

C O M P L E X

Knowledge Based Climate Mitigation Systems for a Low Carbon Economy



Dynamics of climate-energy-economy systems: development of a methodological framework for an integrated system of models

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1. Introduction

Coupled socio-ecological systems (SES) are complex adaptive systems. While changes and out-of-equilibrium dynamics are in the essence of such systems, this dynamics can be of a very different nature. Specifically, it can take a form of either gradual marginal developments along a particular trend or exhibit abrupt non-marginal shifts. As discussed in our previous report D5.2 non-linearities, thresholds and irreversibility are of particular importance when studying coupled climate-economy systems (Filatova et al., 2013a). Worldwide increasing attention on regime shifts, critical transitions, non-marginal changes, and systemic shocks calls for the development of models that are able to reproduce or grow structural changes and understand the circumstances under which they occur. Due to high interconnectedness in the contemporary world coupled SES are more susceptible to sudden abrupt changes, even in the absence of external disturbances (Helbing, 2013). Strong feedbacks between climate and economy are realized through energy: economy needs energy for development in literary any sector, while emissions need to stabilize and be even reduced to avoid catastrophic climate change (IPCC, 2014). Possibilities of passing some thresholds that may drive these climate-energy-economy (CEE) systems in a completely different regime need to be explored. However, currently available models are not always suitable to study non-linearities, paths involving critical thresholds and irreversibility (Stern, 2013). The main types of models used to explore the dynamics of CEE are Integrated Assessment models (IAMs), Computational General Equilibrium (CGE) models, System Dynamics (SD) and Agent-Based models (ABMs). While these four modeling approaches are constantly advancing, when used individually they still exhibit a number of limitations to study CEE, which may encounter non-linearities and critical thresholds (Moghayer et al., 2012). Each of the fours approaches has key advantages in a particular domain, however they may miss some crucial feedbacks or elements that are likely to cause non-marginal changes in CEE. We argue that a hybrid approach engaging several models in an integrated modeling suit might be instrumental for this task. Ideally an integrated system of models (ISM) should combine the strengths of various models by utilizing the state-of-the-art in climate, economics, energy technology, and individual behavioral change literature as well as in modeling techniques including computational, integrated and participatory modeling.

The report is structured as follows. Firstly, we briefly describe specific models representing each of the four modeling approaches (IAM, CGE, SD and ABM) that we intend to integrate in an ISM (section 2.1). Secondly, we present possible integration points, i.e. which models are going to be integrated and how (section 2.2). Next we present the overall integration scheme, which may be instrumental to explore essential policy options related to CEE

(section 2.3). We further outline how the integration of models is going to be operationalized at the software level (section 2.4), and how stakeholders will be involved in the development of our ISM (section 2.5). The report ends up with a section on concluding remarks and the outlook. The strengths and limitations of the four modeling approaches for modeling of CEE and associated non-linearities, thresholds and irreversible changes are discussed in our previous reports (Filatova et al., 2013a; Moghayer et al., 2012).

2. Integrated system of models

An ISM can be used to address policy questions and methodological challenges when assessing CEE dynamics in the presence of nonlinearities. Such an ISM has a potential to combine strengths of different modeling paradigms. At the same time, typical pitfalls of integrated models in the domain of coupled socio-ecological systems should be avoided (Voinov and Shugart, 2013). In what follows we first describe the elements – i.e. individual models – of the ISM, which we aim to combine in WP5 of the COMPLEX project. Different elements of the ISM have different advantages in terms of capturing the dynamics of CEE system, and potential niches where non-linearities, thresholds and regime shifts may emerge.

2.1 Description of models as components of the integrated suit to study the dynamics of climate-energy-economy systems.

2.1.1 IAM: GCAM

The Global Change Assessment Model (GCAM) is a climate IA model descendent of the model developed by (Edmonds and Reilly, 1985) and MiniCAM model (Brenkert et al., 2003; Clarke et al., 2007; Edmonds et al., 1997; Kim et al., 2006). It is developed by the Joint Global Change Research Institute (Pacific Northwest National Laboratory) with research affiliate status at the University of Maryland (USA).¹ It combines representations of the global economy, energy systems, agriculture and land use, with representation of terrestrial and ocean carbon cycles, a suite of coupled gas-cycle, climate, and ice-melt models (see a schematic representation of the model in the figure). GCAM is known as a “bottom-up policy-optimization” model.

¹ Global Change Assessment Model official website: <<http://www.globalchange.umd.edu/models/gcam/>>

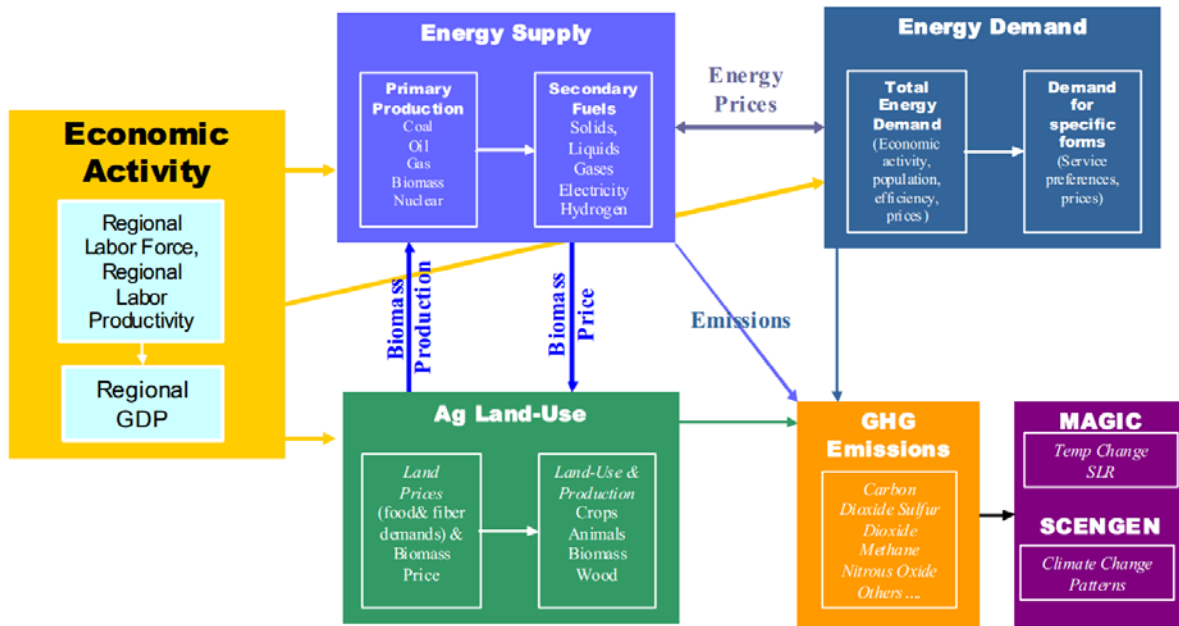


Figure 1: Elements of the GCAM integrated assessment modeling framework. Source: (Wise et al., 2009)

The GCAM is implemented within the Object-Oriented Energy, Climate, and Technology Systems (ObjECTS) framework (Kim et al., 2006). ObjECTS is a flexible, modular, integrated assessment modeling framework. The component-based structure of this model represents the global energy, land-use, and economic systems through a component hierarchy that aggregates detailed technology information up to a global macroeconomic level. Input is provided by the flexible XML standard, where data is structured in an object hierarchy that parallels the model structure. GCAM is then the result of the integration of a bottom-up module (ObjECTS) with a top-down economic module (Edmonds and Reilly, 1985).

GCAM is a dynamic recursive economic partial-equilibrium² model driven by exogenous variables regional population size and labor productivity that determine potential gross domestic product in market exchange rates (GDP MER)³ in each of 31 geopolitical regions⁴ at five (or 15) year time steps. GCAM establishes market-clearing prices for all energy, agriculture and land markets such that supplies and demands for all markets balance simultaneously. The market clearing values at the time “t” will be the initial values for the time “t+1”. The GCAM energy system includes primary energy resource production, energy

² Thus, GCAM has no explicit markets for labor and capital and there are no constraints such as balance of payments.

