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Creating global scenarios of environmental impacts with structural economic models

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Chapter 2

Models for socio-economic scenario analysis and climate change

Abstract

Global climate change scenario studies employ models that range from simple regression models to computable general equilibrium (CGE) models, macro-econometric models and integrated assessment models (IAM). Recently global multi-regional environmentally extended input-output tables (MRIOT) have also been used to model the greenhouse gas (GHG) emissions until 2050 in different socio-economic scenarios. This type of scenario modelling is a new approach in global climate change scenario studies that has recently become possible with the recent creation of global multi-regional input-output tables. In this study it is investigated what the contribution of the global MRIOT based scenario tool can be in this mature research area. For this purpose different model types were evaluated in terms of their description of the economic system, environmental system, the solution mechanism used to calculate the GHG emissions for a particular scenario and how accessible the models (results) are to external researchers. The evaluation shows that all modelling approaches rely on extrapolation of past trends and that they do not contain or have a very limited description of the effects of climate change on the economy. A strength of the global MRIOT based scenario tool is its consistent and comprehensive description of 129 economic activities in each country/region but a weakness is its simple description of the economy. It is recommended to examine if the global MRIOT based scenario tool might be extended with a hard-linked environmental model that is capable of estimating feedback effects on the economy.

2.1 Introduction

Climate change is one of the key challenges that humanity is facing in the coming decades (UNFCCC, 2012). Countries worldwide agreed in the Paris Climate Agreement (UNFCCC, 2015) to keep global average temperature increase to well below 2 °C and preferably even below 1.5°C. Several studies investigated the global emissions targets needed to keep within this 2 °C limit and found that GHG emissions should be reduced about 60% by 2050 (Van Vuuren et al., 2011; UNEP, 2016) compared to 2010 levels. In 2016 global GHG emissions were about 49 Gt CO₂ eq. (Oliver et al., 2017). According to the latest IPCC report the net

carbon emissions should approach zero by 2050 for staying below the 1.5 °C target (Clarke et al., 2014). Such large emission reductions require major changes in production and consumption patterns (Akenji et al., 2016; De Koning et al., 2015). How our global production and consumption will evolve in the coming decades cannot be predicted. Instead of trying to predict the future, scenario studies can be used to investigate possible pathways that brings us upon a route towards meeting that Paris Agreement's climate targets.

Scenarios in the context of this article can be described as "...a coherent, internally consistent and plausible description of a possible future state of the world..." (Parry & Carter, 1998). A way to explore such consistent descriptions of the futures, is to model the scenarios by means of computational abstractions representing a model of the socio-economic-environmental system. Qualitative evaluation of socio-economic scenarios is possible as well but are not considered in this study.

In climate change research, scenarios often describe plausible trajectories of climate conditions and other aspects of the future (Moss et al., 2010). They are built up in discrete steps. The starting point of climate change research is the formulation of so-called socio-economic scenarios. Subsequently models are used to estimate GHG emissions in agreement with these socio-economic scenarios. Emissions scenarios form the basis for the calculation of radiative forcing scenarios, climate change scenarios and finally impact & adaptation vulnerability studies (Moss et al., 2010). For this article, global models that can be used to calculate emission scenarios on the basis of socio-economic scenarios are being reviewed.

Socio-economic scenarios consist of a set of exogenous assumptions, assumptions that may be based on the output of different types of models (e.g. human population development models). These socio-economic scenarios are translated into inputs for the scenario model. The exact inputs of the scenario depend on the model (e.g. economic growth is in some models endogenously calculated, but an exogenous assumption in other models). Examples of key elements of socio-economic scenarios include the future performance of the energy and agriculture systems (Stehfest et al., 2014).

A plethora of different models have been used to calculate future GHG emissions based on exogenously defined socio-economic scenarios. They can strongly differ in their system boundaries, level of detail and core mechanisms. The models range from simple regression models to large coupled models such as integrated assessment models. Recently some new types of models have been used for the implementation of climate change scenarios that are based on detailed global multi-regional input-output tables (De Koning et al., 2015; Hertwich et al., 2015). In these models, multiregional input-output tables (MRIOTs) are constructed that reflect a socio-economic scenario. Given the myriad of other global scenario models available that have a much longer development history, we may ask ourselves what are the additional benefits of this new multi-regional input-output based modelling strategy in reference to all other scenario modelling strategies.

To investigate the role of the detailed global multi-regional input-output models an overview is made of scenario models used in climate change scenario assessment, focusing on selected characteristics of the different modelling strategies, their strengths and weaknesses and their most appropriate application area. From this overview recommendations will be given to which model type can be used for which purpose. In doing so, it shows the positioning of the global multi-regional input-output model in the field of scenario models for climate change.

Overviews of different modelling approaches have been made in the past. An early model review (Cole, 1987) distinguished between systems models, institutional models, de-institutionalized models, politico-economic models and modelling consortia models. Another model typology was introduced by Braat & Van Lierop (1987). The authors classified the models according their intended use, and distinguished between descriptive models, explanatory models, predictive models, prescriptive models and evaluative models. Van den Bergh (1991) made an analysis of dynamic models for sustainable development and used three criteria, i.e. completeness, aggregation and openness to distinguish 12 different classes of dynamic economic-environmental models. An overview of computable general equilibrium models for sustainability impact assessment was made by Böhringer & Löschel (2006). A survey of model approaches to integrated environmental assessment and management was carried out by Kelly et al. (2013). The five different model approaches were: system dynamics, Bayesian networks, coupled component models, agent-based models and

knowledge based models. A review of scenario models that follows a similar characterisation of models as in this research, but focussing on energy - climate scenario models only, was carried out by Krey (2014). A recent review of energy modelling tools by Després et al. (2015) categorise the models according to two dimensions. The first dimension distinguished between optimization and simulation models. The second dimension distinguished between bottom-up, top-down and hybrids thereof.

This overview will focus on global economic-environmental coupled models dealing with climate change impacts. The global focus is a necessity because any GHG emission to air anywhere on the planet contributes to radiative forcing. The economic activities that cause GHG emissions to air are also ever more globally connected through a global market (Krugman et al., 1995). Economic actions in one place of the world can have unforeseen environmental consequences in other parts of the world, for instance land-use change in Brazil due to the stimulation of corn-based ethanol use in the US (Searchinger et al., 2008). Global scenario models are therefore the most appropriate to study climate change.

Given the global focus, models that only address a particular region, or a particular economic sector are left out in the analysis. Among these models are partial equilibrium models such as CAPRI (Britz & Witzke, 2014), an EU wide agricultural sector modelling system, and pure energy sector models such the TIMES model, a descendent of the MARKAL based models (Loulou & Labriet, 2008). Models that analyse the effect of changes in a particular sector against a static background system are also not taken into account. Likewise the partial equilibrium models they do not implement global scenarios for the whole economy. Typically hybrid - IO such as combinations of MARKAL energy models with IO or integrated LCA - IO models fall in this category.

2.2 Methods

2.2.1 Model classification

First of all, the models that fall within the scope of this study are divided into several groups and subgroups. All models are at least used to estimate GHG emission following a set of more

or less detailed socio-economic scenarios. Some models cover further impacts along the DPSIR (Driving forces, Pressures, States, Impacts, and Responses) chain (Smeets & Weterings, 1999) as well. Dividing the models into different artificial classes has the danger that the continuous landscape of modelling approaches is seen as discrete and non-overlapping only. However to be able to get to grips with the variety of models in use, a certain classification and simplification is needed. Nonetheless, there will be a lot of models that do not exactly fit the classification and the classes represent stereotypes.

Introducing classes also has the danger that it sets the perspective for the analysis of the different models without realizing that other classifications and perspectives might be possible as well. For the purpose of this article we will classify the models based on their core working mechanism. The core working mechanism is the implementation of what is seen as a model concept to describe relations between socio-economic drivers and GHG emissions in the form of a computational model. That might be simple correlations, structural relations, chemical processes models, market equilibrium models, actor models etc. A stereotypical description of the core working mechanism is given for each class.

Other classification criteria could have been used as well. For example, a classification based on mathematical characteristics of models such as the distinction between linear and non-linear representation of relationships. Such a classification system might have led to a more strict division between models. However, instead of using these possible classification criteria as such, we will use it as defining characteristics of the different groups of models. These characteristics are the ones that set the models apart and define the stereotypic traits of the groups of models. Key characteristics of the model classes will be defined later. We first describe the stereotypical model classes on the basis of their core mechanism.

