by government policies. Currently available first generation biofuels are with a few exceptions not economically viable in the absence of fiscal incentives or high oil prices. Also the environmental impacts of biofuels as an alternative to fossil fuels are quite ambiguous. The review of the most recent economic models dealing with biofuels and their economic impacts provides a distinction between structural and reduced form models. The review of reduced models is structured toward the time series analysis approach to the dependencies between prices of feedstock, biofuels, and fossil fuels.

Keywords: Biofuels; Ethanol; Biodiesel

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1 Introduction

The oil crisis of the 1970s generated a high interest in biofuels as a possible replacement for fossil liquid fuels used in transportation. In the 1980s and 1990s, increased consciousness of climate change also contributed to the popularity of biofuels as an alternative to fossil fuels. Consequently, global production of biofuels experienced sharp increase, especially in the new millennium. While high oil prices might have contributed to this growth, it was mainly driven by government policies such as mandates, targets and subsidies which were justified on the grounds of energy security and climate change considerations. However, the concerns raised by the global food crisis in 2007/2008 and the ambiguity with respect to environmental impact of biofuels led many governments to reconsider their earlier optimism with respect to biofuels.

This study aims to provide a brief but comprehensive overview of biofuels literature from the point of view of agricultural and natural resource economics. In order to achieve this goal, we structure this article in the following way. In the next section, we define the biofuels with respect to their sources and technologies used for their production. Then we describe the quantitative importance of biofuels both from the point of view of their demand (their use in transportation) and their supply (share on agricultural production). These two primarily technological sections are followed by a review of policy treatment of biofuels in all three key biofuels markets of the European Union, the United States, and Brazil. Next section covers a very wide array of environmental and socio-economic issues connected with biofuels. In the last-but-one section, we discuss the modeling techniques used in the economic evaluation of impacts of biofuels and we mention some of the results obtained by these economic models. The last section provides a brief conclusion to our article.

2 Biofuel Sources and Technologies

Biofuels represent a wide range of fuels which are in some way derived from biomass. The wide definition of biofuels covers solid biomass, liquid fuels and various biogasses. In the further text, we concentrate on liquid biofuels.

The biofuels are generally classified as conventional (the first generation) biofuels and advanced biofuels (the second, third, and fourth generations). The first generation biofuels are made from food crops rich in sugar or starch or vegetable oil. The most common types of the first generation biofuels are bioalcohols (especially ethanol) and biodiesel. The second generation biofuels are produced from residual non-food parts of current crops, such as stems, leaves and husks that are left behind once the food crop has been extracted, as well as other crops that are not used for food purposes, such as switchgrass, jatropha, miscanthus and cereals that bear little grain, and also industry waste such as wood chips, skins and pulp from fruit pressing etc. The third generation biofuels are obtained from algae. Biofuels created from processes other than the first generation ethanol and biodiesel, the second generation cellulosic ethanol, and the third generation algae biofuels are2 referred to as the fourth generation biofuels. Fourth generation biofuels are highly experimental and have not yet been even clearly defined. Some fourth generation technologies are: decomposition of biofuels at high temperatures, artificial photosynthesis reactions, known as solar-to-fuel, and genetically modifying organisms to secrete hydrocarbons.

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. Biochemical technologies for conversion of sugar and starch are also the most technologically and commercially mature today. Currently prevailing fermentation technologies are based on an extraction of simple sugars in sugar crops, their yest-fermentation and distillation into ethanol. Starches crops require an additional technological step. They are initially converted into simple sugars through an enzymatic process under high heat. This conversion requires additional energy and leads to an increase in the cost of production (BNDES and CGEE, 2008). The major drawback of the first generation biofuel crops is that they are important food crops and their use for fuel can have adverse impacts on food supply. Another drawback is that these crops are intensive in the use of one or more inputs such as land, water, fertilizers, pesticides, etc., which have other environmental implications (Ziolkowska and Simon, 2011b).

In the future, the cellulosic sources are expected to displace such crops as the major second-generation source of ethanol. While the first generation ethanol is produced from the sugar or starch part of the plant, which comprises only a small percentage of the total biomass of the plant, the second-generation conversion of lignocellulosic biomass leads to the full use of lignocellulosic material contained in many biomass sources like waste seed husks and stalks and fast growing grasses and trees. Lignocellulosic biomass is composed of polysacharides (cellulose and hemicellulose), which are converted into sugars through hydrolysis or chemical (or combined) processes. The sugar is then fermented into ethanol using the technologies already utilized for the first generation biofuels (Naik et al., 2010, Sims et al., 2011). According to Ziolkowska and Simon (2011a) as of 2011, there is no commercial-scale production of cellulose biomass ethanol, a number of small pilot projects are underway and the first commercial-scale plant is scheduled to open in 2012.

In contrast to ethanol, biodiesel is produced from oilseed crops like soybean, rapeseed, and oil palm. The most common method of producing biodiesel is transesterification. It 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.

The first generation biofuels are widely commercially produced all over the globe. The second and further generation biofuels are still in the stage of research or demonstration bio-refinery plants, which are financed by a mix of government and private research and development funds. Sims et al. (2010) and Carriquiry, Du, and Timilsina (2011) show that a full commercialization of conversion processes for the second generation biofuels still remains as a future task. Sims et al. (2010) argue that unless there is a technical breakthrough that significantly lowers the production costs and accelerates investment and development, the successful commercialization of the second generation biofuels should not be expected before 2020.

3 Production and Use of Biofuels

Biofuel production has increased continuously worldwide over the last years. In 2009, global ethanol production reached nearly 75 billion liters (Scarlat and Dallemanda, 2011) in more than 40 countries. That year, the ethanol production was 40 billion liters in the USA, 26 billion liters in Brazil and 3 billion liters in the EU (FAPRI, 2010). Global biodiesel production totaled almost 19 billion liters worldwide in 2009 (Scarlat and Dallemanda, 2011). The biodiesel production reached 2.2 billion liters in the USA, 1.5 billion liters in Brazil and 9.4 billion liters in the EU (FAPRI, 2010). The FAPRI biofuel production forecasts for 2019 are 65 and 5.4 billion liters of ethanol and biodiesel, respectively for the USA, 52 and 2.9 billion liters of ethanol and biodiesel, respectively for Brazil, 6.9 and 13.1 billion liters of ethanol and biodiesel, respectively for the EU. The land used for biofuels was estimated in 2008 at around 20 million ha worldwide, or around 1% of the global agricultural land, of which about 8 million ha was used for sugarcane plantation in Brazil (Gallagher, 2008, Searchinger et al., 2008).