³ Although GDP input is in market exchange rate, a procedure for converting it to purchasing power parity (PPP) values is set assuming that when income of current non-developed countries reach a threshold, market are integrated enough that the PPP/MER differences are small (Smith et al., 2005).

⁴ GCAM 4.0 is just has been released, the covered regions are: Africa (Eastern, Northern, Southern, Western), Australia_NZ, Brazil, Canada, Central America and Caribbean, Central Asia, China, EU-12, EU-15, Europe_Eastern, Europe_Non_EU, European Free Trade Association, India, Indonesia, Japan, Mexico, Middle East, Pakistan, Russia, South Africa, South America (Northern, Southern), Argentina, Colombia, South Asia, South Korea, Southeast Asia, Taiwan and Global.

transformation to final fuels, and the use of final energy forms to deliver energy services such as passenger kilometers in transport or space conditioning for buildings. GCAM contains detailed representations of technology options in all of the economic components of the system with technology choice determined by market probabilistic competition (Clarke and Edmonds, 1993). The run period goes from 1990 until 2095 (through a calibration process for the past data through to 2005). There is no feedback between the temperature and GDP and climate mitigation and GDP in the Model.

GCAM distinguishes between two different types of resources: depletable and renewable. Depletable resources include fossil fuels and uranium; renewable resources include wind, geothermal energy, municipal and industrial waste (for waste-to-energy), and rooftop area for solar photovoltaic. All resources are characterized by cumulative supply curves; that is, upward-sloping supply-cost curves that represent that the marginal cost of resource utilization increases with deployment. Supply cost-curves for fossil fuels are based on the hydrocarbon resource assessment (Rogner, 1997) (updates have been made for unconventional resources)⁵ and on (Schneider and Sailor, 2008) for uranium.

The agriculture and land use component is fully integrated (i.e., solved simultaneously) with the GCAM economic and energy system components. Since GCAM 3.0, the model data for the agriculture and land use parts of the model is comprised of 151 sub-regions in terms of land use, based on a division of the extant agro-ecological zones (AEZs). Land is allocated between alternative uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per ha), product price, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. This increase in productivity is exogenously set, adopted from projections by (Bruinsma, 2003). Thus, that evolution is not specifically attributed to individual components, which may include changes in management practices, increases in fertilizer or irrigation inputs or impacts of climate change. Emissions of gases related to agricultural productivity, for example N₂O and CH₄, are tied to the level of production. All agricultural crops, other land products and animal products are globally traded within GCAM. A full description of the agriculture and land use module (documentation of the data, methods used and hypothesis considered) in GCAM can be found in (Kyle et al., 2011; Wise and Calvin, 2011; Wise et al., 2009).

⁵ see http://wiki.umd.edu/gcam/index.php/Resource_Supply_Curves.

GCAM it is not a Trade model: Heckscher-Ohlin trade is modeled instead of bilateral trade. It is assumed that traded products are supplied to a global pool and any region can consume from this pool. Trade is allowed for all commodities in the GCAM, except for electricity or CO2 storage services that are assumed to be produced and consumed within a given region (Wiki, 2012).

The GCAM physical atmosphere and climate are represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (Raper et al., 1996; Wigley and Raper, 2002, 1992). Thus, GCAM tracks emissions and concentrations of a high number of greenhouse gases and short-lived species⁶ from land-use-change and energy supply and supply sectors. The GCAM can be run with any combination of climate and non-climate policies in relation to a reference scenario. Policies can take a variety of forms including taxes or subsidies applied to energy markets, activity permits, e.g. cap-and-trade emissions permits, and/or technology standards, e.g. CAFE or new source performance standards. Costs are computed as the integral of marginal abatement cost curve (Wiki, 2012). Thus the model estimates temperature increasing, sea-level rise and radiative forcing, although is not able to estimate impacts or feedbacks of climate change in the economic, energetic and agriculture sectors due to its sequential structure. For this reason ongoing research focus on coupling GCAM with the full-coupled Community Earth System Model (CESM) that will allow it to compute bio-geophysical feedbacks effects of land use change (e.g. (Jones et al., 2011)).

GCAM has been developed over the course of 30 years and regularly participates in model inter-comparison projects, such as the Energy Modeling Forum (Clarke and Weyant, 2009), and is a member of the Steering Committee of the Integrated Assessment Modeling Consortium (<http://www.iamconsortium.org>). Emissions scenarios produced with GCAM or one of its related models, e.g. MiniCAM, have been used extensively by the Intergovernmental Panel on Climate Change (IPCC, 2014, 2011, 2007a, 2007b, 2007c, 2001, 1999, 1995) (and will also participate in the Vth report (Moss et al., 2010) and for research and policy analysis by national governments and other stakeholders (Clarke et al., 2007).

At last, GCAM is a model in constant evolution. This brief presentation refers to the version GCAM 3.1.7 Updates of historical data and extensions are done regularly. For example, future versions are planned to include: water markets, detailed technological options for agricultural sector, replacement of Climate model MAGICC, increasing the number of GCAM

⁶ Including: CO₂, CH₄, N₂O, NO_x, VOCs, CO, SO₂, carbonaceous aerosols, HFCs, PFCs, NH₃ and SF₆.

⁷ <http://www.globalchange.umd.edu/models/gcam/download/>

regions, etc.⁸ These changes and updates are usually documented first in (Wiki, 2012), that we recommend to check when working with GCAM. A selected set of GCAM papers and reports is also available: <http://wiki.umd.edu/gcam/index.php?title=References> .

2.1.2 SD: MADIAMS

MADIAMS (Multi-Actor Dynamic Integrated Assessment Model System) and its prototype SDEM (Structural Dynamic Economic Model) are actor-based system-dynamics models with applications to economics of climate change. The actor-based system-dynamics modelling approach shares with traditional system dynamics a method of describing the economic dynamics by complex nonlinear systems of ordinary differential equations. However the approach is more focused on describing the behavior and decision-making of aggregate economic actors, hence the definition “actor-based”.

The purpose of MADIAMS/SDEM is to assess the efficiency of global and regional mitigation options under conditions of out-of-equilibrium economic dynamics, possible strong nonlinearities (both in climate and economic modules), positive feedbacks and potential abrupt/catastrophic climate change.

MADIAMS is designed in a hierarchical way: the bottom level of model hierarchy (M1) describes the economic dynamics without governmental regulation, the medium level (M2) includes government(s) as actor(s) (notably implementing the climate policy), while the top level (M3) includes the climate module and therefore describes the fully coupled dynamics of climate–socio-economic system (Figure 2).

⁸ http://www.globalchange.umd.edu/data/gcam/2012/Future_Directions_in_GCAM_Development_2012-09-18.pdf

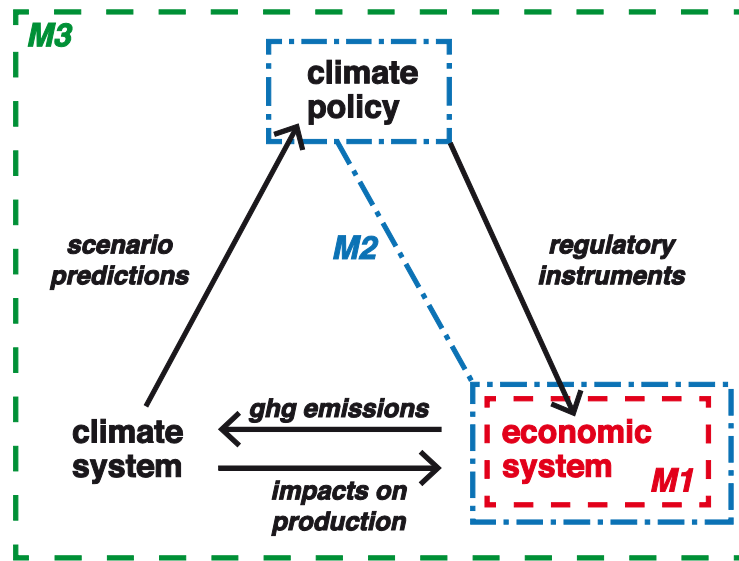


Figure 2: MADIAMS model hierarchy. Source: Hasselmann and Kovalevsky, 2013

The evolution of the economy in MADIAMS/SDEM is governed by the interactions of a few key aggregated actors (a firm, household, a government, a bank etc.). The economy is treated as a nonlinear system described by a set of system-dynamic equations closed by the specification of the actors' control strategies. The model provides a unified framework for studying the dependence of economic growth and transformation on negotiated wage levels, the rate of investment in human capital (technological innovation), consumption versus savings preferences, government policies and various "animal spirit" processes. SDEM comes in a single-region (global-scale) version, while MADIAMS comes both in single-region and multi-region versions (the latter is currently under development). The climate module of MADIAMS/SDEM can account for gradual and (optionally) possible abrupt climate change (including possible shutdown of the Atlantic thermohaline circulation (THC)).