On the basis of the core working mechanism we distinguish the following groups:

Simple models These are regression models, characterized by the absence of mechanistic relationships. Usually, they predict one variable from two or more other known variables. They directly relate simple socio-economic parameters, to (global) emissions. The IPAT equation (Chertow, 2000) and variants thereof like the STIRPAT equation (York et al., 2003)

are typical representations, but also econometric models of eco-innovation and observed emission reductions (Mazzanti et al., 2014) fall into this group. These simple models have also been coined as empirical statistical models that are fitted to past data (Farmer & Foley, 2009). Other stereotypical model groups that are described later may also contain equations or descriptions based on regression analysis but these equations concern relationships between intermediate variables within the model and don't directly relate input parameters and model output. We will consider the STIRPAT model as stereotypical representation of the group of simple models.

Structural models These models use the structural relationships between industry sectors and final consumers to make an estimate of the emissions associated with final consumption of products (Duchin, 1998). The relationships between the industry sectors are the products that are being produced and consumed by the industries themselves as well as other final consumers. These relationships may be expressed in physical and/or monetary terms. At the same time the products consumed and produced by the industry (sectors) are a representation of the in- and outputs of an industrial process. Life Cycle Assessment (LCA) models, Material Flow Analysis (MFA) models and Input-Output Analysis (IOA) models and combinations thereof are typical representations of these models. The integrated LCA model THEMIS (Hertwich et al., 2015) and the IOA based model CECILIA (De Koning et al., 2015) are examples of combinations of structural models.

The structural models can be combined with linear programming models. A typical representation is the World Trade Model (WTM) (Duchin, 2005; Duchin, 2015). The CECILIA models is a comparative static model but dynamic structural models can be used for techno-economic scenario analysis as well (Faber et al., 2007).

Macro-economic models We coin macro-economic models as models that cover the whole economy. They are either computational general equilibrium (CGE) models or structural macro-econometric models. CGE models assume that the prices in an economy are determined at the multiple markets in which supply and demand are in equilibrium (Burfisher, 2011). The models analyse how the choices of economic agents are coordinated across all these markets. The models assume cost-minimizing behaviour by producers, average-cost

pricing, and household demands based on utility maximizing and cost minimization behaviour. The models may be comparative static or dynamic. An early example on an environmental relevant CGE model is the GREEN model (Burniaux et al., 1991, 1992). The GTAP model and its extensions such as GTAP-E (Burniaux & Truong, 2002) are typical examples of CGE models that have recently been used in climate scenarios (Nijkamp et al., 2005; Dandres et al., 2012)

E3ME (Pollitt et al., 2014; Barker et al., 2015) and Ginfors (Meyer & Lutz, 2007; Lutz & Meyer, 2009) are econometric based macro-economic models. The model combines econometric statistical analysis with input-output analysis embedded in a complete macroeconomic framework. Parameters of the econometric models are often estimated econometrically using time series data (Meyer & Lutz, 2007). The econometric models is a further development of the structural models adding behavioural relationships such as price elasticities and endogenous technology progress. In general econometric models differ from the CGE models by assuming demand-driven development of production outputs and using financial multipliers in the investment part. The models use historical data sets to estimate behavioural model parameters and they do not assume optimal behaviour like CGE models do (Barker et al., 2014; West, 1995). Early examples of the macro-econometric based models were called extended input-output models. The Washington Projection and Simulation Model (WPSM) is such an example (Conway, 1990).

Integrated assessment models Integrated assessment models (IAMs) are used extensively in the examination of the impacts of climate change and the search for socio-economic pathways that meet certain temperature targets. See for instance Smith & Bustamante (2014); Van Vuuren et al. (2010, 2011); Riahi et al. (2011); Thomson et al. (2011); Masui et al. (2011). We define an integrated assessment model broadly as any model which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control. Early examples of integrated assessment models include IMAGE v1 (Rotmans, 1990), the DICE model (Nordhaus, 1994) and RICE models (Nordhaus & Yang, 1996), the ICAM models (Dowlatabadi & Morgan, 1993; Dowlatabadi, 1995) and numerous others (Lempert et al., 1996; Manne et al., 1993; Matsuoka et. al., 1995). The

IMAGE version 3 model is currently used for the analysis of possible pathways leading to a two degrees warming (Van Vuuren et al., 2011).

A distinction can be made between two groups of IAMs. The first group concentrates on the trade-off between the level of mitigation, adaptation and climate impacts. These models include a description of the global economy and its relationships with the three costs categories mentioned above. The description of the different subsystems is often quite simple - and we refer to these models here as the cost benefit analysis type (CBA-type). The second category is more focused on providing an understanding of how the energy system and agriculture system functions in relation to earth system elements. These models are typically used to identify mitigation strategies. We refer to this type as the process IAMs. The DICE model family falls into the CBA type and the IMAGE model belongs to the process type.

IAMs typically consist of several loosely coupled, sometimes called soft-linked (Klaassen et al., 1998), models (see e.g. IMAGE 3.0; Stehfest et al., 2014). In that sense IAMs fall outside our classification scheme because it does not have a single core working mechanism. They are composed of parts, each having a different mechanism. For instance IMAGE 3.0 contains an energy simulation model (Timer; Vries et al., 2001) combined with a CGE model (GTAP/MAGNET model; Wolter et al., 2014) and a land-use model that is a regression-based suitability assessment for crop types (CLUMondo, Van Asselen & Verburg, 2013). Parts of the integrated assessment model might even be replaced by other types of models. The different IMAGE model versions indeed show that in the different versions subparts of the IAM were replaced. Nonetheless we have included the IAMs as a group into our analysis because IAMS are the only type of models that attempt to quantify the positive or negative feedback of rising temperatures on the production capacity of the economy. As an illustrative example, we will use the IMAGE 3.0 model. In Figure 2.2 we show a simplified overview of the landscape of models as we introduced above. Figure 2.1: Diagram showing the different modelling types as distinguished in this article (the last row provides individual models as example of each class).

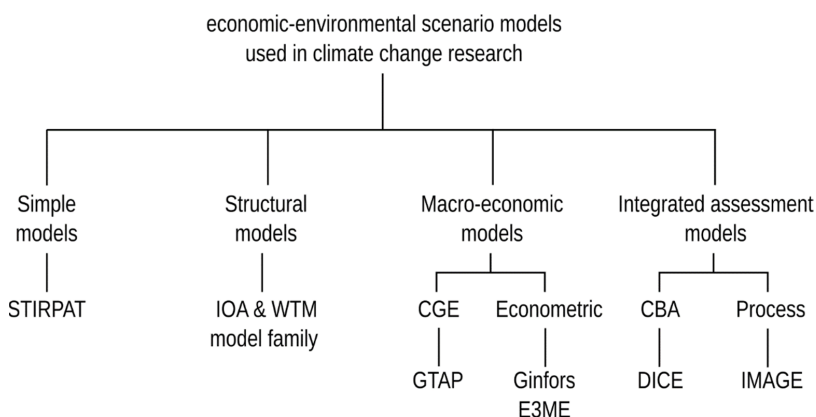


Figure 2.2: Diagram showing the different modelling types as distinguished in this article (the last row provides individual models as example of each class).

2.2.2 Model characteristics

Each of the different (stereotypical) model types will be characterized on the following aspects (1) system boundaries (2) resolution (3) solution mechanism (4) accessibility. Each of these aspects is discussed further below.

System boundaries The models differ in their coverage of the globally connected economy - climate system. The DPSIR chain refers to how economic activity leads to environmental interventions and how these interventions can lead to changes in the environment which can at the same time impact the production capacity of the economy. A typical example would be changes in rainfall patterns (Shilong et al., 2010) that will affect agricultural production. A fully coupled environmental and economic model is necessary to be able to make an assessment of these feedbacks. If feedbacks from the environment to the economy are to be modelled, this request a certain spatial and temporal resolution because climate change impacts are very dependent on location.

We will use the theoretical conceptualization, as shown in Figure 2.2, of the coupled environmental - economics system to characterize the system boundaries for the model groups as shown in Figure 2.3.

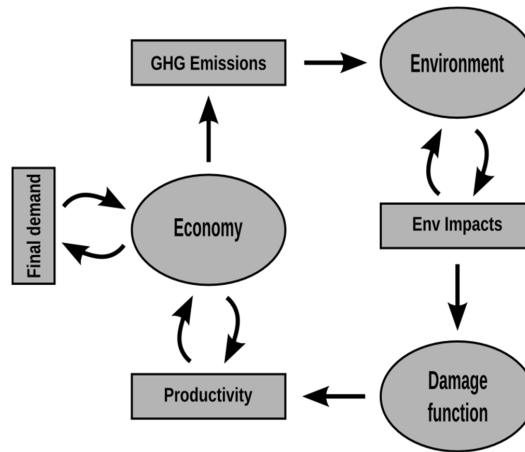


Figure 2.3: Conceptualization of the coupled environmental-economics system

The economy is based on a certain available production capacity, a production capacity that can be influenced by changes in the economy as well. The economy produces products for final consumption and changes in the economy might change final demand and vice versa. The operation of the economy has as a side-effect emissions of GHGs, notably CO₂, CH₄ and N₂O. There is no direct feedback from the emitted GHGs on the economy. However, the accumulation of GHGs in the atmosphere and oceans effects global climate and ocean acidification, which in turn leads to environmental impacts. These environmental impacts such as changes in rainfall patterns, increased CO₂ concentrations, higher average temperatures, sea level rise may in turn damage that production capacity of an economy. If we want to calculate the full effects of a certain socio-economic scenario we need to calculate the fully coupled economic-environmental model. Each of the model types discussed above cover part of this coupled economic-environmental model as will be shown later.

