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Integrating Bioenergy into Computable General Equilibrium Models – A Survey*

Bettina Kretschmer and Sonja Peterson

Abstract: In the past years biofuels have received increased attention since they were believed to contribute to rural development, energy security and to fight global warming. It became also clear, though, that bioenergy cannot be evaluated independently of the rest of the economy and that national and international feedback effects are important. Computable general equilibrium (CGE) models have been widely employed in order to study the effects of international climate policies. The main characteristic of these models is their encompassing scope: Global models cover the whole world economy disaggregated into regions and countries as well as diverse sectors of economic activity. Such a modelling framework unveils direct and indirect feedback effects of certain policies or shocks across sectors and countries. CGE models are thus well suited for the study of bioenergy/biofuel policies. One can currently find various approaches in the literature of incorporating bioenergy into a CGE framework. This paper intends to give an overview of existing approaches and to critically assess their respective power. Grouping different approaches into categories and highlighting their advantages and disadvantages is important for giving a structure to this rather recent and rapidly growing research area and to provide a guidepost for future work.

Keywords: biofuels, CGE model, climate policy

JEL classification: D58, Q42, Q48, Q54

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1. Introduction

In the context of energy security and climate protection, bioenergy is ascribed high importance. Especially biofuels have received increased attention since they are able to replace fossil energy in the transport sector. They are therefore seen as a special option since the transport sector is contributing an increasing share to global carbon emissions and since other renewable energy sources usually only replace fossil fuels in the electricity sector (wind, hydro, photovoltaics) or in the provision of heat (wood pellets, geothermal energy, solar thermal energy). Currently, only Brazil is able to produce bioethanol from sugar cane at sufficiently low costs to be competitive with conventional fuels. But for the reasons just explained, bioenergy and biofuels are part of several climate and energy policy packages in several countries and supported by quotas, tax exemptions or direct production subsidies which has resulted in a growing production and consumption of biofuels worldwide. Plans to further increase the use of bioenergy are already on the table. In Europe, the “Renewable Energy Road Map” (European Commission, 2008a, 2008b) sets a target of a 20% share of renewables – including bioenergy – in total energy use in 2020 and an additional 10% minimum target for the market share of biofuels by 2020[1]. The US Energy Independence and Security Act of 2007 stipulates that by 2022, 36 billion gallons out of total transportation fuels used shall be biofuels which implies a rise of about 386% to be achieved over the whole period of 2008-2022[2]. Ethanol production in the US has even overtaken Brazilian ethanol production recently. Other countries also pursue their own policies in promoting the use and production of biofuels, among these China and India[3]. All these developments indicate a strong rise in biofuel production over the next years. Figure 1 displays projections of the Food and Agricultural Policy Research Institute (FAPRI, 2008).

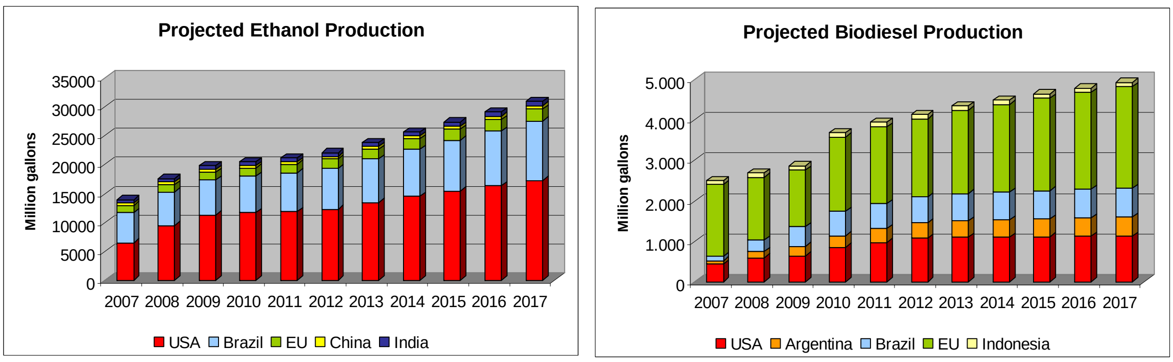

Figure 1. Projected Ethanol and Biodiesel Production, 2007-2017 (Data source: FAPRI, 2008)

1 The 10% biofuel target has been confirmed recently (Council of the European Union, 2008). Next to an envisaged obligation for biofuels imported from third countries of having to meet certain sustainability criteria in order to actually count for the fulfilment of the quota, the most recent legislative developments unveil that the binding character of the 10% quota is further subject to second-generation biofuels becoming commercially available.

2 See USDOE, Energy Efficiency and Renewable Energy Office: http://www1.eere.energy.gov/biomass/federal_biomass.html.

3 For an overview of biofuel policies in OECD countries see OECD (2008). Koizumi and Ohga (2007) discuss the impacts of biofuel policies in Asia.

The governmental support for bioenergy has been heavily criticized especially in the context of rapidly rising food prices in 2007/2008. A heated ‘food vs. fuel’ debate has consequently emerged that reflects the fear that enhanced biofuel production may lead to enormous land use competition that would drive up agricultural product prices and ultimately food prices. It is therefore vital to get a better understanding of the economy-wide impacts of enhanced bioenergy production and especially its impact on land use competition and on agricultural and ultimately food prices.

There are thus two essential dimensions that the study of bioenergy has to take into account: Biofuels should be studied from an international perspective given the hype surrounding biofuels worldwide and the likely reliance on imports for fulfilling mandatory biofuel quotas. Furthermore, one has to analyse economy-wide effects as suggested by the impacts ofbiofuel production on the agricultural and food sectors but also on other sectors of the economy, e.g. on the energy sector to name only one.

Computable general equilibrium (CGE) models have been widely employed in order to study the effects of international climate policies. The main characteristic of these models is their encompassing scope: Global models cover the whole world economy disaggregated into regions and countries as well as diverse sectors of economic activity. Such a modelling framework unveils direct and indirect feedback effects of certain policies or shocks across sectors and countries. CGE models are thus well suited for the study of bioenergy/biofuel policies.