The economic growth in MADIAMS/SDEM takes place under conditions of conflict of interests of a few key powerful aggregate actors (a firm, household, a government, a bank etc.). Energy is linked to output through energy efficiency, while output is linked to emissions through carbon efficiency. The stock of fossil fuel resources is finite. The key mitigation option in MADIAMS/SDEM is introducing the global carbon price through harmonized carbon tax. Carbon tax revenues can be recirculated into the economy in several different ways (as an option, they can be recirculated in the form of investment in endogenous improvement of carbon/energy efficiency).

The latest version of economic module of single-region MADIAMS is described in detail in (Hasselmann and Kovalevsky, 2013). The model is coded in Vensim[®] DSS and can be freely

downloaded (with supporting documentation and selected model runs) from the MADIAMS webpage maintained at the Global Climate Forum website (URL: <http://www.globalclimateforum.org/index.php?id=madiams>). A version of SDEM accounting for possible shutdown of Atlantic THC developed within COMPLEX project is described in (Kovalevsky and Hasselmann, 2014).

2.1.3 CGE: EXIOMOD

EXIOMOD is a large scale and highly detailed world CGE model built on the detailed environmentally-extended database EXIOBASE. The model divides the global economy in 44 countries and a Rest of World, and 164 industry sectors per country. The model includes 5 types of households, a representation of 29 types GHG and non-GHG emissions, different types of waste, land use and use of material resources (80 types). Moreover, it includes a physical (in addition to the monetary) representation for each material and resource use per sector and country. The model is presently calibrated on the data for 2007. The model currently uses the period 2013-2050 as the time horizon for its calculations. The model equations tend to be neo-classical in spirit, assuming cost-minimizing behavior by producers, average-cost pricing, and household demands based on optimizing behavior.

EXIOMOD utilizes the notion of the aggregate economic agent. They represent the behavior of the whole population group or of the whole industrial sector as the behavior of one single aggregate agent. It is further assumed that the behavior of each such aggregate agent is driven by certain optimization criteria such as maximization of utility or minimization of costs. The model divides the global economy in 44 countries and a Rest of World, and 164 industry sectors per country. It also includes the representation of the micro-economic behavior of the following economic agents: several types of households differentiated by 5 income quintiles, production sectors differentiated by 164 classification categories; investment agent; federal government and external trade sector. Table xxx in Appendix A provides an overview of the main elements of the model.

Further development of EXIOMOD for the needs of the COMPLEX project: we use a modular approach for the development of a new version of EXIOMOD which is suited to be integrated to the COMPLEX system of models. A re-structured version of the EXIOMOD will be used as the basis and the following modules will be developed to address the main objectives of the WP5 system of models:

- I. *Detailed nested production and utility function*: Behavior of the economic sectors in EXIOMOD is based on the minimization of the production costs for a given output level under the sector's technological constraint.

In accordance with their production technology, sectors will have substitution possibilities between different intermediate inputs and production factors. They are also able to substitute between their consumption of electricity and other energy types such as gas, coal, oil and refined oil. Existence of the technological substitution possibilities is an important feature of the production process and cannot be neglected while modeling sectoral production, especially for the impact assessment of mitigation policy measures.

Households will also have substitution possibilities between different consumption commodities. They can substitute consumption of transport for the consumption of other goods and services. They are also able to substitute between their consumption of electricity and other energy. The inclusion of substitution possibilities is important for a realistic representation of the consumption decisions of the households and better assessment of the welfare and economic effects of transport and energy policies.

Below is a scheme of the nested production and utility functions, which will be implemented in this module. This structure also allow for the integration of EXIOMOD with ABM. Details are provided in Section 2.2.3 . The utility of household is represented in a single nested CES function, in which we will separate energy in a separate nest, as presented in the figure 3:

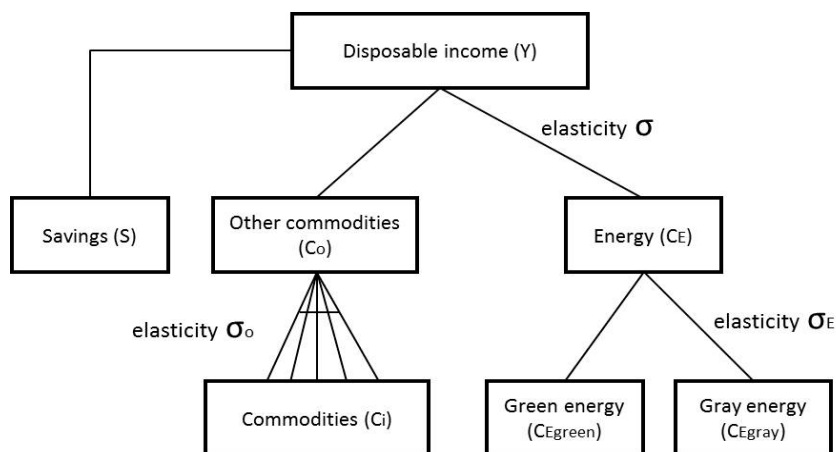


Figure 3: Nested CES with separated energy nest

An alternative way to look at the consumption choices is to assume that the household doesn't derive utility from direct consumption of goods and services provided on the market,

but rather combines existing commodities in order to satisfy its specific needs ⁹. For example, in order to satisfy the need for warm and light housing, the household buys energy, appliances, insulation materials, etc. and combines them (as in a production function) into a single 'housing' commodity. Schematically, the choices of the households can be represented in the following way:

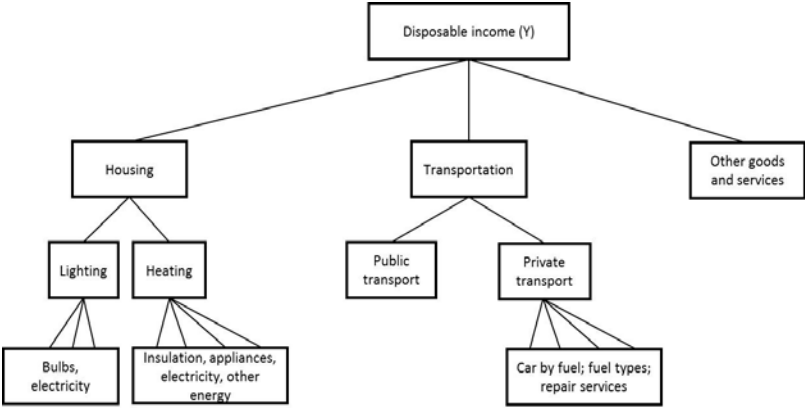


Figure 4: Utility function with a production perspective

Different nests can be represented by **CES** or **LES-CES** preference (top nest) / production (lower nests) functions. The main difference of this approach from a standard nested CES function is that the same marketed commodities can appear in several nests, for example electricity is used for lighting, heating and certain transportation types.