Resolution The resolution is an expression of the level of detail by which the economic and/or environmental systems are modelled. A distinction is made between resolution within the economic system and resolution in the environmental system.

For the economic system the resolution has a temporal and spatial component. The spatial resolution is the amount of regional detail considered. The economic system might be divided into individual countries or into several larger economic regions. The economic system might even be just a single entity without further spatial resolution. The temporal resolution of the economic system is in most cases on an annual basis but some models might have a higher or lower temporal resolution.

Another aspect of economic resolution is the level of detail in economic actors. How many production, consumption and financial sectors are distinguished? Given that the behaviour of each economic actor has to be modelled and data are needed to describe that behaviour, an economic model that has high geographical resolution and high actor resolution needs a large amount of data. This means it is likely that there is a trade-off between actor resolution (and associated economic behaviour modelling) and geographical resolution. Often an actor of interest is modelled in higher resolution than other actors in the economy. For instance, energy sectors are often modelled at higher resolution.

Also the environmental system resolution has a temporal and spatial component. The global warming potential (GWP) which is a measure of the increased radiative forcing by the emission of a substance (Lashof & Ahuja, 1990) is most often used to assess the relative impacts of GHG emissions used in the models discussed later. There is no spatial resolution and often only the GWPs with a hundred year time horizon are being used, offering no temporal resolution. The IAMs are models that have (much) higher temporal and spatial resolution in their environmental systems models. Besides a temporal and spatial resolution also the resolution in the diverse environmental ecosystems can be characterized. Because the IAMs is the only model type that may include specific models for the assessing more detailed ecosystem impacts it is not a distinct feature upon which the models can be differentiated.

Solution mechanism The solution mechanism characterizes the models in relation to four questions: Does the model have a deterministic or stochastic outcome? Is the model static or dynamic? A static model does not contain an endogenous time evolution component in the model. Is the model linear or non-linear? Linearity means that there is a linear dependency between input and output parameters. It does not mean that every equation in the model must

be linear and finally does the model include optimization behaviour. Examples of optimizing model behaviour include optimal distribution of resources, utility maximizing consumers and cost-optimal selection of energy supplying technologies. We find this an important characteristic because it is a core part of a scenario. If a scenario is quantified with a model that is centred around optimal behaviour of economic agents, this optimal economic behaviour is a key ingredient of the requirements to achieve such scenarios as well.

Accessibility Another characteristic of the model is accessibility of the model. Is it possible to obtain, inspect, adapt and run the model? Is it possible to obtain the source code of the model and is this well documented? Can the model be run on current desktop hardware or does it need more powerful hardware such that running the model might not be so easy even though the model itself is available? Accessibility is important for scientific results that depend on computation, because not releasing such code raises needless, and needlessly confusing, roadblocks to reproducibility (Ince et al., 2012). Accessibility is also important because the scenarios are used to suggest policies to mitigate climate change that might have far reaching implications for production and consumption. If the scenarios models are available to others, they might be improved and confidence in the results may improve (Voosen, 2016).

2.3 Results

2.3.1 Simple models

Description The STIRPAT model (Stochastic Impacts by Regression on Population, Affluence and Technology (Dietz & Rosa, 1994, 1997; Rosa & Dietz, 1998) as described by (Chertow, 2000) is an analytical tool which has been used to disentangle the effect of population growth, increased affluence and changing technology on a range of environmental impacts. For instance it has been shown that there is no evidence of an environmental Kuznets curve for total CO₂ emissions (York et al., 2003). The STIRPAT model relates total productivity in an economy to GHG emissions as shown by its equation (York et al., 2003):

$$M_i = aP_i^b A_i^c T_i^d e_i$$

Where M is emission, P , A and T are expressions for population, affluence and technology. The coefficients a , b , c and d have to be estimated and e is an error term. The subscript i denotes that the equation varies across observational units. Typically the equation is fitted to observations from a particular country.

System boundaries The system boundaries of the simple model may be depicted as in Figure 2.4. The size of the economy often expressed in GDP is related to the amount of GHG emissions.

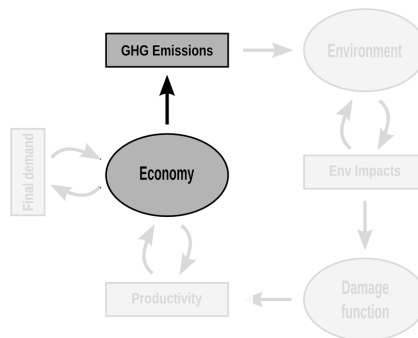


Figure 2.4: Conceptualization of a simple model

Resolution The economic resolution is low both from a spatial and temporal point of view as well as from the number of economic actors point of view. The spatial cover is typically a country or region and covers the whole economy. The model does not distinguish between economic sectors and the measure used for economic activity is GDP.

Solution mechanism The model is calibrated against a set of empirical data. The uncertainty of the model is quantified. Making predictions with the model outside of the range of available empirical data is questionable because no mechanisms are captured by the model.

Accessibility The STIRPAT model can easily be reproduced and adapted to other case studies because the model consists of a single equation only. The STIRPAT model is particular useful for retrospective analysis.

2.3.2 Structural models

Description The CECILIA model (De Koning et al., 2015) is based on global multi-regional supply use table for the year 2000 which is transformed into an input-output table.

A scenario for the CECILIA model consists of exogenous information on population growth, supply and use of energy, general efficiency improvements, and development of specific technologies such as electric vehicles and GHG emission reduction measures such as carbon capture and storage (CCS). This exogenous information is used to adapt the existing supply-use table. For each different scenario a new supply-use table needs to be developed. The new supply-use table incorporating the scenario is subsequently transformed in an IO tables that can be analysed using the familiar Leontief equation (Miller & Blair, 2009):

$$M = B (I - A)^{-1}y + E_{hh}$$

In which M are emissions, B is the matrix of emission per unit of output of each sector, I is the identity matrix, A is the technology matrix that specifies all the inputs per unit of output of each sector, y is final demand and E_{hh} are emissions from household activities. The technology matrix as created in each scenario may be seen as the structural model of the economy and each column in this matrix is a production recipe for each sector.

System boundaries The CECILIA model does not model explicitly environmental impacts as a result of the GHG emissions except that it uses GWP₁₀₀ for characterisation of the substances. The system boundaries of this structural model may therefore be depicted as shown in Figure 2.5.

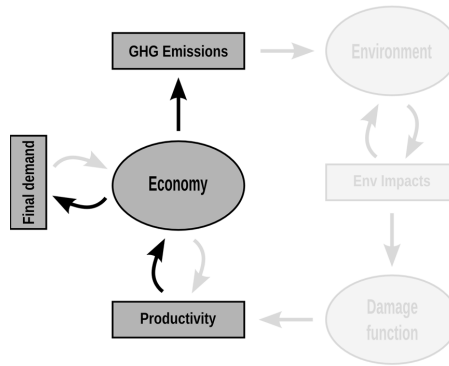


Figure 2.5: Conceptualization of a structural model

Resolution The model consists of four regions, and each of these regions is divided into 160 different industry sectors. It can be used for comparative static analysis.

The core of the CECILIA model is the mechanism by which the exogenous information is incorporated in the supply-use tables and how changes in a particular sector affect the inputs and outputs of the other sector. This macro-economic framework may be depicted as shown in Figure 2.6.

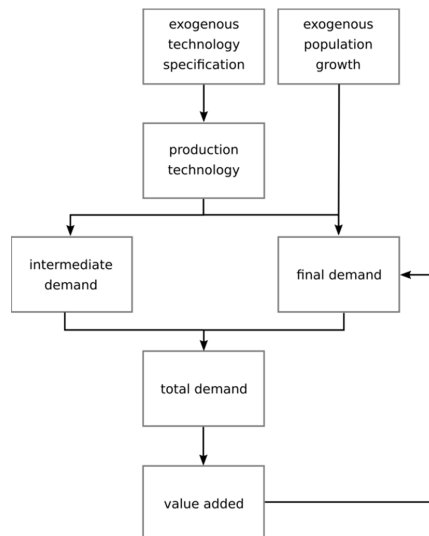


Figure 2.6: Macro-economic framework of CECILIA, inspired by West (2006)

The inputs into CECILIA are technology specifications and expected economic and population growth. The technology specification embodies a technology scenario containing items such as efficiency improvements in industry sectors, expected electricity supply mix, but also changes in the technology used by households. The changes in the technology and population growth leads to changes in the total demand which in turn changes total value added which leads to changes in the total final demand. This structural model assumes that a changing income does not affect spending patterns and the model does not take into account that there may be constraints on the availability of factor inputs. In that sense the CECILIA model contains little additional economic behaviour. Moreover the CECILIA model contains only information on the quantity of goods and services, not about the price of goods and services.

