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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 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 gives an overview of existing approaches, critically assesses their respective power and discusses the advantages of CGE models compared to partial equilibrium models. 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. As the transport sector is contributing an increasing share to global carbon emissions they are seen as an important mitigation option, also because other renewable energy sources usually only replace fossil fuels in the electricity (wind, hydro, photovoltaics) or in the heat sector (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. Nevertheless and for reasons just explained, bioenergy and biofuels are part of 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 on the table. In Europe, the directive on the promotion of the use of energy from renewable sources (henceforth RES directive) targets a 20% share of renewables – including bioenergy – in total energy use in 2020 and additionally imposes a 10% minimum share of renewable energy in transport (cf. Council of the European Union, 2008). Without the widespread availability of alternative renewable transport fuels, these will primarily be biofuels. A crucial element of the RES directive is that both domestically produced and imported biofuels need to meet sustainability criteria. Furthermore, the binding character of the 10% quota is subject to biofuels being produced sustainably and second-generation biofuels becoming commercially available. In 2007, the EU share of biofuels in total fuel consumption was 2.6% corresponding to an estimated combined EU ethanol and biodiesel consumption of 9.9 billion litres. Thus big efforts have to be undertaken in order to reach the 10% target in 2020, which would approximately correspond to a biofuel use of 22.8 billion litres as projected by the European Commission[1]. The 2007 US Energy Independence and Security Act (EISA) stipulates that by 2022, 36 billion gallons (ca. 136 billion litres) out of total transportation fuels used shall be biofuels. Out of that, 15 billion shall be conventional biofuels, which will mostly be corn-based ethanol, thus requiring a substantial increase from a 2008 ethanol production of 9 billion gallons. The remaining 21 billion shall be advanced biofuels, including biodiesel as well as cellulosic fuels[2]. US ethanol production has even overtaken Brazilian ethanol production recently. Other countries also pursue their own policies in promoting the use and production of biofuels, among them China and India[3]. All these developments indicate a strong rise in biofuel production over the next years. 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 emerged that reflects the fear that enhanced biofuel production may lead to enormous land use competition that would drive up agricultural product and food prices. It is therefore vital to get a better understanding of the economy-wide impacts of

[1] EurObserv'ER (2008) and European Commission (2007) for projected biofuel use in 2020 (own conversion into litres).
[2] United States. Cong. Senate. 110th Congress, EISA 2007. For ethanol statistics, see RFA (2009).
[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.

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 biofuel support policies 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 of biofuel 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 (see e.g. Springer 2003). 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 policies.

This paper focuses on different approaches to include bioenergy into CGE models, the advantages and disadvantages of these approaches and implications for future modelling work. In this course we also try to compare and explain major results of different models. Included in this paper are all major multi-region CGE models we are aware of that include bioenergy. These are in particular the models USAGE (Dixon et al., 2007), a GTAP-E version modified at LEI Institute (Banse et al., 2008), WorldScan (Boeters et al., 2008), DART (Kretschmer et al, 2008), EPPA (Reilly and Paltsev, 2007; Gurgel et al., 2007; Melillo et al., 2009) and augmented versions of GTAP (Birur et al., 2008; Hertel et al., 2008; Keeney and Hertel, 2008). Besides CGE models there are of course other types of models that are useful to study bioenergy. Indeed, many studies to-date have used partial equilibrium (PE) models (see Gerber et al., 2008) that mostly focus on the agricultural sector. It is beyond the scope of this paper and also not the aim to provide a detailed survey of modelling bioenergy in PE models. A report that goes into this direction and includes a number of PE models is by Pérez Domínguez and Müller (2008) while Gerber et al. (2008) compare the results of different models with respect to effects of biofuel policies on food prices. Yet, to make the strengths and weaknesses and the limitations of the CGE approach more transparent we also include a section on PE models and their analysis of bioenergy 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. The Global Trade Analysis Project (GTAP) provides every few years new consistent international SAMs that are used by basically all global CGE models.

The most recent data base GTAP7 was published in October 2008 (Narayanan & Walmsley, 2008) and is based on input-output and trade data for the year 2004. Currently most models still run on GTAP6 with 2001 as the base year. The problem is that there was only 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. Figure 1 shows the development of biofuel production in the major producing countries and nicely illustrates the fact that biofuel production in the USA and the EU only really took off after 2001. Brazil on the other hand already had an important ethanol industry much earlier. In addition, even if some production and trade existed in a certain 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 neither - 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 crucially on policy assumptions. Thus, there is a general lack of consistent production and trade data for bioenergy and biofuels.

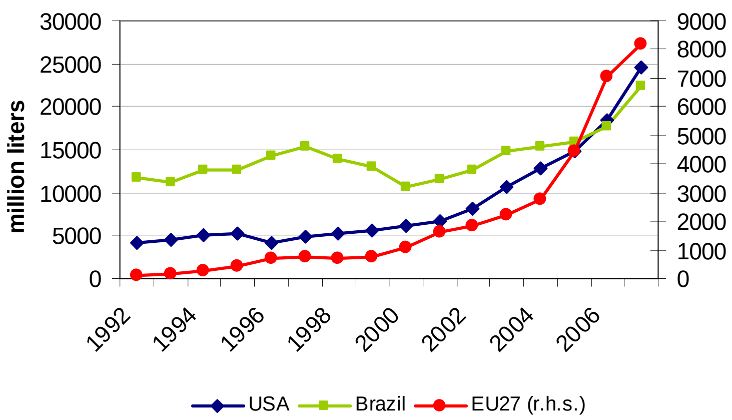

Figure 1. Historical production of ethanol in USA and Brazil and of total biofuels in EU27 (Sources: RFA, 2009; UNICA, 2009; Biofuels Platform, 2009)