- II. *Carbon Market*: Over time, the global Emission Trading System (ETS) becomes the dominant greenhouse abatement policy for all countries including EU countries. It sets the price for carbon permits and allocates the number of permits available to each country. This module aims at assessing the global and sectoral socio-economic and environmental effects of the ETS policy.
- III. *Technological change*: In order to assess and model the interaction of energy, climate and economy a gap between bottom-up energy models and the CGE models arises. Generally energy system models simulate a large number of individual technologies to capture substitution possibilities of energy carriers, energy efficiency and technological development. However, CGE models show technologies on a an aggregated level with a CES production function capturing substitution possibilities and do not rely on the description of individual technologies. Some CGEs used in climate policy research treat technological change as exogenous. On the one hand it

⁹ See Linkage model as an example of this type of final demand representation: <http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTDECPROSPECTS/0,,contentMDK:20357492~menuPK:681018~pagePK:6416540~piPK:64165026~theSitePK:476883,00.html>

can be introduced as a non-price driven improvement in technology and on the other hand by assumptions about future costs of technologies (backstop).

In EXIOMOD we aim to use a Calvo-style vintage mechanism. A vintage approach basically implies that new technologies will be introduced side-by-side with existing technologies, adding rigidity to adoption. (Calvo, 1976) investigates the properties of a model with a basic putty-clay setup. (Kehoe and Atkeson, 1999) discuss an application of such a model in the context of energy use. In this model capital is putty-clay in terms of its energy intensity. Capital and energy are complementary in the short-run but substitutable in the long run. (Mulder et al., 2003) develop a stylised vintage-model of adoption of energy-saving technologies. They show that strong complementarity between vintages and strong learning-by-using increases the time it takes before firms scrap old vintages.

- IV. *Prediction of abatement costs:* The costs of reducing emissions depends importantly on the ease of substitution between different factors of production, meaning that diffusion of existing technologies is an important determinant of abatement costs. Implications for real-world climate policy costs turn on two key issues: the empirical question of how [moveable] capital is likely to be over the time-frame that emission limits are anticipated to bind, and the theoretical question of the manner in which various characteristics of abating economies influence the short-run adjustment costs to which capital rigidities give rise (Lanzi and Wing, 2013) Some other refs to CGE models with capital vintages: (Jacoby and Wing, 1999; Jacoby et al., 2006).
- V. *Climate Damage:* In EXIOMOD we use sectoral damage estimates from FUND model as input to the CGE.

2.1.4 ABM

ABM is a relatively new approach to modeling CEE systems composed of autonomous, interacting agents (Macal and North, 2010). An ABM is “a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules” (Farmer and Foley, 2009). ABM are able to represent behavior of human actors more realistically, accounting for bounded rationality, heterogeneity, interactions, evolutionary learning and out-of equilibrium dynamics, and to combine this representation with a dynamic heterogeneous representation of the spatial environment (An, 2012; Filatova et al., 2013b). ABM is argued to be the best approach to explore policy questions related to sustainable development, and energy policies in particular (Boulanger and Bréchet, 2005; Kelly et al., 2013).

In this project (WP5, COMPLEX), ABM is designed and programmed with an aim to investigate non-marginal changes in energy markets. This agent-based energy market model plays a vital role within the coupled suit of models complimenting macro-economic and climatic models. It aims to trace potential discontinuities in energy markets driven endogenously from within the economic ABM or triggered by changes in the environment. Aggregated consequences of behavioral changes on the demand side of energy markets, and the technology diffusion on the supply side may serve as endogenous triggers of non-linear changes in energy markets. The quantities and prices of various energy sources and corresponding greenhouse gas emissions resulting from the microeconomic choices are some of the indicators (outputs) of an aggregated ABM market dynamics.

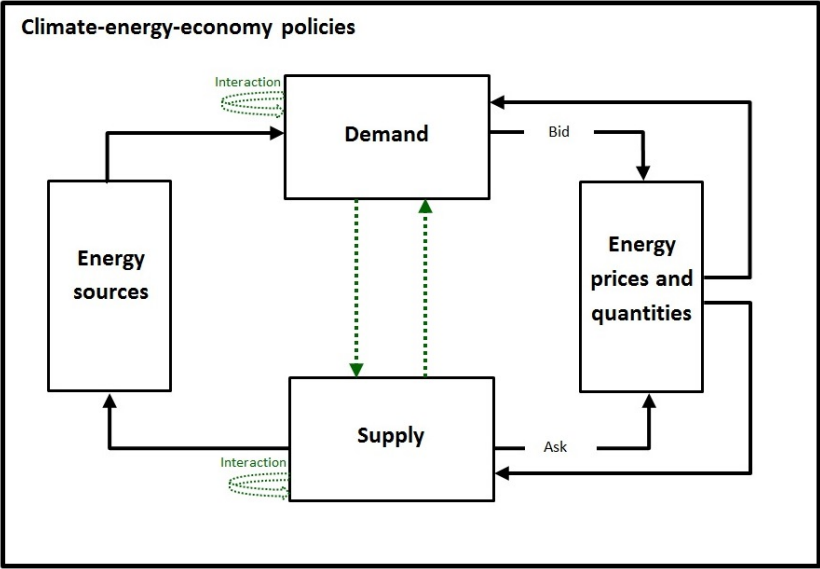


Figure 5: Conceptual diagram of the ABM energy market

The demand side in the ABM is represented by heterogeneous households with different preferences, awareness of climate change, and socio-economic characteristics. Meanwhile, the supply side is presented by heterogeneous energy producers. The microeconomic dynamics on the supply side could include the diffusion of alternative energy technologies (i.e. the transition to low-carbon economy at a higher level).

The ABM will be used to test different scenarios, which potentially could include: (i) various behavioral assumptions and structure of information on micro level, (ii) various regions (case-studies), (iii) various CEE related policies, and (iv) various integration options with other models in the COMPLEX project.

2.2 Integration points

2.2.1 GCAM – CGE

As described in the section 2.1.1, GCAM is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model of intermediate complexity. The model takes population and labor productivity (i.e. GDP) as exogenous inputs. Although there is no feedback between the GDP and other climate variables such as temperature and climate mitigation, the model can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. The model assumes that regional population and labor productivity drive the energy and land-use systems employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. The model can be used to test various policy measures and energy adaptation technologies on energy supply technologies and greenhouse gas emissions.

On the other hand EXIOMOD is a CGE model (section 2.1.2). The model takes into the account of the household sector, labor productivity, government, trade and environment sector and solves for Walrasian equilibrium.

The linkage between the models will take advantage the two main characteristics of both models: the detailed description of the energy and land use modules, together with the climate module, of GCAM, and the comprehensive economic module (including the economic impacts of climate change) of EXIOMOD. The practical integration of both models will be implemented in a sequential way. First, EXIOMOD will report figures for population and labor productivity to GCAM. This information will be introduced in GCAM which will produce figures for the future energy mix, penetration of new energy technologies, energy prices emissions and temperature that will be used as inputs by EXIOMOD. This process of exchange of data between the two models will be repeated until the main outputs of each model (i.e., GDP in EXIOMOD and energy and temperature figures in GCAM) converge.

The integrated framework resulting from the integration of the two models can be used to assess different issues related to climate change such as scenarios, climate policies, or propagation of uncertainty between the two models (e.g. test the aggregate uncertainty on the shape of damage functions in EXIOMOD and the equilibrium climate sensitivity in GCAM).

2.2.2 GCAM – SD – WP2 models

The group of WP2 people developing a top down approach in which they will use global climate change scenarios downscaled to the regional level, in order to produce figures of different meteorological variables such as precipitation, wind speed, etc. enabling the simulation of scenarios for the potential of climate related energies (CRE). For constructing these scenarios, WP2 group will use outputs from the GCAM model, including among others: For Europe:

- time series of the optimal energy mix (including contribution of the different CRE)
- time series of energy prices by energy source
- time series of energy consumption

At Global scale :

- time series of the corresponding CO2 global concentration and RCP

Ideally, this data should be available for different emissions storylines according to different RCP scenarios.