The data base of CGE models are so-called social accounting matrices (SAMs). A SAM is a balanced matrix that summarizes all economic transactions taking place between different actors of the economy in a given period, e.g. one year. Economic transactions are represented in value terms and the SAM is balanced in the sense that the value of, for instance, a production sector’s output equals the value of its inputs, although SAMs can be much more detailed than that including taxes, subsidies, transfer payments etc. It is assumed that a SAM of a certain year represents an equilibrium of the economy and the model is calibrated in such a way that the SAM is a result of the optimizing behaviour of firms and consumers in the model. SAMs are only available with some delay. Since global models require consistent SAMs for all model regions, which are very time consuming and difficult to generate, basically all global models are based on the GTAP data base. The Global Trade Analysis Project (GTAP) provides every few years new consistent international SAMs. The most recent data base GTAP7 was published in October 2008 (Narayanan & Walmsley, 2008). It is based on input-output and trade data for the year 2004, but currently most models still run on GTAP6 with 2001 as a base year. GTAP6 covers 87 countries and world regions and 57 sectors. The problem is that there was only very little production of bioenergy until recently and that the SAMs used for the calibration of existing models thus give little information on the production and trade patterns of bioenergy that begin to emerge today. In addition, even if some production and trade existed in the base year, it is not shown explicitly in the SAMs, but aggregated e.g. to total fuel use. Furthermore, current bioenergy production is mainly the result of a variety of different governmental support measures that are also - at least not explicitly - included in the SAMs yet. Future production and trade patterns are likely to look very different from today's patterns and depend very much on policy assumptions. Finally, there is generally a lack of consistent production and trade data for bioenergy and biofuels.

Summarized, the general modelling challenge for bioenergy is that on the one side, bioenergy is not a production sector that is included in the base year SAMs of CGE models, so that it cannot be calibrated in the usual way. On the other side, it is also not a pure future technology but one has to account for the production and trade patterns that exist today as a result of governmental support. One can currently find various approaches in the literature to overcome these difficulties and to incorporate bioenergy into a CGE framework. This paper intends to give an overview of existing approaches and to critically assess their respective power. Grouping different approaches into categories and highlighting their advantages and disadvantages is important for giving a structure to this rather recent and rapidly growing research area and to provide a guidepost for future work.

The first type of modelling approach that we distinguish is a rather ad-hoc approach that avoids an explicit modelling of bioenergy production technologies but instead prescribes the amount of biomass necessary for achieving a certain production level (that would for instance comply with a biofuel policy target). We thus call this approach "implicit approach". A second category of models includes biofuel production with the help of so-called latent technologies. These are production technologies that are existent but not active in the base year of the model and that can become active at a later stage or in counterfactual scenarios. The third approach intends to actually disaggregate bioenergy production sectors directly from a social accounting matrix (SAM), the underlying data structure of CGE models. The next three sections present models that are grouped into these three categories. Section 5 then focuses on the way land is incorporated into the models. Section 6 concludes.

2. Implicit modelling of bioenergy

A first CGE application presented here is the study by Dixon, Osborne and Rimmer (2007) that use the dynamic CGE model USAGE that represents the US economy in order to study the effects of partially replacing crude oil inputs by biomass inputs in the refining industry producing motor fuels. An international dimension is thus not explicitly incorporated in this study. The benchmark results for the year 2020 are compared to results derived from a policy simulation that is characterized by a 25% replacement rate of crude oil inputs by biomass in the refining industry that is competitive at 2004 prices, specifically at a crude oil price of 40$ per barrel in 2004. In other words, the same amount of motor fuel that is produced in the benchmark scenario in 2020 using only crude oil as a resource input is produced in the policy scenario in 2020 using 25% less of crude oil and an amount of biomass to make up for it. This amount of biomass, which is derived from the feed grains industry, needs to fully replace these 25% so as to produce the same amount of motor fuels in the end. Additionally, its cost valued at 2004 prices must equal the cost of the replaced crude oil input at 2004 prices (i.e. 40$ per barrel) so that the biomass-replacement technology is competitive with purely petroleum-based refining. The underlying assumption needed to achieve identical per unit costs of the two technologies is a 33% reduction in the cost of producing biofuels relative to the cost of fossil fuels over the period 2004-2020.

The chosen approach is on the one side very elegant since it circumvents all the problems described in the last section and does not require any additional data work. On the other hand, the underlying assumptions on the development of production cost of biofuels are not motivated by any engineering studies but simply assume the cost reduction necessary to reach a 25% share of biofuels in 2020 without any government support. With this approach it is thus not possible to assess the welfare implications of governmental support for bioenergy or the optimal role of bioenergy support in the context of greenhouse gas mitigation. The only thing that this approach can show is the necessary cost development of producing bioenergy to reach a certain target without any government support and the economic implications of such a scenario. It is thus also not a real surprise that with this favourable development of bioenergy production cost Dixon et al. (2007) find that private and public consumption as well as post-tax real wages increase each by around 0.4% and that real GDP increases by 0.2%. The authors attribute these results mainly to reduced input costs in petroleum refining (brought about by increasing real crude oil prices in combination with declining real prices of feed grains in the USAGE benchmark), a world crude oil price that is 4.8% lower in the policy simulation compared to the benchmark, an increase in aggregate employment (primarily driven by increases in agricultural employment) and an increase in export prices. It is doubtful, though, whether these results would hold with higher production costs for bioenergy and necessary government support to reach the 25% quota.

Another implicit approach to model bioenergy that avoids the major problems of the Dixon et al. approach is chosen by Banse et al. (2008) who introduce biofuels to an extended version of the global GTAP-E CGE model. They specifically transform the nesting structure of the non-coal element in GTAP-E's capital-energy composite into a multi-level nesting structure with vegetable oil, oil, petroleum products and ethanol being nested into 'Fuel'.