Hence, the general challenge in modelling 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 paper is organized as follows: We first compare the advantages and disadvantages of general and partial equilibrium models in section 2 and discuss general modelling issues in the context of biofuels in section 3. Section 4 describes the first type of modelling approach that we distinguish, the *implicit approach*, which 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. Section 5 deals with a second category of models that include 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. Section 6 outlines the third approach that intends to actually disaggregate bioenergy production sectors directly from a social accounting matrix (SAM), the underlying data structure of CGE models. Section 7 summarizes results with respect to agricultural price effects across studies and section 8 concludes.

2. Comparing partial and general equilibrium approaches

Besides general equilibrium (GE) models the second class of models that is used to assess the implications of extended bioenergy production are partial equilibrium (PE) models that focus in most cases on the agricultural sectors[4]. The advantages and disadvantages of both model categories when analysing bioenergy are similar to those for modelling climate policy and land use in general which are discussed in van der Werf and Peterson (2009): Partial equilibrium models allow for a detailed representation of agricultural and bioenergy production and land use restrictions. Furthermore, they are able to include detailed biophysical land use characteristics even though there is some trade-off between geographic scope on the one hand, and economic, geographic and biophysical detail on the other hand. The PE models are able to simulate detailed policy proposals such as differentiated agricultural and bioenergy policies and to capture local or regional environmental and economic effects. However, these models mostly do not account for links to non-agricultural sectors and to regions or countries other than the one(s) under scrutiny. GE models are able to capture macro-economic and international feedback effects through changes in relative prices of inputs and outputs. Agricultural and bioenergy sectors are only part of a larger model and linked to the rest of the economy that uses the agricultural products for production or consumption and provides the necessary inputs to the production process. Via trade there is also a link to the rest of the world. However, the high level of sectoral and regional aggregation goes at the expense of modelling the details of agricultural and bioenergy production and land use restrictions. One major advantage of GE models is that bioenergy policies can be compared to other climate mitigation options.

Probably the best known PE models are the ones by different reputed institutes with established know-how in agricultural commodity markets (see also Gerber et al., 2008). In particular, these are the AGLINK/COSIMO model (OECD, 2006) of the Organisation for Economic Cooperation and Development (OECD) and the Food and Agricultural Organization of the United Nations (FAO), the FAPRI model (Fabiosa et al., 2008) of the Food and Agricultural Policy Research Institute and the IMPACT model (Msangi et al., 2007)

[4] Two models in the report by Pérez Domínguez and Müller (2008) are energy system models that include bioenergy technologies.

of the International Food Policy Research Institute (IFPRI). All these models are global models with a focus on agricultural markets.

The AGLINK/COSIMO model is used for the annual OECD-FAO Agricultural Outlook (e.g. OECD-FAO, 2008). One shortcoming is that it does not consider trade in biofuels. In the most recent analysis focusing on biofuels (OECD, 2008) the model is inter alia used to analyse the combined effects of current biofuel policies, including the EISA for the US and the EU RES directive as well as 2nd generation biofuels. One result is that this scenario leads to an increase in real prices for biofuel feedstocks (2013 to 2017 average) compared to a baseline without biofuel support ranging between 7 or 8% (oilseeds and wheat) to 36% for vegetable oils. The FAPRI model is used in particular to analyse different US biofuel support including the effects of the US EISA (FAPRI, 2008a, 2008b) but also some international bioenergy scenarios with exogenous increases of bioethanol demand in different world regions (Fabiosa et al, 2008). Findings include that the EISA leads to increases in 2011/12-2016/17 average producer prices of 7% (wheat) to almost 20% (corn and soybeans) compared to a reference without EISA mandates with biofuel credits and tariffs expiring as scheduled. IMPACT is used to analyse different global biofuel scenarios with different productivity changes in biofuel production, with and without 2nd generation biofuels and different targets (Msangi et al., 2006, 2007; von Braun 2007). The effects on feedstock prices of the different biofuel scenarios are substantial. In a scenario that is based on actual biofuel production plans and projections in relevant countries and regions international feedstock prices in 2020 increase from 8% (wheat) to 26% (maize) relative to the baseline without biofuels. Under more aggressive biofuel expansion, prices increase by 20% (wheat) to 72% (maize) (von Braun, 2007). This is also the range of price increases for other global scenarios (Msangi et al., 2006, 2007). All the models mentioned so far include biofuels (ethanol and biodiesel) only. The PE model FASOM, which is a model for the US with a detailed representation of the agricultural and forests sectors, is set up in a different way in order to analyse electricity generated from biomass (McCarl et al., 2000). The study considers power plants fuelled with milling residues, whole trees, logging residues, switch grass, or short-rotation woody crops. It mainly focuses on bioelectricity competitiveness issues and finds that this crucially depends on successful technological innovations in producing short-rotation woody crops.