SD models MADIAMS/SDEM can be integrated with GCAM in a sequential scheme. GCAM uses as input data the GDP and population projections for all macro-regions to which the GCAM model world is divided. These projections could be provided by MADIAMS/SDEM. Particularly, single-region versions of SDEM and MADIAMS (available at the moment) generate projections of aggregate world GDP (i.e. of GWP) by self-consistent simulations of coupled climate–socioeconomic dynamics. In the first phase of MADIAMS/SDEM-to-GCAM linking these GWP projections could be disaggregated down to regional GDP projections under assumption that the ratio of regional growth rates can be regarded as fixed within modeling time horizon (by 2050/2100).

The MADIAMS team is then planning to develop a multi-region version of MADIAMS with exactly the same macro regions as in GCAM. This multi-region version of MADIAMS will provide the regional GDP projections that could be used as inputs to GCAM directly, without the artificial disaggregation procedure outlined above.

The MADIAMS team is also exploring the option to go beyond exogenous population projections in MADIAMS (as implemented currently) and to explicitly model instead the exogenous population dynamics. When this model feature is implemented, endogenous population projections generated by MADIAMS could be used as inputs to GCAM as well.

2.2.3 CGE – ABM

The energy market ABM is planned as an individual piece of software with the ultimate goal of linking it with the EXIOMOD CGE within the ISM. The integration of an ABM and a CGE in the energy domain is rather innovative. While the CGE model simulates the connections across economic sectors as an annual equilibrium on many markets within an economy, the ABM will zoom into only the energy market (Figure6). On the demand side our ABM will be disaggregated only residential sector demand taking the energy demand of all other sectors from CGE (updated annually). When modeling changes in individual energy demands between annual equilibria of the CGE we would like to explicitly trace changes in preferences and energy consumption choices driven by individual assessments, pro-environmental attitudes and social interactions (norms). This will result in the new budget shares a household spends on (i) energy vs other goods, and (ii) LCE vs. fossil fuel energy sources. On the supply side we plan to take a two-stage approach. Specifically, we first will differentiate between energy production based on fossil fuels and low-carbon energy (LCE) sources taking the aggregate supply equations structurally similar to the ones in the CGE. Second, we intend to disaggregate the LCE part by explicitly modeling technology diffusion. Ideally, this process will result in new elasticities, which could serve as inputs to the CGE.

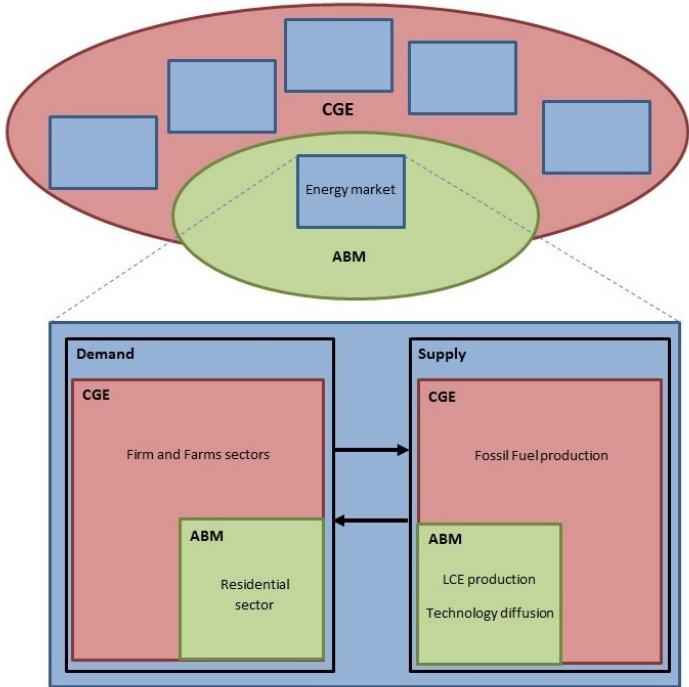


Figure 6: CGE-ABM integration general schema

While the CGE simulates the connections across economic sectors as an annual equilibrium, ABM run quarterly to investigate non-marginal changes in energy market.

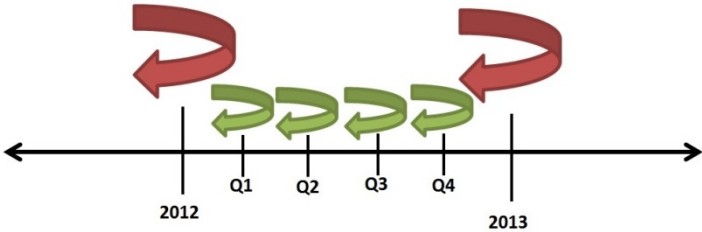


Figure 7: CGE-ABM timeline

Following diagrams is illustrated the exchange variables and input/output of ABM and CGE.

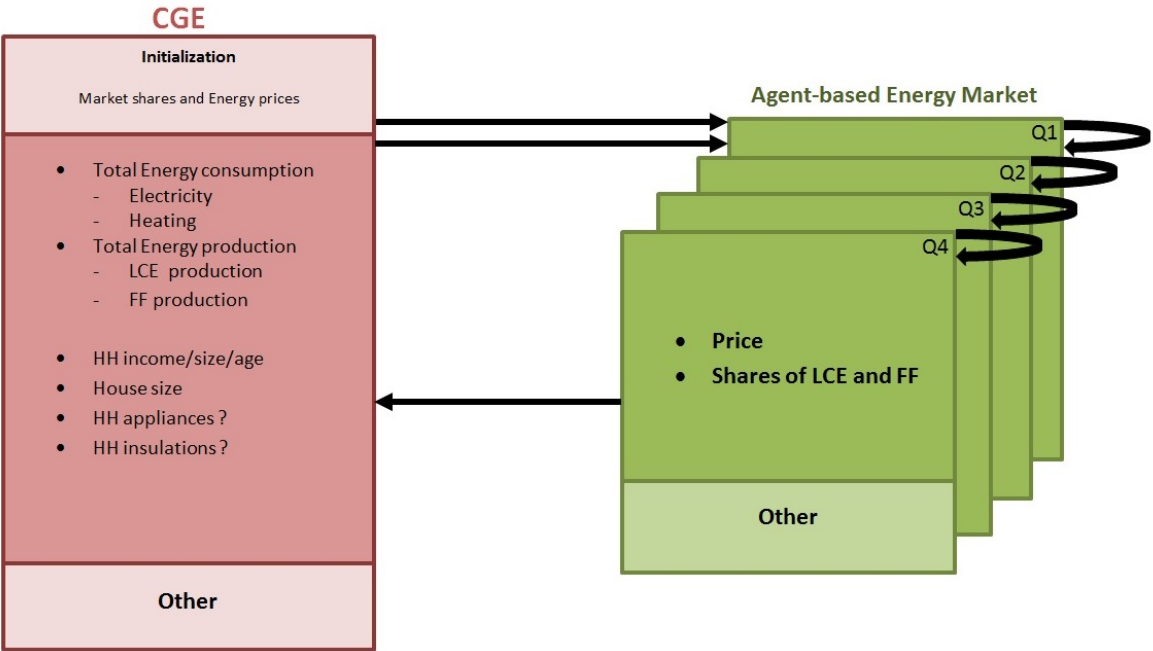


Figure 8: CGE-ABM integration framework

Figure 9 shows CGE-ABM integration on demand side of energy market. As it is illustrated, ABM is focused on “Electricity” and “Heating” as the households energy consumption. Households could use less energy by switching off the extra devices,