Ethanol is produced by a nest of sugar beet/cane and cereals. In that way, biofuels are modelled as intermediate inputs to the petroleum industry and the demand for them crucially depends on their price and thus on the price of the main agricultural inputs in relation to fossil energy prices. The authors adjusted the original GTAP6 database in order to derive initial biofuel shares in the petroleum industry. This is done by keeping total national intermediate use of grain, sugar and oilseeds constant but letting its split into non-petroleum and petroleum use be determined so as to come up with the actual biofuel shares of the year 2004 and adjusting non-petroleum intermediate inputs (p.126).[4] A major contribution of their study is the inclusion of substitutability between different land types and a land supply function, which is elaborated in section five below.

[4] Unfortunately there is no further information on the procedure of adjusting the GTAP database.

For the design of policy scenarios the biofuel share can be influenced by introducing a mandatory blending requirement. This is modelled by exogenously setting the targeted blending ratio and letting the necessary subsidy needed to achieve this ratio be determined endogenously. In order to ensure the budget-neutral nature of such a policy, the subsidy has to be counter-financed, in this case by an end-user tax on petrol consumption.

The authors then compare an EU policy scenario (mandatory blending of 5.75% by 2010 and 10% by 2020) to a reference scenario which assumes no biofuel blending obligations. Under the reference scenario, real agricultural world prices actually decline and the share of biofuels in fuel consumption remains well below the EU's blending targets. Modest growth in biofuel production results from the decline in agricultural prices relative to crude oil prices that rise in absolute terms over the projection period. Declining real agricultural prices are likely a result of the considerable degree of trade liberalization as well as agricultural market liberalization assumed in the reference scenario. The policy scenario only displays slowly rising world oilseed prices (around 2% over the projection period leading to a price in 2020 that is 8% higher than in the reference), while sugar and cereal prices again decline in real terms, though to a lesser extent than in the reference situation, thus ending up at a roughly 2% and 5.5% higher level in the 2020 policy scenario, respectively (p.128). As possible explanations the authors point out that only EU biofuel policy is considered here (neglecting blending obligations in the rest of the world) and that land is endogenized so that it is potentially 'less limiting' and pushing up prices to a lesser extent since more land can be taken into production as a response to increased feedstock demand. The EU biofuel industry is characterized by a high import share in biofuel crop demand of 42% in 2020 in the reference scenario, which increases to over 50% in 2020 in the policy scenario thus raising the EU trade deficit for agricultural goods. Land use (and thus land prices) increase in all regions under the policy compared to the reference scenario though in the case of the EU this increase is in fact a smaller decrease in land use over the projection period (due to trade liberalization and the resulting high import shares of biofuel crops).

The approach by Banse et al. (2008) avoids the major problems associated with the approach of Dixon et al. (2007) and allows analysing a much larger set of policy questions, such as the effects of a subsidized blending target. Bioenergy is modelled more directly than in the Dixon approach and also the issue of imported grains for bioenergy is considered. Yet some problems remain. By modelling only the crop inputs that are needed to produce biofuels the approach only captures part of the production technology. Depending on the crop its cost share varies between 55 and 80% - the remaining costs are capital, labour and energy cost that are not accounted for in this approach. Furthermore, what we observe in reality so far is that in the case of ethanol there is hardly any trade in crop inputs but only in the end product bioethanol, which cannot be accounted for with the chosen approach. Finally, even though the adjustment of the GTAP data base is not entirely clear from the study, the approach obviously assumes that the 2004 biofuel shares are reached without any government support which is certainly not true and disturbs the results.

Both the approach of Dixon et al. (2007) and Banse et al. (2008) thus have in common that they do not include an explicit bioenergy production sector. This is realized in the studies presented in the following subsections.

3. Modelling latent technologies

Latent technologies are production technologies that are existent but not active in the base year of the model. They are mostly existing but not yet profitable since production costs exceed prices. Through changes in relative input or output prices or certain policies a latent technology can become profitable at a later stage in the modelling process or in a counterfactual scenario so that production in the latent technology sector takes off. In addition, one can choose a certain year in a dynamic model where the technology is available. The approach of latent technologies is often used in the context of carbon-free backstop technologies that are available at a certain price. The approach also fits to the market situation of biofuels at the beginning of this millennium where the technology for producing biofuels existed, but where basically no biofuels where produced yet. Modelling latent technologies requires information about the input and cost structures of the different types of biofuels to be included and the difference between production costs and prevalent (fossil fuel) prices (called mark-up). This section provides three examples of differentiated latent technology approaches to model bioenergy in CGE models that are grouped into models dealing with first-generation and those dealing with second-generation biofuels. A last subsection deals with the important issue of trade.

3.1. Modelling first-generation biofuels

The two studies presented in this section are both conducted from a European perspective and incorporate the European emissions trading scheme (ETS) while simulating the 10% EU biofuel target in their policy scenarios. Both Boeters et al. (2008) and Kretschmer et al. (2008) consider ethanol derived from sugar cane/beet, maize and wheat as well as biodiesel from vegetable oil.

The study by Boeters et al. (2008) is based on the GTAP-based CGE model WorldScan. Biofuel production cost data (derived from the Well-to-wheels report) form the basis for modelling bioenergy and are available for Brazil, the EU and the USA; technologies (as represented by the respective cost data) can be adopted by other countries or regions, whenever the needed feedstock is available domestically. The cost structures are then updated by taking into account country- and region-specific prices of the main feedstock inputs. In that way, ethanol and biodiesel production cost data for each region are derived. Technologies considered are ethanol based on sugar cane, maize and wheat as well as biodiesel from vegetable oil. In the case of ethanol the cheapest technology available in a region/country is chosen to prevail over the whole projection period. This implies that only wheat-based production is considered for the EU-27 neglecting sugar beets as a feedstock input. Biofuels and fossil fuels are assumed to be perfectly substitutable, both entering the sectors ‘road and rail transport’ (a production sector) and ‘consumer transportation’ (demand side) as inputs.

