Linking Global CGE models with Sectoral Models to Generate Baseline Scenarios: Approaches, Challenges, and Opportunities

BY RUTH DELZEIT[a], ROBERT BEACH[b], RUBEN BIBAS[c], WOLFGANG BRITZ[d], JEAN CHATEAU[e], FLORIAN FREUND[f], JULIEN LEFEVRE[g], FRANZISKA SCHUENEMANN[h],TIMOTHY SULSER[i], HUGO VALIN[j], BAS VAN RUIJVEN[k], MATTHIAS WEITZEL[l], DIRK WILLENBOCKEL[m], AND KRZYSZTOF WOJTOWICZ[n]

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[a] Kiel Institute for the World Economy, Kiellinie 66, 24105 Kiel, Germany (e-mail: ruth.delzeit@ifw-kiel.de)

[b] RTI International, 3040 Cornwallis Road, Research Triangle Park, NC, USA (e-mail: rbeach@rti.org)

[c] Organisation for Economic Cooperation and Development, 2 Rue André Pascal, 75016 Paris, France (e-mail: ruben.bibas@oecd.org)

[d] Institute for Food and Resource Economics, University of Bonn, Nussallee 21, 53115 Bonn, Germany (e-mail: wolfgang.britz@ilr.uni-bonn.de)

[e] Organisation for Economic Cooperation and Development, 2 Rue André Pascal, 75016 Paris, France (e-mail: jean.chateau@oecd.org)

[f] Thünen Institut, Bundesallee 50, 38116 Braunschweig, Germany (e-mail: florian.freund@thuenen.de)

[g] Centre international de recherche sur l'environnement et le développement, 45bis Avenue de la Belle Gabrielle, 94130 Nogent-sur-Marne, France (e-mail: jlefevre@centre-cired.fr)

[h] Kiel Institute for the World Economy, Kiellinie 66, 24105 Kiel, Germany (e-mail: franziska.schuenemann@ifw-kiel.de)

[i] International Food Policy Research Institute, Eye Street, 1201 I St NW, Washington, DC 20005, USA (e-mail: t.sulser@cgiar.org)

[j] International Institute for Applied Systems Analysis, Schloßpl. 1, 2361 Laxenburg, Austria (e-mail: valin@iiasa.ac.at)

[k] International Institute for Applied Systems Analysis, Schloßpl. 1, 2361 Laxenburg, Austria (e-mail: vruijven@iiasa.ac.at)

[l] European Commission, Joint Research Centre, Edificio Expo, Calle Inca Garcilaso, 3, 41092 Sevilla, Spain (e-mail: matthias.weitzel@ec.europa.eu)

[m] Institute of Development Studies at the University of Sussex, Brighton, UK (e-mail: d.willenbockel@ids.ac.uk)

[n] European Commission, Joint Research Centre, Edificio Expo, Calle Inca Garcilaso, 3, 41092 Sevilla, Spain (e-mail: krzysztof.wojtowicz@ec.europa.eu)

When modeling medium and long-term challenges we need a reference path of economic development (the so-called baseline). Because sectoral models often offer a more fundamental understanding of future developments for specific sectors, many CGE modeling teams have adopted approaches for linking their models to sectoral models to generate baselines. Linked models include agricultural sector, energy sector, biophysical and macroeconomic models. We systematically compare and discuss approaches of linking CGE models to sectoral models for the baseline calibration procedure and discuss challenges and best practices. We identify different types of linking approaches which we divide into a) one-way, and b) two-way linking. These two types of linking approaches are then analyzed with respect to the degree of consistency of the linkage, information exchanged, as well as compromises in aggregations and definitions. Based on our assessment, we discuss challenges and conclude with suggestions for best practices and research recommendations.

1. Introduction

Computable general equilibrium (CGE) models are widely applied in economic analysis to analyze feedback effects of policy measures across sectors and regions. They are also used to capture impacts of trends such as population growth, changes in productivity, and preference changes such as those linked to climate change or energy transition. Especially for global multi-regional CGE models, their ability to address repercussions across sectors and regions comes at the cost of less sectoral detail compared to partial equilibrium (PE) models. Furthermore, CGE models focus on market variables, but do not explicitly represent biophysical processes surrounding climate, energy transformation, land use, crop growth, human and animal diets, or interactions with the environment such as emissions, ground water abstraction or other resource depletion captured in more detailed models. Additionally, sectoral-focused models often control for mass, energy, or nutrient balances or consider bio-physical limits (e.g. limits to crop yields or to energy efficiency of processes) (e.g. Després et al., 2018). Linking CGE to sectoral models thus provides additional quality assurance and credibility of CGE-based assessment by more robust sectoral foundations and additional dimensionality (explicit technologies, time and spatial resolution, biophysical constraints, etc.), as well as better reflecting the specific domain knowledge of the teams involved in sectoral models and sectoral baseline construction. This knowledge feeds not only into decisions on appropriate model structure, data sources and parameterization, but also allows for plausibility assessments of detailed results beyond what CGE

modelers could provide. This includes more informed judgement about potential development of future policies and various trends, for instance with regard to partial productivities or preferences. Here, sectoral models often rely on more detailed biophysical modeling exercises or assessments such as climate change impacts on productivities or future changes in primary factor availability (e.g. irrigation water and crop land in the case of agriculture). Model linking has thus become a way to address caveats of CGE models in baseline construction and beyond.

Few papers have attempted to demonstrate in quantitative terms the limits of standalone CGE models and the benefits of model linking. Kaya et al. (2017) quantify how applying constant elasticity of substitution (CES) functions in CGE models for the substitution of technical factor inputs fails to match historically observed patterns in energy transition dynamics and call for linking to physical modeling. Other papers quantify at the national level the outcome gaps between standalone and linked CGE models that reflect erroneous or limited sectoral representations in standalone CGE models. For instance, Krook-Riekkola et al. (2017) show that linking a CGE model to an energy model for baseline projections in Sweden results in significant change in the structure of the economy and energy use compared to standalone CGE projections. Further, differences in substitution possibilities for energy sectors and energy-intensive industries between the CGE and the linked model lead to considerably different production costs, energy use and broader economic structural change. Similar studies can be found for climate policy analysis beyond baselines (Fujimori et al., 2019, Lanz and Rausch, 2011). They show that standalone CGE models can significantly over- or underestimate macroeconomic mitigation costs compared to linked approaches that better reflect "real-world" substitution possibilities. Another example is a study by Britz and Hertel (2011) who compare a standalone CGE simulation of global land use and greenhouse gas (GHG) emission impacts due to EU biofuel mandates with a linked agricultural PE-CGE[1] simulation that is deemed to offer a more accurate representation of EU supply responses. They conclude that the standalone CGE results overestimate GHG emission impacts by nearly 20 percent.

For these reasons, CGE modeling teams focusing on long-term developments have adopted different kinds of linking approaches with different model types for baseline generation (see Section 2). Most CGE linkages are with PE models for agricultural and energy sectors. Given that both CGE and PE models can only capture impacts of policies or other exogenous factors through market interactions, some CGE models are linked with biophysical models such as crop growth models or simple climate models to capture impacts of climate or other ecological processes. Some rely on linkages to both PE and biophysical models. Some others are linked to a macro model to calibrate macroeconomic projections.

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[1] See section 2 below for an outline of the linkage approach adopted in this study.

CGE models can also be embedded into a larger integrated assessment modeling framework consisting of several models (e.g. Crespo del Granado et al., 2018).

However, the rapidly growing number of linking approaches and their variety makes it difficult to compare and qualify them. Previous modeling comparison initiatives such as the Agricultural Model Intercomparison and Improvement Project (AgMIP) (von Lampe et al., 2014) and the Energy Modeling Forum (EMF) projects (Weyant and Kriegler, 2014) have shown that comparative assessments of results from different models requires an understanding of underlying assumptions and drivers. In this spirit, a workshop co-organized by the Global Trade Analysis Project (GTAP) and the Organisation for Economic Cooperation and Development (OECD) in January 2018 had the objective to contrast and compare the different strategies across modeling teams in baseline development. One of the outcomes of this workshop was the observation that linking approaches vary considerably from, for instance, solely using selected variables projected by one model as inputs into another to a full integration between multiple models (Dellink et al., this issue).

In this paper, we systematically compare and discuss approaches of linking CGE models for baseline generation, and discuss challenges and best practices. We first identify different types of linking approaches which we divide into one-way and two-way linking. These two types of linking approaches are then reviewed with respect to the degree of consistency between linked variables, information exchanged (e.g., prices, volumes, values, land availability), and compromises in aggregations and definitions. Based on this, we discuss challenges and conclude with suggestions for best practices and research recommendations.

2. Review of model linking approaches

Two general approaches can be distinguished in model linking (see Figure 1). In a one-way linkage, outputs from one model serve as exogenous parameters or variables in another model. The one-way linkage with CGE models can be bottom-up or top-down. Top-down links from a CGE to a PE or other type of model typically relate to endogenous variables generated by the CGE model that are then treated as exogenous to the more disaggregated model to which it is being linked, either on the input side (e.g. prices of primary factors or goods) or on the output side (e.g. demand). In this paper we concentrate on bottom-up links. Simple bottom-up links from PE to CGE models usually imply some productivity or preference shifts to line up CGE results to PE results without changing functional forms or elasticities. Consistency is generally not achieved in the case of one-way linking when the models share endogenous variables (Britz et al., 2012).

Conversely, a two-way linkage takes into account the feedback between models to reach better convergence of overlapping variables. As exemplified for CGE-PE energy model linking in Figure 1, the energy supply structure and cost from a PE

energy model is used to inform a CGE model to modify the energy demand structure in the CGE model that is fed back into the energy supply model. Therefore the two-way linkage provides better convergence between the linked models for both energy supply and demand variables. Both one- and two-way linkages can be improved by moving from point calibration to the integration of response surfaces. This might require changes in functional forms or parameterization or even introducing new functional relation in models.