According to Schnepf (2011), , the share of ethanol on the US total gasoline motor transportation fuel use measured in gasoline-equivalent gallons was 6.5% in 2010. Corresponding share of biodiesel on the US diesel transport fuel use was 0.8% in 2010. Since the US use of diesel as transportation fuel at less than 50 billion gallons yearly is equal to approximately 1/3 of gasoline use, the overall share of biofuels on the US transportation fuel use was 5.1% on an energy-equivalent basis in 2010. This relatively small share sharply contrasts with a very large contribution in Brazil, where ethanol from sugar cane replaced already 50 percent of gasoline for transport in 2009, according to REN21 (2010) .

Biofuel use represents an important share of global cereal, sugar and vegetable oil production. According to Agricultural Outlook of OECD-FAO (2010), sugarcane will remain the single most biofuel-oriented commodity. Its global share to be used for the ethanol production is expected to raise to 35% in 2019 as opposed to 20% in the baseline period of 2007-2009. The next most used category is molasses with the expected share of slightly less than 25% as compared to slightly less than 20% in the baseline period. Vegetable oil and coarse grains, which have the same share of 9% of their production being used for biofuels in the baseline period, are predicted to diverge somehow with about 13% of the global production of coarse grains being used to produce ethanol in 2019, while the corresponding forecast for vegetable oil conversion to biodiesel is 16%. For sugar beets, a modest increase from currently less than 10% biofuel utilization to about 11% utilization is expected in 2019. Relatively high rate of increase of the biofuel utilization is expected for wheat. But given its low baseline share about 1%, only about 3-4% of its 2019 production is expected to be used for biofuels.

4 Biofuel Policies

This section is dealing with biofuels policies in three main biofuels markets of the European Union, the United States, and Brazil. It is based primarily on Al-Riffai et al. (2010a), Serra, Zilberman, and Gil (2011), and Ziolkowska et. al (2010).

4.1 Brazil

Ethanol policies in Brazil were initially promoted through government intervention as a response to the petroleum shortage caused by the 1973 oil crisis (Goldemberg, 2006). Strong support for both demand and supply of ethanol, and for an increase of the share of domestically produced fuel were provided in the framework of the Proalcool program, which started in 1975. The government run of the Proalcool program was gradually terminated in the 1990s, but a combination of market regulation and tax incentives continued to be maintained. Transition to a full liberalization took place between 1996 and 2000. Currently, no direct control over ethanol production and trade exists but number of incentives supporting demand are maintained.

Current blending obligation for ethanol are 18-25% for gasoline. This blending mandate is concerned only with anhydrous ethanol which is used for blending with conventional gasoline. It is not relevant for pure hydrous ethanol sold at filling stations for use in flex-fuel vehicles, which can run on any ethanol-gasoline blend up to 85% of anhydrous ethanol or on up to 100% hydrous ethanol fuel. The success of flex-fuel vehicles together with 18-25% mandatory blend have allowed ethanol fuel consumption in Brazil to replace 50% of gasoline for transport, as mentioned in the previous section. More recently, Brazil also introduced biodiesel blending targets of 2% in 2008 and 5% in 2013. In order to reach these obligations, the Brazilian federal and state governments grant tax reductions and exemptions. The level of these biofuel supports varies based on the size of agricultural producers and on a level of development of each Brazilian region. Brazilian taxes on flex-fuel vehicles are lower than those on petrol-powered vehicles and ethanol also benefits from a favorable tax treatment at the pump relative to petrol.

The Common External Tariff of Mercosur (an economic and political agreement between Argentina, Brazil, Paraguay and Uruguay) also protects Brazilian domestic biofuel production with ethanol duties of 20% and biodiesel duties of 14%. These tariffs could be eliminated or significantly reduced under the Doha and/or the EU-Mercosur trade negotiations. There are no non-tariff barriers constraining Brazilian imports of biofuels (e.g. there is no tariff-rate quota on biofuels in Mercosur).

Further important explanatory factor in the growth of the ethanol sector in Brazil is the role of foreign investment with recent investments coming especially from Europe and the United States. The investments include not only ethanol distillation plants but also sugarcane production. The low prices of raw materials and the high technological level of the whole production process leads to lower costs for ethanol production in Brazil and it also provides the motivation for international investors.

4.2 United States

Similarly to Brazil, the US biofuel policies were initiated already in 1970. The policies were motivated by numerous interests including the desire to reduce dependence on imported fossil fuels, to reduce greenhouse gas (GHG) emissions, and to increase demand for domestic farm commodities serving as a raw material for biofuels. The US fiscal incentives and mandates vary from state to state and they are complemented by those at the federal level. The Energy Tax Act of 1978 introduced tax exemptions and subsidies for the blending of ethanol in gasoline. The biodiesel subsidies are more recent and were introduced with the Conservation Reauthorization Act in 1998 .

Mandates on biofuels consumption were initiated under the federal Energy Policy Act of 2005. Under this Act, the objective of purchasing 4 billion gallons of biofuels in 2006 and 7.5 billion gallons in 2012 was declared. From the beginning of the Energy Policy Act of 2005, the US biofuel targets were specified as mandates in volumetric terms as a part of the Renewable Fuel Standard (RFS) program. The Energy Independence and Security Act of 2007 expanded the RFS program by adding a biodiesel mandate and it also expanded the total mandated quantity of renewable fuel to be blended into transport fuel to 9 billion gallons in 2008, growing to 36 billion gallons in 2022. Of the total 2022 mandate (36 billion gallons), at least 21 billion gallons have to be the advanced second or higher generation biofuels, while the conventional first generation grain-based ethanol cannot be more than 15 billion gallons. The 2022 mandate for biodiesel is 1 billion gallons.

The current US biofuel policies consist of three main instruments – output-connected measures, support for input factors and consumption subsidies. Tariffs and mandates benefit biofuel producers through direct or indirect price support. While the mandates are indirect subsidies and do not provide direct price support, the tax credits serve as the largest direct subsidies. Tariffs on ethanol (24% in ad-valorem equivalent) are much higher than on biodiesel (1% in ad-valorem equivalent). This difference in tariff treatment limits imports of ethanol, especially from Brazil. Ethanol producers significantly benefit from tax credits based on biofuel blended into fuels.

Fuel consumers benefit from the blender's tax credit as well – in the form of a lower fuel price – when the tax credit is combined with a binding blend or consumption mandate. Fuel consumers do not benefit, however, when the tax credit is the only binding policy. In this case, the consumer fuel price does not depend on the level of the tax credit, as shown by de Gorter and Just (2008).

