Top-down and Bottom-up: Combining energy system models and macroeconomic general equilibrium models

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1 Introduction

The world needs energy! Availability of energy is an important driver for economic prosperity, since energy is an indispensable prerequisite for performing work.

In principle we have plenty of energy available. The sun provides vast amounts of energy every day by fusing hydrogen into helium. Some of that energy has been stored on Earth in the form of chemical energy in energy carriers as biofuel or fossil fuels as oil, gas and coal. The thermal radiation from the sun creates wind and evaporates water on Earth – which respectively represents kinetic and potential energy. This energy can be utilized directly to do mechanical work, or indirectly to generate electric energy which is a very flexible energy carrier that can be transported effectively over long distances. Energy from the sun can also produce electricity directly by using photovoltaics, or it can produce thermal energy by heating water in solar collectors.

From this we notice that energy takes many different forms, and most of the energy that we use originates from the sun. When the sun eventually goes out in some billions of years, we will still have access to energy from other sources. Mass represents energy, described by Einstein's famous equation $E = mc^2$. The sun transfers mass to energy by a nuclear fusion process. On Earth we are able to produce power from nuclear fission in nuclear reactors. Fusion power is also possible on Earth (but is far from practical use), and we have access to geothermal energy generated and stored in the Earth from radioactive decay.

From a technical perspective and a macro perspective we have no shortage of energy on Earth! Even though each country could have enough energy from a technical perspective, the *costs* for different technologies varies and many technologies are far from being economically viable. Therefore the costs necessary to supply and utilize energy are important, and differ a lot from country to country.

- Countries have access to different energy sources. Different energy forms have different properties, and hence different economic value.
- Countries have different infrastructure, which is needed to utilize the energy (e.g. electricity grids, oil and gas pipelines, shipping harbours).

Energy security of supply is a highly important issue for most countries - especially for countries that are net importers of energy. Norway is a net exporter, and Norway is ranked as the least riskiest energy provider among 158 countries, with the U.S. next (Marín Quemada, García-Verdugo et al. 2012). For Norway, energy security is primarily a subject of uncertain supply and demand of electricity.

Priority number one with regards to energy is to have *access* to energy. Then it is a matter of the cost. What determines the price of energy? The natural way to decide prices is to let the market work – but the market can fail. The use of fossil fuels causes release of greenhouse gases into the atmosphere, which is believed to cause temperature rises that can have serious consequences for life on Earth. These uncertain side-effects from pollution of

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the atmosphere cause costs that affect other parties than the polluters, and thus represent an externality in economics terms. The EU has created a market for emission trading (EU ETS), in order to adjust the prices - taking the externality into account.

We notice that the prices of energy carriers affect the ability to fulfil energy demand in a country. So does also the investment decisions to build infrastructure. Therefore we have to consider more information than the set of technical possibilities. Policy-makers need to understand the effectiveness and cost of policies whose purpose is to shift energy systems toward more environmentally desirable technology paths (Hourcade, Jaccard et al. 2006). Understanding energy-economy coupling is crucial when we want to analyse regional effects of energy policy.

The rest of this report is structured as follows: In the next chapter we describe the two main modelling approaches, continuing with individual chapters describing each of these: The bottom-up engineering approach and the top-down macroeconomic approach. Chapter 5 discusses the linking of these model types, and chapter 6 describes examples of linked hybrid models. Chapter 7 summarises the report and draws conclusions for empirical work.

2 Modelling approaches

Two contrasting modelling types have developed, in order to solve the problem of fulfilling energy demand in an economical sound fashion: the bottom up engineering approach and the top-down macroeconomic approach (Wene 1996, Hourcade, Jaccard et al. 2006).

The engineering approach is to develop bottom-up models with thorough descriptions of technologic aspects of the energy system and how it can develop in the future. Energy demand is typically provided exogenously, and the models analyse how the given energy demand should be fulfilled in a cost-optimal fashion.

The economic approach is to build top-down models that describe the whole economy, and emphasize the possibilities to substitute different production factors in order to optimize social welfare. These models do not include many technical aspects. The interplay between energy and other production factors to create economic growth is captured in production functions, and opportunities to make changes in fuel mixes are described by elasticities of substitution. Another key parameter with regards to responses to energy policy is the autonomous energy efficiency improvement, which allows the production to improve due to assumed technical improvements (Murphy, Rivers et al. 2007).