Solution mechanism Equilibrium in the CECILIA model is achieved by balancing demand and supply of products. We classify the economic model in CECILIA as being very simple. As such the model does not allow for the evaluation of economic policy measures such as cross border taxation or subsidy schemes.

A typical application for CECILIA is the implementation of long term technology development scenarios. These scenarios can be used to examine how technology (not necessarily optimal technology) would influence resource use and a broad range of other environmental interventions. The CECILIA model is not suitable for forecasts or predictive scenarios because it lacks mechanisms that model the short term behaviour of economic agents in response to market changes.

Accessibility A proper uncertainty analysis or validation of the model by comparing modelled results with historical time series has not been made yet. It does reproduce some of the GHG emission scenarios calculated through with other and well established models (De Koning et al., 2015). The model is freely available in the form of a collection of Matlab files and

accompanying input and output data¹. It can easily be run by a single user and does not pose special hardware or software.

2.3.3 Macro-economic models

2.3.3.1 Computable general equilibrium models

Description CGE models can be comparative static or dynamic. Dynamic means that the CGE model explicitly traces each variable through time, often at annual intervals. The GTAP model has a comparative static as well as dynamic variant called GDyn (Ianchovichina & McDougal, 2000). This description is based on the original comparative static model.

The theoretical underpinnings and the operation of the GTAP model has been documented extensively (Ianchovichina & McDougal, 2000; Burfisher, 2011). The GTAP model is the basis of many specific scenario models (Burniaux & Truong, 2002; Nijkamp et al., 2005; Adams, 2005; Dandres et al., 2012) It is also an important part of the IMAGE3.0 model (Stehfest et al., 2014). The behaviour of the model is well studied.

System Boundaries An energy extended version of the GTAP model, called GTAP-E (Burniaux & Truong, 2002), incorporates carbon emissions from the combustion of fossil fuels. The CGE models do not explicitly model environmental impacts. As such the system boundaries may be depicted as shown in Figure 2.7.

Notice that in comparison with structural model the difference lies in the interaction between production capacity and final demand. In an IO model a given final demand leads to higher production. In a CGE model demand and production change as in response to price changes.

¹ See <http://cml.leiden.edu/research/industrialecology/researchprojects/projects/cecilia.html>. Accessed 12 October 2017

Resolution The latest version of GTAP database (GTAP 9), a set of social accounting matrices (SAM), distinguishes 140 regions and 59 sectors. The SAMs are used to parametrize the GTAP model. The GTAP models are however never run at the dimensionality provided by the GTAP SAMs. Typically the SAMs are aggregated based on the application of the model. While we do not know every application of the GTAP model, in GTAP-E 8 sectors and 8 regions are distinguished (Burniaux & Truong, 2002) which is at a much lower resolution than multi-regional IO models and lower than the macro-econometric models, see Section 2.3.3.2.

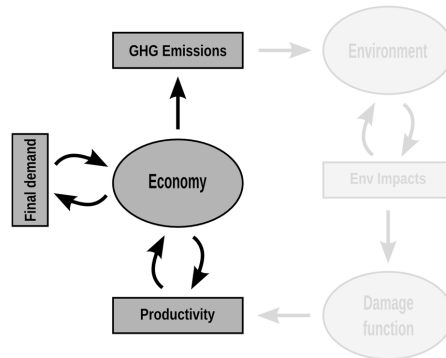


Figure 2.7: Conceptualization of a CGE model.

GTAP contains (non-linear) models for consumption, production, capital and labour markets, international trade, and taxation. It is both a quantity and price model. The prices are established by demand and supply and these prices in return determine for instance the choice between the use of domestically or imported products, see Figure 2.8. Substitution elasticities are the exogenous parameters in the CGE model that describe the responsiveness of supply or demand to a change in prices or incomes. Final demand is governed by demand functions that describe the quantity of goods bought in response to price changes and income changes. In GTAP model different demand functions can be chosen based on the application of the CGE model.

In GTAP, commodity demand by consumers is determined by maximizing utility under a given consumption budget. If the consumers buy domestically produced commodities or

imported commodities is determined by minimizing the commodity cost and producers are cost-minimizing their production (Burfisher, 2011).

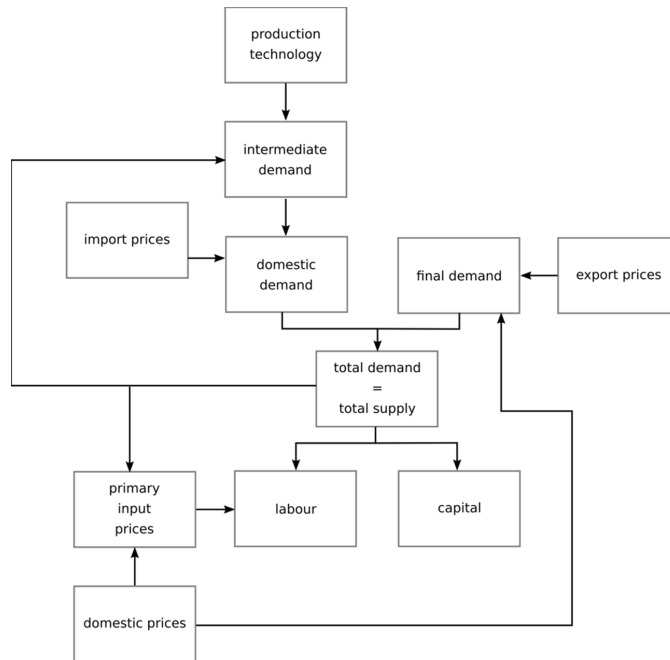


Figure 2.8: Conceptualization of a CGE model, After West (2006).

Solution mechanism CGE models have optimizing behaviour of economic agents and market equilibrium as a core mechanism in the model. The behaviour is described in differential equation. The solution of the set of non-linear equations (differential equations) in GTAP is done by the software package GEMPACK (Harrison & Pearson, 1996). GEMPACK will solve the set of non-linear equations by making a linearized representation of the model and approaching it as an initial value problem (Harrison & Pearson, 1996).

Accessibility The GTAP model and many of its variants can easily be run by a single user and does not pose special hardware but often does have special software requirements. All equations describing the CGE models have been described (Hertel & Tsigas, 1997) and ready-made software is available.

2.3.3.2 Macro-econometric models

Description Macro-econometric models combine econometrically estimated demand equations with input-output analysis embedded in a complete macro-economic framework. An econometric model is a step away from the structural models discussed earlier by encapsulating the IOTs in a macro-economic framework but retains the sector detail and much of the rich detail in environmental accounts. The macro-econometric model is different from the CGE models discussed earlier because they do not assume market equilibrium, optimal economic behaviour and supply-side constraints. We use here GINFORS as a typical example of this type of models, since GINFORS has been frequently used to analyse questions around climate change and resource-efficiency (e.g. Stocker et al., 2011; Distelkamp & Meyer, 2017). The GINFORS macro econometric model can be characterized as an evolutionary model based on bounded rationality of the economic agents and imperfect markets (Meyer & Lutz, 2007).

System Boundaries Like the CGE models the macro-econometric models focus on the economic system and processes in the environment are not modelled. The system boundaries of the macro-econometric models are similar to the CGE based models, see Figure 2.9.

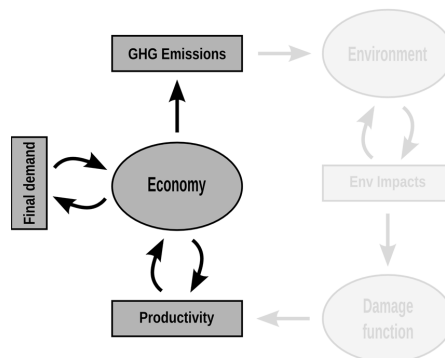


Figure 2.9: Conceptualization of a global macro-econometric model.

Resolution In the macro-econometric model GINFORS covers the whole world distinguishing 50 countries and 2 regions (Meyer & Lutz, 2007). These are all connected with bilateral trade matrices for 25 products. The input-output of each of the countries and regions

are connected through the trade matrices. The input-output tables of a country are connected to a macro-economic model for that specific country. It also contains a detailed energy model and materials model. Energy emissions, land use, material input are all estimated with the GINFORS model (Meyer & Lutz, 2007). The resolution of this macro-econometric model is comparable to that of the structural model. It has more geographical detail but less sector/product detail.