The business-as-usual (BaU) scenario replicates actual biodiesel and ethanol production over the period 2001-2004 and fixes biofuel use at its 2004 level until the end of the projection period in 2020. Against the BaU scenario the authors construct a policy baseline scenario that includes the EU ETS (excluding JI and CDM) and additional cap-and-trade systems in other Annex I countries after 2012. This policy baseline scenario is then compared to various biofuel policy scenarios applying targets of 10, 15 and 20% while allowing for full excise tax exemption versus a competitive excise on biofuels that equalizes biofuel and fossil fuel prices versus full taxation of biofuels. Boeters et al. find that across scenarios enhanced biofuel production has a more considerable impact on land rents than on agricultural and food prices. As an example, a biofuel target of 10% by 2020 with biofuels being fully exempted from excise tax leads to a 2.2% increase in arable land prices for the EU-27 as a whole while agricultural producer prices and food consumer prices increase by only 0.5% and 0.1% with respect to the policy baseline, respectively (p.14). Model attributes that are believed to contribute to these results are the inclusion of biofuel trade and of an annual yield improvement rate of 1.5% thus assuming productivity growth in the agricultural sector. The increases in arable land rents, measured as the percentage deviation in the year 2020 from the policy baseline value for the year 2020, are, however, very modest as well. The world arable land price increases by 0.5% while the EU-27 price increases by 2.2%. These 2.2% are checked for robustness in a subsequent sensitivity analysis where the authors alter the elasticity of transformation for different uses of arable land to a lower-end value of 0.5 and an upper-end value of 15, implying very high transformability (see section on modelling land below). It turns out that land rents are quite insensitive to these changes (p.36).

The DART model is a multi-sector, multi-region recursive dynamic CGE model based on the GTAP6 dataset and that is extended to include bioenergy (Kretschmer et al., 2008). Biodiesel and ethanol substitute for conventional diesel and gasoline consumption, which are part of the aggregated GTAP sector “refined oil products”, from which they were disaggregated. In order to do so, expenditure share data (net of taxes) of diesel and gasoline consumption in consumption of refined oil products, expenditure shares (net of taxes) of diesel and gasoline in refined oil product imports and excise and value added taxes on diesel, gasoline and other refined oil products in all DART regions were needed. In a similar way, corn was extracted from the sector “cereal grains neglected” as it is an important feedstock for ethanol production. Details on the disaggregation procedure including the generation of expenditure shares and on how bioenergy has been included in the DART model can be found in Kretschmer et al. (2008).

The production structure of the latent technologies is such that the various forms of bioenergy included in the DART model are produced by a value-added component of capital and labour, electric energy and a nest of domestically produced and imported intermediate inputs. Feedstock inputs can thus either be of domestic origin or imported from other regions or countries. The input factor land is included implicitly as an input to feedstock production. Production cost data for ethanol, biodiesel and biogas have been received from the meó Consulting Team that has built up considerable expertise on bioenergy industries (personal communication with meó Consulting Team, 2007). A mark-up factor of bioenergy production costs relative to the cost of energy derived from fossil sources taking into account the different energy contents of bio- versus fossil fuels is thus constructed. This mark up factor together with the presence of policies supporting the use of bioenergy crucially determine the level of bioenergy production. Biofuels are incorporated in the model as of 2005 onwards. Different to the approach in Boeters et al. ethanol and diesel can be produced from different feedstocks even within one region. At that point (and also up to now), only the Brazilian ethanol industry is able to produce profitably without policy intervention. Actual shares of Brazilian ethanol production in 2005 are reproduced by adjusting the mark-up factor. For the other countries and regions endogenous subsidies are imposed on biofuel production so as to replicate the actual shares of biodiesel and ethanol in total fuel consumption in 2005. These capture all explicit and implicit support policies that have lead to these shares such as tax exemptions and blending targets. In the biofuel reference scenario, the 2005 shares are assumed to remain constant over the projection period (until 2020). The European 10% biofuel target to be met by 2020 is simulated under differing policy assumptions in various policy scenarios. As in Boeters et al. (2008), the ETS is included in the DART model in the reference and policy scenarios. The imposition of a 10% EU biofuel quota while allowing for trade in biofuels leads to increases in world agricultural sector prices in the range of 0.3% to 1.9% compared to the biofuel reference scenario. The highest increases are found for the sectors raw milk, other grains and corn. Increases in European prices are of course much more pronounced, average EU price increases range from 0.7% to 5.2% for the agricultural sectors, the highest increases being found for raw milk, sugar beets, wheat and other grains. In contrast to Boeters et al. welfare measured in terms of equivalent variation hardly changes in the policy scenario for the EU as a whole (it increases by 0.01%).

Since the models by Boeters et al., Kretschmer et al. as well as Banse et al. run comparable policy scenarios we will briefly compare their results. All of the models include the 10% biofuel target for the EU to be reached by 2020. Comparing the different results in terms of agricultural price effects displays a rather wide spectrum. We here discuss comparative static effects, i.e. comparisons between the end-of-projection-time levels in the policy scenarios to the corresponding baseline levels, since different underlying policy assumptions render a comparison of the development over time less meaningful. The so defined world price increases found in Banse et al. (2008) are much more pronounced than in the other two studies. To sum it up, Banse et al. report increases in world oilseeds, cereals and sugar prices of 8%, 5.5% and 2%, respectively. Boeters et al. (2008) do not report effects by sector or commodity category but find overall increases in world agricultural producer and food consumer prices of mere 0.2% and 0.1%, respectively. The increases in world agricultural sector prices found in Kretschmer et al. (2008) in the range of 0.3% to 1.9% are somewhat in between the two studies but clearly closer to the more moderate price effects found by Boeters et al. Reasons for such diverging effects are of course manifold and due to differences in modelling and characteristics of scenarios. An important aspect might be the issue of trade: Since Boeters et al. and Kretschmer et al. actually have separate biofuel production sectors, the commodities produced by these sectors can be traded whereas the modelling approach of Banse et al. only allows for trade in agricultural inputs. Trade would likely lead to lower price effects, since production can take place where it is most competitive. A last point concerns the efficiency of climate policies incorporating a biofuel quota as part of their strategy. Boeters et al. come to the conclusion that EU welfare decreases in a biofuel target compared to a reference scenario both including the ETS and the 20% CO_2 reduction target by 2020. These results indicate that it might be more costly to reach the EU GHG emission reduction targets when linking them to a biofuel target. Kretschmer et al. do not find further evidence for this claim, though the extremely small increase in welfare of 0.01% found in their study does not refute it either.