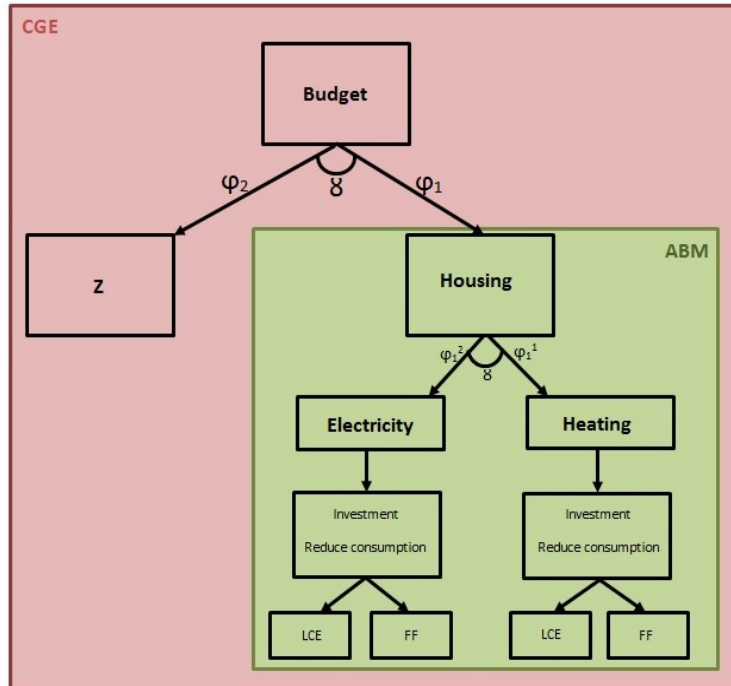


Figure 9: CGE-ABM integration - demand side

reducing home temperature (behavioral change), or improving insulation, changing into devices which have better energy saving label (investment). Meanwhile, they can also consider the source of their energy. They can shift to low-carbon (Green) energies sources. In other words, households can reduce their CO2 footprint by means of one of three actions: (1) investing in energy efficient devices and equipment, (2) reducing energy consumption through behavioral change, and (3) by switching to low-carbon energy.

The lowest scale of operation of the CGE model is NUTS2 regions, while the highest scale of the ABM would be NUTS2. The lowest scale of ABM is a household on the demand side and energy-producing firms on the supply side. Therefore, the ABM outputs to CGE are going to be scaled up to NUTS 1 (country scale). We envision doing that by means of endowing households agents in the ABM with the key attributes of households groups following the structure of the EU Household Budget Survey (HBS) (European Commission, 2003). Thus, changes in behavior with respect to energy consumption in the ABM can be scaled up to bigger groups of households in other NUTS2 regions in CGE, attributes of which are also harmonized with the EU HBS.

We plan to use empirical data for our agent-based energy market model. Namely, the available EU statistical data, i.e. data on energy use in other sectors, current behavioral functions on demand and supply side (from the CGEs model we link to), past and current energy consumption by households as well as production and etc. We chose 5 countries in

European Union in order to participate in our survey. At this moment these countries tentatively are: Sweden as the representative of Scandinavian countries, UK as the western European country, Poland as an eastern European country, Spain as the representative of Mediterranean countries, and Germany as a central case (Please see the Appendix B).

2.2.4 ABM – SD

ABM and SD will not be linked explicitly, i.e. no data exchanged is planned at this stage of our modeling framework development. However, we envision a possibility to compare the performance, scope and output of ABM and SD models as we gradually increase the complexity of the latter. By doing this we would like to explore whether potential non-linearities emerge or disappear as the complexity of a model increases (this will be done as part of WP6 activities).

2.2.5 CGE – SD

Despite the fact that actor-based system dynamics modeling approach implemented in MADIAMS/SDEM deliberately avoids the general equilibrium/market clearing paradigm on which EXIOMOD is based, MADIAMS/SDEM and EXIOMOD still have many common points (most notably, they both avoid the inter-temporal optimization procedure from which a controversial debate on proper values of discount rates in integrated assessment models has originated).

The MADIAMS team is intending to develop a simple prototype system dynamics version of EXIOMOD by implementing certain actor-based decision making features in basic EXIOMOD model equation structure. This prototype model will not reach the level of regional/sectoral disaggregation of EXIOMOD: instead, a simple single-region one-sector version and a few-region one-sector version are planned for development. Despite the simplicity, this conceptual system dynamics model is expected to provide interesting insights in such features (currently underexplored or not explored by EXIOMOD) as unemployment dynamics, labor mobility across regions, possible regimes of idle physical capital and out-of-equilibrium economic dynamics. Global climate damages evaluated in highly aggregated MADIAMS/SD model will be further disaggregated to regional/sectoral level on the basis of EXIOMOD simulations.

2.3 Integrated system of models

The bilateral links (sections 2.2.1-2.2.4) are uniquely combined to constitute the ISM employed in WP5 of the COMPLEX project (Figure 10).

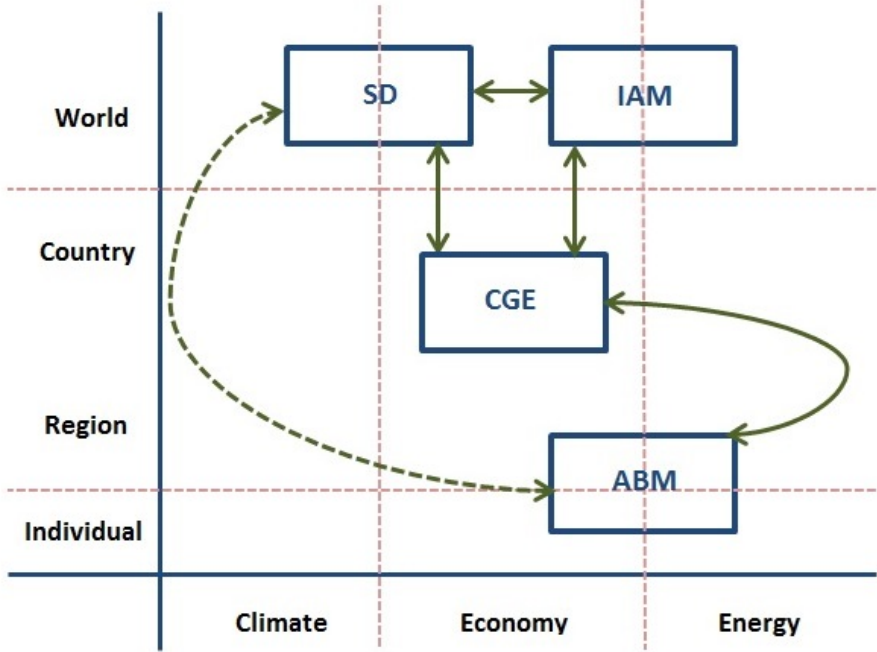


Figure 10: The overall scheme of the ISM as a framework to explore dynamics of CEE systems

Below we outline a potential list of typical policy options that aim to promote a transition to green economy. In Table 3 we sketch how our ISM could be instrumental in quantifying the impacts of these policies. These list and specific nuances related to an operationalization of a policy and the impacts in CEE a policy-maker is interested will be refined during a participatory workshop (section 2.5).

Table 3: Potentially possible scenarios to be run with ISM

Mitigation policies	IAM	SD	CGE	ABM
Regulatory approaches: emission standards, technology standards, product standards	GCAM is an energy rich technology model, It allows the development of new energy technologies. With the prior information of emission standards, the model can indirectly tests the regulatory approaches (through changes in technology coefficients)		Emission/technology/product standards through changes in technology coefficients	Emissions standards as a constrain at an individual firm level
Economic instruments: taxes and changes, border tax adjustments, subsidies, emissions trading systems	All price-based MBIs, but limited to the energy system through taxes and subsidies, prices of carbon, and allocation scheme of carbon permits	Single-region version of MADIAMS/SDEM: carbon tax harmonized worldwide. Multi-region version of MADIAMS: carbon tax introduced in a part of macroregions; emission trading between macroregions; possible recirculation of carbon tax revenues in the economy in the form of investments in endogenous carbon/energy efficiency improvement; border tax adjustments (optionally)	All price-based MBIs with impacts across sectors, markets system through taxes and subsidies, prices of carbon, and allocation scheme of carbon permits	Consumer related taxes and subsidies, which impact households and firms budget constrains
Information policies: providing relevant info for producer and consumer decisions (eco-labels, certificates)				ABM can be instrumental here as they can trace the changes in preferences influenced by information campaigns and amplified by social interactions
Government provision of public goods and services procurement: for example infrastructure planning and provision, public transport etc. (changes in build codes, eco-labeling)		Government investment in green economy (incl. green infrastructure)	Yes, through changes in emissions coefficients. But as exogenous scenarios .	Potentially yes if transport is considered: then ABM can also trace e.g. switching to bike as a social norms of a city commute. But modeling transport choices is outside the scope of this project.