Accessibility The GINFORS model has been well-described in the literature (Meyer & Lutz, 2007). The model itself is not freely available.

2.3.4 Integrated assessment model

2.3.4.1 Process based integrated assessment models

Description The IMAGE3.0 model is a state of the art integrated assessment model. The model is well documented (Stehfest et al., 2014). The IMAGE model is known for the construction of climate change scenarios leading to a radiative forcing of 2.6 W/m^2 (Van Vuuren et al., 2011) consistent with an average global temperature increase of 2°C , the so-called RCP2.6 scenario (Moss et al., 2010). Other integrated assessment models used for the construction of climate change scenarios are RCP8.5 based on the IIASA modelling framework (Riahi et al., 2011), RCP6.0 based on the Asia-Pacific Integrated Model (AIM) (Masui et al., 2011) and RCP4.5 based on the global integrated assessment model (GCAM) (Thomson et al., 2011). Key inputs into the model, so-called drivers of the model can be divided into eight groups: 1) population projections, 2) economic development 3) trade regimes, tariffs and barriers 4) environmental and other policies 5) technological change in agriculture and forestry 6) technological change in the energy system 7) life style parameters 8) energy and land resources.

The IMAGE3.0 model consists of several soft-linked modules that cover the so-called human system, earth system and environmental impacts. Soft-linked means that the model are not run together as a single system, but instead information exchange occurs via input and output files. A module produces output and another module treats the 1st module's output as input. The economic system, in IMAGE called human system, consists broadly of two groups of

models covering agriculture & land use and energy supply & demand. The output of these two groups of models are 1) land cover and land use and 2) GHG emissions.

Subsequently the land cover and land use and the GHG emissions are inputs for models that estimate effects on carbon, water and nutrient cycles and climate. Finally based on the estimated changes in the environment impacts on biodiversity, land degradation, ecosystem services and human development are calculated.

System boundaries The process based IAMs incorporate economic as well as in the environmental system models. IAMs are also in principle capable to model the effect of the emitted GHGs and subsequent climate change on the production capacity of an economy. In Figure 2.10 a conceptual picture of a global process based IAM is shown. Some feedbacks are included in IMAGE while others are not. An example of a (positive) feedback incorporated in the IMAGE model is the fertilizing effect of CO₂ on crops. In contrast, the feedback of a changed environment on the economic system in the IMAGE model is not covered. In the last case, uncertainty has been an important reason not to fully include this impact. Second because the IMAGE model is a soft-linked model it is impossible to iteratively model the full feedbacks. As we will see later cost-benefit type IAMs iteratively try to model full feedbacks.

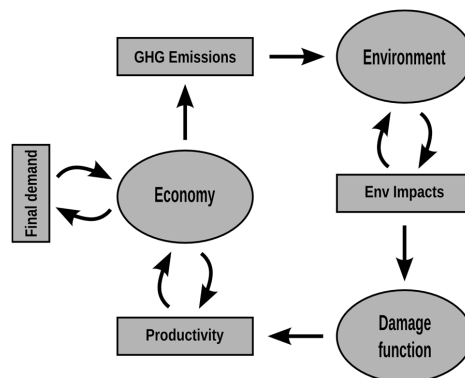


Figure 2.10: Conceptualization of a process based integrated assessment model.

Resolution The IAMs being the only global models incorporating an economic and environmental system, the resolution in the economic and environmental system are discussed separately.

The economic system of the integrated assessment model covers the world, subdivided into 26 regions with a relative high degree of coherence within each region. The economic system model consists of the energy simulation model TIMER that describes 12 primary energy carriers. Output of the model is long-term development of bio-energy production and energy demand and production. Another part of the economic system model is the agricultural economy model. The MAGNET model is used which is based on the standard GTAP model, discussed earlier. The MAGNET model covers the entire economy but has a special focus on agricultural sectors and further distinguishes a few¹ other aggregate sectors (Stehfest et al., 2014). Everything said about the GTAP model applies to the MAGNET model as well. See Figure 2.8 for an overview of a CGE model. The output of the MAGNET model is demand for crops livestock, forest products and all other commodities. Subsequently the location of crop production is modelled using a spatially explicit land use allocation model on a 5x5 minute resolution.

The environmental system is modelled at different resolutions by the different model components. The global vegetation growth model LPJmL distinguishes 12 crop types on a 5x5 minute resolution. Climate impacts are modelled with MAGIC6.0 which calculates the effect of GHG emissions on CO₂ concentration, ocean carbon uptake, radiative forcing, global mean temperature and precipitation. From there on GLOBIO model assesses biodiversity impacts, flood risk and a number of other impacts.

Solution mechanism IMAGE is run in a simulation environment. In this simulation environment, the baseline scenario results are driven by year to year decisions such as development of population, demand for energy services and GDP. There are two major exceptions. The MAGNET model (run via a soft-link) is run on the basis of its optimisation assumptions. Second, in climate policy runs information on the option to reduce emissions in

¹ Unfortunately texts describing IMAGE3.0 are unclear about the number of sectors distinguished.

different part of the system is forwarded to the policy-model FAIR that optimises the reductions in various sectors.

Accessibility The IMAGE3.0 model and its sub models have been well documented (Stehfest et al, 2014). Sensitivity and uncertainty analysis have been performed. The IMAGE3.0 model is a collection of complex models which require large amount of external data. Therefore, it cannot be run by a single person and requires specialized hardware and software. Scenario modelling with IMAGE is a multi-institute effort. The models and data are not freely available. The IMAGE model might be seen as the most inaccessible model of all climate scenario models discussed in this paper.

2.3.4.2 Cost-benefit analysis type integrated assessment models

Description The DICE model is a dynamic model which was used to calculate the economic costs and benefits of climate mitigation scenarios. To be able to do so, first the damage costs to the production capacity of the economy by unmitigated climate change had to be estimated. Second the costs of climate mitigation scenarios had to be estimated.

The DICE model calculates the quantity GHGs emitted by economic activity based on the rate of economic activity and the amount of GHG emissions per output of that activity. The GHG emission intensity decreases over time. A climate change mitigation scenario leads to faster decreases in GHG emission intensity. The development of economic activity over time is influenced by the exogenous input parameters population growth and technological development. The GHG emissions lead to a higher concentration of GHGs in the atmosphere. A simple relationship was used to estimate mean global temperature on the basis of the accumulated GHGs. Finally a damage function expressed the damage done to the production capacity of the economy (Nordhaus, 1994). This whole system of equations is solved at once.

System Boundaries The DICE model incorporates both the economic and environmental system although in a superficial manner. Its system boundaries can be shown as in Figure 2.11.

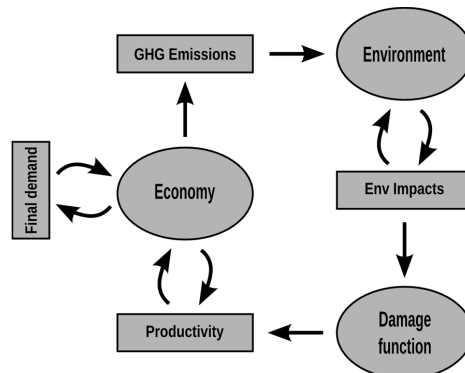


Figure 2.11: Conceptualization of a CBA type integrated assessment model.

Resolution The DICE model does not subdivide the global economy and as such its spatial resolution is low. There is also no further modelling of interactions between actors such as done in the IO, CGE and macro-econometric models where changing output of one sector affects the output of other sectors. The economic model in DICE is very simple indeed. Just as simple as in the simple models category.

The environmental model is also simple. There is a simple model that accounts for the half-time of GHGs in the atmosphere. GHG emission rate and half-time of GHG emissions determines the evolution of GHG concentrations.

Solution mechanism The model consists of a few (non-)linear functions that have to be solved for each time step.

Accessibility The model is simple enough to be reproduced as demonstrated by Kaufmann (1997).

2.4 Discussion

2.4.1 System boundaries

It is quite clear that IAMs are the only type of models that potentially are capable of exploring the full effect of a particular climate change scenario because they are the only models that include feedback mechanisms from the environment to the economy. Critical here is climate feedbacks on agriculture and forestry. Agriculture and forestry sectors are needed to support the increasing demand for biofuel, biofuel that is critical for the climate change scenarios in which the well below 2 °C target is met. The simple, structural, and macro-economic models do not take climate feedbacks into account (unless their input parameters somehow take it into account).