The advantage of the approach by Boeters et al. and Kretschmer et al. is that bioenergy production technologies are explicitly modelled so that all relevant interlinkages between other sectors of the economies are captured. To analyse mid-term bioenergy support policies the approaches seem to fit best. Yet, some problems remain. One is to model trade in biofuels, which is difficult for the latent-technology approach and yet important in the context of quotas. This is discussed in more detail below. Another problem that remains are the existing support measures that – if at all – are only modelled indirectly in the form of an ad valorem subsidy.

3.2. Modelling second-generation biofuels

Reilly and Paltsev (2007) do not actually model first-generation biofuels, such as ethanol made out of starchy or sugar crops or biodiesel made out of vegetable oils, but instead focus on second-generation or cellulosic biofuels that can use a much broader range of feedstocks including woody crops. Their crucial advantage is that cellulosic conversion can use entire plants and that these plants can possibly also be grown on land not suited for conventional agriculture and thus food production. This would then lead to reduced competition for land and a more favourable climate balance. The study is conducted with the EPPA model, a multi-region, recursive dynamic CGE model based on the GTAP5 database. Unlike the other studies mentioned in this paper, Reilly and Paltsev (2007) look much further into the future and project the world economy into the year 2100. This very long-term perspective serves as an argument for the adoption of second-generation technologies that should dominate today's technologies over the long run. They specifically introduce two bioenergy technologies, liquid fuels and electricity derived from biomass, which produce perfect substitutes for refined oil and conventional electricity, respectively. The technologies are described by their respective input shares. Both types of bioenergy are produced using only land as a resource input and a composite of capital, labour and other (industrial) inputs. Land requirements for biofuel production are derived so as to be consistent with an IPCC projected average yield of 300 GJ/ha/year. The input factor 'land' is specified further in a follow-up study by Gurgel, Reilly and Paltsev (2007) that includes various land types and the possibility of conversion from one type to another as outlined in section three below. Mark-up factors of

2.1 and 1.4-2.0 reflect the base-year cost differentials between bio- and conventionally produced fuel and electricity, respectively (Reilly and Paltsev, 2007, p.7). The initial take-off and subsequent levels of bioenergy production then depend on bioenergy's competitiveness relative to the remaining energy technologies, which is determined by changing input prices and imposed climate policy.

Greenhouse gas stabilization scenarios of varying stringency lead to a growing importance of biomass as an energy source or more precisely of second-generation biofuel as a substitute for fossil fuel. Bioelectricity on the other hand turns out to be rather uncompetitive relative to alternative low-carbon electricity generation technologies, which is also due to the rise in land prices resulting from enhanced biofuel production that does not compete with other alternative fuels. The main result of an alternative scenario focusing on proposed US cap-and-trade legislation is that the USA would mainly import biofuels in a scenario that allows for unrestricted trade in biofuels, while strengthening its role as a net exporter of agricultural products. Prohibiting biofuel trade leads to large increases in domestic US biofuel production with the consequence of the USA becoming a large net importer of agricultural products. Gurgel et al. (2007) also report the development of global price indices for agricultural goods and find that the climate policy scenarios (characterized by enhanced bioenergy production) lead to rather modest price increases compared to the reference scenarios. Given their long-term perspective and the option of land conversion the authors conclude that large-scale cellulosic biofuel production might be possible in the long run with agricultural markets adjusting to new realities.

This approach by Reilly et al. avoids an explicit modelling of the feedstock inputs that would be needed for first-generation bioenergy production since second-generation technologies can use a much broader range of biomass all grown on the input 'land'. Also, this approach has the advantage that the technology being modelled is really a latent technology in the sense that there is not yet any production of second-generation biofuels. The authors thus do not run into the problem of calibrating a near-term path of bioenergy production that matches reality. If one believes that second-generation biofuels will become viable and that they will have a clear cost advantage over first-generation biofuels and if the aim is to analyse long-term climate policy and GHG stabilization scenarios this approach is very valid and gives relevant insights. It is not suited, though, to analyse the mid-term biofuel targets and policies of e.g. the EU and the USA, their economic consequences and abatement costs.

3.3. Incorporating biofuel trade

An important issue when it comes to fulfilling mandatory biofuel quotas is the modelling of trade, since especially the EU is believed to only be able to meet its targets by relying on imported biofuels. The fact that the latent technology approach actually models biodiesel and ethanol as distinct commodities entails the possibility of trading these commodities, which can be considered as an additional advantage of the latent technology over the implicit modelling of bioenergy. The latter approach is constrained to modelling trade in agricultural products. In reality, however, latent technology modellers are somewhat constrained by the limitations of the latent-technology approach as well as by problems arising from data (un-)availability. In order to project future trade flows, an underlying trade structure has to be included in the model at some point that provides starting values from which trade can evolve over time. If there is no trade in the calibration year, then it is impossible to see trade in any future period. One possibility to avoid this problem is to simply model bioenergy as a perfect substitute for conventional energy and not differentiate anymore between conventional and biofuel in the trade of fuels. In this case it is not possible though to model a quota of consumed (thus domestic and imported) biofuel in total fuel consumption. If one wants to explicitly model trade in biofuels, it is necessary to formulate assumptions in order to come up with a reasonable trade pattern. Boeters et al. assume that biodiesel import shares in the EU countries/regions follow observed vegetable oil import shares while ethanol import shares correspond to production levels of the main ethanol inputs limited by an assumed home bias of 80% (2008, p.34). This might be problematic due to the fact that there is hardly any trade in biodiesel today and only little trade in bioethanol. Based on observation so far and expectations about future production potentials, Kretschmer et al. (2008) only include trade in bioethanol between Brazil and the industrialized. Trade in biodiesel is only taking place between Indonesia/Malaysia and the industrialized countries and India. Reilly and Paltsev (2007) do take trade in biofuels into account and distinguish between scenarios with unrestricted trade in biofuels and others that prohibit biofuel trade. Underlying assumptions are, however, not made explicit. Gurgel et al. (2007) add the trade specification of biofuels being a homogenous good so that each country is either ex- or importing biofuels, whereas trade in agricultural and food goods is modelled according to the Armington assumption of differentiated goods.