The two approaches differ considerably in their identification of the relevant system, and may therefore produce different guidance for policy-makers. The production functions in top-down models will usually have smooth substitution - a small price change leads to small changes in the mix of inputs or outputs. The bottom-up engineering models will often react in a more binary way: a small price change can lead to *no* effect at all, or it can produce *large* shifts in the mix of inputs or outputs. An evaluation between a few top-down and

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bottom-up approaches and their usefulness to policy makers is given in (Algehed, Wirsenius et al. 2009).

Our view is that these modelling approaches complement each other. Combining bottom-up engineering models with top-down macroeconomic models should be essential when we want to design energy systems compatible with sustainable economic growth.

3 Engineering bottom-up models

We can divide such models in four main types (Fleiter, Worrell et al. 2011, Herbst, Reitze et al. 2012):

- Optimisation models
- Simulation models
- Accounting models
- Multi-agent models

Optimisation models optimise the choice of technology alternatives with regard to total system costs to find the least-cost path. Such models are also categorised as partial equilibrium models, since they balance demand and supply in the covered sectors.
Simulation models constitute a very broad and heterogeneous group. Their modelling aspects depart from the pure optimisation framework. They can include econometrically estimated relations. Large simulation models can include partial optimization (e.g. from a company perspective), and can consist of different modules covering more aspects.
Accounting models are less dynamic, and do not consider energy prices. These models mainly apply exogenous assumptions on the technical development.
The *multi-agent models* are a broader modelling class than the optimisation models, since they include the simultaneous optimisation by more agents.

Even though we define four types here, the borders are not sharp and well defined, and some models show characteristics of more than one group. Models may develop over time and change type. The classifications do also differ in different sources.

Table 1 below gives examples of engineering bottom-up models of the different types, covering most of the energy demand (different sectors and energy carriers). Further descriptions and numerous references can be found in (Wolfgang 2006, Connolly, Lund et al. 2010, Balabanov 2011, Fleiter, Worrell et al. 2011).

Model type	Model
Optimisation models	ENERGYPLAN IKARUS MESSAGE PRIMES TIMES/MARKAL

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Simulation models	ENPEP INFORSE LEAP MESAP PLANET POLES
Accounting models	MAED MED-PRO MURE
Multi-agent models	LIBEMOD MULTIMOD

Table 1 Examples of engineering bottom-up models

Numerous models are made for analysis of specific energy carriers. The goal of this report is to discuss linking with top-down economic models, and we want to cover the full energy system with all energy carriers. Furthermore, we focus on optimization models as these models constitute the most homogenous group with certain characteristics that can be exploited to form a sound hybrid model. Three engineering bottom-up models that are relevant in this context are described closer in the next section.

3.1 Bottom up optimisation models that have been linked

The Norwegian energy system is extensively modelled in the **TIMES Norway model**. The TIMES[1] model is a generic model developed through an IEA implementing agreement; Energy Technology Systems Analysis Program (ETSAP). ETSAP was established in 1976, and there are national teams in nearly 70 countries according to the website (www.iea-etsap.org). The generic model is tailored by the input data to represent a specific region, ranging from global models down to single city models. The planning period is usually 20 to 50 years. The predecessor of TIMES is the **MARKAL[2] model**, which is also in widespread use. MARKAL is used to provide analysis for the IEA's Energy Technology Perspectives reports (ETP) – published every second year. Much of the model structure is similar between MARKAL and TIMES. The main difference is that TIMES allows the user to define more flexible time periods. Further model improvements are now being developed in TIMES, and not in MARKAL.