The Volumetric Ethanol Excise Tax Credit and the Volumetric Biodiesel Excise Tax Credit provide the largest subsidies to biofuels, while there are some smaller additional subsidies connected to biofuel outputs both on the states and federal levels.

4.3 European Union

The EU biofuels policy was designed primarily in order to meet obligations made under the commitment to the Kyoto targets of GHG emissions and to meet a pressure from the EU population to address environmental issues. The policy is implemented by the EU Energy Directorate with a little regard for the impact on the EU farmers, as it was understood from the beginning that the majority of either the fuel or the feedstock for the production would be imported. Similarly to the EU energy policy (Jenicek and Krepl, 2009), the EU biofuels policy is not captured in a single document but in a number of documents issued by different parts of the EU governance structure.

In 2003, the EU introduced Biofuels Directive 2003/30, which set a target of 2% of biofuels to be used in the transport sector by 2005 and 5.75% by 2010 at the EU level. The target of 2% by 2005 was not achieved since the share of biofuels in fuel consumption amounted to 1.06% in the EU-27 in 2005, and it was 2.6% in 2007. Only Germany and Sweden exceeded the 2005 target with 3.86% and 2.11% of biofuels use in total fuel consumption, respectively.

In 2009, the EU Renewable Energy Directive (2009/29) established a ”20-20-20 Policy” for the post Kyoto period beyond 2012, which includes the targets on the biofuel consumption. Under this ”20-20-20 Policy”, the share of renewable energy in the total EU energy consumption is set at 20% by 2020. This includes 10% share in the transport sector of each EU Member Country. The other part of ”20-20-20 Policy”' are the reduction of GHG emissions by 20% from the 1990 level and the 20% reduction of total energy consumption in the EU-27 by 2020.

The EU trade policies also affect the domestic biofuel production and reduce production incentives and export opportunities for foreign biofuel producers (e.g. the US, Brazil, Indonesia, Malaysia, etc.) The most-favored-nation duty for biodiesel is 6.5%, while the ethanol tariff barriers are higher on the level of EUR 19.2/hectoliter for the HS6 code 220710 (undenatured ethyl alcohol) and EUR 10.2/hectoliter for the HS6 code 220720 (denatured ethyl alcohol). Even if tariffs for biodiesel were to be reduced, trade would still have to face more restrictive non-tariff barriers in the form of quality and environmental standards, which already mostly affect exporters of developing countries. Some countries already benefit from a duty-free access to the EU market for biofuel under the Everything But Arms Initiative, the Cotonou Agreement, the Euro-Med Agreements and the Generalized System of Preferences Plus (GSP+). Many ethanol exporters, such as Guatemala, South Africa and Zimbabwe, use this free access opportunity. However, most ethanol imports have come from Brazil and Pakistan under the ordinary European GSP without any preference for either since 2006.

The support for bioenergy in the EU was also incorporated into the Common Agricultural Policy (CAP) in 1992. An example of this policy is an introduction of energy-crop-premium of EUR 45/ha on a maximum of 2 million ha of set-aside land. As a part of 2007 reform of CAP, the energy-crop premium and the compulsory set-aside have been abolished from 2009 onwards. As a result of this change, no support for bioenergy production is included in the first pillar of CAP. However, within the Rural Development policy, which constitutes the second pillar of CAP, and through the modulation instrument, several measures supporting bioenergy development have been reinforced. These are biogas production, support for perennial energy crops, processing of agricultural and forest biomass for renewable energy, and investment in the infrastructure for renewable energy using biomass.

A detailed description of the EU biofuel support mechanisms is provided on the example of the Czech rapeseed production and biofuel processing by Souckova (2006). The author discusses the evolution of the Czech National Program of the Efficient Energy Use and the Renewable and Secondary Resources Utilization since its inception in the early nineties. She also describes Czech biofuel-related institutions, regulations and production capacities together with the corresponding EU facts and figures.

5 Environmental and Economic Impacts of Biofuels

The biofuels production and consumption is closely interrelated with a number of environmental, social, and economic issues (Zilberman et al., forthcoming). These issues are very relevant for technological development, market viability and government policies related to biofuels. Both popular and scientific assessments of the role of biofuels in sustainable development range from very pessimistic to very optimistic. The prevailing opinion is that impacts of the current first generation biofuels may be quite controversial but that many of the problematic issues may be solved with the commercial introduction of the second and higher generations of biofuels. In the following subsections, we briefly introduce major issues connected to the question of a sustainable development of biofuels.

5.1 Environmental Impacts

5.1.1 Greenhouse Gas Related Impacts

Since the reduction of greenhouse gas (GHG) was one of the major incentives for government public policies supporting the wider use of biofuels, the evaluation of GHG emissions and carbon stock change is a primary question to ask when discussing the contribution of biofuels to sustainable development. The literature review by Timilsina and Shrestha (2010) shows that most studies conclude that biofuels provide some GHG emission reduction relative to fossil fuels when GHG emissions from a direct or an indirect land use changes caused by biofuel feedstock production are excluded.

The most widely used technique for determination of energy balance and related environmental aspects of biofuels is a Life Cycle Assessment (LCA) approach. This technique aggregates the material (quantity of fuel, electricity, water, chemicals, pollutants etc.) and the embodied energy flow associated with the production or consumption of a particular commodity. In the case of fuels, LCA looks at the whole system of the fuel production and consumption beginning with farming, followed by harvesting, processing, distribution, end use and waste disposal.

The term LCA generally means supply-chain focused LCA, i.e. the one that does not consider an indirect effect although some types of indirect effects are included in an Economic Input Output LCA (EIOLCA) approach. Another type of LCA studies are policy-focused LCA which use computable general equilibrium modeling. These policy-focused LCA deal with estimation of impact of mandates and other economic policies.

The review of LCA studies provided by Rajagopal and Zilberman (2007) shows that the life cycle of ethanol and sugarcane has been the most widely studied. Ethanol from sugarcane offers the highest energy and carbon dioxide benefits, followed by cassava. Ethanol from corn provides much lower energy and environmental benefits. Important factors in the LCA of biofuels are the environmental values of crop rotation, intercropping and the utilization of co-products. Important co-product is electricity production, which is developed especially in Brazil, in some cases as a part of electricity grid, in some cases as an isolated electricity production in sugarcane processing plants which are located in remote places without access to electricity grid. Since there are multiple options for producing energy from the biomass, LCA studies are sensitive to approach they take in differencing the reduction in emissions when biomass is used both for production of gasoline and electricity. Rajagopal, Hochman, and Zilberman (2011) also show that possible problem with LCA studies is a common assumption that biofuel simply replaces an energy-equivalent amount of fossil fuel and that total fuel consumption remains unchanged.