Results of different complex models are always difficult to compare, not only because different policy scenarios are analysed but also because output variables and driving forces are different. One impact of biofuel support that has received increased attention and that has also been compared across models is the increase in agricultural and food prices. While – as we will also see in this paper – there are large differences even between models of the same type, based on the same basic data, there is some evidence that GE models lead to smaller increases of agricultural prices than PE models. This is in accordance with expectations since there are more possibilities for economic adjustments in GE models compared to PE models. Gallagher (2008) therefore argues that GE models are representing what is likely to happen in the medium term when markets can adjust while PE models give a better picture of what happens in the short term and in circumstances when adjustment is difficult. One possibility to combine the advantages of PE and CGE models is to link both types of models and there are indeed first approaches in this direction (see van der Werf and Peterson 2009). In a recent study (Melillo et al, 2009) this approach is also used to analyse bioenergy policies.

3. General modelling issues

There are some general issues that are relevant for all approaches to model bioenergy and that greatly affect the results of the different CGE models that we consider in this study. The following subsections therefore deal with the issues of modelling land use, land use change and biofuel trade.

3.1. Modelling land use

The cultivation of bioenergy crops increases demand for arable land. In combination with increasing food demand due to a growing world population this leads to increasing 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 the approaches chosen by the studies that will be discussed in detail below. A comprehensive overview on modelling land use can be found in the recently published book by Hertel et al. (2009).

The simplest approach is to treat land as a homogenous factor of production in the agricultural sectors that is fixed in supply. Dixon et al. (2007) and Kretschmer et al. (2008) follow this approach. One 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 in the WorldScan model 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. 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 aggregates 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). Also, this approach allows to not only model land in value terms but to account for physical land availability.

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), that includes 18 agro-ecological zones (AEZ). An agro-ecological zone is characterized by similar climatic and soil conditions. 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. The AEZ framework allows for reporting changes in land use and land cover in productivity-adjusted hectares.

A different approach is chosen by Gurgel et al. (2007), which is an extension of the work done by Reilly and Paltsev (2007) who introduce cellulosic conversion technologies for producing bioenergy to the EPPA model as depicted below. Gurgel et al. do not choose the CET framework as they are interested in longer-term and hence possibly radical land use changes, which they claim cannot be adequately represented in a 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%. When conversion takes place, one hectare of land of one type is converted to one hectare of land of another type and takes on the productivity level of the average for that type for that region. 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. Natural grass and natural forest land add to the representative agent's utility and their convertibility is restricted in an alternative version of the model by including a fixed factor to replicate historically observed conversion responses. The original version of the model allows for unrestricted conversion of land types given that conversion costs are covered. Finally, EPPA has also been linked to the Terrestrial Ecosystem Model (TEM) that uses spatially referenced information on climate, elevation, soils, vegetation and water availability to estimate monthly vegetation, soil carbon and nitrogen fluxes and sizes (Melillo et al., 2009). With the help of TEM detailed land use changes and resulting emissions can be estimated for the EPPA scenarios (see also section 3.2)

Generally, the ease of movement of land between different uses plays a critical role in determining the responsiveness of individual land supplies to biofuels. Together with the overall availability of land it is critical in determining the indirect land use change due to biofuels – an issue that is discussed in the next section 3.2.

3.2. The importance of (indirect) land use change

One underlying reason for promoting biofuel use is the aim to reduce GHG emissions in the transport sector. This goal is, however, undermined when areas with high carbon storage values such as forests, peat lands or savannahs are converted into cropland in order to grow energy crops. The resulting emissions from land use change (LUC) might render biofuels actually worse in terms of their carbon balance than fossil fuels (see e.g. Fargione et al., 2008 on this difficulty). In order to prevent such biofuel-related land clearing the European RES directive includes sustainability criteria for biofuels. An issue that is more difficult to tackle are the indirect land use changes (ILUC) induced by growing demand for energy crops. A frequently cited example refers to Brazilian sugarcane production crowding out soy production and displacing it to formerly rainforest-covered areas. In principle, ILUC effects are possible on a global scale where increases in biofuel production in some country lead to land use changes in very different parts of the world via linked global agricultural markets. Overall, direct and indirect land use change is probably the most significant factor for the overall greenhouse gas balance and thus the overall environmental impact of biofuels. Estimating the potential (I)LUC effects of increased biofuel use is high on the scientific and political agendas not least because the EU RES directive contains a provision that calls for the European Commission to report on ways to deal with the ILUC problematic by the end of 2010 the latest. It is clear that the direct and indirect land use change can only be estimated with the help of models that include the relevant linkages world wide.

Because of their encompassing scope with intersectoral and interregional feedback effects, GE models are in general well suited for analysing issues related to direct and indirect land use change. Models that distinguish between different land uses and land covers can give an idea about the expected magnitude of land use/cover change resulting from increased biofuel production. The conversion of high-carbon-storage areas such as forests or grasslands are most crucial with respect to LUC emissions. The models can also show where LUC will take place, which is important as well: A high share of LUC in tropical zones potentially implies massive deforestation of rainforests with a particularly harmful climate implications. As will be mapped out in more detail below, Gurgel et al. (2007) find that especially natural forest and pasture land are converted to crop land as a result of growing biofuel production. Hertel et al. (2008) furthermore find that forest and pasture cover decline most in the US, Brazil and Canada. In Mellilo et al. (2009), the increased global use of biofuels either leads to the clearing of large swathes of natural forests or to the intensification of agricultural operations world wide. Most affected are Africa and Latin America. If in addition, models want to adequately simulate the GHG savings of biofuels and determine an optimal policy mix they should include the emissions from land use changes which are mainly methane (CH_4) and nitrous dioxide (N_2O). From the models assessed in this paper only the EPPA model and the GTAP model potentially include non-CO_2 GHG.