The literature sometimes distinguishes between soft and hard linkages, albeit with different connotations: Wene (1996) focuses on the technical link by distinguishing between data exchanges controlled by model users versus computer programs. If the same data are exchanged between linked models, this should not affect the solution computed.[2] A two-way linkage in recursive-dynamic baseline construction implies exchanging information between the two models in between solution points (see Figure 1) and therefore renders a hard-link likely. Overall, the importance of information technology (IT) issues in model linkage is decreasing as modern software packages used for modeling (e.g. R, MATrix LABoratory (MATLAB), General Equilibrium Modelling Package (GEMPACK) or Generalized Algebraic Modeling System (GAMS)) provide tools for format conversion and/or application programming interfaces to ease model interfacing. Alternatively, some scholars refer to hard linking when the linked models are solved simultaneously as opposed to iterative runs with data exchanges towards convergence (e.g. Krook-Riekkola et al., 2017). However, Böhringer and Rutherford (2008, 2009) show that in some cases the same mathematical problem can be solved by either iterative or simultaneous solving of the linked models to achieve identical final outcomes.

Under both definitions, soft and hard linkage can hence lead to identical results. With regard to numerical results, what actually matters is the degree of convergence of the overlapping variables between the two-way linked models in the computed solution, whatever the method used to compute the combined solution. Perfect consistency and convergence of overlapping variables is a specific case of model linking where one model is fully integrated in another model. Such approaches (see also appendix) have mainly been developed in national / sub-national energy context and for specific purpose (Böhringer, 1998; Böhringer and Rutherford, 2008; Lanz and Rausch, 2011). An intermediate case provides the response surface approach mentioned above.

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[2] For instance (Krook-Riekkola et al., 2017) perform a soft-linkage whereas (Helgesen et al., 2018) perform a hard-linkage under this definition, but both studies carry-out similar data exchange and feed-back between a CGE and a PE energy model
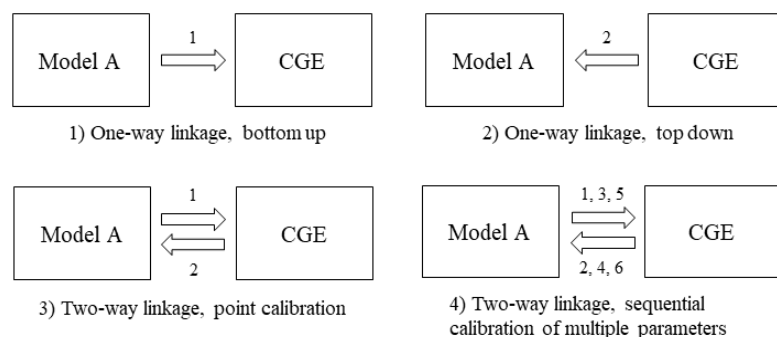
Figure 1: Overview on PE-CGE linking approaches

Source: Authors construction.

In comparative static analysis, two-way linkages might require an iterative procedure that involves solving both models multiple times; a process called sequential calibration (Britz 2008; Jansson and Britz, 2010; see also the discussion below). The CGE models discussed here for baseline construction are all recursive-dynamic ones such that a two-way linkage can be integrated in the step-wise solution process over time as indicated in Figure 1, where for each simulated time point, information is exchanged between the two models in both directions.

Model linkage typically involves scale changes in multiple dimensions. PE or other types of economic models and CGE models typically work with a yearly temporal resolution or at least summarizes results to calendar years such that no temporal scale changes are necessary, while biophysical models such as crop growth models work on finer time scales. Likewise, energy system models might operate on sub-annual time steps. Here some aggregator function might be needed to pass information to a CGE model. Scale changes on the spatial domain for between different economic models are in most cases also not demanding as most PE and CGE models provide results at the level of countries or group of countries. If country groupings do not match, some proportioning is required, often using a benchmark share of nations. We found only a few cases where information was passed bottom-up between sub-national layers in sectoral or biophysical models and CGE models in baseline construction.

Scale changes in the sector or product as well as item domain are more frequent and typically more demanding as models focused on sectors such as energy or agri-food typically use physical units for quantity variables (supply, different demand categories, resource use, partial productivity such as crop yields) whereas CGE models use volumes, and can be based on different accounting concepts. For example, market balances and bi-lateral trade for agricultural products reported by the United Nations Food and Agricultural Organization (FAO) are the most frequently used global data source in agri-food models and are based on the concept of so-called "primary product equivalent" such that what is reported as

food or feed demand of wheat aggregates over the value chain involved in wheat use. This does not fit well with the input-output accounting of CGE models. We will discuss such challenges involved in more detail in the sub-sections.

Table 1 provides examples of recent applications relying on linkages between CGE and sectoral models with a focus on global CGE models. These approaches as well as implications of alternative methods for linking models will be discussed in the following subsections.

Table 1. Selected applications linking CGE and sectoral models.

Linkage type	CGE model name	Linked model name	Linked model type	Linkage approach	Publication(s)
One-way linkage	Applied Dynamic Analysis of the Global Economy (ADAGE)	Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG); Integrated Planning Model (IPM)	Agricultural sector PE model; Energy sector PE model	Bottom-up: Incorporation of GHG offset supply curve into ADAGE. Top-down: ADAGE projections of CO_2 allowance prices and percent change in electricity demand are passed to IPM	EPA, 2008 Beach et al. 2010 Cai et al., 2018
	ADAGE*	FASOM-GHG	Agricultural sector PE model	Bottom-up: Adjustment of agricultural productivities based on agricultural yield projections	Ross et al., 2009
	Environment and Climate Change Canada Multi-Sector Multi-Region CGE Model (EC-MSMR)*	Energy-Emissions-Economy Model for Canada (E3MC) (applied for Canada only)	Energy sector PE model	Bottom-up: Incorporation of gross domestic product (GDP), population, energy flows, and energy efficiency improvements from E3MC into EC-MSMR for the Canada region of the model.	Zhu et al., 2018
	ENV-Linkages	International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT); IIASA GLOBIOM; IEA World Energy Model (WEM); ENV-Growth	Agricultural sector PE model; Energy sector PE model; Macroeconomic model	Bottom-up: Macroeconomic projections are taken from the ENV-Growth Model and entirely reproduced in the CGE model (see Fouré et al., same issue) Energy system: Energy demands, supply and policies are taken from the WEM model (IEA "CPS scenario"), energy demands are calibrated through changes in autonomous energy efficiency, energy supply through sectoral TFP, evolution of energy prices is mimicked by altering energy supply elasticities. Agriculture: Food and feed demands, crops and land supply are taken from IMPACT model, demands are calibrated through changes in preference parameters. Land supply is fixed in the baseline to the IMPACT values, crop supply is calibrated through TFP. IMPACT elasticities are used to calibrated CET-parameters in the CGE model.	Chateau et al., 2014a Chateau et al., 2014b
	GLOBE	International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)	Agricultural sector PE model	Bottom-up: GLOBE is calibrated to several exogenous drivers of IMPACT by changing labor productivity, TFP in agriculture to match GDP and producer prices in agriculture.	Ringler et al., 2016 Willenbockel et al., 2018

Linkage type	CGE model name	Linked model name	Linked model type	Linkage approach	Publication(s)
	Global Trade Analysis Project (GTAP)	Common Agricultural Policy Regionalised Impact (CAPRI)	Agricultural sector PE model	Bottom-up: GTAP production functions replaced by a dual revenue function parameterized to capture price response of aggregate farm models at European Union level; GTAP price changes afterwards passed to supply models as exogenous changes in prices	Britz and Hertel, 2011; Pelikan et al. 2015
	Global Trade Analysis Project - Agriculture (GTAP-AGR)	European Simulation Model (ESIM)	Agricultural sector PE model	Top-down: Changes in import prices of agricultural commodities simulated in GTAP-AGR as exogenous inputs to ESIM	Henseler et al., 2013
	Join Research Centre General Equilibirum Model for Economcy – Energy – Environment (JRC-GEM-E3)	Prospective Outlook on Long-term Energy Systems (POLES) and Price-Induced Market Equilibrium System (PRIMES)	Energy sector PE models	Bottom-up: Energy model balances by fuel, sector, and region from POLES and PRIMES are mapped into JRC-GEM-E3 to reproduce energy balances in volumes as well as monetary values	Rey Los Santos et al., 2018
	Modular Applied GeNeral Equilibrium Tool (MAGNET)	Worldwide Agribusiness Linkage Program (AGLINK)	Agricultural sector PE model	Bottom-up: Projections of production changes and trade balances from AGLINK are incorporated into MAGNET by adjusting three parameters: armington elasticities, technical change, and sectoral productivity	Boulanger et al., 2016
	MAGNET	CAPRI	Agricultural sector PE model	Bottom-up: Projections of agricultural commodity production from CAPRI are used to calculate and apply shocks in MAGNET that will mimic CAPRI production levels	Phillipidis et al., 2017
	Modelling International Relationships in Applied General Equilibrium-Biofuels (MIRAGE-BioF)*	Agricultural Supply Model for Micro-economic policy Analysis (ASMMA) for France	Farm-based microeconomic supply model	Top-down: Relative price changes simulated using MIRAGE-BioF were passed to ASMMA to model farm-level reactions to an exogenous change in prices	Louhichi and Valin, 2012
	MIRAGE - Energy (MIRAGE-e)	Macroeconometrics of the Global Economy (MaGE)	Econometrically estimated long-run growth model	Bottom-up: Projections of current accounts imbalances, energy productivity, population growth, and regional GDP from MaGE are used to define exogenous values in MIRAGE-e	Fontagné et al., 2013
	Total Economy Assessment (TEA)	COmputable Framework For Energy and the Environment (COFFEE)	Energy sector PE model	Bottom-up: Projections of autonomous energy efficiency improvements, share of power generation by technology, energy trends, and GHG emissions from COFFEE are incorporated into TEA	Cunha et al., 2020
Two-way linkage	Dynamic Applied Regional Trade (DART)	Processes of Radiation, Mass and Energy Transfer (PROMET)	Crop model	Marginal profit functions of crops to land from DART and potential ecological yields are used to re-allocate sample points used in the crop model to generate agro-economic yields by agro-ecological zone (AEZ) for two climate scenarios. Resulting yields are used to change the land	Mauser et al., 2015, Delzeit et al., 2018