The use of LCA for biofuels is strongly criticized by de Gorter and Just (2009c). They argue that sustainability standards based on LCA will at best be ineffective and therefore will provide little guidance to policymakers. They also argue that the use of LCA for biofuels may be misleading. Their criticism concerns LCA both with or without the inclusion of indirect land use changes.

Based on LCA, the Brazilian ethanol from sugarcane provides the greatest reduction in GHG emissions. This is due to the high yields and the use of sugarcane waste for process energy as well as for co-generation of electricity (Macedo et al., 2008). The second generation biofuels from cellulosic biomass, which may provide higher reduction in GHG emissions than the Brazilian sugarcane in the future, are the next best option (Doornbosch and Steenblik, 2007). Substantial GHG emission savings are also obtained from palm oil biodiesel. Sugar beets, wheat, sunflower, soybean and rapeseed provide a middle range GHG saving while corn is clearly the worst biofuel feedstock with respect to GHG emission. Hill et al. (2006) show that among current food-based biofuels, soybean biodiesel has much higher GHG reduction potential than corn grain ethanol. However, Liska et al. (2009) argue that the GHG reduction potential of corn could be significantly improved to the levels of sugar beets or soybeans through enhanced yield and crop management, biorefinery operation, and co-product utilization.

Cui, Lapan, Moschini and Cooper (2010) construct an open economy general equilibrium model to investigate the effects of government energy policy on the US economy, with an emphasis on the corn-based ethanol. They show that the optimal choice of the US government policies may reduce the US emissions of carbon dioxide by approximately 7 percent as compared to the current status quo. The estimated 7 percent reduction is robust with respect to the first best choice of instruments (including border policies) or the second best choice allowing only for domestic instruments (fuel tax and ethanol subsidy). Earlier study by Khana, Ando, and Taheripour (2008) already showed that the existing US policies (fuels tax and ethanol subsidy) reduce the US carbon emission by 5 percent relative to the situation without taxes.

As was pointed out by a very influential study by Searchinger et al. (2008) and by a number of other studies, the GHG saving potential of biofuels dramatically worsens when the release of carbon stored in forests or grasslands during land conversion to crop production is considered. Searchinger et al. (2008) found that as long as land use change is considered, corn-based ethanol, instead of producing a 20 percent savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years. Hertel et al. (2010) consider Searchinger et al. (2008) scenario in the framework of general equilibrium model and they conclude that the number of years required to offset GHG released from land conversion by the emission reduction through the replacement of fossil fuels with biofuels is 28 years instead of 167 years. One of the factors contributing toward currently estimated shorter period required to offset GHG related to biofuels when compared to Searchinger et al. (2008) is a gradual increase in the technological efficiency of ethanol production. The ethanol yield per unit of input feedstock increases, the processing material and energy costs are declining and the production yields of feedstock are increasing. Therefore the estimated GHG emissions are lower.

Dumortier et al. (2011) use the same CARD model as Searchinger et al. (2008) but they include some extensions of the model and they provide extensive sensitivity analysis with respect to key assumptions. Their results indicate that GHG emissions connected with biofuels are in general lower than those estimated by Searchinger et al. (2008). However, their precise values depend heavily on assumptions. Dumortier et al. (2011) argue that since the assumptions in GHG emission analysis are connected with predicting long-run human behavior, legitimate differences can be present in various assumptions of the models dealing with GHG emissions impact of biofuels.

When considering GHG effects of biofuels, the carbon leakage, where emissions reductions by an environmental policy are partially or more than offset because of market effects, have to be taken into consideration as well. Drabik, de Gorter, and Just (2010) show that the carbon leakage due to a tax credit is always greater than that of a mandate, while the combination of a mandate and subsidy generates a greater leakage than a mandate alone. Their results show that one gallon of ethanol replaces only 0.35 gallons of gasoline and not one gallon as assumed by life-cycle accounting. For the United States, this translates into one (gasoline-equivalent) gallon of ethanol emitting 1.13 times more carbon than a gallon of gasoline if indirect land use change (iLUC) is not included in the estimated emissions savings effect and 1.43 times more when iLUC is included.

5.1.2 Other Environmental Impacts

While the carbon emissions and reduction of GHG are the leading environmental considerations related to biofuels, there is a number of other environmental concerns. Change from the existing agricultural crops into a biofuel feedstock or development of new biofuel acreage may lead to increased soil erosion and deforestation. An increase of an acreage devoted to biofuels may lead to the decrease in biodiversity. The extensive production and the use of biofuels may increase the hazard of air pollution both during the growth of biofuel feedstock and during the burning of biofuel when it is actually used. All of these possible detrimental effect are very much dependent on particular geographical, climate, and technological details of any considered biofuels production, processing and utilization project. In some cases, biofuels may actually improve or be neutral with respect to any of the environmental concerns mentioned in this paragraph.

Their effect on water supplies is also a very important environmental aspect of biofuels. While an increased use of biofuels may lead to a higher demand for water resources both during the production of biofuel feedstock and during their processing, there is also a question of water pollution. Here, a danger of a small scale water pollution from biofuel feedstock may be compared with a danger of a large scale or an accident-related water pollution caused by the production of fossil fuels. While the water-pollution-related hazards of conventional oil drilling are well understood and publicized, there are also important water-pollution hazards connected with new technologies of fracking or tar sands mining. According to Glassman, Wucker, Isaacman and Champilou (2011), petroleum from the Canadian tar sands extracted via surface mining techniques can consume 20 times more water than conventional oil drilling. Hydraulic fracking, which is considered to be the most important North American energy development in recent decades according to Glassman, Wucker, Isaacman and Champilou (2011) , is a technique that pumps liquids under high pressure to create fractures in rocks that previously could not release their natural gas. This method of natural gas extraction leads to a significant pollution of local water resources in some cases.