Altogether, the modelling of latent technologies allows for a more realistic representation by actually including bioenergy production processes and thus introducing new commodities into the CGE structure that can consequently also be traded. On the downside, the breaking up of an existing modelling structure in order to include new sectors is a rather complex process, potentially rendering the model instable and increasing the computational burden. A further problem is that one naturally has to work with a broad array of assumptions given the fact that biofuels were not readily available in the base years of most models and relevant data on bioenergy production quantities, cost structures and trade flows are oftentimes insufficient. These problems could be overcome if bioenergy is already explicitly included in the underlying SAM of a model. This last approach is described in the next section.

4. Disaggregating the SAM

There are not yet available SAMs that explicitly include bioenergy production but the insufficiency of bioenergy data should be overcome during the next years due to their growing importance in terms of production volumes. The approach that is depicted in the following subsection 4.1 can be considered to be the most promising future approach. It consists of disaggregating biofuel sectors directly from the SAM, which should become increasingly feasible as more extensive and more reliable data on the growing biofuels sector become available. In 4.2 we describe first modelling approaches based on the new database.

4.1. The GTAP-BIO databases

A first effort to disaggregate bioenergy sectors from the SAM is the study by Taheripour et al. (2007) on “Introducing Liquid Biofuels into the GTAP Data Base”. They basically create four new databases: GTAP-BIO introduces three new commodities to the GTAP6 database being ethanol from coarse grains (mainly corn) named eth1, ethanol from sugarcane (eth2) and biodiesel from oilseeds (biod). Intermediate use of biofuels is added in the subsequent GTAP-BIOA database. Specifically, 75% of US eth1 household consumption are attributed to the p_c sector as an intermediate input, i.e. an additive to gasoline. The database is developed further to include by-products, in a first step DDGS as a by-product of eth1 production (GTAP-BIOB) before also adding biodiesel by-products (BDBP) such as soy and rapeseed meals (GTAP-BIOC).

Biofuels production data are derived from the IEA sources, which, however, only provide aggregate biofuel data. These data were split into ethanol and biodiesel based on IEA biodiesel production capacity reports and ethanol was split further into eth1 and eth2 in accordance with the main feedstock input used in a country. Potential future biofuel production was accounted for by introducing negligibly small production levels into the 2001 database (especially relevant for Malaysian and Indonesian biodiesel that is being produced today but where no commercial production took place in 2001). Ethanol trade figures are constructed based on IEA and additional data sources under the assumption that countries import from/ export to the nearest location. Biodiesel is assumed to be only consumed domestically (Taheripour et al., 2007). Having allocated production and trade data, the subsequent step is to split the new biofuel commodities from existing GTAP sectors. Taheripour et al. proceeded along the following lines: Eth1 is split from the food processing (ofd) sector, eth2 from the chemicals, rubber, plastics (crp) sector and biod from the vegetable and oilseeds (vol) sector (cf. pp.7-8 for further details).

4.2. Applying the GTAP-BIO databases

An application of the newly developed GTAP-BIO database can be found in Birur, Hertel and Tyner (2008). This paper provides a detailed description of the whole model set up along with offering a historical analysis for the period 2001 to 2006 in order to calibrate key parameters of the model. Biofuels are incorporated as an extension to the GTAP-E model. In order to model the production sector land in a more detailed way, the authors adopt the GTAP-AEZ framework from Lee et al. (2008), see section 4 below. They furthermore follow Keeney and Hertel (2008) in allowing for yield improvements triggered by biofuel policies and subsequently higher prices and adopt their long-run yield response to price of 0.4 (p.16).

The newly derived sectors ethanol1, ethanol2 and biodiesel are included on the consumption side and on the production side of the model. Household demand is divided into energy and non-energy commodities. Petroleum products and biofuels form a sub nest under the energy composite nest. The elasticity of substitution of this sub nest between the use of petroleum products and biofuels is deemed to be one of the crucial elasticities and is calibrated in the historical analysis of the period 2001-2006. Birur et al. (2008) thus deviate from the assumption of (nearly) perfect substitution between biofuels and fossil fuels and instead find values of 1.35, 3.95 and 1.65 for their main regions of interest Brazil, the United States and the EU, respectively. For the remaining regions, the default value of 2 is assumed to prevail. While biofuels and fossil fuels are substitutes in consumption, they are modelled as perfect complements in production. Biofuels and petroleum products are nested with an elasticity of substitution of zero and the resulting composite enters the non-coal nest, which is itself part of the nesting structure below the capital-energy composite. Modelling biofuels in such a Leontief manner on the production side allows to model the use of ethanol as a fuel oxygenate (p.10).

For the historical analysis of the years 2001-2006 three main factors are identified as the main drivers underlying the expansion in biofuel production over the period: the rise in crude oil prices, the ban of MTBE as an additive to gasoline (replaced by ethanol) and biofuel subsidies in the US and the EU. Appropriate elasticities of substitution between consumption of biofuels and fossil fuels as reported above are derived by imposing these three historically observed “shocks” and letting the model replicate observed data on biofuel use for the US, the EU and Brazil. The sectoral effects especially in the agricultural and biofuel industries from imposing the shocks within the calibrated model are then compared to the actually observed changes over 2001-2006 and it is found that they match reasonably well.

The historical analysis further serves for identifying the relative importance of the main drivers underlying the growth in biofuel production and agricultural output over the period 2001-2006. The by far most important drivers behind the expansion in US ethanol production have been rising oil prices with the ban of MTBE as an additive to gasoline being the next strongest driver. European biodiesel production was primarily boosted by tax exemptions and secondly by rising oil prices. Similarly, coarse grain production in the US is foremost influenced by rising oil prices and secondly by the MTBE ban, while biodiesel subsidies in the EU have been somewhat more influential than rising oil prices in boosting oilseed output. In Brazil, sugarcane and ethanol production have been almost exclusively driven by rising oil prices (cf. Table 6 in Birur et al., 2008, p.46). With regard to crop area, the results indicate that area is being diverted from other uses to coarse grain cultivation in the US, oilseed cultivation in the EU and sugarcane cultivation in Brazil (cf. Table 8 in Birur et al., 2008, p.48).