Linkage type	CGE model name	Linked model name	Linked model type	Linkage approach	Publication(s)
				productivity in the CGE model which results in new marginal profit functions of crops, a new re-allocation, and so on.	
	ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE)	Global Agriculture Perspectives System (GAPS)	Agricultural sector PE model	Point calibration of multiple parameters: macroeconomic information (GDP, share of agricultural sector on GDP, total GHG emissions), of ENVISAGE passed to GAPS. ENVISAGE is conditioned to the GAPS agricultural productivity, agricultural output and emissions from crops and livestock per scenario.	FAO, 2017
	GTAP	CAPRI	Agricultural sector PE model	Sequential calibration between CAPRI and GTAP until reaching convergence.	Jansson and Britz, 2010
	IMACLIM-R	Several PEs	Energy, transport sector PE models	Time recursive linking: the CGE model passes information about prices and sectoral demands at time t to PE models which compute and pass energy intensities and fuel mixes to the CGE model for computation at time t+1	Waisman et al., 2012
	MAGNET	AGMEMOD; Global Biosphere Management Model (GLOBIOM)	Agricultural sector PE models	Agricultural yields projected by GLOBIOM and agricultural production projected by AGMEMOD are incorporated into MAGNET, while trade outcomes simulated by MAGNET are fed back into AGMEMOD.	Wolf et al., 2016
	MAGNET	Land Simulation to Harmonize and Integrate Freshwater Availability and the Terrestrial Environment (LandSHIFT); BioENergy SImulation Model (BENSIM)	Land use change PE model; Bioenergy PE model	Production from MAGNET enters LandSHIFT and yields from LandSHIFT are fed to MAGNET. Prices from MAGNET enter BENSIM and biofuel supply from BENSIM are fed to MAGNET.	Thrän et al., 2016

Notes: In general, these studies conducted comparisons of the assumptions and outputs across the multiple models being used and made adjustments accordingly to increase consistency between the models, though the extent to which assumptions were harmonized and models were calibrated to be consistent varies across studies. In this table, we focus on the linkage approach and information passed between models.

* These are links to national models, see Appendix for details

Source: Author review of relevant literature.

2.1 One-way linkage

This section details several examples of one-way coupled models, which we grouped thematically into agricultural, energy, and macroeconomic linkages. One-way linkage is the most common linking approach and some models are even linked to multiple sector models to calibrate global CGE models to the baseline path of more detailed PE models. We provide here only an overview on the approach and return to a discussion of the methodological challenges involved in a later section.

2.1.1 Examples of agriculture and food system linking

This section elaborates on several examples of one-way baseline linking on agricultural and food systems.

ENV-Linkages is a CGE model developed and run at the OECD (Chateau et al., 2014a) and uses two PE models for the baseline calibration of its agricultural sector in bottom-up manner. While livestock feed efficiencies are obtained from the GLOBIOM model (Havlik et al., 2014), the general calibration of the ENV-Linkages agriculture system is based on the agricultural and food projections from the International Food Policy Research Institute's (IFPRI's) IMPACT V.3. model (Robinson et al., 2015). To link the two models, the nesting of crop land supply across agricultural activities in ENV-Linkages is adjusted to fit with IMPACT's elasticities of land supply by crops. In a second step, several parameters of the CGE model are calibrated to the IMPACT projections: (i) floor levels of per capita consumption for agriculture and food products are aligned to reproduce household demand of IMPACT, (ii) exogenous land efficiency from IMPACT (including the impact of climate change on these efficiency parameters) is imposed on ENV-Linkages and, (iii) total factor productivity for crops is adjusted to reproduce each regional share of crop production in world total production.

IFPRI performs a similar linking approach between the GLOBE CGE model (Ringler et al., 2016; Willenbockel et al., 2018) and the IMPACT model (Robinson et al., 2015). The starting point is a dynamic baseline scenario simulation generated by the IMPACT model. The IMPACT baseline paths for several exogenous drivers (i.e. GDP and population growth, supply price projections for matched agricultural commodities and the agricultural land use projections generated by IMPACT) are aggregated to match with the regional and sectoral aggregation structure of the GLOBE model. These time paths are passed to GLOBE and serve as inputs into the dynamic baseline calibration of the CGE model. Technically, the time paths for the parameters governing the growth rates of economy-wide labor-augmenting technical progress and the activity-specific total factor productivity parameters for agricultural sectors are calibrated such that GDP growth and the matched agricultural producer prices by region in the dynamic GLOBE baseline exactly replicate the aggregated IMPACT baseline.

Along the same lines, the European Joint Research Centre (JRC) performs a one-way linkage between the CGE model MAGNET (Woltjer and Kuiper, 2014) and the PE model AGLINK (Enciso et al., 2015) for the European Union (EU). Data from AGLINK projections on production change and trade balance evolvement over time is incorporated into MAGNET by adjusting by adjusting sectoral productivity, Armington elasticities, and technical change augmenting import of given commodities in the CGE model (Boulanger et al., 2016). The construction of the AGLINK projections not only involves market experts inside the European Commission but is also linked to a global medium-term market outlook organized jointly by the FAO and OECD, which draws on global Delphi processes among other things. The link between AGLINK and MAGNET thus provides an example how borrowing from a sectoral model implicitly transfers expert knowledge and detailed plausibility assessments into CGE baseline construction.

Britz and Hertel (2011) and Pelikan et al. (2015) combine bottom-up the PE model CAPRI (Britz and Witzke, 2014) and the GTAP model in a comparative-static analysis of policy shocks. Their approach is subsequently explored by Philipidis et al. (2017) in baseline generation. The approach can be understood as a meta-modeling exercise where the CGE model's supply response is parameterized to replicate the aggregate behavior of the more detailed PE. It is an example of a more advanced one-way PE-CGE linking based on the integration of a response surface within the CGE model beyond simple point calibration.[1] CAPRI disaggregates the EU to around 280 sub-national units with more details for crop and animal production compared to GTAP, including details on policy instruments such as coupled and decoupled payments, production quotas and set-aside obligations. The parameters that govern the crop supply responses in the non-linear programming approach of CAPRI are econometrically estimated (Jansson and Heckelei, 2011). That characteristic, along with the more detailed depiction of production technology and policy instruments in CAPRI motivates the tuning of the CGE supply responses to those of the PE model. To ease the linking exercise, the authors replace the usual CES-based depiction of production decision in the CGE model with a revenue maximization approach employing a quadratic normalized functional form. The Hessian of that function is simulated based on price sensitivity instruments with the PE and afterwards introduced in the CGE model. The authors show that the aggregate supply responses to price shocks with the CGE and PE models are very close, but deviate considerably from the unchanged CGE model. This is a concrete illustration of the benefit of model linking. The final top-down step uses the CGE price changes from a policy experiment to shock the PE model to derive more detailed impacts for individual crops and sub-national regions, including environment indicators. The approach

[1] EPA (2008) performs similar advanced one-way linkage between the ADAGE CGE model and the FASOM-GHG PE model.

is interesting as it ensures consistency in the behavioral response between the PE and the CGE model without requiring a two-way linkage between the models while opening the door to spell out more sectoral detail and additional indicators based on a PE model.

2.1.2 Examples of energy system linking

In the field of energy models linked to CGE models, the approaches are similar to the ones discussed for agricultural PEs.

OECD and the International Energy Agency (IEA) collaborate annually for the World Energy report. For this purpose a strategy of linking bottom-up ENV-Linkages to the energy-oriented IEA World Energy Model (WEM) (IEA, 2018) has been developed by Chateau et al. (2014a). Despite large differences in the nature and functioning of the two models, ENV-Linkages is calibrated to reproduce all energy-related patterns from the World Energy Outlook (WEO) scenarios and then to derive economic implications of IEA scenarios in its CGE framework. While it is possible to have a two-way coupling by feeding back information from ENV-Linkages to the WEM (by passing through GDP, energy prices and sectoral changes) this is rarely done.

Calibration efforts when coupling WEM to ENV-Linkages are devoted to key trends in (i) energy consumption by fuel, sector and country; (ii) fossil-fuel supply by country; and (iii) changes in electricity generation mix by country. These energy trends are captured indirectly by adjusting some of the CGE model parameters to accurately reproduce the outcomes of the WEO scenarios. Firstly, the sectoral autonomous energy efficiency rates of improvement by fuels of ENV-Linkages are adjusted to fit IEA energy demand projections. In addition, technical progress experienced in sectors of fossil-fuel extraction are adjusted to fit IEA fossil fuel production, CES parameters of electricity are calibrated to reproduce IEA power mix, and household preferences parameters are adjusted to match projected transportation fuel and heating fuel demands.