[1] TIMES is an acronym for The Integrated MARKAL-EFOM System
[2] The name MARKAL is created from MARKet ALlocation model

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Institute for Energy Technology (IFE) has been modelling the Norwegian energy system extensively using both MARKAL and TIMES. These models have been developed and expanded gradually:

MARKAL Norway (single region)	~ (1990-2010)
MARKAL Norway (4 single-county models)	~ (2004-2010)
TIMES Norway (7 regions, 2050, 260 timeslices)	~ (2009-->)

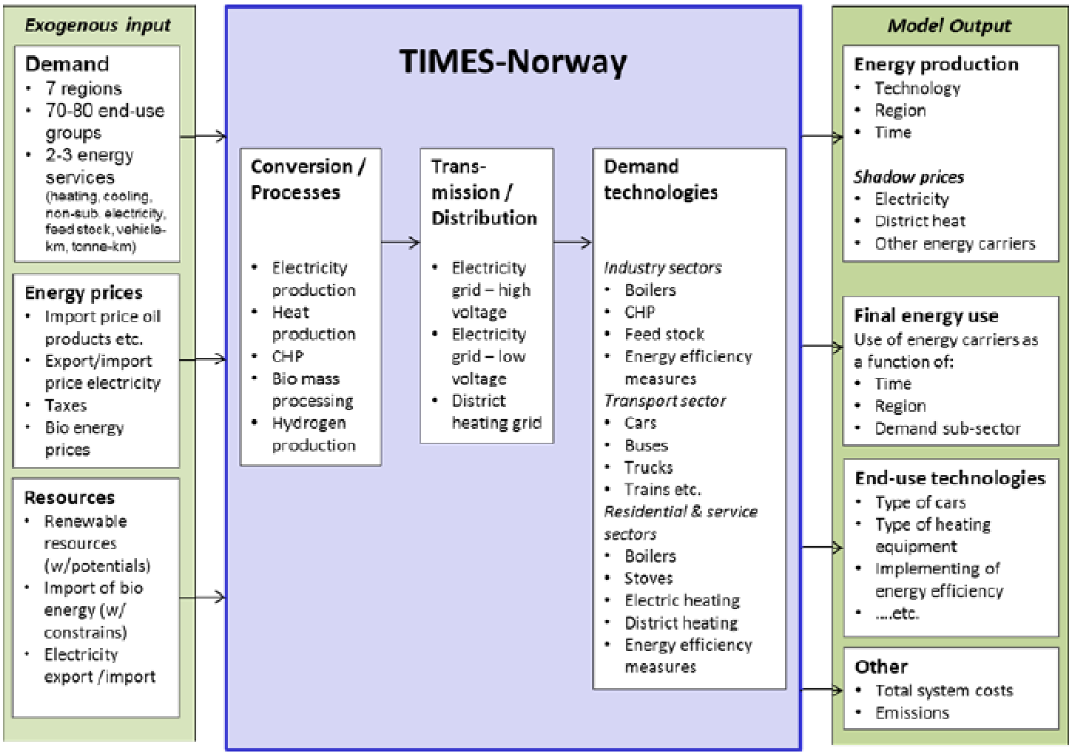

Figure 1 Principal drawing of TIMES Norway

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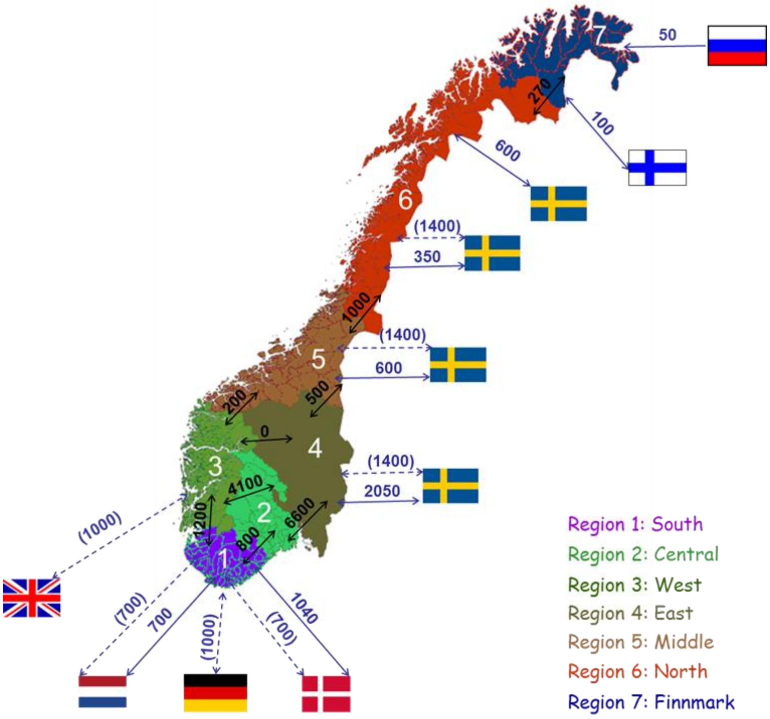

Figure 2 Geographic regions and grid capacities in TIMES Norway

The IEA TIMES model is an internationally recognized model that has been used in Norway for several years. We are currently not aware of other holistic Norwegian energy systems models in widespread use. TIMES-Norway can be linked with the EMPS electricity model, providing a better representation of the regional (zonal) electricity prices.