Important environmental aspect of biofuels production is their role in the discussion of environmental and health related desirability/nondesirability of some biotechnologies, especially genetic modifications. The advances in the biofuel feedstock relevant biotechnology are an important technological factor determining a successful development of biofuel sector. Rajagopal, Sexton, Roland-Holst, and Zilberman (2007) consider a possibility that agricultural biotechnology may be used to target improvements in the photosynthetic efficiency and content of cellulose, hemi cellulose and lignin in the biofuel feedstock. They raise the idea that it may be possible to engineer plants to allocate greater quantities of carbon to stem growth as opposed to height growth and in this way to enhance biomass production. While this conceptual idea is related primarily to the second generation biofuels, the agricultural biotechnologies (especially genetic engineering) are highly relevant already for the first generation biofuel feedstock. Currently, three out of four main genetically modified crops (cotton, corn, soybeans, rapeseed) are major biofuel feedstocks. In their simulation analysis based on the econometric estimation, Sexton and Zilberman (2012) show that at the height of the 2008 global food crisis, the additional output generated by genetically engineered crops yield gains significantly mitigated price increases. They argue that already the first generation genetically engineered crops permit the intensification of agriculture, which effectively frees land for production of biofuel, or at least diminishes the demand for new cropland induced by rising food and fuel needs.

The increase of a biofuel feedstock productivity through the implementation of genetically modified crops and other biotechnologies therefore serves as a mitigating factor in the food versus fuel dilemma. While the conversion of land and other agricultural resources into the biofuel feedstock production naturally increases food prices, the increased productivity may offset this price-increase pressure. Successful biotechnology provides a clear way toward increased productivity which may resolve food versus fuel dilemma at the level of commercial use of both the first and the second generation biofuels.

Since biofuels convert energy that was originally captured from solar energy via photosynthesis, there is an obvious possibility of comparison between biofuels and a direct use of solar energy. Reijnders and Huijbregts (2007, 2009) provide a comparison of the efficiency of solar energy conversion for automotive purposes. They show that conversion of lignocellulosic biomass into electricity to power an electric vehicle may do substantially better than the use of the most energy efficient first generation biofuel (ethanol from sugarcane) in converting solar energy to automotive power. And the conversion of solar energy into automotive power based on solar cell is even more efficient.

5.2 Social and Economic Impacts

Out of many social and economic implications of production and consumption of biofuels we very briefly address the following ones in this section. Firstly, we mention that production of biofuels has many intended and unintended consequences which complicate any welfare analysis. Then we touch on the relation of farmers and refineries in the evaluation of welfare beneficiaries of biofuels demand growth. The main part of this section is a discussion of connections between the prices of food, biofuels, and energy. This topic is further in detail elaborated in the section (6.2) which deals with economic models of price links between energy and agricultural markets. Our overview of social and economic impacts of biofuels ends with a brief list of some of these impacts and with references to some papers which deals with them in more detail.

The evaluation of social and economic impacts of biofuels is particularly complicated by a fact that production of biofuels serves only as an indirect way of achieving the primary goals of reducing dependency on the fossil fuels and a mitigation of the climate changes. As highlighted by Jaeger and Egelkraut (2011), significant increase in the production of biofuels may cause many social and economic externalities in the form of feedback effects and other unintended consequences that impose additional costs on the society.

This may be the case to which a general warning of the theory of second-best apply. According to this theory, the government interventions to correct market failure may actually reduce welfare because other optimality conditions do not hold.

While it may be argued that main beneficiaries of the biofuel demand growth should be farmers because of higher prices of corn and other biofuel feedstock, Hochman, Sexton and Zilberman (2008) provide reference to the argument that the distribution of biofuel policy benefits accrue largely to ethanol refinery owners. However, Hochman, Sexton and Zilberman (2008) also show that the biofuels refineries are inherently risky business. They show that it may become unprofitable to operate the bio-refineries when negative supply shocks are present. Firms locked into long-term contracts to supply biofuel may operate with losses while other firms may exit. Food price variability also suggests that the biofuel industry may experience cycles of boom and bust, with investment in capacity during periods of low crop prices and high energy prices and loss of capacity when crop prices are high and energy prices are low. If this price uncertainty is ignored by the biofuel industry, then the bio-refinery capacity may exceed the socially optimal size during booms and demand costly corrections in the times of bust.

The weak link in biofuel production is frequently the conversion from the feedstock to the final product. There is evidence of significant reduction in costs associated with learning by doing in refineries. Processing costs of sugarcane ethanol (including capital costs) have declined by 70% since 1975 while processing costs of corn ethanol declined by 49% since 1983 (Hettinga et al., 2009). These reductions of processing costs combined with expected increased yields of both sugarcane and corn ethanol will contribute to their economic feasibility especially under high fuel prices.

The social and economic impacts of biofuels are complicated by a connection of biofuels with both energy and food markets. Rajagopal et al. (2007) provide a discussion of interconnection between biofuels and the prices of both energy and food (especially corn). Their analysis of the US corn ethanol suggests that the impact of producing biofuels from food crops will be greater on food prices than energy prices. Hochman, Rajagopal, and Zilberman (2010) show that the introduction of biofuels reduced global fossil fuel consumption and international fuel prices by about 1% and 2%, respectively. While this result is based on 2007 data, they also show that a 20% increase in fuel demand more than doubles the impact of biofuels on fuel markets.

The importance of understanding the behavior and volatility of global food prices was highlighted by sharp changes in the global food commodity prices before, during and after 2008 food crisis (Onour and Sergi, 2011).

This food crisis inspired a number of studies concerned with the sources of this crisis (Carter, Rausser, and Smith, 2011), including a possible impact of biofuels. Hochman, Rajagopal, Timilsina, and Zilberman (2011) use an empirically estimated storage demand function incorporated into a partial equilibrium framework to simulate the effect of different types of shocks on crop prices. Their simulations show that growth in food demand and biofuel demand were both major contributors to demand growth for corn and soybean. In their paper concentrated on corn and soy markets, Rajagopal et al. (2009) show that on average, the introduction of biofuels was responsible for one quarter of food price inflation in 2007 and 2008. According to Baier et al. (2009), the worldwide biofuel production growth over the two years ending June 2008 accounts for approximately 12 percent of the rise in the IMF's food price index. More detailed overview of the literature dealing with impact of increased biofuel production on food prices is provided by Timilsina and Shrestha (2010).

One of the major forces through which the biofuels may contribute to the increase of the food prices is the diversion of land use from food-crops production to the production of biofuel feedstock. The comparison of historical trends in land use with the modeling results is provided by Rajagopal and Zilberman (2011). Their analysis of historical data of the US corn shows that for brief periods of up to 3 year acreage expansion could occur at the high rates predicted by several model-based studies. In the long-run, a net expansion is likely to be smaller than such model predictions.