Although the CBA type IAMs take climate feedbacks into account, it is modelled in such a simple manner that no additional insight is gained into for instance the effect on agricultural productivity. In the process type IAMs the large number of soft-linked models and the limited climate feedback mechanism incorporated prevent a full assessment of the climate feedback mechanism. An example is feedback effects on crop productivity. In the IMAGE model elevated CO₂ concentrations are expected to lead to higher crop yields. However any other effects of climate change such as extreme weather events, increased susceptibility to insect damage, increased nutrient limitation are not taken into account (Stehfest et al., 2014). Furthermore the increased crop productivity does not lead to further chain effects in the economic system.

Climate feedbacks on agriculture and forestry are not a theoretical possibility that does not happen at average global temperature increases of 1.5 - 2 °C. Even at current level of temperature increase, Canadian pines forest are decimated by pine beetles that now thrive due to increasing temperatures (Kurz et al., 2008).

This indicates that there is a need for an integrated economy - environment model in which climate feedback mechanisms can be modelled to the fullest extent to be able to assess effects on at least agricultural and forestry productivity. This is becoming even more important now that there is a real threat that the 2 °C cannot be met (Tollefson, 2015). At least it should be

established that climate change mitigation using bioenergy in combination with CCS is not hampered or obstructed by climate change itself.

Fully integrating economic and environmental models likely means sacrificing some of the highly detailed environmental process modelling against the ability to solve a full coupled economy-environment model at once. This also means that this model cannot be soft-linked because it would be time consuming to iteratively solve the combined set of models.

The structural models with their simple description of the economy but very detailed sector resolution, especially in the agricultural and energy sectors might be used for such a model if they would be extended with a sufficiently detailed environmental model that can reasonably model feedback effects on the economy.

2.4.2 Economic model resolution

The simple models have a very low resolution. As such they can be used for interpretation of past trends. Their aggregated nature prevents makes them unsuitable for the implementation of meaningful socio-economic climate scenarios. Given that the DICE model relies on a very simple economic model as well, it is doubtful that such a CBA type IAM is very useful to inform us about the optimal economic climate mitigation measures.

The CGE and macro-econometric models are capable of investigating the effect on the economy and GHG emissions of all kinds of (economic) policy measures. The CGE model typically distinguishes fewer sectors and fewer regions than the macro-econometric models. The CGE and macro-econometric models calculate economic effects from a different point of view. The CGE models assume an economic optimal operation of the economy. The econometric based models are empirically grounded. A side by side comparison of GINFORS with the EXIOMOD CGE model (Meyer & Ahlert, 2017) concluded that the core paradigms of the econometric models and CGE models had decisive consequences when it came to evaluation of environmental tax reforms.

The economic model within the process based IAM is not meant for economic analysis but is used to quantify the amount of activities taking place in an economy under different scenario

assumptions. The economic model can be in the case of IMAGE as complex as the MAGNET CGE model and it is further enriched by inputs from the energy simulation model TIMER. However the soft-linked TIMER and MAGNET CGE model does not provide the detailed and integrated view on inter-industry connections and industry outputs as available in a structural model.

All the economic models discussed above have more or less elements that are extrapolations of past trends. For the simple model it is obvious because it represents a regression line fitted to past data. For the more complex models the extrapolation is found in endogenous factors incorporated in the model. For instance the structural models have the input-output coefficients that were observed in a certain year. CGE models and econometric models additionally use for instance observed price and substitution elasticities. These endogenous factors represent our understanding of the world as we know it today.

When investigating long term explorative scenarios we must be aware that the world might function quite differently from the way it functions today. On time scales of decades' inventions and innovations may strongly alter what is being produced and consumed and how is being produced and consumed. In such a future world, with new classes of technology, it is not known how price elasticities and consumer preferences will look like for products and technologies that are currently in their infancy or do not exist at all. If these (endogenous) factors are not known - factors that are crucial for the modelling of economic behaviour - modelling of economic behaviour becomes difficult. Models in which it is easy to identify and alter endogenous factors based on exogenous information or scenarios would support long term explorative modelling. Structural models with their simple structure fulfil an important role here.

The structural models which are based on combinations of linear functions. The assumption of linearity in economic systems might be seen as a weakness of the structural models. However, while the specification of economic mechanism in CGE models is done using (non-linear) differential equations, the solution of CGE models (among which the MAGNET model used in IMAGE) is done on the basis of a linearized version of these equations. The linearity of structural models is therefore less of a drawback compared to CGE models.

The CGE models and the economic models in the process based IAMs all contain mechanisms where optimal economic behaviour and/or optimal allocation of resources is assumed. A scenario analysis with these models will therefore contain as a major assumption that this optimal behaviour will take place. The results of CGE models and IAMs are therefore to be interpreted likewise.

2.4.3 Environmental model resolution

The IAMs are the only type of models that include a model of the environmental system. The CBA type IAM examined here (DICE; Nordhaus, 1994) has a rather simple environmental system model. A distinct feature of the model is the inclusion of a damage function that expresses the effect of changed mean global temperature on the economy. The CBA type IAMs can in principle calculate the full economic effect of a scenario but as argued before they fall short of that goal because they are too simple.

The process based IAMs incorporate very complex environmental models. Part of the environmental models have a high level of spatial resolution and environmental mechanisms are modelled in great detail. Some effects of increased GHG emissions in the atmosphere on the economic system have been incorporated into the modelling framework. One such an effect is the fertilizing effect of CO₂ on crop growth. However only this positive fertilizing effect has been taken into account, none of the possible negative effects of crop growth have been taken into account making the model biased. A full analysis of the feedback effects is not possible as described in Section 2.4.1.

We have seen that the CGE model and the economic models incorporated in the process based IAMs contain elements of optimal economic behaviour. Given that the environmental models in the IAMs cannot analyse the full feedback effects of the environment on the production capacity of the economy, we conclude that CGE containing process based IAMs can be optimistic about the effort needed to reach a certain climate target.

2.4.4 Accessibility

If a model becomes more complex, more information is needed and it takes more effort to run the model and hence the model becomes less accessible. It is an inherent problem. The structural models are relatively easily accessible because the required data are available, the software is available and they do not require special hardware and software. Accessibility also means that the model has been described and the behaviour of the model is well understood. Typically this means that sensitivity, uncertainty analysis has taken place and the model has been validated. Most of the models (or parts thereof) have to a certain extent been validated. The CECILIA model has not seen such a validation yet. This is clearly a drawback of the model.

2.4.5 Combinations of models

The discussion above centred on the stereotypical representations of the model categories. Model categories with their own strength and weaknesses. By combining/integrating the different models types, one can try to overcome the limitations of the individual model categories. The number of combined models that have been used in scenario analysis is enormous, we just name a few interesting examples of these model combinations to show that almost any combination between model categories is possible.

For instance Manne & Wene (1992) made a combination of a macro-economic model and a MARKAL model. The paper summarizes the development of a new hybrid MARKAL-Macro (M-M) energy system model for the UK. This hybrid model maintains the technological and sectoral detail of a bottom-up optimization approach with aggregated energy demand endogenous and GDP impacts from a single sector neoclassical growth model (Strachan & Kannan, 2008). This paper has demonstrated the feasibility of a formal hard link between MARKAL (a systems engineering model) and MACRO (a long-term macro-economic growth model). The merger combines MACRO's aggregate view together with MARKAL's detailed analysis of technical options for future energy systems.

An example of an LCA model in combination with a partial market equilibrium is the U.S. Forest Products Module (USFPM). The LCA is used to analyse an energy demand scenario in

which wood use increases to 400 million cubic meters in the United States for ethanol production (Earles et al., 2013).

An example of an IOA model used in combination with a partial equilibrium model is the combination of the EIPRO IOA model with the CAPRI model (Tukker, et al., 2011; Wolf, et al., 2011). The agricultural CAPRI model was linked to the static IOA model and used to investigate changes in agricultural production as a response to changes in the final demand for agricultural products in the EU.

2.4.6 Positioning the structural model

The CECILIA model, as a specific example of a structural model, focusses on technical and supply chain relationships within the global economy. Its sector resolution, especially in the agricultural sectors and energy sectors, is in general higher than in any of the other model types. This makes the CECILIA model well suited to examine the industry interrelationships in a comprehensive and consistent manner. Process based IAMs like IMAGE lack this full integration of linkages between different economic sectors, but treat for instance agriculture and energy in separate model modules. Most CGE and Econometric models discern just one agricultural and resource-extraction sector, implying they cannot analyse well how a higher use of biofuels impacts land use or how a higher use of solar cells impacts the level of extraction of specific metals (De Koning et al., 2018). Another example is that in the energy - CGE model combinations a direct link is lost between for instance the output of coal power plants and coal mining with all its associated inputs (including demand for that same electricity), because two separate models are used for the energy sectors and the rest of the economy.