Voluntary actions: actions going beyond regulatory agreements		Consumer preferences shifting toward climate-friendly consumer goods (optionally)	Changes in technological coefficients . Open questions: what share of companies will go for voluntary actions. E.g. front-runners in innovation	Through technology diffusion, most innovative firms are the ones that innovate – voluntary eco- labeling that is perceived as a brand
Other	CCS, land use policies, dietary changes, renewals targets Scenarios: definition of global carbon budgets/targets, fossil fuel depletion			

2.4 Model wrapping tool and implementation

Integration of models requires addressing technical, semantic, and dataset aspects of interoperability. Technical integration of models enables models to communicate with each other. However, integration of existing models may be challenging since they can be developed using different tools, languages and techniques. Yet, when policy and research questions require exploration of processes at different scales in socio-environmental systems, coupling of models in an integrated suite is required. In the case when involved models are independently built, one model cannot easily access the available methods and functionalities of the other model. Thus, one needs to establish “few well-known dependencies” (Rosen et al., 2008) among those independent models. This is called loose coupling.

Technical interoperability among models can be achieved by using various techniques, which usually require implementation of some standards in model interfaces (Janssen et al., 2011; Peckman et al., 2013)(Brown et al., 2002). Thus, one needs a mechanism to transfer existing models into interoperable components and enable coupling among them. Development of wrappers that provide a new interface to launch existing models serves this purpose (Peckman and Goodall, 2013). A model wrapper should satisfy the following main requirements: (1) it should convert a model into a plug-and-play component; (2) it should not be constrained to one programming language, meaning that models wrapped using different languages should not require language interoperability to communicate with each other; (3) it should expose meta-model information for semantic and dataset interoperability tasks.

To meet these requirements for the models employed in the COMPLEX project we propose using web services for model wrappers. A web service is a component, which can be accessed by other programs over the web and which provides standardized machine-readable metadata information about available functionalities, input-output, and messaging format for communicating (Erl et al., 2009) . Web services are language-interoperable and loosely-coupled. Web services can facilitate the model integration effort because the “intrinsically interoperable” (Erl et al., 2008) nature of web services enables the establishment of loose coupling among disparate multidisciplinary models. Model-wrapping web services can be designed using a mixture of different technologies (programming languages), e.g. Java, .NET, etc. depending on the ease of implementation. At the same time, models that are to be integrated can be developed using NetLogo, GAMS, C++, Scala, Java, etc. Yet, given the mediation service of the web-based wrappers they can still be part of the

integrated suite. A development of such wrappers requires an understanding of data exchange among models (input and output data), coherence between temporal, spatial and institutional scales of exchanged data, and identification of the parts of the models to be 'exposed' during the integration.

2.5 Refining the stakeholders needs for the integrated system of models in participatory settings

A value of a model largely depends on whether its results are used, or not, in an actual policy development. Participatory modeling, also known as companion modeling, mediated modeling, or group model building, is a useful element of a good modeling practice in applications that study the dynamics of coupled socio-ecological systems (Voinov and Bousquet, 2010) and can significantly increase the model 'uptake' by the users. As discussed by (Voinov and Bousquet, 2010), participatory modeling exists in various forms varying in the level and intensity of stakeholder engagement (Fig.11). There are examples of participatory modeling using IAMs and CGE (de Kraker et al., 2011; Salter et al., 2010), SD (Gaddis et al., 2010; van den Belt, 2004) and ABMs (Barreteau et al., 2001)(Bousquet et al., 2005). Yet, active stakeholder engagement has not yet been used with ISM, especially to study dynamics of CEE systems.

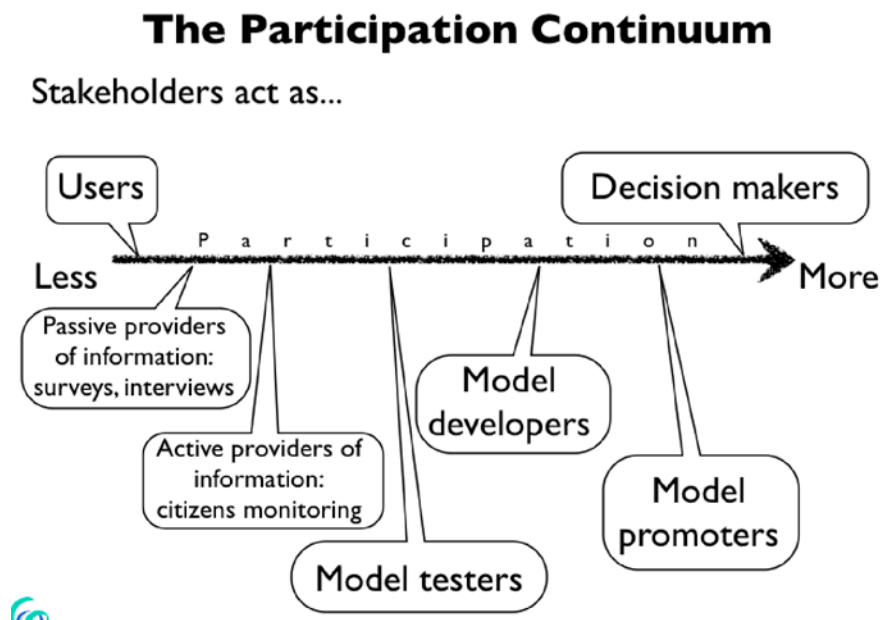


Figure 11: Various levels of stakeholder involvement in modeling

Early in 2015 the participating WP5 organizations with the support of WP6 will organize a workshop where potential stakeholders will be invited. In terms of relevant stakeholders we primarily aim to address EU policy-making institutions in the domain of energy, economy

and climate. Specifically, we aim to attract representatives from DG ENERGY and DG MOVE, and potentially also from DG CLIMA and DG ENV.

The primary aim of this first participatory workshop is twofold. Firstly, we would like to identify the specifications of CEE-relevant scenarios that these policy-makers might be interested in. We plan to discuss our pre-selection of CEE policies outlined in (IPCC, 2007a), (IPCC, 2014) and EU 2050 Energy Roadmap or in “A Roadmap for moving to a competitive low carbon economy in 2050”, and refine the questions, scenarios and expected system behaviors (transitions, growth, decline, shocks, etc.) given the needs from the policy side. This will ultimately result in a list of specific policy options to be tested with our ISM, as well as in the understanding regarding the level of details and any nuanced policy-makers are concerned of. Secondly, we intend to discuss with our stakeholders the scope and assumptions of the IAM, CGE, SD and ABM models employed within WP5 and on the potential added value of our ISM. Ideally, one wants to have an interactive session with stakeholders to receive feedback on the models and discuss plans regarding their development. Ultimately, such a participatory modeling exercise should increase stakeholders’ understanding of and trust in the models and the chances that they will be actually used in practice.

3. Conclusion and outlook

The climate-energy-economic impact assessment models have improved over the years, including expanded treatment of externalities, technological innovation, and regional disaggregation. But, there is still tremendous scope for further improvement, including the difficulty to represent pervasive technological developments, the difficulty to represent non-linearities, and the insufficiently developed representation of economic sectors with a significant potential for mitigation and resource efficiency. Moreover, the majority of these models appear to mischaracterize the behavior of economic agents and depict the behavior of all consumers and businesses as a “representative agents” that do not interact with each other, except very indirectly and only in response to price signals.