While responsible and sustainable development of biofuels may contribute to poverty reduction in many developing countries and to improve rural development over the world, there are still many social and economic concerns connected with the growing biofuel sector. Lora et al. (2010) highlight connections between biofuels and working conditions, rural development and the impact of biofuel production on communities. Solomon (2010) adds the problems of small-scale financing, employment generation and health and gender implications to this list.

6 Economic Models of the Impact of Biofuels

In this discussion, we leave aside purely theoretical models like the one by Hochman, Rajagopal, and Zilberman (2010, 2011), modeling influence of biofuels on OPEC, or the primarily theoretical models allowing for numerical examples (Hochman, Sexton, and Zilberman, 2008). We concentrate on quantitative models working with empirical data.

A variety of economic modeling techniques are used to model the impact of biofuels from different points of view. Basic distinction may be made between structural and reduced form models. Structural models are based on economic theory complemented with some technological assumptions. Reduced form models are usually concerned only with statistical properties of time series and do not take the economic or technological factors which generated those time series explicitly into account.

6.1 Structural Models

Conceptually most simple type of structural models are engineering-like cost accounting models which are used to estimate profitability of an activity for a single price-taking agent, such as an individual farmer or a processor. The production function in such models is typically assumed as a fixed-proportion one. Classical representatives of this class of models are crop budget models which have been used to estimate profitability of cultivation of energy crops based on assumptions about yield, output prices, cost of production and other technological and economic parameters. An example of this approach is provided by Khanna, Dhungana, and Clifton-Brown (2008) who 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.

More theory-based economic studies, which evaluate the impact of biofuels, are based on partial equilibrium or computable general equilibrium (CGE). These models explain the interaction among supply, demand, and prices through the market clearance using a system of equilibrium equations. Detailed taxonomy of these models and their results with respect to economics of biofuels is provided by Rajagopal and Zilberman (2007), who provide a comprehensive overview of the biofuels related models, Al-Riffai, Dimaranan, and Laborde (2010b), who concentrate on modeling of biofuel mandates impacts, and Nassar et al. (2011), who are interested in modeling relations between biofuels and land-use changes. A recent survey of CGE modeling of biofuels was provided by Kretschmer and Peterson (2010) who give an overview of existing approaches, critically assess their respective power and discuss the advantages of CGE models compared to partial equilibrium models.

In the partial equilibrium structural models, which are also labeled as sector models, clearance in the market of a specific good or sector is obtained under the assumption that prices and quantities in other markets remain constant. Partial equilibrium models are therefore suitable for providing good indication of short-term response to shocks. Partial equilibrium models often provide a detailed description of the specific sector of interest but do not account for the impact of expansion in that sector on other sectors of the economy. The examples of partial equilibrium models used in the assessment of the impact of biofuel development include AGLINK/COSIMO model developed by OECD and FAO, ESIM model, which was developed by the Economic Research Service of the US Department of Agriculture and which is used by the European Commission since 2001, FAPRI model of the Food and Agricultural Policy Research Institute, and the IMPACT model of the International Food Policy Research Institute.

A number of smaller partial equilibrium models is used for analysis of specific questions related to biofuels. An example of this type of models is GLOBIOM model, which is a global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors. GLOBIOM model is used by Havlik et al. (2011) to provide policy analysis of global issues concerning land use competition between the major land-based production sectors. A review of modeling energy crops in agricultural sector using partial equilibrium models is provided by Witzke et al. (2008).

CGE structural models compute equilibrium by simultaneously taking into account the linkages between all sectors in the economy. The CGE modeling framework provides an understanding of the impact of biofuels on the whole economy by taking into account all the feedback relations between biofuels and other markets. The most well known CGE studies of biofuels are based on variants of GTAP model which is under continuous development under the leadership of Thomas Hertel since 1991.

The recent applications of the GTAP model and its extensive database include Hertel and Beckman (2011), Beckman, Hertel, and Tyner (2011), and Al-Riffai, Dimaranan, and Laborde (2010a, b). Hertel and Beckman (2011) argue that while the agricultural and energy commodity prices have traditionally exhibited relatively low correlation, the recent increases in biofuel production have altered the agriculture-energy relationship in a fundamental way. This increase has drawn on corn previously sold to other uses, as well as acreage devoted to other crops. They estimate that, in the presence of the binding US Renewable Fuels Standard, the inherent volatility in the US coarse grains market will rise by about one-quarter. They also estimate that the volatility of the US coarse grains price will rise by nearly one-half due to supply side shocks in that market. Al-Riffai, Dimaranan and Laborde (2010a, b) use the GTAP database in their modification of MIRAGE model, which allows for substitutability between different sources of energy, including biofuels. They investigate the impacts of the U.S. and the EU biofuel policies and their model simulations show that the effect of the EU biofuels policies on food prices and on incomes will remain quite limited. Beckman, Hertel, and Tyner (2011) address often raised issue of CGE models of biofuels not being sufficiently validated. This happens because key parameters are often not econometrically estimated and the performance of the CGE model is not sufficiently checked against historical outcomes.

The major disadvantage of CGE approach to modeling biofuels is that global CGE models are much stronger in a treatment of the developed countries than in the treatment of the developing countries. In the case of biofuels, this is a serious deficiency since the developing countries are expected to be a big supplier of biofuels in the future. They are also currently a focus of the debate about social and environmental consequences of biofuels production and of the fuel versus food discussion. Other drawbacks of CGE modeling of biofuels are outlined by Rajagopal and Zilberman (2007). The possibilities of combining the strength and eliminating the weaknesses of partial equilibrium and CGE models are investigated in the integrated modeling framework presented by Birur et al. (2010).

In addition to accounting, recursive mathematical programming, partial and general equilibrium models, there are also other types of models. For example, Chakravorty et al. (2011) develop a dynamic model of transportation and food demand with a number of unique features not considered previously in the literature.

6.2 Reduced Form Models

The most important representative of reduced form models dealing with the economic impact of biofuels are models of price links between energy and agricultural markets. They usually use the time series econometric approach to investigate dependencies among agricultural commodities, biofuels, and fossil fuels. Since we are not aware of any recent review of the relevant literature (as opposed to the already mentioned reviews of the structural models), we devote somehow more space to recent advances in reduced form models of dependencies between prices of biofuels and other commodities.

We start this review with Tyner (2010) who notes that, since 2006, the ethanol market has established a link between crude oil and corn prices that did not exist historically. He finds that the correlation between annual crude oil and corn prices was negative (-0.26) from 1988 to 2005; in contrast, it reached a value of 0.80 during the 2006- 2008. The corresponding correlation from September 2007 to October 2008 was 0.92. He discusses in detail economic and institutional reasons which may explain these correlations. However, Tyner (2010) does not provide any discussion how his correlations were obtained, leaving impression that he reports simple correlation coefficients among the prices time series leaving the problem of non-stationarity untouched.