There are no endogenous economic model mechanisms within the structural model. They lack for instance price elasticities and endogenised relations between capital savings and investment, and how productivity changes due to investments. Econometric and CGE models contain such information, and hence are better suited for modelling the impacts of economic policy measures and other predictive analyses, particularly on the short to medium term. For scenario analysis several decades ahead, it is questionable if the build in endogenous mechanism in econometric and CGE models, parametrized using historical data, are still a

reasonable representations of a future world. On this point, the lack of endogenised information in structural models in fact may be an advantage. In the structural models without endogenous mechanisms all information on the future state of the world has to be exogenously supplied. This makes it transparent what the assumptions are on which the scenario rests. When doing long term what-if analyses, this is in our view a clear advantage of the structural models over CGE or Econometric models.

The linearity of the structural models cannot be seen as a drawback of these types of models compared to CGE models. The widely used CGE models are in practice also often linearized.

Compared to both process and CBA IAMs, CECILIA has the advantage of a comprehensive, detailed and integrated economic coverage, but misses endogenised economic mechanisms, modelling of environmental processes, and feedback of environmental change to economic sectors. Part of these limitations of structural models like CECILIA can be overcome by hard-linking it to an environmental systems model that includes a feedback on economic production. Of particular interest is the full feedback of increasing global mean temperature on agricultural and forestry sectors.

The CECILIA model has not yet been validated by comparing modelled results with historical time series. Recently a time series from 1995 to 2011 of supply-use tables have become available. This time series would allow the CECILIA model to be validated. For further use of structural models in climate change scenario studies this validation is an important next step. At this point this structural model hence must be used with caution in modelling future climate scenarios. At the same time there is reason for optimism. Some of the CECILIA model results were compared to other climate change scenario models. These first comparisons showed that the CECILIA model reproduced (almost spot on) the BAU scenarios from RCP 8.5 (De Koning et al., 2015).

2.5 Conclusions and recommendations

This research examined the position of structural economic models in relation to other model types used in climate scenario studies. The structural model takes up an interesting position with respect to the partial equilibrium and CGE models. Structural models may particularly be used for long term what-if scenario analysis and a consistent approach towards modelling the economy without optimality assumption. The apparent drawback, i.e. that various parameters like economic growth have to be brought in exogenously, is in fact a strength for such long term scenarios since such assumptions are made transparent. The structural models can however not replace IAMs because they model only the economic system and lack modelling of environmental processes and feedback of these on the economy. To overcome the last drawback, it is recommended to examine if the structural models might be extended with a hard-linked environmental model that is capable of estimating feedback effects on the economy. At this moment there does not seem to be a process based IAM that fully takes into account feedback effects on the economy. Further, it is recommended to execute, as a first step to further use in climate scenario studies, to carry out a validation of the CECILIA model by checking how good the model is able to match historical time series of economic development and emissions and resource extraction.

2.6 References

- Adams, P. D. (2005) Interpretation of results from CGE models such as GTAP. *Journal of Policy Modeling* 27(8)941-959.
- Akenji, L., Bengtsson, M., Bleischwitz, R., Tukker, A., Schandl, H. (2016) Ossified materialism: Introduction to the special volume on absolute reductions in materials throughput and emissions. *J. Clean. Prod.* 132, 1-12.
- Barker, T., Pollitt, H., Chewpreecha, U., Alexandri, E., Gonzalez-Martinez, A., Higson, A., Billington, S. (2014) E3ME Technical Manual, Version 6.0. Cambridge. 136pp.
- Barker, T., Alexandri, E., Chewpreecha, U., Ogawa, Y., Pollitt, H. (2015) GDP and employment effects of policies to close the 2020 emissions gap, *Climate Policy*, 16(4)393-414.
- Böhringer, C., Löschel, A. (2006) Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. *Ecological Economics* 60(1)49-64.
- Britz, W., Witzke, P. (eds.) (2014) CAPRI model documentation. 277pp.
- Burfisher, M. M. (2011) Introduction to Computable General Equilibrium Models. Cambridge University Press. 346pp. ISBN: 978-0-521-13977-9.
- Burniaux, J.-M., Martin, J. P., Nicoletti, G., Martins, J. O. (1991) The costs of policies to reduce global emissions of CO₂: Initial simulation results with Green. Tech. rep.
- Burniaux, J.-M., Martin, J. P., Nicoletti, G., Martins, J. O. (1992) Green - a multi-region dynamic general equilibrium model for quantifying the costs of curbing CO₂ emissions; a technical manual. Tech. rep.
- Burniaux, J.-M., Truong, T. P. (2002) GTAP-E: An energy-environmental version of the GTAP model. Tech. rep.
- Chertow, M. W. (2000) The IPAT equation and its variants; Changing views of technology and environmental impacts. *Journal of Industrial Ecology* 4, 13-29.
- Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., Van der Zwaan, B, Van Vuuren, D. P., (2014) Assessing Transformation Pathways. In: *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Cole, S. (1987) Global models, a review of recent developments. *Futures* 19(4)403-430.

- Conway, R. S. (1990) The Washington Projection and Simulation Model: a regional interindustry econometric model. *Interregional Science Review* 13(1-2)141-165.
- Dandres, T., Gaudreault, C., Tirado-Seco, P., Samson, R. (2012) Macro-analysis of the economic and environmental impacts of a 2005-2025 European Union bioenergy policy using the GTAP model and life cycle assessment. *Renewable and Sustainable Energy Reviews* 16(2)1180-1192.
- De Koning, A., Huppes, G., Deetman, S., Tukker, A. (2015) Scenarios for a 2°C world: a trade-linked input-output model with high sector detail. *Climate Policy* 16, 301-317.
- De Koning, A., Kleijn, R., Huppes, G., Sprecher, B., Van Engelen, G., Tukker, A. (2018) Metal supply constraints for a low-carbon economy? *Resources Conservation and Recycling*. 129, 202-208.
- Després, J., Hadjsaid, N., Criqui, P., Noirot, I. (2015) Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. *Energy* 80, 486-495.
- Dietz, T., Rosa, E. A. (1994) Rethinking the Environmental Impacts of Population , Affluence and Technology. *Human Ecology Review* 1, 277-300.
- Dietz, T., Rosa, E. A. (1997) Effects of population and affluence on CO₂ emissions. *Proceedings of the National Academy of Sciences of the United States of America* 94, 175179.
- Distelkamp, M., Meyer, M. (2017) Pathways to a Resource-Efficient and Low-Carbon Europe. *Ecological Economics*, In Press.
- Dowlatabadi, H., Morgan, M. G. (1993) Integrated Assessment of Climate Change. *Science* 259, 1813-1932.
- Dowlatabadi, H. (1995) Integrated assessment models of climate change. *Energy Policy* 23(4-5)289-296.
- Duchin, F. (1998) *Structural Economics; Measuring Change in technology, lifestyles, and the environment*. Island Press 220pp. ISBN: 1-55963-606-8.
- Duchin, F. (2005) A world trade model based on comparative advantage with m regions, n goods, and k factors. *Economic Systems Research* 17(2)141-162.
- Duchin, F., Levine, S. H., Strømman, A. H. (2015) Combining multiregional Input-Output analysis with a world trade model for evaluating scenarios for sustainable use of global resources, Part I: Conceptual Framework. *Journal of Industrial Ecology* 20(4)775-782.

- Earles, J. M., Halog, A., Ince, P., Skog, K. (2013) Integrated Economic Equilibrium and Life Cycle Assessment Modeling for Policy-based Consequential LCA. *Journal of Industrial Ecology* 17(3)375-384.
- Faber, A., Idenburg, A. M., Wilting, H. C. (2007) Exploring techno-economic scenarios in an input-output model. *Futures*, 39(1)16-37.
- Farmer, J. D., Foley, D. (2009) The economy needs agent-based modelling. *Nature* 460 (7256)685-686.
- Harrison, W. J., Pearson, K. R. (1996) Computing Solutions for Large General Equilibrium Models Using GEMPACK. *Comput. Econ.* 9, 83–127.
- Hertel, T.W., Tsigas, M.E. (1997) Structure of GTAP. Chapter 2 In: T.W. Hertel (ed.), *Global Trade Analysis: Modeling and Applications*. Cambridge University Press, 403pp. ISBN: 0-521-56134-5.
- Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., Shi, L. (2015) Integrated lifecycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*. 112(20)6277-6282.
- Ianchovichina, E., McDougal, R. (2000) Theoretical structure of dynamic GTAP. Tech. rep.
- Ince, D. C., Hatton L., Graham-Cumming, J. (2012) The case for open computer programs. *Nature* 482, 485-488.
- Kaufmann, R. K. (1997) assessing the dice model: uncertainty associated with the emission and retention of greenhouse gases. *Climatic Change* 35,435-448.
- Kelly, R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., El- Sawah, S., Hamilton, S. H., Henriksen, H. J. R., Kuikka, S., Maier, H. R., Rizzoli, A. E., Van Delden, H., Voinov, A. A. (2013) Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software* 47, 159-181.
- Klaassen M.A.W., Vos, D., Seebregts, A.J., Kram, T., Kruitwagen S. Huiberts R.G.J. Van Ierland E.C. (1998) MARKAL- IO Linking an MARKAL- IO input-output model with MARKAL Energieonderzoek Centrum Nederland, Petten. ECN rapport: ECN-C--97-106 88pp. ISBN: 9058510050.
- Krey, V. (2014) Global energy-climate scenarios and models: a review. *Wiley Interdisciplinary Reviews: Energy and Environment*. 3(4)363-383.