The framework ISM, which is presented in this report, is designed to use an integrated approach to tackle some of the aforementioned shortcomings and limitations of the the current Climate-Energy-Economy impact assessment models. Here we use a hierarchy to explore the system along the complexity gradient, learning to build simplified models based

on the more complex ones, and vice versa, understanding how the qualitative behavior observed in some simplified models (non-equilibrium dynamics, flips, thresholds, etc.) can be interpreted quantitatively by means of the more complex models. Such modelling studies are not possible with the stand-alone version of each of the model components. Trade-offs between different policy goals, such as developing a resource efficient economy, decarbonizing the energy system with green energy sources, or climate change mitigation are also only possible in the coupled system. The coupled system also provides the possibility to assess the impact of mitigation policy at different geographical scales: global, country, regional, and individual.

The process modelling of COMPLEX ISM also includes methods drawn from the participatory approach and involve relevant stakeholders and policy makers. More specifically we use the so-called 'Participatory Impact Assessment' approach. This new way of analyzing the future and the effects of policy options combines stakeholder workshops with the use of a reduced form of the system of models. The use of the ISM can range from individual to regional, country and global models. The ABM model can calculate impacts on for example emissions of changes in perceptions and behavior of an individual whereas global models can educate stakeholders about global issues like aging, climate change etc.

The integrated CEE baseline and policy scenarios will be developed based on the policies outlined in (IPCC, 2007a), (IPCC, 2014) and EU 2050 Energy Roadmap or in "A Roadmap for moving to a competitive low carbon economy in 2050" and refine the questions, scenarios and expected system behaviors (transitions, growth, decline, shocks, etc.) given the needs from the policy side. The policy analysis using the ISM will be further undertaken by: 1) envisioning two possible medium (2030) to long-term (2050) futures – i.e. "where do we get", and 2) elaborating alternative scenarios and policy mixes for a low-carbon economy Europe identifying which global, EU level and territorial (within the EU) governance and policy changes are needed – i.e. "how we get there" – as well as measuring alternative scenarios impacts, by means of coupled models. These will be reported in D5.4 along the 'Integration of Climate Scenarios in the Modelling System'. In our stakeholder participatory workshops we will also discuss our pre-selection of policy mixes and if necessary refine the questions, scenarios and expected system behaviors (transitions, growth, decline, shocks, etc.) based on the outcomes of our stakeholder participatory exercise.

The methodological framework for the further development of the model components, and the logical, the technical and the data problems of the integration have been solved by now. For the future, the challenge will still be to solve the linked system. This will not preclude a

successful completion of the exercise, but it will take some time and it may be necessary to marginally change the approach.

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Annex A

Table A.1: Key elements of the EXIOMOD CGE

<i>N</i>	<i>Element of EXIOMOD</i>	<i>Dimension</i>	<i>Main outputs</i>
1	Households	Five income quintiles	Consumption of goods and services, expenditures, incomes and savings
2	Firms	Grouped into 164 types of sectors	Outputs, value added, use of factors of production and intermediate inputs, investments and capital stock
3	Governments	Federal governments	Governmental revenues and expenditures by type including main taxes and subsidies, social transfers to households, unemployment benefits
4	Markets for factors of production	Three education levels, gender, 28 occupation types, 171 types of natural resources including land, water, materials, biomass and energy	Wages, unemployment levels, natural resource rents, return to capital, supply of and demand for factors of production
5	Markets for goods and services	200 types of goods and services	Prices of goods and services, supply of and demand for goods and services
6	International trade	44 countries and five Rest-of-the-World regions, 200 types of goods and services	Trade flows of goods and services between the countries, use of international transport services
7	Savings and investments	National investment bank	Total savings, depreciation, new investments and change in sector-specific capital stock
8	Use of materials	80 types of physical materials	Use of materials by each of 129 production sectors and their extraction
9	Generation of emissions	29 types of GHG and non-GHG emissions	Emissions associated with energy use, emissions associated with households' consumption and emissions associated with general production process
10	Waste and recycling	Various types of waste treatment and recycling by type of material	Representation of waste treatment and recycling sectors as a part of the economy

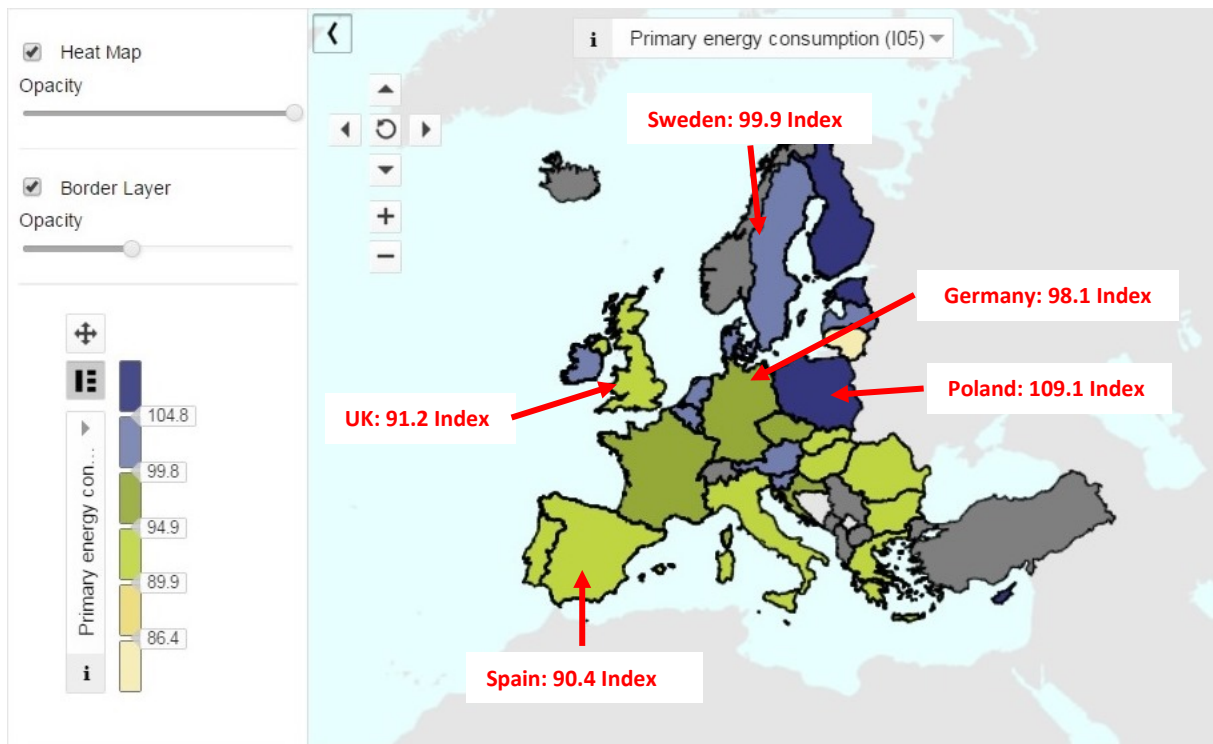
Annex B

In what follows one can find the criteria for choosing the 5 countries, which our ABM will zoom into. In particular, we are looking at:

- Different European Climatic zones (e.g. south vs. north)
- Geographical (Scandinavian, Central Europe, Mediterranean and Eastern countries)
- Household pro-environmental behavior (More green behavior like Sweden and Germany)

Moreover, we used the visual statistics maps from “European Commission Database” to grasp countries difference in:

(i) Categorized by primary energy consumption, 2010



By "Primary Energy Consumption" is meant the Gross Inland Consumption excluding all non-energy use of energy carriers (e.g. natural gas used not for combustion but for producing chemicals). This quantity is relevant for measuring the true energy consumption and for comparing it to the Europe 2020 targets.

(ii) Categorized by Greenhouse gas emission, 2010 (Base year 1990)