Similarly, the linking procedure between the CGE model TEA (Cunha et al., 2020) and the COFFEE energy model (Rochedo, 2016; Rochedo et al., 2018) relies on harmonization of base year data and trends, including: (i) energy production and consumption (fossil fuel used in electricity generation, fuel plants' energy consumption, and non-energy use); (ii) explicit technological representation of nuclear, hydro, wind, solar and biomass sources in TEA based on COFFEE parameters and data; (iii) implementation of autonomous energy efficiency improvement (AEEI) in TEA compatible with COFFEE assumptions; (iv) share of power generation and energy trends in TEA based on information from COFFEE; and (v) GHG emissions (CO_2, CH_4 and N_2O) in TEA based on data and projections from COFFEE. Data for electricity generation (in energy physical units) and production factors (capital, labor, services, resources, fuel and land) are inputted into TEA to explicitly represent nuclear, hydro, wind, solar and biomass

technologies. The production functions of these technologies are being changed from CES to Leontief structures such that the simulated energy mix from COFFEE fully drives the TEA energy coefficients. The power generation branch has fixed input proportions and the penetration of different technologies is determined by the COFFEE model.

A different approach is used by the JRC. They apply a procedure used to generate baselines for the JRC-GEM-E3 (Capros et al., 2013) model called PIRAMID (Platform to Integrate, Reconcile and Align Model-based Input-output Data): they first create input-output tables for future periods that reproduce outcomes from the PE energy models POLES-JRC (Després et al., 2018) and PRIMES (E3MLab, 2014) and then calibrate JRC-GEM-E3 to these input-output tables (Rey Los Santos et al., 2018). This approach maps the energy model balances across fuels, sectors and regions (in volumes) to the CGE model structure to create a similar energy balance in JRC-GEM-E3. The energy balances are converted to monetary terms (in values) using the energy prices from the PE energy models. Finally, these elements become part of input-output tables that the PIRAMID procedure produces. In essence, PIRAMID rebalances the input-output tables, taking the energy balance as a constraint. The energy use from the PE models can thus be directly reflected in the CGE model. This means that it goes beyond linking an energy model with a CGE model, as it also allows other exogenous assumptions (e.g. final demand structure, consumption of particular goods) to be reflected in the baseline. Although the creation of input-output tables with PIRAMID is to some extent model dependent, in principle the tables could be used by any other CGE model.

In addition, there are approaches where detailed country-based information is included into CGE models. Environment and Climate Change Canada (ECCC) uses two CGE models for policy analysis: an international multisector multi-regional CGE model (EC-MSMR) (ECCC, 2011) and a Canadian provincial CGE model (EC-PRO) (ECCC, 2018). To generate the integrated energy, emissions and economy baseline for its CGE models, ECCC first generates a long-term projection (i.e., either to 2030 or 2050 or beyond) using ECCC's Energy, Emissions and Economy Model for Canada (E3MC) (ECCC, 2011). A two-step procedure is followed for linking the baseline with the E3MC projection. First, a consistency check is conducted in benchmark input-output data and those in the E3MC energy, emissions and economic data. A recalibration exercise to minimize the differences in the energy flows in the E3MC data and those in the input-output table is undertaken. At the second step a forward projection routine is employed using GDP, population, energy flows and energy efficiency improvements (Zhu et al., 2018). The details are described in the oil and gas section of Faehn et al. (this issue).

2.1.3 Examples of macroeconomic linking

Finally, CGE models are sometimes linked to macroeconomic models to replicate growth paths of conditional convergence. The Centre d'Etudes Prospectives et d'Informations Internationnales (CEPII), OECD and Potsdam Institute for Climate Impact Research (PIK) all maintain both growth models and CGE models. Macroeconomic models provide a set of consistent macroeconomic projections for individual countries: investment and savings projections are determined jointly with GDP projections in such a way that at the global level current accounts are balanced. These one-sector growth models are generally not used for any policy purpose and by such rely on very simple and comprehensible economic relationships that make projections transparent to the users. These models are augmented Solow growth models, where a central piece is the notion of conditional convergence for individual drivers of the potential output (e.g. total factor productivity, human capital). The projections of GDP, investment and trade balances from macroeconomic models are aggregated across regions and are imposed on CGE models during the calibration of the baseline scenarios. These GDP projections are then endogenized in the CGE model to allow assessment of the impacts of alternative scenarios. Thus, the exogenous parameters in the CGE model, for example, productivity changes, are adjusted in the calibration process to mimic the macroeconomic growth paths from macroeconomic models. The two models are thus mutually consistent.

CEPII for example links the CGE model MIRAGE-e to the macro model MaGE that projects growth scenarios for 147 countries to 2050 (Fouré et al., 2013). This is done by aligning several variables between the two models that determine the macroeconomic projections and also play a significant role in CGE model. The link between the models is one-way from the macro to the CGE model but consistency is maintained in the sense that the CGE (MIRAGE-e) baseline trajectory is based on the output from the macroeconomic model MaGE (i.e. GDP, education, labor force, savings rate, current account, and energy efficiency) and both models share the same exogenous sources for population growth and energy prices (Fontagne et al., 2013).

The OECD proceeds in a similar way linking the ENV-Linkages model to the ENV-Growth model that projects 230 individual countries' growth paths up to 2060 (see Annex in OECD, 2019). The ENV-Growth model differs from the MaGE model in three aspects: first the saving-investment behavior slightly differs across the two models, secondly the law of motion of total factor productivity is not exactly estimated in the same way, and lastly the OECD model also encompasses some projection of natural resource rents for crude oil and natural gas as part of the projections of GDP for main fossil fuel exporters countries. Details on macroeconomic drivers are discussed in Fouré et al. (this issue).

2.2 Two-way linkage

The two-way linking approaches reviewed for generating global CGE baselines are based on the iterative or sequential calibration methods which consist of repeatedly interchanging certain variables between models until mutual consistency is achieved. At the same time, mutual consistency implies that responses of model variables to certain shocks are comparable. In CGE models like GTAP this is usually obtained by adjusting shifting-parameters (e.g. for technical change) (Jansson et al., 2009). Furthermore, if the interest is in the results of key variables in all models involved in the linking rather than on the "receiving" model alone, a two-way link is preferable over a one-way link. For example, one might be interested in combining detailed information on land use from a biophysical model with production and trade values from an economic oriented CGE model. In this case, a two-way link allows consistent reporting on production and trade values (CGE) along with detailed land use variables (biophysical model) within a baseline and for further scenario analysis.

2.2.1 Examples of agriculture and food system linking

In Wolf et al. (2016), a two-way linking approach is applied for the three models MAGNET (CGE), AGMEMOD (agricultural PE model of the EU, Chantreuil et al., 2012; Salamon et al., 2017) and GLOBIOM (global agricultural PE model with biophysical underpinnings, Havlik et al., 2014). They aim at a baseline with agri-food sector and land use detail, for instance for yield developments under consideration of biophysical aspects, factor movements between agricultural and non-agricultural sectors, considering in detail agricultural policies. The baseline generation iteratively links all models in the following sequence. Yield and land use changes from the global GLOBIOM model, which also models agricultural land expansion, are fed to AGMEMOD, a recursive-dynamic model with national resolution. Next, a MAGNET run takes production changes from AGMEMOD into account. Afterwards, information on changes in trade flows from MAGNET are incorporated into GLOBIOM. Finally, AGMEMOD re-runs with updated yield and land use changes from GLOBIOM and trade flows from MAGNET. This iterative process is repeated until convergence.

The MAGNET model is also combined with the LandSHIFT (Schaldach et al. 2011) and BENSIM (bioenergy PE model, Millinger et al., 2017) in an application to Germany as described in Thrän et al. (2016). This two-way coupling involves one feedback loop between MAGNET and LandSHIFT where production from MAGNET enters LandSHIFT and yields from LandSHIFT enters MAGNET until cropland area between both models converges. In a second feedback loop, prices from MAGNET enter BENSIM and biofuel supply from BENSIM enters MAGNET until prices between the models converge.

The FAO runs a two-way linking approach using point calibration of multiple parameters where ENVISAGE, a global CGE model (van der Mensbrugghe, 2013), is used complementary to the GAPS model (agricultural and food PE model, FAO 2017, Annex III). ENVISAGE is used 1) to inform data in GAPS to ensure that the size of the agricultural sector is consistent with the evolution of the economy (namely the assumed GDP) and the emissions of all economic activities as per representative concentration pathway (RCP) underlying each scenario and the allocation of the emissions to economic sectors as per the scenario narratives of the report, and 2) inform variables such as employment in agriculture and relative size of agriculture in the economy, which cannot be obtained by the GAPS model only. ENVISAGE is conditioned to the GAPS agricultural productivity, agricultural output and emissions from crops and livestock per scenario as well as to the GDP and population used in the GAPS projections and to the RCP-specific emission ranges. Specific adjustments in ENVISAGE were developed when checking the results against the scenario narratives, especially looking at capital accounts, investment to GDP ratios, energy efficiency and food preferences (the latter again to reflect the GAPS results on food [caloric] intake and consumer theory on food expenditure). However, definition incompatibilities between the data used in GAPS on agro-food commodities and ENVISAGE (that is between FAOSTAT's commodity balance sheets and the GTAP commodities) did not allow more systematic linkage of the two models (FAO, 2017).

In a recent OECD (2017) report, the OECD ENV-Linkages has also been coupled with the IMAGE model (Stehfest et al., 2014) hosted by the Netherland's Environmental Agency (PBL). Compared with the linking approach between ENV-Linkages and IMPACT (one-way coupling), the coupling is more integrated because ENV-Linkages first runs its baseline and then transmits to IMAGE the projections of agricultural output by crop and region as well as macroeconomic projections ones. Then IMAGE calculates changes in crops' yields and land use because of various shortages in water availability (or in response to some policy scenario) and these are fed back to ENV-Linkages as exogenous shocks on land efficiency and change of management practices in agricultural production.