The EPPA model includes inter alia CH_4 and N_2O emissions from agriculture. The aggregated agriculture sector and the way these emissions are modelled do not allow for assessing the emissions from land use changes, though. As mentioned above, in Melillo et al. (2009) EPPA is linked to the Terrestrial Ecosystem Model (TEM) that is able to give detailed information on land use changes and to calculate resulting emissions. TEM contains estimates of the carbon stored in vegetation and soils for every ecosystem type and feeds back changes of crop, pasture and forest productivity resulting from different GHG emission paths to EPPA. Vice versa regionally aggregated land use types in EPPA are downscaled to the 0.5 to 0.5 degree grid level of TEM and TEM calculates how much carbon is lost from land conversion in EPPA. In Melillo et al. (2009) the coupled model system is used to simulate two global bioenergy scenarios and to assess the unintended environmental consequences in terms of substantial emissions from land use change, biodiversity and habitat loss (see also section 5.2). What has not yet been done is to calculate an optimal use of biofuels accounting for the land use change emissions which is probably much more difficult and requires a true integration of land use emissions into EPPA.

The second model that is powerful in assessing direct and indirect land use changes is the GTAP model with its 18 agro-ecological zones. A version of this model has also been used to assess the potential for GHG mitigation in agriculture and forestry (Golub et al., 2008) and includes emissions from agriculture tied to explicit input or output levels and forest carbon sequestration. The approach is only able to capture minor parts of the emissions from land use change, though. So far, the model applications with biofuels do not include any emissions. Extending the GTAP model with biofuels to incorporate CO_2 and other GHG emissions including those associate with land use changes is seen as a logical next step (Hertel et al., 2008, Birur et al., 2008).

3.3. Biofuel trade

An important issue when it comes to fulfilling mandatory biofuel quotas is the modelling of trade, since probably not only the EU will have to rely on imported biofuels to meet their targets. Figure 2 shows historic ethanol exports of Brazil being the most important biofuel exporter up to date. Just as it is the case for biofuel production, biofuel trade only took off after 2001. And even today there are only small and few trade flows which will most likely change in future.

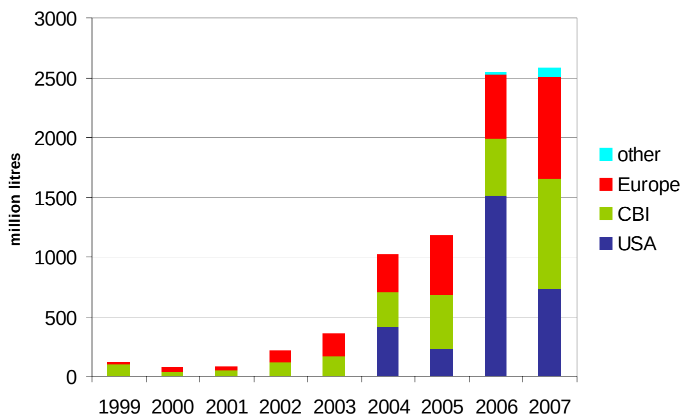

Figure 2. Composition of Brazilian fuel ethanol exports 1999-2007 (Source: FO Licht, 2008). Note: Exports to CBI (Caribbean Basin Initiative) countries are largely re-exported to the US.

Only some of the approaches to model bioenergy that we discuss below allow to explicitly model trade in bioenergy. Dixon et al. (2007) do not consider biofuel trade at all and Banse et al. (2008) only consider trade in feedstocks. The general problem is that in order to model bilateral trade flows in general equilibrium models, an underlying trade structure has to be included 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. In order to explicitly model trade in biofuels, a reasonable initial trade pattern has to be assumed. Boeters et al. (2008) 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 observations so far and expectations about future production potentials, Kretschmer et al. (2008) only include trade in bioethanol between Brazil and the industrialized countries and trade in biodiesel is only taking place between Indonesia/Malaysia and the industrialized countries and India. Biofuel import duties are calculated based on OECD-FAO (2008) where excise duties are transformed into ad-valorem tariffs. Reilly and Paltsev (2007) distinguish between scenarios with unrestricted trade in biofuels and others that prohibit biofuel trade without discussing further details. Gurgel et al. (2007) model biofuels as 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. Taheripour et al. (2007) include ethanol trade data for 2001 in the newly developed GTAP-BIO database. They derive their figures from IEA (International Energy Agency) data bases and additionally from international trade data. Given its limited importance in 2001, biodiesel trade is not considered. The prime exporter of ethanol is Brazil with most of its exports going to the US and Canada.

Due to the data problems discussed above there is a trade-off for modellers to either let the model find the optimal trade flows according to cost differentials or to calibrate the model to the actually observed trade flows that have, however, only emerged recently and are scarcely documented so far. Furthermore, trade flows will most likely change considerably as new biofuels producers enter the markets and as biofuel targets become more stringent. Before we explain the different approaches to include bioenergy into a CGE in more detail, table 1 summarizes the main features of the different models as discussed section 3.