- Krugman, P., Cooper, R., Srinivasan, T. (1995) Growing World Trade: Causes and Consequences. *Brookings Papers on Economic Activity* 1995(1)327-377.
- Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T., Safranyik, L. (2008) Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452, 987-990.
- Lashof, D. A., Ahuja, D. R. (1990) Relative contributions of greenhouse gas emissions to global warming. *Nature*. 344(6266)529-531.
- Lempert, R., Schlesinger, M., Banks, S. (1996) When we don't know the costs or benefits: Adaptive strategies for abating climate change. *Climatic Change* 33, 235-374.
- Loulou, R., Labriet, M. (2008) ETSAP-TIAM: the TIMES integrated assessment model part I: Model structure. *Computational Management Science* 5(1)7-40.
- Lutz, C., Meyer, B. (2009) Environmental and economic effects of post-Kyoto carbon regimes: Results of simulations with the global model GINFORS. *Energy Policy*. 37(5)1758-1766.
- Manne, A. S., Wene, C.-O. (1992) MARKAL-MACRO: A linked model for energy-economy analysis. Tech. rep., Brookhaven National Laboratory, New York.
- Manne, A., Mendelsohn, R., Richels, R. (1993) Merge: A model for evaluating regional and global effects of GHG reduction policies. *Energy Policy* 23, 17-34.
- Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., Kato, E., Shukla, P., Yamagata, Y., Kainuma, M. (2011) An emission path-way for stabilization at 6 Wm⁻² radiative forcing. *Climatic Change* 109(1-2)59-76.
- Mazzanti, M., Marin, G., Mancinelli, S., Nicolli, F. (2014) Carbon dioxide reducing environmental innovations, sector upstream/downstream integration and policy: evidence from the EU. *Empirica*. 42(4)709-735.
- Meyer, B., Lutz, C. (2007) The GINFORS Model - model overview and evaluation. Tech. rep., Gesellschaft für Wirtschaftliche Strukturforchung mbH (GWS), Osnabrück. 19pp.
- Meyer, B., Ahlert, G. (2017) Imperfect Markets and the Properties of Macro-economic-environmental Models as Tools for Policy Evaluation, *Ecological Economics*, Article in Press.
- Miller, R. A., Blair, P. D., 2009. Input-output analysis: foundations and extensions, 2nd Edition. Cambridge University Press 750pp. ISBN: 978-0-521-73902-3.
- Matsuoka, Y., Kainuma, M., Morita, T. (1995) Scenario analysis of global warming using the Asian-Pacific Integrated Model (AIM), *Energy Policy* 23(4/5)357-371.

- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., Wilbanks, T. J. (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756.
- Nijkamp, P., Wang, S., Kremers, H. (2005) Modeling the impacts of international climate change policies in a CGE context: The use of the GTAP-E model. *Economic Modelling* 22(6)955-974.
- Nordhaus, W. D. (1994) *Managing the Global Commons: The economics of climate change* MIT Press, Cambridge, MA. 213pp. ISBN: 0-262-14055-1.
- Nordhaus, W. D., Yang, Z. (1996) A regional dynamic general-equilibrium model of alternative climate-change strategies. *American Economic Review* 86, 741-765.
- Pollitt, H., Lee, S., Park, S-J. and Ueta, K. (2014) An Economic and Environmental Assessment of Future Electricity Generation Mixes in Japan - An assessment using the E3MG macro-econometric model, *Energy Policy*, 67, 243-254.
- Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P. (2011) RCP 8.5 - A scenario of comparatively high greenhouse gas emissions. *Climatic Change* 109 (1-2), 33-57.
- Rosa, E. A., Dietz, T. (1998) Climate Change and Society; Speculation, construction and scientific investigation. *International Sociology* 13 (4)421-455.
- Rotmans, J. (1990) *Image: An integrated model to assess the greenhouse effect*. Kluwer Academic Publishers, Dordrecht, The Netherlands. 289pp. ISBN: 978-94-010-6796-6.
- Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5867)1238-1240.
- Shilong, P., Philippe, C., Yao, H., Zehao, S., Shushi, P., Junsheng, L., Liping, Z., Hongyan, L., Yuecun, M., Yihui, D., Pierre, F., Chunzhen, L., Kun, T., Yongqiang, Y., Tianyi, Z., Jingyun, F. (2010) The impacts of climate change on water resources and agriculture in China. *Nature* 467, 43-51.
- Smeets, E., Weterings, R. (1999) *Environmental indicators : Typology and overview*. Tech. rep., European Environment Agency, Copenhagen.

- Smith, P., Bustamante, M. (2014) Agriculture, Forestry and Other Land Use (AFOLU). In: Working Group III - Mitigation of Climate Change. Ch. Agriculture, pp. 1-179.
- Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Muller, C., Prins, A.G. (2014) Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications. PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands 336pp. ISBN: 978-94-91506-71-0.
- Stocker, A., Oman, I., Jäger, J. (2011) The socio-economic modelling of the ALARM scenarios with GINFORS: results and analysis for selected European countries. *Global Ecology and Biogeography*, 21(1)36-49.
- Strachan, N., Kannan, R. (2008) Hybrid modelling of long-term carbon reduction scenarios for the UK. *Energy Economics* 30(6)2947-2963.
- Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E., Edmonds, J. A. (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change* 109(1-2)77-94.
- Tollefson, J. (2015) The 2 °C dream. *Nature* 527, 437-438.
- Tukker, A., R. A. Goldbohm, A. de Koning, M. Verheijden, R. Kleijn, O. Wolf, I. Pérez-Domínguez & J.M. Rueda-Cantuche (2011) Environmental impacts of changes to healthier diets in Europe. *Ecological Economics* 70(10)1776–1788.
- UNEP (2016) The Emissions Gap Report 2016. United Nations Environment Programme (UNEP), Nairobi. 61pp. ISBN: 978-92-807-3617-5.
- UNFCCC (2012) Quantified economy-wide emission reduction targets by developed country parties to the convention: Assumptions, conditions, commonalities and differences in approaches and comparison of the level of emission reduction efforts. Tech rep. UNFCCC document FCCC/TP/2012/2, United nations Framework Convention on Climate Change (UNFCCC).
- UNFCCC (2015) Adoption of the Paris Agreement. Proposal by the President. FCCC/CP/2015/L.9/Rev.1. United nations Framework Convention on Climate Change (UNFCCC)
- Van Asselen, S., Verburg, P. H. (2013) Land cover change or land-use intensification: simulating land system change with a global-scale land change model. *Global Change Biology* 19(12)3648-3667.

- Van den Bergh, J. C. (1991) Dynamic models for sustainable development. Ph.D. thesis, Vrije Universiteit Amsterdam.
- Van Vuuren, D. P., Isaac, M., den Elzen, M. G., Stehfest, E., Van Vliet, J. (2010) Low Stabilization Scenarios and Implications for Major World Regions from an Integrated Assessment Perspective. *The Energy Journal* 31 (Special Issue 1), 165-192.
- Van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., Van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., Oostenrijk, R., van Ruijven, B. (2011) RCP2.6: exploring the possibility to keep global mean temperature increase below 2 C. *Climatic Change* 109 (1-2)95-116.
- Voosen, P. (2016) Climate scientists open up their black boxes to scrutiny. *Science* 354(6311)401-402.
- Vries, B. J. M. D., Vuuren, D. V., Elzen, M. D., Janssen, M. (2001) Targets IMage Energy Regional (TIMER) Model, Technical Documentation. Tech. rep.
- West, G. R. (1995) Comparison of input-output, input-output + econometric and computable general equilibrium impacts models at the regional level. *Economic Systems Research*, 7(2)209-227.
- Wolf, O., I. Pérez-Domínguez, J.M. Rueda-Cantuche, A. Tukker, R. Kleijn, A. de Koning, S. Bausch-Goldbohm & M. Verheijden (2011) Do healthy diets in Europe matter to the environment? A quantitative analysis. *Journal of Policy Modeling* 33(1)8-28.
- Wolter, G. B., Kuiper, M., van Meijl, H., Powel, J., Rutten, M., Shutes, L., Tabeau, A. (2014) The Magnet Model - Module description. LEI, part of Wageningen University and Research Centre, The Hague.
- York, R., Rosa, E. A., Dietz, T. (2003) STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics* 46(3)351-365.