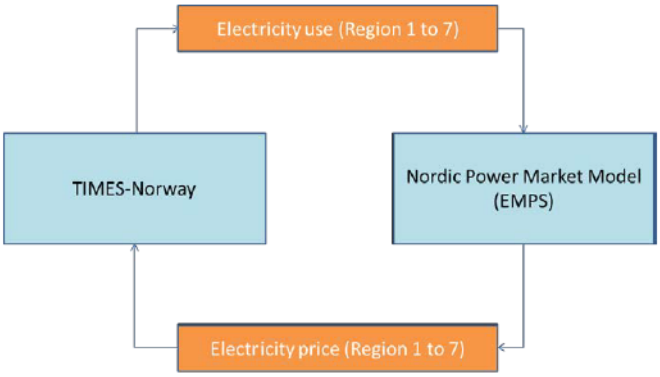

Figure 3 Interaction between TIMES Norway and EMPS

The **MESSAGE** model is another energy systems model, developed at the International Institute for Applied Systems Analysis (IIASA) in Austria. It is part of IIASA's Integrated Assessment Scenario Analysis Framework. MESSAGE is a time-dependent linear programming model which provides an optimal allocation of fuels to meet a given demand. MESSAGE has a reference energy system (RES) that represents the most important energy carriers and conversion technologies. Energy demands are exogenous to the model. The general model characteristics are therefore the same as for TIMES and MARKAL.

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4 Macroeconomic top-down models

Top-down models in general can be divided in four main types (Herbst, Reitze et al. 2012):

- Input-output models
- Econometric models
- Computable General Equilibrium models
- System dynamic models

Input-output models follow the monetary flows between different sectors of the economy, and include both intermediate and end-use deliveries from each sector. From these interrelations one can estimate monetary effects of economic shocks or structural changes in the economy. These models are not dynamic in prices, and assume that prices are given exogenously. *Econometric models* deal with time series analysis and estimate statistical relations between economic variables over time in order to calculate projections from the resulting model. *Computable general equilibrium models* (CGE) are based on microeconomic theory and calculate how both prices and activities in all sectors change in order to reach a general equilibrium in the economy. Like the first group, these models also build on the input-output data from national accounts. *System dynamic models* have pre-defined rules for the behaviour of different actors in the model, and are able to make complex non-linear simulations on this basis.

In this report we are focusing on Computable General Equlibrium models for the top-down modelling. The engineering bottom-up model can provide cost-optimal prices for a given demand. Thus we want to take price effects into account, and the input-output models do not handle this. We also want to analyse long term effects of energy policy, and the statistical relations based on historical data will not necessarily remain for 30 years in the future. The Lucas critique argues that econometric models cannot predict effects of a change in economic policy on the basis of relationships observed in historical data (Lucas 1976). The system dynamic models often have a narrower focus, and are less general than the CGE models.

The CGE models are directly based on microeconomic theory: Consumers are demanding goods in order to maximize utility, and producers are supplying goods in order to maximize profits. The theoretical origins can be traced back to the work of Léon Walras over a century ago. The proof of existence of a general equilibrium was established in (Arrow and Debreu 1954). The first successful implementation of an applied general equilibrium model without the assumption of fixed input-output coefficients was made in 1960 by Leif Johansen (Johansen 1960, Jorgenson 1982).