Table 1. Major issues in modelling bioenergy in CGE models

Paper	Modelling approach	Bioenergy types included	Land use modelling	Biofuel trade	Non-CO_2 emissions	Biofuel scenarios
Dixon et al. (2007)	Implicit modelling	Ethanol (though not clearly specified)	Land as a homogenous factor	No	No	25% replacement rate of crude oil inputs by biomass in the refining industry
Banse et al. (2008)		Ethanol (sugar beet/ cane, cereals); Biodiesel (vegetable oil)	3-level CET nesting structure; Regional land supply curves	No (only trade in feedstocks)	No	10% EU blending target by 2020 (through budget-neutral subsidy)
Reilly & Paltsev (2007)	Latent technologies	Cellulosic biofuels and bioelectricity	Land as a homogenous factor	Yes	i.a. N_2O & CH_4 in agric.; no emissions from LUC	GHG stabilization scenarios of varying stringency and varying assumptions on land availability; biofuels are result of global carbon price.
Gurgel et al. (2007)			Conversion cost approach with 5 land types	Yes; homogenous good assumption		
Melillo et al. (2009)					(I)LUC emissions from linked eco-system model	
Boeters et al. (2008)		Ethanol (sugar cane, corn, wheat); Biodiesel (vegetable oil)	One-level CET function	Yes; ethanol and biodiesel trade; various Europ. importing countries	No	10% EU blending target by 2020 (on top of 20% EU GHG emission reduction by 2020 relative to 1990)
Kretschmer et al. (2008)		Ethanol (sugar cane/ beet, corn, wheat); Biodiesel (oilsseds, vegetable oil)	Land as a homogenous factor	Yes; ethanol and biodiesel trade; Brazil & Malaysia/ Indonesia mainly to industr. countries	No	10% EU blending target by 2020 (on top of 20% EU GHG emission reduction by 2020 relative to 1990)
Birur et al. (2008)	Disaggregating the SAM	Ethanol (coarse grains, sugar cane); Biodiesel (oilseeds)	GTAP-AEZ approach with two-level CET nesting structure for each of the 18 different agro-ecological zones	GTAP-BIO includes trade data for 2001 on ethanol only; mostly Brazil to Canada and USA	No; agric. emissions are included in similar GTAP version without biofuels	Historical analysis of 2001-06 (incl. US and EU support biofuel schemes)
Hertel et al. (2008)						Add 2015 policy targets: US: 15 bn gal. ethanol use; EU: 6.25% biofuel share (individually or simultaneously)
Taheripour et al. (2008)		As above but including by-products (DDGS and oilseed meals				Simultaneous US and EU 2015 target (as defined above)

4. Implicit modelling of bioenergy

We now move to the different approaches of modelling biofuels in CGE models. A first CGE application is the study by Dixon et al. (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[5] 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 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 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 elegant since it circumvents many problems described above and does not require any additional data work. On the other hand, the underlying assumptions on the development of production cost of biofuels are rather strong and optimistic; they are not motivated by engineering studies but simply assume the cost reduction necessary to reach a 25% share of biofuels in 2020 without 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 GHG 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% from the 2020 benchmark to the 2020 policy case. 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 – and thus possibly more realistic – production costs for bioenergy and necessary government support to reach the 25% quota.

[5] One barrel equals ca. 159 litres.

Another implicit approach to model bioenergy is chosen by Banse et al. (2008) who introduce biofuels to an extended version of the global GTAP-E 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 (representing biodiesel), crude oil, petroleum products and ethanol being nested into 'Fuel'. Ethanol is produced from sugar beet/cane and cereals. In that way, biofuels are modelled as intermediate inputs to the petroleum industry and their demand depends on the price of the agricultural inputs in relation to fossil energy prices. The authors adjusted the original GTAP6 database by keeping total national intermediate use of grain, sugar and oilseeds constant and adjusting the use in the non-petroleum sector to reproduce 2004 biofuel shares in the petroleum sector (p.126). The small input quantities in the petroleum sector are scaled up artificially by lowering their input-specific productivity coefficient until actual feedstock use for energy production is reached. A major contribution of their study is the inclusion of substitutability between different land types and a land supply function (see section 3.1 above).

For simulating policy scenarios, mandatory blending requirements are 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 in Banse et al. (2008) is counter-financed by an end-user tax on petrol consumption. Another approach of modelling mandatory blending requirements would be a subsidy that is not offset by a tax, which would lower fuel prices, while the former approach which better represents the mandates introduced e.g. by the EU and the USA increases fuel prices. 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 target. 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 a result of the considerable degree of trade liberalization and agricultural market liberalization assumed in the reference scenario as well as the inherent assumptions on productivity growth rates. The policy scenario only displays slowly rising world oilseed prices (around 2% over the projection period leading to a price in 2020 that is 8.5% 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 6% 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 endogenised 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 now modelled more directly 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 merely 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, 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 sections.

5. Modelling biofuels as latent technologies

Latent technologies are production technologies that are existent but not active in the base year of the model since their production is not profitable. Through changes in relative input or output prices or certain policies a latent technology can become profitable at a later stage in a dynamic 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 when the technology for producing biofuels existed, but when basically no biofuels had been produced yet. Modelling latent technologies requires information about the input and cost structures of the different types of biofuels to be included and the mark-up (i.e. difference) between production costs and prevalent (fossil fuel) prices. This section provides three examples of 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.