To integrate climate change induced yield changes into a CGE baseline construction, a two-way linkage between the crop growth model PROMET (Mauser and Bach 2009), and the CGE model DART-BIO (Calzadilla et al., 2016) has been developed. As explained in detail in Mauser et al. (2015), agro-ecological potential yields (by PROMET), harvested areas, and crops' marginal profitability to land (both by DART-BIO) determine an agro-economic potential yield in an iterative approach. The background is as follows. The crop growth model simulates potential yields under different climate scenarios for 18 crops and 246,000 randomly chosen sample locations. Many such locations are found in each agro-ecological zone (AEZ), which is the level of disaggregation used as the land use simulation unit of DART-BIO. To take into account that land allocation to

crops changes under climate change in the crop growth model and to aggregate information on yields per crop for the sample location to 23 world regions and AEZs (used in DART-BIO), an iteration process is followed. Using the first derivative of crops to land, a function for the marginal productivity to land is derived. Along these functions, for 10 crop aggregates harvested areas per crop are reallocated assuming that marginal profits (taking into account potential yields by PROMET in tons per hectare) are highest for the first cultivated hectare of a crop since its production can take place at the most suitable location for the considered crop within a selected AEZ and region. Results are potential yields for 10 crop aggregates. To implement climate change into a baseline, potential agro-economic yields for two climate periods (1981-2010 and 2011-2040) are simulated, their relation is used as a shifter to the crop production functions of DART-BIO. Afterwards, the iterations between PROMET and DART-BIO are repeated until all land use and marginal profits converge (for details see Delzeit et al., 2018).

2.2.2 Examples of energy system linking

Two-way linkages to create consistency between energy PE models and CGE models seem to be implemented less often, at least for global models (see Krook-Riekkola et al., 2017 and Helgesen et al., 2018 for national examples). One example at global scale is Waisman et al. (2012). In the IMACLIM-R model, the two-way linkage between CGE and PE modules is sequential in time. At each annual time step, the PE modules for energy and transport sectors update their detailed supply projections based on input prices, mainly for energy, and sectoral demands (electricity, transport services, etc.) from the last CGE solution. To do so, the PE model defines first a projection of future demand under adaptive but imperfect expectations. From there, it computes the required incremental production capacities and their technological content. Finally, total updated production capacity is passed to the next year in the CGE model (i.e. capital stock and technical coefficients). The CGE model is then run with Leontief production functions with possible adjustment of the rate of utilization of installed capacities. As the linking is sequential in time, the demand projected under imperfect expectations by the PE model in a year will somewhat deviate from demand simulated by the CGE model. But the adaptive expectations in PE models guarantee the convergence in trend.

3. Methodological challenges

To pass information between models, models should start with a consistent baseline for the analysis. However, there are challenges to make baselines consistent when the different models use different modeling concepts or use variables that are inconsistent between the two models. Sometimes the distinction between model scope, boundary, and aggregation is blurred. In addition, there are practical issues that might hamper implementation, particularly when creating a consistent baseline. These aspects are discussed in some detail in the following sub-sections.

3.1 Differences in model scope, model boundaries and model concepts

Linking model aims at exploiting their complementary strengths but needs to deal with differences in model scope and resolution as well as modeling concepts and related underlying (implicit) assumptions. Best-practice linkage approaches aim at minimal differences in endogenous variables simulated by both the CGE and sectoral models and at harmonized exogenous assumptions driving the linked models, a point addressed later in more detail.

The more detailed PE models treat prices as exogenous that are endogenous to CGE models. This involves often primary factors and intermediates used in the production of goods on which the PE models focus. That motivates the use of a sequential top-down link from the CGE to the PE model as a recommendable practice where CGE price changes are passed to the PE model to increase coherence in baseline construction. In the opposite bottom-up direction, input demand changes from the sectors covered by the PE model should be made consistent to those simulated in the CGE model. Convergence in such two-way linkages involving input markets can be improved if the PE model does not treat input prices as fixed but instead uses an input supply function, which is parameterized to match the CGE model's behavior. That is especially relevant in soft linking without iterative exchange of results between time points as it helps to reduce differences.

Other drivers of the PE model should also be consistent with the baseline developed in the CGE model. Two cases can be differentiated here. The first one relates to drivers that are endogenous in the CGE model such as income or input prices, but exogenous in the PE model. That case was already discussed above. Secondly, it refers to drivers exogenous to both models of which some might even not be considered or treated as fixed at benchmark levels in specific models.

The calibration process of the ENV-Linkages baseline illustrates this point. The aim is to (1) reproduce IEA energy projections with the same underlying projections of economic activity (at least for energy-intensive activities) and (2) also implement the same energy policy reforms that IEA designed in its scenarios. If these drivers of energy demands were not aligned between the two models then

the adjusted parameters mentioned before, like autonomous energy efficiency improvements by sectors, would be wrongly adjusted and any future policy experiment with the CGE model could be wrong. In other words: the baseline could be approximatively similar between the two models but some trends would be inadequate in the CGE model[2].

The different foci of a specialized PE vs. a CGE vs. a macroeconomic model will mean that each modeling team will scrutinize certain outcomes far more than others. Having domain experts collaborate with CGE modeling teams can be extremely beneficial as sector-specific results receive greater scrutiny and insights from teams with sectoral expertise. However, that will also likely mean more iterations in refining results in baseline construction. Equally, the involved modelers or sectoral experts will probably differ in their assessment of plausible or likely developments, both exogenous and simulated, which can also slow down completion of modeling efforts.

Different classes of models might also use differing behavioral assumptions. Some agricultural models for example explicitly consider production and market risk in supply behavior. However, the resulting risk premium as a difference between marginal production costs and producer prices is absent when cost-minimization is assumed in a CGE model. This provides a challenge when aligning the supply response of the CGE model to PE results in a linking exercise.

CGE baseline construction can benefit from the more explicit representation of policy instruments in specialized PE models. For example, in the agricultural modeling context, risk-based instruments in the United States or the decoupling of farm support from production decisions might be hard to integrate in a CGE model. Similarly, complex tariff instruments, including quotas and tariffs differentiated by season and non-tariff measures might be explicitly considered in PEs. In some of cases, PE results could be used to derive ad-valorem equivalents which can be passed bottom-up to the CGE analysis. In other cases, shifters in the CGE model can be applied to align its response to changes in more complex policy instruments to the PE model. However, these differences in representing policies are clearly also a further cause for inconsistencies.

Furthermore, different functional forms or parametrizations imply inconsistencies (e.g. Schäfer and Jacoby, 2005). Some of these issues can be addressed, as discussed in the best practices developed in Section 4.

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[2] The one-way linkage calibration of the OECD ENV-Linkages energy system to the IEA-WEM model also take into accounts IEA information about energy efficiency investments, and the corresponding energy savings technologies in various sectors. For sake of simplicity this procedure is not described here; for more information please see the original paper Chateau et al. (2014a).

3.2. *Differences in data aggregation and data definition*

In addition to differences in model scope and boundaries, differences in data definition or aggregation are methodological challenges in linking models. In this sub-section, we refer to overlapping variables that are present in both models and will serve as the connector to link models. A frequent challenge that arises is that the same variable is defined differently in the models being linked, because of different underlying data sources or different modeling concepts. Generally, harmonization of such variables is difficult. We provide some examples where differences in variable definitions or conventions commonly appear in model linkages.

First, gaps can exist between the linked models about variable definitions in terms of aggregation and coverage. Differences can first occur in regional coverage between the models, for example, when aggregate regions are defined differently. Second, there are usually differences regarding how goods and sectors are defined in PE and CGE models. For instance, the aggregation of energy goods in the GTAP database differs from those of energy models. To give three examples, in the GTAP database: i) the petroleum and coal products sector includes both solid- (coke) and liquid-based (oil) products whereas energy models usually distinguish between the two – additionally, coke and oil products have different emission factors; ii) a single sector includes both electricity and heat production whereas energy models usually distinguish between the two; and iii) there are two gas sectors (extraction and distribution) whereas energy models do not make this distinction. The gap in variable definition can also be about end-use demand for energy and agricultural commodities. For instance, in PE agricultural models, total final demand for agricultural products is a single variable for a given commodity, whereas CGE models distinguishes between final consumption from households and intermediary consumption of agricultural products from food processing sectors, following the standard economic accounting of final vs. intermediary consumption. Similar differences can appear for final energy consumption where CGE models distinguish between household energy consumption (for housing or own transport services) and intermediary consumption of different productive sectors (e.g., industry and transport service sectors).

A second challenge relates to the different accounting approaches of variables that measure the same phenomenon, but are expressed in different units in the linked models. For instance, most agricultural PE models implement the concept of primary product equivalents underlying the commodity balances of FAOSTAT. Final demand of processed products - such as bread - is expressed based on conversion factors in weight of the main agricultural primary commodity. That accounting scheme does not fit well to the description of value chains and volumes via input-output coefficients as found in CGE models. More fundamentally, PE models are often based on physical accounting of energy or agricultural flows,

whereas CGE models rely on economic accounting. Thus, energy PE models account for energy flows in physical units (e.g., million tons), whereas CGE models accounts for the same flows in value terms calibrated on national accounts. Although this is usually done for practical reasons and the choice of quantities in either physical units or in base year dollars, conversion rules have thus to be implemented between the linked models (Krook-Riekkola et al., 2017). Using functions that preserve value but not quantity like CES functions in the CGE model can be an additional difficulty to the task. In practice, a mismatch between physical and economic accounting appears when different "qualities" (and hence different prices) of energy or other goods are aggregated within a single economic sector. For example, in the GTAP framework, both heat and electricity are aggregated in the "ely" sector whereas energy models distinguish heat and electricity physical flows. Yet, electricity is much more valuable than heat in economic terms and hence reaches a higher price per kilowatt hour. Therefore, a gap can appear in practice about the evaluation of "ely" consumption across end-uses, whether it is based on energy accounting or economic accounting derived from an average price index. Physical flows may not be proportional to economic "volumes" in the CGE model. This difficulty also applies to different refined products in an aggregated refined products sector. This is also an issue for agricultural modeling when counting tons or calories vs. value flows.