Another paper by Hertel, Tyner and Birur (2008) adds a forward-looking analysis for the period 2006-2015 and considers the effects of both US and EU biofuel support policies as well as their combined impact on the global economy. The respective policy targets included are 15 billion gallons of ethanol use by 2015 in the US and a 6.25% biofuels share in the EU by the same year. The policies are in turn applied individually as well as simultaneously. It is found that the effects felt in the US are largely and across sectors attributable to the domestic policy, with the exception of oilseed output that is strongly and positively influenced by the European biofuel target. The reason for this is that the EU requires large amounts of imported oilseeds to meet its targets. The EU biofuel policy also has a large impact on the Brazilian market, where oilseed output increases by 20.5% over the period considered. The US policy, on the other hand, increases sugarcane production by roughly 9% in Brazil. Concerning land use and specifically the types of crops cultivated, the largest changes are found in oilseed area and are thus a result of the EU policy while the change in sugarcane area is less dramatic. Oilseed area increases most significantly in the EU itself (by 40%) but the effect is also large in other regions and countries (the most affected single countries being Brazil and Canada with increases in oilseed area of 16% and 17%, respectively). There are also quite some effects on land cover: The EU is affected most heavily with forest and pasture land declining by 8.3% and 9.7%, respectively, while crop cover increases by 1.9%. Further important effects on land cover in terms of reduced forest and pasture area are found in the US, Brazil and Canada.

The results of Hertel et al. (2008) form a kind of reference scenario for a further application of the GTAP-BIO database. Taheripour et al. (2008) use the database GTAP-BIOB developed in Taheripour et al. (2007). The structure of the ethanol1 and the biodiesel sectors is altered so that these sectors can produce two commodities, the respective fuel and the corresponding by-products DDGS (Dried Distillers Grains with Solubles) and BDBP (soy and oilseed meals). DDGS and BDBP enter the composite input "Feed" and are thus demanded by the livestock industry. In particular, BDBP substitutes for feed derived from the food industry and DDGS for cereal grains. Both of the elasticities of substitution are chosen to be very high (125 and 30, respectively) so as to reproduce the price development over the period 2001-2006 of rapeseed meal in the EU and DDGS in the US, respectively (Taheripour et al., 2008, p.13).

The model then projects the period 2006-2015 with biofuel support policies in the EU and the US in place just as in the policy scenario of Hertel et al. (2008). The results of the two studies are consequently compared in order to asses the influence of including by-products. Highlighting some of their results: US cereal grain output rises considerably less over the period 2006-2015 when by-products are included (10.8 compared to 16.4%). Cereal grain output even falls by 3.7% for the EU while it grew by 2.5% in the absence of by-products. Prices of the main biofuel feedstocks used in the US and the EU rise to a considerably lesser extent: Cereal grain supply prices in the US grow by only 14.0% compared to 22.7% and oilseed prices in the EU increase by 56.4% compared to 62.5% in the no-by-product scenario[5]. A further remarkable difference is found in land cover changes: While the change in forest area is hardly affected by the inclusion of by-products, the decreases in pasture area over the projection period are much less pronounced in four regions considered, the US, the EU, Brazil and a region of Latin-American energy exporters.

[5] Note that the percentage changes reported here refer to changes over the whole projection period and do not reflect a comparative static comparison between reference and policy scenarios as reported in some of the previous studies.

As of now, the approach described in this section and the latent technology approach do not seem to clearly deviate from each other in terms of the precision with which biofuels are modelled. As Taheripour et al. state themselves in their conclusion, they "relied on imperfect biofuel production and trade information. These deficiencies can be removed with more research and improved data" (2007, p.11). This assessment is in line with our opinion that the future approach to be pursued will likely be the direct inclusion of biofuels in the SAM, which will prove to be superior once more data will become available.

5. Modelling land use

Cultivating bioenergy crops increases demand for arable land. Together with increasing food demand due to a growing world population this ultimately leads to land use competition. In order to represent changes in land use due to the expansion of bioenergy production, it is desirable to model the factor land and land conversion in an explicit way. This section presents some of the approaches chosen by the studies mentioned so far.

A popular way of introducing some more detail to the representation of the input factor land is via a constant elasticity of transformation (CET) framework. The idea is that land can be transformed to different uses, the ease of this transformation being represented by the elasticity of transformation. Boeters et al. (2008) choose a CET framework to include different types of arable land use. Their default value for the elasticity of transformation between different types of arable land use is two, which is altered to a lower-end value of 0.5 and an upper-end value of 15 (very high transformability) in order to assess the sensitivity of results. This sensitivity analysis shows that the results for arable land rents and economic welfare based on the default value of 2 are quite robust to changes in the elasticity of transformation. The CET structure can be rendered more complex by nesting several levels. An example for such an approach is given in Banse et al. (2008), who deviate from the GTAP assumption of uniform transformability across all types of land uses and incorporate a three-level CET nesting structure with differing land use transformability across types of land use. This approach is based on the OECD PEM model structure. A first nest distinguishes horticulture, Other crops and Field Crops/Pasture. The latter is split up further into Pasture, Sugar and Cereals/Oilseeds/Proteins, which again consist of a nest of wheat, coarse grains and oilseeds. Along this structure, the ease of transformability increases (Banse et al., 2008, p.125). The authors furthermore introduce a land supply curve in order to endogenise processes of land conversion and land abandonment. The land supply curve models the relationship between land supply and land rental rate for each region and captures the idea that increased feedstock demand will have a larger impact on rents in land-scarce countries than in land-abundant countries which influences local biofuel production costs and hence their competitiveness (p.125).