5.1. 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, corn 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) constitute the basis for modelling bioenergy and are available for Brazil, the EU and the USA. Technologies (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, corn 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 benchmark 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 benchmark scenario the authors construct a policy baseline scenario that includes the EU ETS and the EU-27 GHG reduction target of 20% by 2020 relative to 1990 (excluding the use of *joint implementation* (JI) and the *clean development mechanism (CDM)*) and further GHG reduction targets in other Annex I countries. 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). This is in line with trade theory and an example of the magnification effect that entails that a rise in a product’s price leads to an over-proportionate rise in the price of the factor used intensively in that sector (see for instance Feenstra, 2004). Model attributes that are believed to contribute to the weak response of agricultural prices are the inclusion of biofuel trade and of an annual yield improvement rate of 1.5%. 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, modest as well. The world arable land price increases by 0.5% while the EU-27 price increases by 2.2%. In a subsequent sensitivity analysis, the authors alter the elasticity of transformation for different uses of arable land between 0.5 and 15, implying very high transformability. It turns out that land rents are quite insensitive to these changes (p.36). With a 10% biofuel target and either no excise or competitive excise on biofuels welfare of the EU-27 slightly increases (by 0.03%). This is explained by the fact that carbon taxes in the non-ETS sectors decrease because part of the mitigation effort is already accomplished by substituting biofuels for fossil fuels in road transport.

The DART model is a multi-sector, multi-region recursive dynamic CGE model based on the GTAP6 dataset that is extended to include bioenergy (Kretschmer et al., 2008). The newly included commodities biodiesel and ethanol substitute for conventional diesel and gasoline consumption, which have been disaggregated from the GTAP sector “refined oil products”. In order to do so, expenditure share data (net of taxes) of diesel and gasoline in the consumption and the imports of refined oil products 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 abroad. The input factor land is included implicitly in biofuel production as it is an input to feedstock production. Production cost data for ethanol and biodiesel 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 determines the level of bioenergy production. Biofuels are incorporated in the model as of 2005 onwards. At that point (and also up to now), only the Brazilian ethanol industry is able to produce profitably without policy intervention. Adjusting the mark-up factor reproduces actual shares of Brazilian ethanol production in 2005. 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). There are two biofuel technologies – one for biodiesel based on different oilseeds (rapeseed, soya, palm) and one for bioethanol based on sugar cane/beet, wheat or corn. Different to the approach in Boeters et al. ethanol can be produced from different feedstocks even within one region. Feedstock shares are derived from production in 2005 and an elasticity of substitution of 16 between the different feedstocks is assumed. The European 10% biofuel target to be met by 2020 is simulated under differing policy assumptions in various policy scenarios and reached by an endogenously determined subsidy. While the 2005 benchmark shares are imposed as ethanol- and biodiesel-specific quotas, the optimal mix beyond that for achieving the 10% target is determined endogenously. As in Boeters et al. (2008), the EU-ETS with a 20% emission reduction target by 2020 relative to 1990 is included 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[6]. Increases in European agricultural sector prices are much more pronounced and range from 0.7% to 5.2%. World crude prices on the other hand decline by 1.7% thus responding to declining demand for fossil fuels. Similar to Boeters et al. welfare measured in terms of equivalent variation slightly increases in the policy scenario for the EU as a whole (though the change is almost negligible with 0.01%).

The advantage of the approaches by Boeters et al. and Kretschmer et al. is that bioenergy production technologies are explicitly modelled so that all relevant linkages between other sectors of the economies are captured. To analyse mid-term bioenergy support policies the approaches seem to fit well. Yet, some problems remain. One is to model trade in biofuels, which is difficult – since one has to assume some trade structure –yet important in the context of mandatory quotas. Generally, the fact that the latent technology approach actually models biodiesel and ethanol as distinct commodities entails the possibility of trading these commodities. This can be considered as an additional advantage of the latent-technology over the implicit modelling of bioenergy that is constrained to modelling trade in agricultural products. 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.

5.2. Modelling second-generation biofuels

Reilly and Paltsev (2007) and the follow-up studies by Gurgel et al. (2007) and Melillo et al. (2009) do not 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 studies are conducted with the EPPA model, a multi-region, recursive dynamic CGE model based on the GTAP5 database and look much further into the future then the studies mentioned so far 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. Reilly and Paltsev (2007) introduce two bioenergy technologies, liquid fuels and electricity derived from biomass, which produce perfect substitutes for refined oil and conventional electricity, respectively. Of all the CGE models presented here the EPPA model is the only one that also includes bioelectricity. 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

[6] The high price increases of raw milk and 'other grains' – themselves not being biofuel feedstocks – is due to their production being crowded out by increased biofuel feedstock production as can be seen in Kretschmer et al. (2008). Milk prices are furthermore put under pressure by rising input (cattle feed) costs.

input factor ‘land’ is specified further in a follow-up study by Gurgel et al. (2007) that includes various land types and the possibility of conversion from one type to another as outlined in section 3.1 above. In an additional recent study (Melillo et al., 2009) EPPA is coupled to the ecosystem model TEM to calculate different environmental effects of increased global bioenergy production. 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.

GHG stabilization scenarios of varying stringency lead to a growing importance 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.

Running similar GHG stabilization scenarios as in Reilly and Paltsev (2007), Gurgel et al. (2007) unsurprisingly find that production under unrestricted conversion exceeds production under restricted conversion by 10-20%. In some regions (Mexico and Australia/New Zealand), however, biofuel production is actually higher in the restricted-conversion 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 too sensitive to biomass expansion, a fact that is explained by relatively price inelastic food demand (p.23). Gurgel et al. 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 result can probably be explained by their assumptions about productivity growth of land; for the region with the greatest biomass potential, Central and South America, the authors assume a doubling of the current biomass potential until 2100 (Gurgel et al., 2007 p.9).