A specific problem when linking CGE with biophysical models is to identify and then take into account the difference between physical areas and harvested areas. The underlying database in CGE models using the GTAP database are harvested areas by crop. These areas include multiple cropping. Plant growth models run on physical areas such that a multiplier needs to be added once information on areas is exchanged.

A third type of challenge appears when the same variables are calibrated or conceived differently in the linked models and thus are already initially inconsistent. For instance, price variables can be highly inconsistent between models for a range of reasons. In some cases when the definition/calibration of baseline trade and transport margins are significantly different, it results in very different gaps between producer and consumer prices (e.g., IMPACT and GLOBE models). Other price inconsistencies come from the fact that CGE models usually rely on uniform prices of, for example, energy commodities across consumers (outside taxes and transport/commercial margins), whereas PE models account for sector-specific consumer prices (e.g., differentiated gas and electricity prices for households and industries).

Because of the differences in representations between PE and CGE models, harmonizing the specifications of technologies may entail specific difficulties. Most importantly, modeling the evolution of technology efficiencies in baselines poses a challenge. For instance, the production of electricity with different technologies is typically expressed differently in CGE and PE models. An energy

PE model will rely on thermodynamic efficiency (1 million tons of coal is transformed into a given amount of kilowatt hour of electricity). In contrast, in a CGE model, economic accounting will translate how one monetary unit of electricity requires a given economic amount to be produced, although the use of additional data in calibration can remedy this problem. Harmonization becomes even more complex when looking at other inputs like capital, which is represented as a fixed cost in a PE model and discounted at a given rate, while it is a more fluid factor input in CGE models, remunerated at a rate that results from the capital market.

3.3. *Implementation issues*

Further challenges that might impede model linking are of a practical nature. Models written in different software platforms might make it more cumbersome to run on the same computing environment or exchange information in data formats tailored to specific modeling software. Exchanging information between models is especially challenging in two-way linkages. Repeatedly interchanging variables between models with different characteristics (e.g. different software or data formats) is technically challenging, time consuming and error prone. Doing this in a largely automated way however is not always a solution. When the reactions to changes in the update process do not fulfill certain mathematical stability requirements, convergence may not be achieved (Jansson et al., 2009). Furthermore, when coupling models using two-way linking, the convergence is frequently assessed based on one or some variable endogenous to the models, only.

Running models from different teams on a single infrastructure might raise fears on model ownership. Running the models by different teams will increase the effort required to send intermediate data between models. With a trend toward more open-source modeling tools, this issue might become less relevant over time.

The implementation strategy can further influence the outcome. Soft-linking approaches are often implemented using ad hoc approaches rather than a systematic framework. Therefore, the variables that are linked can vary considerably depending on prejudices of the model scenario in question (i.e. the scenario design or type of shocks) (M'Barek et al., 2017).

4. Best practices in current models and suggestions for the future

The frequent use of model linkage suggests that CGE modelers expect benefits from model linkage. We found that inconsistencies can however challenge these benefits which motivates us to thrive for greater consistency in the data being used within linked models and to implement relatively advanced two-way linkages. However, the development and maintenance of sophisticated modeling systems that often involve multiple institutions will also tend to be more resource-intensive. Thus, it is important to consider the tradeoffs associated with

incorporating more data and models through linkages within a broader modeling system then defining best practice cases.

Inconsistencies can question potential improvements from linking but need to be compared with not linking. Especially if the CGE model does not consider an important driver at all, such as impacts of climate change on agricultural yields, inconsistencies might be accepted in order to integrate the driver in the CGE baseline construction.

Both types of linking require consistent data. Harmonization of baselines across models as started in AgMIP (von Lampe et al., 2014) helps to set up standards and increase comparability across models. Such model comparison exercises have also elaborated harmonized formats for comparing model results across the CGE and PE models participating in these efforts. Careful attention to harmonization of inputs and outputs and ensuring data consistency is valuable not only for comparing across models, but for individual modeling teams utilizing multiple linked models. Several modeling teams have put efforts in creating consistent databases for the models to be linked, the JRC being one example with the PIRAMID approach (Wojtowicz et al., 2019). Likewise, best practice in case of consistency in baseline pathways implies that models involved in linking start from the same consistent baseline or calibrate to the same pathways generated with other models, for instance, macroeconomic and population projections (e.g. FAO, 2017).

Best practices depend on the modeling objective: one-way linking is sufficient if the focus is on an economy-wide picture based on given sectoral pathways/constraints. Two-way linking is a better choice if modelers seek a broader PE/CGE consistent picture with multiple dimensions. To support this choice, we identified a best practice example, the linking of ENV-Linkages and IMAGE: a two-way linking is only performed if the global feedback effect of a one-way link on the parameter that is passed from one model to the other is larger than 1% and not large on regional levels either.

In most one-way linking approaches, linkages are simply calibration exercises with little effort to make responses between models more similar. A best practice example for one-way linking is the link developed by Pelikan et al. (2015) to render the behavioral responses between a PE and CGE model consistent. By using a response-surface approach instead of simple point calibration, the authors move towards harmonized model behavior to decrease divergence in overlapping endogenous variables. This application for a policy shock can be applied to baseline generation.

Advanced two-way linking promises the most consistency but also requires the most effort to develop and maintain. Substantial investments of resources and close collaboration are preconditions for more advanced two-way linking approaches. Aiming to implement the impact of climate change on crop yields, the linking approach developed by Mauser et al. (2015) is a good example, because it

takes into account changing land allocation to crops over time because of changing cropping decisions of farmers, food consumption behavior, climate change or technological progress. Reflecting economic behavior in land allocation overcomes the important drawback of crop models that keep cropped areas constant over time when simulating yields. In the case of energy PE models and CGE modes, two-way linkages seem to be implemented less often, at least for global models. Here the approach followed by Krook-Riekkola et al. (2017) using national models, shows that this is a useful exercise and can improve the energy projections in baselines. It could be promising future research to implement this approach into global models.

Another challenge for model linking is different opinions of involved modelers in their assessment of plausible or likely developments. A best practice approach is performed in the development of the AGLINK baseline (used in Boulanger et al. 2016) where Delphi panels or agreements on who checks what, combined with clear timelines agreed beforehand, ensure convergence and avoid conflict escalation to a point where cooperation collapses.

There remain important questions related to how rigorously linkages must be implemented for them to improve model results. Is linking to a PE model that relies on data and parameters that are not entirely consistent with the CGE model better than not linking at all? At what point are models consistent enough to reflect key interactions in a reasonable way? How much do differences in methods used for model linkages account for variation in outputs across different CGE models? Are there patterns in the way that models are likely to respond to a given policy shock based on the methods used for their linkages? Would the same model provide substantially different results if the model linkage were implemented in a different way? Which linkages are most important for accurate depiction of key outcomes? How large must interactions be for models with more sophisticated linkages to provide substantially different answers? The answers to many of these questions will depend on the research or policy questions being addressed but are important to consider more broadly when generating baselines.

Modeling comparison activities, possibly conducted within existing initiatives that focus on specific topics (e.g. AgMIP on food and agriculture, EMF on energy) could test different linking approaches within individual models as well as across models. For instance, ad hoc rules for maximum feedback effects in one-way linking approaches could be tested across modeling teams. Furthermore, differences between stand-alone and combined solutions should be reported and the choices made in model linking should be motivated clearly in future research. This allows not only systematic comparison of different outcomes, but also assessment of linking approaches with respect to efficiency measures evaluating resources required for model development and application vs improvement in results. In the literature we see a first approach by linking MAGNET to different PEs in various ways (see Table 1).

We did not discover low-hanging fruits in model linking because these efforts come along with substantial investments in time and/or human resources. Only teams with sufficient personnel are able to do so. Thus, it is important for research funding agencies (as well as researchers themselves) to have a greater understanding of the extent to which resources devoted to increasing the quantity and quality of model linkages are likely to result in better baseline characterization and improved insights from model results. In areas where such model enhancements offer substantial improvements, research funding agencies should enable (more) funding measures across research groups regardless of the country where they are based to encourage more inter-institutional and international cooperation among research groups best-suited to specific components of more comprehensive modeling systems.

This relates to the fact, that there are often institutional reasons for selecting specific models for linking. We believe that there could be significant improvements in linking if the model choice was based on structural and no institutional reasons.

Acknowledgements

References

Beach, R. H., D. M. Adams, R. J. Alig, J. S. Baker, G. S. Latta, B. McCarl, B. C. Murray, S. K. Rose, and E. M. White. 2010. "Model documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG)." Prepared for U.S. Environmental Protection Agency. http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf

Böhringer, C. 1998. "The synthesis of bottom-up and top-down in energy policy modeling." *Energy Economics*, 20: 233–248.

Böhringer, C., and T.F. Rutherford. 2008. "Combining bottom-up and top-down." *Energy Economics,* 30: 574–596.

Böhringer, C., and T.F. Rutherford. 2009. "Integrated assessment of energy policies: Decomposing top-down and bottom-up." *J. Econ. Dyn and Control,* 33: 1648–1661.

Boulanger, P., H. Dudu, E. Ferrari, M. Himics, and R. M'barek. 2016. "Cumulative economic impact of future trade agreements on EU agriculture." JRC Science for Policy Report, EUR 28206 EN. doi: 10.2788/194880.

Britz, W. 2008. "Automated model linkages: the example of CAPRI." *German Journal of Agricultural Economics*, 57(8):363-367.

Britz, W. and T.W. Hertel. 2011. "Impacts of EU biofuels directives on global markets and EU environmental quality: An integrated PE, global CGE analysis." *Agriculture, Ecosystems & Environment*, 142(1–2):102-109. doi: 10.1016/j.agee.2009.11.003.