The studies by Hertel et al. (2008) and Birur et al. (2008) also deploy a CET framework; they do so, however, within the framework of the GTAP-AEZ module (see e.g. Lee et al., 2008), where AEZ stands for agro-ecological zones (AEZ). An agro-ecological zone is characterized by similar climatic and soil conditions; a total of 18 AEZs are distinguished. Within each AEZ, a two-level nested CET function determines the allocation of land among different uses. The upper nest determines the allocation into crop, pasture and forest land cover before the second nest splits up the crop cover into its different uses, i.e. various types of crops.

A different approach is chosen by Gurgel et al. (2007), which is an extension of the work done by Reilly and Paltsev (2007) who introduced cellulosic conversion technologies for producing bioenergy to the EPPA model as depicted above. Gurgel et al. do not choose the CET framework as they are interested in longer-term and hence possibly radical land use changes, which cannot be adequately represented in the CET framework. They instead introduce conversion costs that accrue when one type of land is changed into another type. Five different land types are considered in total: crop, pasture, harvested forest, natural grass and natural forest land. Each type of land is characterized by an annual exogenous productivity increase of 1%. Cropland replaces the aggregate factor land in Reilly and Paltsev (2007) as an input to bioenergy production. Since cropland is furthermore demanded by the crop sector, land use competition between these two uses arises. The latter two land types mentioned, natural grass and natural forest land, add to the representative agent's utility. The convertibility of these two land types is restricted in an alternative version of the model by including a fixed factor in the land conversion process so as to replicate historically observed conversion responses (thus assuming that these responses do not fundamentally change in the long run). The original version of the model allows for unrestricted conversion of land types given that conversion costs are covered. Not surprisingly, bioenergy production is higher in the unrestricted conversion model. Running similar greenhouse gas stabilization scenarios as in Reilly and Paltsev (2007), production under unrestricted conversion exceeds production in the restricted conversion model by 10-20%. The disaggregation into regional effects, however, shows that in some regions (Mexico and Australia/New Zealand) biofuel production is actually higher in the OLSR model specification, which is explained by high land supply elasticities and open agricultural markets (p.19). Results for global land use implications show that the most affected land types are pasture and natural forest land (in the unrestricted conversion model), while crop area is surprisingly not very sensitive to biomass expansion, a fact that is explained by relatively price inelastic food demand (p.23). This qualitative result of decreasing forest and pasture area is thus in line with the results of Hertel et al. (2008), though the very different modelling approaches and projection period lengths chosen do not allow for concrete quantitative comparisons.

6. Summary and Conclusion

The intention of this paper was to highlight various techniques of introducing bioenergy technologies into CGE modelling frameworks. We classified the various approaches into three broad categories, each characterized by its particular advantages and disadvantages as summarized in Table 1. Theoretically, the most promising approach is to directly start out with a SAM that disaggregates bioenergy activities in separate sectors. If this approach were already widely established there would be no need for discussing the various approaches as we just did. However, up till now the accuracy of the SAM approach is limited by insufficient data for the model base year (2001). The recently published database GTAP7 is calibrated to the base year 2004 thus rendering the bioenergy data scarceness somewhat less problematic due to the rapidly growing importance over the last years. Together with the GTAP-BIO database it will be likely that we will soon see further approaches of incorporating bioenergy directly into SAMs. At the same time, we believe that latent technologies will continue to play an important role in the future. Bioenergy production is developing quickly and will expand into regions that are currently not producing on a commercially relevant scale yet. These include Malaysia and Indonesia who are expected to become important biodiesel producers (and possibly also exporters), as well as Latin America and Africa. Furthermore, second-generation biofuels will in the medium to long term play an important role as well. The approach of modelling bioenergy with the help of latent technologies is very flexible to account for such new developments and also for modelling long-term scenarios. The first approach discussed above of implicitly modelling bioenergy for example by assuming a certain input share of feedstocks into refined oil production is in our opinion rather an intermediate step towards a more advanced modelling of bioenergy.

Table 1. Three approaches of modelling bioenergy

Approach	Advantages	Disadvantages	Studies
Implicit approach	Elegant approach avoiding a breaking up of the original model structure	No explicit bioenergy production sector → no commodity “biofuel” → trade in biofuels cannot be modelled	Dixon, Osborne and Rimmer (2007) Banse et al. (2008)
Latent technologies	More realistic representation of bioenergy production processes by including separate sectors Allows for including trade in biofuels Allows for including new developments (second generation biofuels; new producing countries)	Projections based on limited time series of biofuel production and trade data or even on pure assumptions Complex procedure, increase in computational burden	Boeters et al. (2008) Kretschmer et al. (2008) Reilly and Paltsev (2007) Gurgel et al. (2007)
Disaggregating the SAM	Ex-ante inclusion of bioenergy technologies in underlying database Coherence of modelling framework	Full potential is so far still restricted by data limitations Limitations to model new developments	Birur, Hertel and Tyner (2008) Hertel, Tyner and Birur (2008) Keeney and Hertel (2008)

One issue that remains especially important not only in the context of bioenergy is modelling land availability and land restrictions in a more sophisticated way. Here, models still experiment with different approaches. Some of these approaches are also used in the models with bioenergy that are described in this paper. Another approach is to couple CGE models to specific agricultural or land-use models. Examples of such an approach also exist for CGE models (e.g. Ronneberger et al., 2008). A more detailed overview about the different approaches to model land use in environment-economy models in general and in CGE models in particular can be found in van der Werf & Peterson (2007). The importance of the issue is also displayed by the fact that a whole book has been devoted to land use issues in economic modelling (Hertel, Rose and Tol, forthcoming; the introductory chapter is available as Hertel, Rose and Tol, 2008).

The results that have been cited in this paper surely highlight the need for further modelling efforts. It has been seen that models that work with different assumptions come to partly greatly diverging results, showing that the assumptions used today need to be constantly checked for their future validity. Part of the problems associated will disappear or at least become less severe over time with the gathering of more reliable data on biofuel production and trade. We believe that the challenge of future work will be to come up with models that allow for an integrated assessment of first- as well as second-generation technologies and also tackle issues surrounding land use change, which is still subject to a high degree of uncertainty.

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