4.1 Data

Statistical data from national accounts are essential for Computable General Equilibrium models. As regards to international statistics, the most widely used database today is

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maintained by GTAP[3], coordinated by Center for Global Trade Analysis housed in the Department of Agricultural Economics at Purdue University. GTAP version 8 covers 129 regions with 57 sectors with 2007 as reference year. Another project called EXIOPOL has produced a more detailed global database (EXIOBASE) for the base year 2000. This is an environmentally extended database. As a follow-up, the CREEA project will develop a similar database for base year 2003. The World Input Output Database project (WIOD) has produced a database with input-output tables for the time-series 1995 to 2006. The EORA project funded by the Australian Research Council provides a time series of high resolution input-output (IO) tables covering the period 1990-2011. (Dils, Van der Linder et al. 2013)

Norway has had input-output tables integrated in the national accounts since as early as 1952, and has adopted the emerging international standards throughout the years. The fourth generation of international guidelines (SNA2008/ESA2010) (Bos 2011) will be implemented in the Norwegian national accounts in 2014.

4.2 Global CGE models

The GTAP database was mentioned above, and GTAP also has a multiregion CGE model, with perfect competition and constant returns to scale (Hertel 2013). Other well-known global CGE models are

- WorldScan, developed by CPB Netherlands Bureau for Economic Policy Analysis
- EPPA[4], developed at the MIT Joint Program on the Science and Policy of Global Change
- Phoenix, developed at the Joint Global Change Research Institute, University of Maryland, successor to *SGM*
- ENV-Linkages, developed by OECD, successor to *GREEN*
- GEM-E3, developed at NTUA in Athens, used by the European Commission. (The European model version uses Eurostat data.)
- GEMINI-E3, developed by the French Energy Atomic Agency since 1994
- GTEM, developed by the Australian Bureau of Agricultural and Resource Economics

All these models are dynamic recursive, multiregional computable general equilibrium models of the world economy - and all use the GTAP database. Further descriptions and references can be found in (Bohringer and Loschel 2006, Wolfgang 2006, Balabanov 2011).

4.3 Norwegian General Equilibrium Models

Five Norwegian CGE models currently running are:

- MSG (Statistics Norway, Troll platform)

[3] Global Trade Analysis Project
[4] Emissions Prediction and Policy Analysis

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- SNoW (Statistics Norway, GAMS MPSGE, GTAP data structure)
- GRACE (CICERO, GAMS MPSGE, GTAP data)
- PINGO (Institute of Transport Economics, GAMS MPSGE)
- FOOD.CGE.MOD04 (Institute for Research in Economics and Business Administration/SNF, GAMS MPSGE)

MSG is an abbreviation for Multi Sectoral Growth. The model was originally developed by Leif Johansen (Johansen 1960). This model has been further developed by Statistics Norway and applied in several different versions. The model is implemented on the "Troll" development platform.

SNoW[5] is a new CGE model that is under development at Statistics Norway, using GAMS as modelling language and exploiting the MPSGE module which is specialised for CGE-models. The SNoW model structure is tailored to GTAP granularity, in order to easily expand the model with more countries in the future.

GRACE is a general CGE model which has been used at Cicero for many years. The model structure is tailored towards GTAP data, so the model can easily be adapted to different countries.

The PINGO[6] model was developed at the Institute of Transport Economics (TØI) and is described in (Ivanova, Vold et al. 2002). This is a *spatial* CGE model, implemented in GAMS and utilizing MPSGE. The model is currently under further development.

There is also a CGE model in use at the Institute for Research in Economics and Business Administration/SNF in Bergen, implemented in GAMS MPSGE. The model has been used to analyse Norwegian food sectors, and was named FOOD.CGE.MOD04 for this purpose (Gaasland 2008). This model has recently been used to analyse regional policy (Gaasland 2013) and the agricultural sector in Norway (Gaasland, Rødseth et al. 2013).

4.4 Spatial CGE models

Spatial Computable General Equilibrium modelling is a relatively new and fast developing field. The difference from the (global) multiregional models mentioned above is the introduction of New Economic Geography elements such as increasing returns to scale, transport costs and labour mobility (Krugman 1998).

We have already mentioned the Norwegian SCGE model PINGO. This model is a modified version of a prototype SCGE model developed by (Brocker 1998). The first full-scale SCGE model was probably CGEurope developed by Bröcker. Other early SCGE models are RAEM (Netherlands), BROBRISSE (Denmark) and STRAGO (Sweden) - in addition to the Norwegian PINGO.

[5] Statistics Norway's World model
[6] Prediction of regional and INterreGiOnal freight transport

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The RAEM model was described in (Oosterhaven, Knaap et al. 2001), and RAEM has been further developed into a *dynamic* SCGE model in its version 3 (Ivanova, Heyndrickx et al. 2007).