Melillo et al. focus on the environmental consequences of an increased global biofuel production. They assess the same GHG stabilization scenario in two variants as in Gurgel et al. Emissions from land use change, though, are only accounted for in TEM as mentioned in section 3.2 above so that due to land use change actual emissions are potentially higher than the emission targets. The first scenario makes all land available for biofuel crops or other managed uses as long as the economic return on the land exceeds the cost of conversion and improvement. In the second scenario there is only limited access to unmanaged land. The authors find again that cellulosic biofuel production could contribute substantially to future global energy needs but that this has significant unintended environmental consequences. The global landscape either experiences the clearing of large swathes of natural forests (first scenario), or the intensification of agricultural production worldwide (second scenario). In both scenarios numerous biodiversity hotspots suffer from serious habitat loss while GHG implications vary. In the first scenario the carbon debt – that is emissions from land use change – of biofuels is equal to 8-37% of the cumulative emissions for the period 2000-2050. Even under most favourable assumptions net GHG reductions will be realized from biofuels only after 2045. In the second scenario the carbon debt is much lower or even positive. Even in the worst case, biofuels now start to reduce net emissions in the middle of the century.

The EPPA-approach 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. The downside is that the approach has to rely almost entirely on assumptions about input shares and cost developments that are not backed by real data since there is no commercial large-scale production of second-generation fuels yet. Experience shows that assumptions on future technologies have often been speculative and turned out to be wrong. Nevertheless, this approach can yield relevant insights from studying long-term climate policy and GHG stabilization scenarios if one believes that second-generation biofuels will become viable and that they will have a clear cost advantage over first-generation biofuels. 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.

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. This is especially true for second-generation fuels that cannot rely on any reliable data. But also the results from first-generation biofuel modelling should be carefully checked by means of sensitivity analyses in order to account for the uncertainty associated with the approach. These problems can be overcome if bioenergy is already explicitly included in the underlying SAM of a model. This last approach is described in the next section.

6. Disaggregating the SAM

The approach that is depicted in subsection 6.1 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 6.2 we describe first modelling approaches based on the new database.

6.1. 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 starchy crops (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 is attributed to the refined oil product sector as an intermediate input, i.e. an additive to gasoline. The database is developed further to include “Dried Distillers Grains with Solubles” *(*DDGS) as a by-product of eth1 production used as animal feed in GTAP-BIOB and then also biodiesel by-products (BDBP) such as soy and rapeseed meals in GTAP-BIOC.

Biofuel production data are derived from IEA sources which provide aggregate biofuel data. These data were split into ethanol and biodiesel based on IEA biodiesel production capacity reports. Ethanol was split further into eth1 and eth2 in accordance with the main feedstock input used in a country. Potential future biofuel production is accounted for by introducing negligibly small production levels into the 2001 database (especially relevant for biodiesel production in Malaysia and Indonesia). Ethanol trade figures are constructed based on IEA and additional data sources under the assumption that countries trade with 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: 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. Taheripour et al., 2007 pp.7-8 for further details).

6.2. Applying the GTAP-BIO databases

An application of the newly developed GTAP-BIO database can be found in Birur et al. (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) as explained above. 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 sectors eth1, eth2 and biodiesel are included on the consumption side and on the production side. 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 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, a default value of 2 is assumed. 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 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. 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).

The paper by Hertel et al. (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 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 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. One result is e.g. that 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 grows 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[7]. 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.

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 conclusions, they “relied on imperfect biofuel production and trade information. These deficiencies can be removed with more

[7] 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.

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.

7. Explaining and comparing price effects across models

Having presented various applications of the three approaches we now try to draw comparisons between the results of selected studies. We focus on changes in agricultural sector and/or food prices (where reported) since these were the focal point of the food vs. fuel debate. It has to be kept in mind that a comparison of price effects is difficult. Besides different underlying parameter and data assumptions as well as modelling approaches, agricultural sectors are not identically defined across studies, results may be reported in a comparative-static fashion (i.e. comparisons between the end-of-projection-time levels in the policy scenarios to the corresponding baseline levels) as compared to reporting dynamic effects over time and time horizons are not identical across studies. An elaborate discussion of these issues along with an overview of price effects across different partial as well as general equilibrium models can be found in Gerber et al. (2008).

We start out with the studies by Boeters et al., Kretschmer et al. as well as Banse et al. which all model the 10% biofuel target of the EU RES directive to be reached by 2020. We focus on comparative-static effects, 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. In summary, Banse et al. report increases in world oilseed, cereal and sugar prices of 8.5%, 6% 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. One explanation for the small effects is that the average also includes agricultural prices that are not directly affected by biofuel production. The increases in world agricultural sector prices in Kretschmer et al. (2008) range from 0.3% to 1.9% and are somewhat in between the two studies though closer to the more moderate price effects found by Boeters et al. An important aspect in explaining the differences might also 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 should lead to lower price effects, since production can take place where it is most competitive – i.e. in Brazil where bioethanol is already competitive to conventional fuels. Also, the higher the trade elasticities of agricultural goods, the smaller the overall effects since there is again more flexibility.

Taheripour et al. (2008) compare price changes *over the period* 2006-2015 with simultaneous US and EU biofuel policies in place for model versions with and without by-products and find (see section 6.2) that the inclusion of by-products significantly renders price increases more modest. One would expect that price changes tend to be larger than in the EU studies since the global biofuel target is larger but the fact that Taheripour et al.

report price changes over time and not for a reference compared to a policy scenario as well as for a different time horizon than for instance Banse et al. (2008) would make any further comparison spurious.