Britz, W. and H.P. Witzke (Eds.). 2014. "CAPRI model documentation 2014." https://www.capri-model.org/docs/capri_documentation.pdf

Britz, W., M. van Ittersum, A.O. Lansink, and T. Heckelei. 2012. "Tools for integrated assessment in agriculture. State of the art and challenges." *Bio-based and Applied Economics*, 1(2):125-150. doi: 10.13128/BAE-11232.

Cai, Y., R. Beach, K. Antonio, and J. Jones. 2018. "Documentation of the Recursive-Dynamic Version of the Applied Dynamic Analysis of the Global Economy (ADAGE) Model." Report prepared for the U.S. Environmental Protection Agency.

Capros, P., D. Van Regemorter, L. Paroussos, P. Karkatsoulis, C. Fragkiadakis, S. Tsani, I. Charalampidis, and T. Revesz. 2013. "GEM-E3 model documentation." JRC Scientific and Policy Reports 2603. doi: 10.2788/47872.

Calzadilla, A., R. Delzeit, and G. Klepper. 2016. "Assessing the Effects of Biofuel Quotas on Agricultural Markets." In *World Scientific Reference on Natural Resources and Environmental Policy in the Era of Global Climate Change,* edited by T. Byrant, 3: 399-442. doi: 10.1142/9789813208179_0013.

Chateau, J., B. Magné, and L. Cozzi. 2014a "Economic Implications of the IEA Efficient World Scenario." OECD Environment Working Papers, 64, OECD Publishing, Paris, doi:10.1787/5jz2qcn29lbw-en.

Chateau, J., R. Dellink, and E. Lanzi. 2014b. "An Overview of the OECD ENV-Linkages Model: Version 3.", OECD Environment Working Papers, 65, OECD Publishing. doi:10.1787/5jz2qck2b2vd-en.

Chantreuil, F., K. F. Hanrahan, and M. van Leeuwen, ed. 2012. *The Future of EU Agricultural Markets by AGMEMOD*. Dortrecht, Springer. doi: 10.1007/978-94-007-2291-0.

Crespo del Granado, P., R.H. van Nieuwkoop, E.G. Kardakos, and C. Schaffner. 2018. "Modelling the energy transition: A nexus of energy system and economic models." *Energy Strategy Reviews*, 20: 229-235. doi: 10.1016/j.esr.2018.03.004.

Cunha, B. S. L., R. Garaffa, and A. C. Gurgel. 2020. "TEA Model documentation", FGV EESP – FGVAGRO n.001. Working Paper Series 520. São Paulo, Brazil. https://hdl.handle.net/10438/28756

Dellink, R., van der Mensbrugghe, D. and B. Saveyn. 2020. "Shaping baseline scenarios of economic activity with CGE models: introduction to the special issue". *Journal of Global Economic Analysis* 5(1):1-27.

Delzeit, R., G. Klepper, F. Zabel, and W. Mauser. 2018. "Global economic-biophysical assessment of midterm scenarios for agricultural markets - biofuel policies, dietary patterns, cropland expansion, and productivity growth." *Environmental Research Letters*, 13(2). doi: 10.1088/1748-9326/aa9da2.

Després, J., K. Keramidas, A. Schmitz, A. Kitous, and B. Schade. 2018. "POLES-JRC model documentation – 2018 update." JRC Technical Report EUR 29454 EN, doi:10.2760/814959.

E3MLab. 2014. "Primes model 2013-2014: Detailed model description. " https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/primes_model_2013-2014_en.pdf.

ECCC. 2011." Canada's Emissions Trends, Annex 3" https://www.ec.gc.ca/doc/publications/cc/COM1374/ec-com1374-en-annx3.htm

ECCC. 2018. "Carbon Pricing in Nunavut–Potential Impact Analysis" https://www.gov.nu.ca/sites/default/files/carbon_pricing_analysis_-_nunavut_-_jan_2018.pdf

Enciso, S. R.A., I. Pérez Dominguez, F. Santini, and S. Hélaine. 2015. "Documentation of the European Comission's EU module of the Aglink-Cosimo modelling system." JRC Science and Policy Reports, JRC92618, EUR 27138 E. doi: 10.2791/675854.

Fæhn T., G. Bachner, R. Beach, J. Chateau, S. Fujimori, M. Ghosh, M. Hamdi-Cherif, E. Lanzi, S. Paltsev, T. Vandyck, B. Cunha, R. Garaffa, and K. Steininger 2020. "Capturing key energy and emission trends in CGE models: Assessment of Status and Remaining Challenges". *Journal of Global Economic Analysis*, 5(1): 196-272.

FAO. 2017. "The future of food and agriculture: Trends and challenges." Food and Agriculture Organization of the United Nations: Rome, Italy. http://www.fao.org/3/a-i6881e.pdf.

Fontagné, L., J. Fouré, and M.P. Ramos. 2013. "MIRAGE-e: A General Equilibrium Long-term Path of the World Economy." CEPII Working Paper 2013-39, CEPII. http://www.cepii.fr/PDF_PUB/wp/2013/wp2013-39.pdf.

Foure, J., A. Aguiar, R. Bibas, J. Chateau, S. Fujimori, J. Lefevre, M. Leimbach, L. Rey-Los-Santos and H. Valin, 2020. "Macroeconomic drivers of baseline scenarios in dynamic CGE models: review and guidelines proposal". *Journal of Global Economic Analysis*, 5(1): 28-62.

Fujimori, S., K. Oshiro, H. Shiraki, and T. Hasegawa. 2019. "Energy transformation cost for the Japanese mid-century strategy." *Nat. Commun*, 10: 1–11.

Havlik, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, P. K. Thornton, H. Bottcher, R. T. Conant, S. Frank, S. Fritz, S. Fuss, F. Kraxner, and A. Notenbaert 2014. "Climate change mitigation through

livestock system transitions." *Proc Natl Acad Sci U S A*, 111(10):3709-14. doi: 10.1073/pnas.1308044111.

Helgesen, P.I., A. Lind, O. Ivanova, and A. Tomasgard. 2018. "Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport" *Energy*, 156: 196–212.

Henseler, M., I. Piot-Lepetit, E. Ferrari, A.G. Mellado, M. Banse, H. Grethe, C. Parisi, and S. Hélaine. 2013. "On the asynchronous approvals of GM crops: Potential market impacts of a trade disruption of EU soy imports." *Food Policy*, 41(2013):166-176. doi: 10.1016/j.foodpol.2013.05.005.

International Energy Agency (IEA). 2018. World Energy Model Documentation, Version 2018. https://www.iea.org/media/weowebsite/energymodel/WEM2018.pdf

Jansson, T., M.H. Kuiper, and M. Adenäuer. 2009. "Linking CAPRI and GTAP, SEAMLESS Report No.39, SEAMLESS integrated project." EU 6th Framework Programme, contract no. 010036-2, www.SEAMLESS-IP.org, 100 pp. ISBN no. 978-90-8585-127-1.

Jansson, T., and W. Britz. 2010. "Sequential calibration of economic simulation models, the cases of CAPRI and a CAPRI-GTAP link." Paper presented at the Annual Conference on Global Economic Analysis, Bangkok, Thailand, June 9-11, 2010. https://www.gtap.agecon.purdue.edu/resources/download/4991.pdf.

Jansson, T., and T. Heckelei. 2011. "Estimating a Primal Model of Regional Crop Supply in the European Union." *Journal of Agricultural Economics*, 62(1): 137-152. doi:10.1111/j.1477-9552.2010.00270.x.

Kaya, A., D. Csala, and S. Sgouridis. 2017. "Constant elasticity of substitution functions for energy modeling in general equilibrium integrated assessment models: a critical review and recommendations" *Climate Change*, 145: 27–40.

Krook-Riekkola, A., C. Berg, E.O. Ahlgren, and P. Söderholm. 2017. "Challenges in top-down and bottom-up soft-linking: lessons from linking a Swedish energy system model with a CGE model." *Energy*, 141: 803-817. doi: 10.1016/J.ENERGY.2017.09.107.

Lanz, B., and S. Rausch 2011. "General equilibrium, electricity generation technologies and the cost of carbon abatement: A structural sensitivity analysis" *Energy Economics*, 33: 1035–1047.

Louhichi, K., and H. Valin. 2012. "Impact of EU biofuels policies on the French arable sector: A micro-level analysis using global market and farm-based supply models." *Review of Agricultural and Environmental Studies*, 93(3):233-272.

Mauser, W., G. Klepper, F. Zabel, R. Delzeit, T. Hank, B. Putzenlechner, and A. Calzadilla. 2015. "Global biomass production potentials exceed expected future demand without the need for cropland expansion." *Nature Communications*, 6. doi: 10.1038/ncomms9946.

Mauser, W., and H. Bach. 2009. "PROMET – Large scale distributed hydrological modelling to study the impact of climate change on the water flows of mountain watersheds." *Journal of Hydrology*, 376(3): 362-377. doi: 10.1016/j.jhydrol.2009.07.046.

M'barek, R., J. Barreiro-Hurle, P. Boulanger, A. Caivano, P. Ciaian, H. Dudu, M. Espinosa, T. Fellmann, E. Ferrari, S. Gomez y Paloma, C. Gorrin Gonzalez, M. Himics, K. Louhichi, A. Perni, G. Philippidis, G. Salputra, P. Witzke, and G. Genovese. 2017. "Scenar 2030 - Pathways for the European agriculture and food sector beyond 2020." EUR 28797 EN, Publications Office of the European Union, Luxembourg, doi:10.2760/887521, JRC108449.

Millinger, M., J. Ponitka, O. Arendt, and D. Thrän. 2017. "Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany." *Energy Policy*, 107:394-402. doi: 10.1016/j.enpol.2017.05.013.