A recent dynamic SCGE model is the EU-wide RHOMOLO model (Brandsma, Ivanova et al. 2011). See (Brocker and Korzhenevych 2013) for recent developments in this area.

5 Linking the models

The macroeconomic and systems engineering approaches differ in their identification of the *relevant system*. These systems differ, but the relevant systems must also overlap if we shall be able to link them in a consistent and controlled way. Linking of models is achieved through iterations with feedback of information between the models.

The first example of linked energy-economy models was reported by (Hoffman and Jorgenson 1977). They linked the Brookhaven Energy System Optimisation Model (BESOM) with a general equilibrium model, and later with an input-output model. During the following decades several studies linked economic and systems engineering models, but all the links were *informal*, i.e. the information transfer between the models was directly controlled by the user. This brings us to the problem of categorizing different linking types.

Some terms that are commonly used to describe the model linkage are *hardlinking* versus *softlinking*. These terms are not used consistently in the literature. We use the terms as defined in (Wene 1996), where softlinking is information transfer controlled by the user and hardlinking is formal links where information is transferred without any user judgment – usually by computer programs. The first example of hardlinking energy-economy models was reported by (Manne and Wene 1992), and is described later in this report.

One step further from hardlinking would be to *integrate* the models. This distinction is harder to define. Integrated models are run together, instead of exchanging information between separate model runs.

Term	**Description**
Soft-linked	Processing and transfer of information is controlled by the user. The user evaluates results from the models and decides if and how the inputs of each model should be modified to bring the two sets of results more in line with each other, i.e. how to make the models converge.
Hard-linked	All information processing and transfer is formalized and usually handled by computer programs. In areas where the models overlap an algorithm may be used to negotiate results. Usually one model is given control over certain results, and the other model is set up to

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	reproduce the same results.
Integrated	The models are directly influencing each other, and are not run independently in stand-alone mode.

Table 2 Linking types

Softlinking can be more or less dependent of user judgment. For consistency, the models should exchange feedback information through iterations, providing adjustments in the model inputs. Wene develops a methodological basis for what he defines as internally controlled softlinking (Wene 1996). The methodology requires exact identification of areas where the two models overlap. Such identification is achieved by describing the two models in a common formalized language, the Reference Energy System (RES).

From this overlap betweem the two models, Common Measuring Points (CMP) must be defined where the two models should yield identical results, e.g. for energy flows. Assume that we have linked two models by exchanging feedback through iterations. For consistency we need criteria to know whether the models have converged. It must be possible to compare model results within the overlapping areas and then decide whether the models are describing the same phenomena and the same future. This requirement is not necessarily fulfilled in empirical work. The convergence criteria are usually based on the percentage change of the results compared to the previous iteration, and not on differences between models.

The advantages of softlinking can be summarized by practicality, transparency and learning. Likewise the advantages of hardlinking can be characterized by productivity, uniqueness and control. Softlinking seems the most practical starting point for linking models based on different approaches. Initial investments in computer programming are kept low, and the modellers can fairly quickly obtain results for evaluation and learning. But for reasons of productivity, hardlinking is the preferred end product. As the volume of model runs increases, and more model users become involved, more resources are needed to retain the quality of softlinked than of hardlinked models.

Hardlinking produces one unique result for each set of assumptions and data. Both assumptions and data may be well documented. The quality of the results is controlled by reviewing these assumptions and data. Softlinking often produces noise in the form of differences between the results of the models for energy flows, prices and technologies within the common region. Noise control is complicated because most of the useful sets of common measuring points turn out to be non-exclusive. Due to softlinking noise, uncertainty analysis becomes very difficult. In spite of stringent procedures, each case of softlinking contains an element of human judgement. This fact complicates outside review.

Integrated models that are directly influencing each other are described in the next section.