In a pair of papers focusing on the co-integration of prices for oil, ethanol and feedstocks, Serra, Zilberman and co-authors study the US (Serra, Zilberman, Gil, and Goodwin, 2011) and Brazilian (Serra, Zilberman, and Gill, 2011) ethanol markets. In the case of the US, they find the existence of a long-term equilibrium relationship between these prices, with ethanol deviating from this equilibrium in the short term (they work with daily data from 2005 to 2007 in the case of the US, and weekly data in the case of Brazil). For the US, they find the prices of oil, ethanol and corn to be positively correlated as might be expected, although they also find evidence of a structural break in this relationship in 2006 when the competing fuel oxygenator (MTBE) was banned and ethanol demand surged to fill this need. The authors estimate that a 10% perturbation in corn prices boosts ethanol prices by 15%. From the other side, they find that a 10% rise in the price of oil leads to a 10% rise in ethanol, as one might expect of products that are perfect substitutes in use (perhaps an overly strong assumption in this case). In terms of temporal response time, they find that the response to corn prices is much quicker (1.25 months to full impact) than for an oil price shock (4.25 months).

In the Serra, Zilberman, and Gil (2011) study of the Brazilian market, sugarcane is the relevant feedstock. The authors build on the long-run price parity relationships between ethanol and oil, on the one hand (substitution in use), and ethanol and refined sugar on the other (substitution in production). They find that sugar and oil prices are exogenously determined and focus their attention on the response of ethanol prices to changes in these two exogenous drivers. The authors conclude that ethanol prices respond relatively quickly to sugar price changes, but more slowly to oil prices. A shift in either of these prices has a very short-run impact on ethanol price volatility as well. Within one year, most of the adjustment to long-run equilibrium in both markets has occurred. However, it takes nearly two years for the full effect of an oil price shock to be reflected in ethanol prices. So overall, these commodity markets are not as quick to regain long-run equilibrium as those in the US, based on the results in these two studies. The authors do not find evidence of ethanol prices or oil prices affecting long run sugar prices over the period of their analysis (July 2000-February 2008). These results are confirmed by semi-parametric approach of Serra (forthcoming).

Zhang et al. (2008) apply portfolio theory of Markowitz to the investigation of vehicle-fuel prices and volatility using 1998-2007 data for the Brazilian ethanol, the US gasoline and the US ethanol. Similar approach to the US data was recently used by Bailis, Koebl, and Sanders (2011), who investigate the possibilities of reducing fuel volatility by adding biofuels to the fuel portfolio.

Zhang et al. (2009) investigate volatility in ethanol and commodity prices using cointegration, vector error correction model (VECM), and multivariate generalized autoregressive conditional heteroskedasticity (MGARCH) models. Their data set includes weekly wholesale price series for the US ethanol, corn, soybean, gasoline, and oil, from the last week of March 1989 through the first week of December 2007. Their results indicate that in the period up to the end of the year 2007 there were no long-run relations among fuel (ethanol, oil and gasoline) prices and agricultural commodity (corn and soybean) prices.

Zhang et al. (2010) use prices of fuels and agricultural commodities in order to investigate the cointegration of these prices simultaneously with their multivariate short-run interactions. They employ cointegration estimation and vector error corrections model with Granger-type causality tests on price data for the agricultural commodities (corn, rice, soybeans, sugar, and wheat) along with energy prices for ethanol, gasoline, and oil from March 1989 through July 2008. Their results indicate no direct long-run price relations between fuel and agricultural commodity prices, and limited if any direct short-run relationships.

Du, Yu, and Hayes (2011) investigate the spillover of crude oil price volatility to agricultural markets (specifically corn and wheat). In their paper, stochastic volatility models are applied to weekly crude oil, corn, and wheat futures prices from November 1998 to January 2009. Their model parameters are estimated using Bayesian Markov Chain Monte Carlo methods. They find that the spillover effects are not statistically significant from zero over the period from November 1998 to October 2006. However, when they look at the period October 2006 – January 2009, the results indicate significant volatility spillover from the crude oil market to the corn market.

Similar results were obtained by Wu, Guan, and Myers (2011). Using a volatility spillover model, they find evidence of significant spillovers from crude oil prices to US corn cash and futures prices. Similarly to Du, Yu, and Hayes (2011) they show that these spillover effects are time-varying. Their results reveal that corn markets have become much more connected to crude oil markets after the introduction of the Energy Policy Act of 2005. They also show that when the ethanol–gasoline consumption ratio exceeds a critical level, crude oil prices transmit positive volatility spillovers into corn prices and movements in corn prices are more energy-driven.

Another contribution to the literature on volatility spillovers between oil, feedstock and biofuel markets is provided by Trujillo-Barrera, Mallory and Garcia (2011) in their analysis of US oil, corn and ethanol prices. In order to study the volatility linkages they use a trivariate model in which exogenous shocks from the oil market are transmitted to the corn and ethanol markets. Because corn and ethanol markets interact they allow for volatility spillovers between them. For the estimation Trujillo-Barrera, Mallory and Garcia (2011) follow a two-stage procedure. In the first stage, they estimate a vector error correction model (VECM) of the cointegrated corn and ethanol prices. In the second stage, they use the residuals from the VECM, to model ethanol and corn volatilities in a Multivariate Generalized Autoregressive Conditional Heteroskedasticity (MGARCH) framework jointly with the exogenous random shock from the crude oil market. Their results suggest that spillovers from crude oil to corn and ethanol markets are similar in magnitude over time, and are particularly significant during periods of high turbulence in the crude oil market. They show that volatility spillovers between corn and ethanol also exist, but primarily from the corn to ethanol market. Their results suggest that corn and ethanol are becoming more closely connected as measured by the changes in their conditional correlations, by the cointegrating relationship, and by systematic nature of the volatility spillovers from the crude oil market.

Chang and Su (2010) use the bivariate EGARCH model to investigate relation between prices of corn, soybean and crude oil. They use daily data of corn and soybean futures traded on the Chicago Board of Trade and of WTI crude oil futures traded on New York Mercantile Exchange from January 2000 to July 2008. They find out that the price spillover effects from crude oil futures to corn and soybean futures are insignificant during the lower crude oil price period but are positively significant during the higher crude oil price period.