OECD. 2017. "The Land-Water-Energy Nexus: Biophysical and Economic Consequences." OECD Publishing, Paris, doi:10.1787/9789264279360-en.

OECD. 2019. "Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences." OECD Publishing, Paris, doi:10.1787/9789264307452-en.

Pelikan, J., W. Britz, and T.W. Hertel. 2015. "Green Light for Green Agricultural Policies? An Analysis at Regional and Global Scales." *Journal of Agricultural Economics*, 66(1):1-19. doi: 10.1111/1477-9552.12065.

Philipidis, G., J. Helming, A. Tabeau. 2017. "Model linkage between CAPRI and MAGNET: An exploratory assessment." EUR 28625 EN, Publications Office of the European Union, Luxembourg. doi:10.2760/712139, JRC106595.

Rey Los Santos, L., K. Wojtowicz, M. Tamba, T. Vandyck, M. Weitzel, B. Saveyn, and U. Temursho. 2018. "Global macroeconomic balances for mid-century climate analyses - Supplementary material to Global Energy and Climate Outlook 2018." JRC Technical Report EUR 29490 EN, doi: 10.2760/858469.

Ringler, C., D. Willenbockel, N. Perez, M. Rosegrant, T. Zhu, and N. Matthews. 2016. "Global Linkages among Energy, Food and Water: An Economic Assessment." *Journal of Environmental Studies and Sciences*, 6:161-171. doi: 10.1007/s13412-016-0386-5.

Robinson, S., D. Mason-D'Croz, S. Islam, T.B. Sulser, R. Robertson, T. Zhu, A. Gueneau, G. Pitois, M. Rosegrant. 2015. "The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3." IFPRI Discussion Paper No 01483. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.

Rochedo, P. R. R. 2016. "Development of a global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios." PhD thesis, PPE-COPPE/UFRJ, 08 2016.

Rochedo, P.R.R., B. Soares-Filho, R. Schaeffer, E. Viola, A. Szklo, A. F.P. Lucena, A. Koberle, J. Leroy Davis, R. Rajão, and R. Rathmann. 2018. "The threat of political bargaining to climate mitigation in Brazil." *Nature Climate Change*, 8(8): 695. doi: 10.1038/s41558-018-0213-y.

Ross, M. (2009). Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) Model. Working paper 09_01. Research Triangle Park, NC: RTI International.

Ross, M.T., B.J., DeAngelo, R.H. Beach, M.P. Gallaher, S.K. Pattanayak, C. Poulos, and S. Waldhoff. 2009. "Representing the impacts of climate change in a US economic model." *IOP Conference Series: Earth and Environmental Sciences*, 6, 522007. Copenhagen, Denmark. https://iopscience.iop.org/article/10.1088/1755-1307/6/52/522007/pdf.

Salamon, P., M. Banse, J. Barreiro-Hurle, O. Chaloupka,T. Donnellan, E. Erjavec, F. Fellmann, K. Hanrahan, M. Hass, R. Jongeneel, V. Laquai, M. Van Leeuwen, A. Molnara, M. Pechrova, G. Salptura, W. Baltussen, J. Efken, S. Helaine, J. Jungehülsing, O. Von Ledebur, I. Rac, and F. Santini. 2017. "Unveiling diversity in agricultural markets projections: from EU to Member States. A medium-term outlook with the AGMEMOD model." JRC Technical Report, 29025 EUR, Publications Office of the European Union, Luxembourg. ISBN 978-92-79-77335-8, doi:10.2760/363389.

Schäfer, A., and H.D. Jacoby. 2005. "Technology detail in a multisectoral CGE model: transport under climate policy." *Energy Economics*, 27(1):1-24. doi: 10.1016/j.eneco.2004.10.005.

Schaldach, R., J. Alcamo, J. Koch, J., C. Kölking, D.M. Lapola, J. Schüngel, and J.A. Priess. 2011. "An integrated approach to modelling land-use change on continental and global scales." *Environmental Modelling & Software,* 26(8):1041-1051. doi: 10.1016/j.envsoft.2011.02.013.

Stehfest, E., D. van Vuuren, T. Kram, and L. Bouwma. 2014. "Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications." PBL Netherlands Environmental Assessment Agency, The Hague. https://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2014-integrated%20assessment%20of%20global%20environmental%20change%20with%20image30_735.pdf.

Thrän, D., R. Schaldach, M. Millinger, V. Wolf, O. Arendt, J. Ponitka, S. Gärtner, N. Rettenmaier, K. Hennenberg, and J. Schüngel. 2016. "The MILESTONES modeling framework: An integrated analysis of national bioenergy strategies and their global environmental impacts." *Environmental Modelling & Software,* 86:14-29. doi: 10.1016/j.envsoft.2016.09.005.

EPA.(U.S. Environmental Protection Agency). (2008. "EPA Analysis of the Lieberman-Warner Climate Security Act of 2008." EPA Analysis of S. 2191.

https://archive.epa.gov/epa/sites/production/files/2016-07/documents/s2191_epa_analysis.pdf.

van der Mensbrugghe, D. 2013. "Modeling the global economy - Forward-looking scenarios for agriculture" In *Handbook of Computable General Equilibrium Modeling*, edited by P.B. Dixon and D.W. Jorgenson. Elsevier, 1B: 933–994. www.sciencedirect.com/science/article/pii/B9780444595683000146.

von Lampe, M., D. Willenbockel, H. Ahammad, E. Blanc, Y. Cai, K. Calvin, S. Fujimori, T. Hasegawa, P, Havlik, E. Heyhoe, P. Kyle, H. Lotze-Campen, D. Mason-D'Croz, G.C. Nelson, R.D. Sands, C. Schmitz, A. Tabeau, H. Valin, D. van der Mensbrugghe, and H. van Meijl. 2014. "Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison" *Agricultural Economics*, 45(1): pp. 3-20. doi: 10.1111/agec.12086.

Waisman, H., C. Guivarch, F. Grazi, and J.C. Hourcade. 2012. "The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight." *Climatic Change*, 114(1):101–120. doi: 10.1007/s10584-011-0387-z.

Wene, C.O. 1996. "Energy-economy analysis: Linking the macroeconomic and systems engineering approaches." *Energy*, 21(9):809:824. doi: 10.1016/0360-5442(96)00017-5.

Weyant, J., and E. Kriegler. 2014. "Preface and introduction to EMF 27." *Climatic Change*, 123(3-4):345-352. doi: 10.1007/s10584-014-1102-7.

Willenbockel, D., S. Robinson, D. Mason-D'Croz, M.W. Rosegrant, T.B. Sulser, S. Dunston, and N. Cenacchi. 2018. "Dynamic Computable General Equilibrium Simulations in Suport of Quantiative Foresight Modeling to Inform the CGIAR Research Portfolio: Linking the IMPACT and GLOBE Models." IFPRI Discussion Paper 01738. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/132757.

Wojtowicz, K., L. Rey, U. Temursho, B. Saveyn, T. Vandyck, M. Tamba, and M. Weitzel. 2019. „PIRAMID: a new method to generate future input-output tables for baseline building." Presentation at the 22nd GTAP conference, Warsaw, Poland. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5696

Wolf, V., A. Deppermann, A. Tabeau, M. Banse, S. van Berkum, M. Haß, P. Havlik, G. Philippidis, P. Salamon, and M. Verma. 2016. "Linking three market models to project Russian and Ukrainian wheat markets till 2030." Presentation at the 155th EAAE Seminar, Kiev, Ukraine. https://literatur.thuenen.de/digbib_extern/dn057299.pdf.

Woltjer, G., and M. Kuiper. 2014. "The MAGNET model: Module description." The Hague: LEI Wageningen UR. http://edepot.wur.nl/310764.

Zhu, Y., M. Ghosh, D. Luo, N. Macaluso, and J. Rattray. 2018. "Revenue Recycling and Cost Effective GHG Abatement: An Exploratory Analysis Using a Global Multi-Sector Multi-Region CGE Model." *Climate Change Economics,* 9(1):1840009. doi: 10.1142/S2010007818400092.

Appendix

Some modeling teams use country-specific information to feed their CGE model. In the United States, the U.S. Environmental Protection Agency has used soft linkages between ADAGE (Ross, 2009) and partial equilibrium models such as FASOM-GHG (Beach et al., 2010) and IPM to assess economy-wide environmental legislation. FASOM-GHG is a detailed PE model of the U.S. forest and agricultural sector that was used to simulate carbon offset supply curves that were then used within ADAGE for carbon policy analyses. Key ADAGE outputs such as CO_2 allowance prices and percentage change in energy demand under a variety of policy scenarios were passed to IPM, which then simulated detailed changes in energy supply, fuel use, and emissions based on those aggregate impacts from ADAGE (EPA, 2008). There is ongoing work to link additional global and national PE models of the agricultural, energy, and transportation sectors to ADAGE in support of analyses at multiple scales. In another study, FASOM-GHG was used to simulate potential changes in agricultural productivity and production under alternative climate change scenarios and the model outputs were used to provide aggregate agricultural productivity impacts as an input to ADAGE to explore interactions between the agricultural under climate change and the rest of the economy (Ross et al., 2009).

Though not used for baseline calibration but for an analysis of a policy, an interesting approach is to link CGE and farm models. In Louhichi and Valin (2012), a soft modeling linkage between the MIRAGE-BIOF CGE and a French farm model, ASMMA (sampling 2,534 representative farms), projects a baseline from 2006 to 2020 to test the impact of biofuel policies. The supply side of the CGE is recalibrated to fit the supply response functions of the farm model and ensure consistent model responses. Price outputs from the recalibrated CGE model were fed as input to the ASMMA farm model to derive the impacts on representative farms in France on an extended set of indicators, including farm income and pesticide applications.