In Gurgel et al. there are no specific biofuel policies but bioenergy production is triggered by GHG stabilization and a general carbon price in the policy scenario. As the baseline scenario has only little bioenergy production over the period 2020-2050 the authors suggest to compare agricultural prices for that period as most of the additional price increases can thus be attributed to bioenergy. They report crop, livestock and food price increases of about 5% in the climate policy scenario compared to the baseline scenario, with the price changes in the restricted-conversion model specification being 2 to 3 percentage points higher (Gurgel et al., 2007). Comparisons with other results are again problematic because of the different time horizon and the fact that bioenergy targets are not comparable. One likely reason for the comparably low price changes are the extensive possibilities to increase either land area or productivity.

As has been seen in section 2, the price effects found in some of the PE studies are considerably higher. Partially this is the case because scenarios are not comparable and the PEs assumed global biofuel targets, while e.g. the studies on the RES directive only focus on the EU target; the larger global biofuel production, the larger expected price increases. In addition, as has been mentioned above as well, GE models have more adjustment channels so that price-driving effects are partly mitigated thus explaining the weaker effects.

8. Conclusions

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 2.

Theoretically, the most promising approach is to calibrate the model to a SAM that disaggregates bioenergy activities in separate sectors. If the data for this approach were already easily available there would be little need for using the other approaches in the context of first-generation biofuels. However, up till now the accuracy of the SAM approach is limited by insufficient data for the model base year (2001) and the fact that in this year there was still little biofuel production and trade. The GTAP-BIO database which marks the first attempt to disaggregate biofuels in the SAM suffers from these weaknesses and is based on a number of more or less realistic assumptions (e.g. that sugarcane-based ethanol is disaggregated from the ‘chemical, rubber, plastic’ sector). The recently published database GTAP7 is calibrated to the base year 2004 thus rendering the bioenergy data scarceness for first-generation technologies somewhat less problematic due to their rapidly growing importance over the last years. To disaggregate the SAMs correctly one would need to have detailed information on where biofuel production is included in the national SAMs, which inputs it uses and how biofuel is traded. Gathering these data is probably still not easy and very time consuming. For the research community it would be of great help if the GTAP-BIO database was updated for the 2004 dataset GTAP7 based on newest data. In any case, it will be likely that we will soon see further approaches of incorporating bioenergy directly into SAMs and that many models will switch to using these SAMs to model first-generation biofuels. 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 to regions that are currently not producing on a commercially relevant scale yet. These include Malaysia and Indonesia that are expected to become important biodiesel producers (and possibly also exporters), as well as countries in 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 flexible to account for such new developments and also for modelling long-term scenarios. The downside of this approach is that it is based more or less on mere speculations about cost developments and availability of advanced technologies. 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 2. 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) Melillo et al. (2009)
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)

The results that have been cited in this paper 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. In addition there are numerous issues for future research.

The most important issue 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. Most of these approaches are also used in the models with bioenergy that are described in this paper. The most advanced CGE model in this respect is the adjusted GTAP model that distinguishes between 18 different agro-ecological zones (AEZs) which restrict the possibility of land to move between uses. In order to limit the complexity of single models and to combine advantages of different modelling designs a promising way approach is couple models such as e.g. done in Melillo et al. (2009). Coupling a detailed ecosystem model to the CGE model EPPA allows calculating emission from direct and indirect land use changes, which is a high-priority topic for scientists and policy makers since these emissions determine the overall GHG savings that can be achieved with the help of biofuels. What is still missing is a CGE model that truly endogenizes the calculation of land use emissions so that it is possible to calculate the role of biofuels in an optimal policy mix accounting for direct and indirect emissions. This is clearly an important task for future research.

Besides this major task there are a few smaller issues that need to be considered in future CGE analysis of biofuel policies. One is the so-called ‘blending wall’. Conventional engines can only safely take up low-percentage blends of biofuels of up to 10% or even lower, with the precise figure being debated and depending on the exact engine type. Only flex-fuel vehicles can take up higher blends, but these have not penetrated the majority of car markets yet. Their widespread availability would, however, be a prerequisite for imposing targets beyond 10%. One could possibly account for this by introducing transaction costs (representing the costs of replacing parts of the car fleet with flex-fuel vehicles) associated with reaching blends beyond 10%. For modelling current European biofuel policy, this is not an issue. Even if biofuel production in some countries exceeded 10%, the excess production could be thought of as being exported to other countries in order to reach a 10% share of biofuel use there. This brings us directly to the issue of trade in biofuels – which is only partially modelled in the existing models even though this has a major impact on the effects of certain biofuel targets. As trade patterns begin to emerge more clearly, models should be improved to reflect these patterns. A further issue is that so far most models focus on bioethanol and biodiesel only and neglect other possibilities to generate bioenergy such as bioelectricity or direct burning of biomass to generate heat. This is especially important since these bioenergy options are preferable to biofuels in terms of emission reduction costs and potential and are likely to play an important role in a cost-effective policy mix. This as well as modelling by-products of bioenergy production – included in only one study so far – should also be on the agendas.

Hopefully, this paper will contribute to a better understanding of modelling bioenergy in CGE models and of the results of different studies and will help to improve and extend the models to better capture relevant driving forces of bioenergy and the determinants of their economic and environmental impacts.

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