The interdependencies in the bioethanol price system were recently extensively analyzed in a series of papers by Rajcaniova and her coauthors. Rajcaniova et al. (2011) investigate relationship among the German, the US, and Brazil bioethanol prices. Their impulse response function analysis shows that the impact of bioethanol price change in one country has only a small impact on bioethanol prices in other countries. Rajcaniova and Pokrivcak (2011b) are interested in the relationship between fuel prices of oil, gasoline, bioethanol and prices of food (corn, wheat, sugar) serving as bioethanol feedstock. They do not find any cointegration in the period January 2005 – July 2008, while they find cointegration among majority of their price time series for more recent time period August 2008 – August 2010. Rajcaniova and Pokrivcak (2011a) investigate the relationship among the prices of ethanol, gasoline and crude oil in a vector autoregression and impulse response function framework. Their results confirm the usual finding in the literature that the impact of oil price shock on transport fuels is considerable larger than vice versa.

The interaction between prices of crude oil, US gasoline and US ethanol in investigated in a joint structural vector auto regression (VAR) model by

McPhail (forthcoming). His structural VAR model allows to decompose price and quantity data into demand and supply shocks. Since the US ethanol demand is driven mainly by government support through blending mandates and tax credits, he assumes that ethanol demand reflects primarily changes in government policy. As opposed to policy driven demand, ethanol supply shocks are determined by changes in feedstock prices. McPhail (forthcoming) shows that policy-driven ethanol demand expansion leads to statistically significant decrease in real crude oil prices and US gasoline prices. He also shows that ethanol supply expansion does not have a statistically significant influence on real oil prices.

Peri and Baldi (2010) apply threshold cointegration approach to investigate the presence of asymmetric dynamic adjusting processes between the prices of rapeseed oil, sunflower oil, and soybean oil, and the price of a diesel. Their results suggest a two-regime threshold cointegration model only for the rapeseed oil–diesel price pair. Thus, the rapeseed oil price adjusts rapidly to its long-run equilibrium, determined by fossil diesel prices, but this adjustment is asymmetric: it differs if the divergence between the two prices is above or below a critical threshold.

The analysis of Peri and Baldi (2010) was extended by Ziegelback and Kastner (2011), who investigate the relationship between the futures prices of European rapeseed and heating oil. They use 2005-2010 daily data to show the asymmetry in price movements. The results of their three-regime threshold cointegration model are similar to the results of Peri and Baldi (2010).

Related paper by Busse, Brummer, and Ihle (2010) deals with the connections between prices of rapeseed oil, soy oil, biodiesel and crude oil during the rapid growth of the German biodiesel demand since 2002 until its decline in 2009. Due to the numerous changes in the market they use a regime-dependent Markov-switching vector error correction model. Their results indicate that regimes with differing error-correction behavior govern the transmission process among the various considered prices. They found an evidence for a strong impact of crude oil price on German biodiesel prices, and of biodiesel prices on rapeseed oil prices. However, in both cases, the price adjustment behavior was found to be regime dependent,

While the time series models discussed in the previous paragraphs were pure reduced form models presented without any connections to economic models of relevant markets, there also exists a growing literature of cointegration time series models explicitly connected with structural market models. Ciaian and Kancs (2011) and Rajcaniova, Drabik, and Ciaian (2011) build their analysis of time series of biofuels, fuels, and feedstock on the extension of the market modeling introduced in a couple of papers by de Gorter and Just (2009a, b) who are dealing with welfare implications of alternative biofuels supports through mandates or subsidies.

Highly innovative approach to characterizing relationship between prices of fossil fuels, biofuels and related agricultural commodities is undertaken by Kristoufek, Janda, and Zilberman (2011), who utilize the methods of minimal spanning trees and hierarchical trees. These relatively recent methods are being used primarily in econophysics literature to uncover the most important connections in the network of assets. Kristoufek, Janda, and Zilberman (2011) are the first to apply these approaches to biofuels network. They find that in short-run the connections between prices in the biofuels network are rather week. However in the medium and long run the network of biofuel feedstocks, biofuels and fossil fuels obtains a well-defined structure. The system splits into two well-separated branches – a fuels part and a food part. Biodiesel tends to the fuels branch and ethanol to the food branch of the network.

7 Conclusions

Biofuels are steadily gaining recognition as an important part of agricultural and energy sectors. They are still in early stages of technological development. The major technological challenges facing biofuels are a cost-efficient commercialization of the second generation biofuels and a successful development and adoption of biotechnologies (especially genetically modified crops) for both the first and the second generation biofuels. While the expected graduation of the first generation biofuels to the second and further generations may alleviate current debates about the use of basic food crops like sugarcane, corn or oilseeds for non-food purposes of the biofuels generations, the ultimate questions of the use of land and other scarce resources will still remain relevant. The patterns of land use for biofuel feedstocks will be influenced by policy concerns and by advances in production technologies and in increased understanding of environmental impacts of biofuels production and consumption.

Current economic policy debate about biofuels is very much concerned with a discussion of optimal economic instruments and regulation related to biofuels (mandates, taxes, subsidies). But an ultimate success or failure of biofuels will be determined by their technological and environmental properties and production, distribution and environmental management costs of biofuels as compared to the other energy sources. While the technological properties and environmental management costs of conventional energy sources are relatively well understood, there are new energy developments like extraction of oil from Canadian tar sands or hydraulic fracking which, on one hand, provide new supplies of oil or gas but, on the other hand, may require very large cost of their complex environmental management. Similarly, the cost of the government mandated biofuels supports should be compared to government involvement in conventional oil drilling, for example the US government subsidization of oil drilling in the Gulf of Mexico through not charging a royalty.

An important question for further economic research is a better understanding of the relations between prices and quantities of foods, biofuels and fossil fuels. The economic quantitative analysis of these relations may be undertaken through structural models, which explicitly model underlying economic, technological and behavioral processes, or through reduced form models which concentrate directly on statistical evidence provided by time series of relevant prices. While the structural models are clearly suitable for comparative statics analysis and investigation of the impact of parameter changes, the reduced form models are promising tools for providing the connection to financial market analysis and for investigation of fluctuation and statistical dependences in prices of biofuels and related commodities.

The economic research of biofuels made an important progress in the development of basic theoretical models of biofuel markets, in the integration of biofuels into CGE models and in the direction of more sophisticated reduced form modeling of price series of biofuels and related commodities. Despite this progress, the understanding of the economics of biofuels is still hampered by a lack of good models of food and fuel security as well as by a lack of appropriate models of political economy issues related to biofuels.

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