5.1 Hybrid modeling - from linked models to integrated models

As we have seen in the previous section, there are several ways to link models into hybrid models. A slightly different classification based on different model types instead of linking

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types is given in (Bohringer and Rutherford 2008, Bohringer and Rutherford 2009). They define three broad categories of hybrid modeling efforts that aim to combine bottom-up engineering models with top-down economic models:

a) Linking between individual stand-alone models (typically soft-links)
b) Linking where one of the models dominates and is complemented by the other. The sub-dominant model is usually implemented in a reduced form. This is a typical model constellation that enables hard-links between the models (although hard-linking can also be implemented between individual stand-alone models).
c) Combining bottom-up and top-down characteristics directly in an integrated model, belonging to a more general model class.

We notice that the choice of linking is related to the characteristics of the included models. Figure 4 below shows typical model constellations with different types of linking.

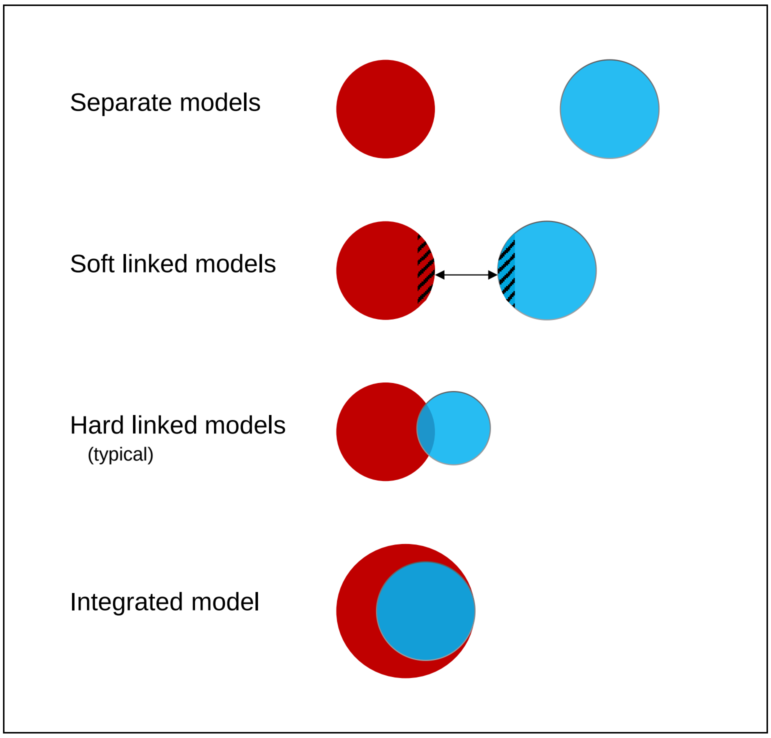

Figure 4 Different types of linking

The CGE-models belong to the broad class of *complementarity problems*. This class includes various nonlinear and non-convex problems, as well as linear and quadratic programming problems. The class of complementarity problems is included in the broader classes of variational inequality problems (VI) and Quasi-variational inequality problems (QVI) (Facchinei and Pang 2003, Gabriel, Conejo et al. 2012). A complementarity problem could be modeled as an optimization problem if the Jacobi matrix is symmetric. If this is not the case, the problem can be viewed as a game between different actors, where the objectives are competing and cannot be combined into a single common objective.

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From the discussion above, we notice that the optimization problem of the bottom-up engineering models is a sub-class of the complementarity problem class. Thus the cost minimization problem of the energy-systems models could be incorporated in an extended version of a computable general equilibrium model, where the engineering-processes of energy supply is represented. This would be an integrated model, as pictured in Figure 4 above.

Such an approach has been described by (Bohringer 1998), and a possible implementation is described for pedagogic purposes in (Bohringer and Rutherford 2008). Furthermore, a decomposition approach to improve the solution algorithms for solving such a model is described in (Bohringer and Rutherford 2009). We are currently not aware of large-scale implementations of such an approach.

5.2 Hybrid models

The word "hybrid" is used to indicate that we will mix together parts from different worlds, because we expect that the whole should exceed the sum of the parts. We focus on combining top-down and bottom-up models, in order to get hybrid models that provide more insights than the individual models do on their own.

As we noticed in the previous section, hybrid models today are not implemented as integrated models solving complementarity problems. Later in this report we describe examples of hybrid models consisting of top-down CGE-models and bottom-up optimization models that are soft- or hard-linked.

There are of course also other hybrid models, which combine different modules into hybrid models – possibly simulation or equilibrium models. Specialized modules are combined in order to produce projections for different scenario assumptions. *Climate* projections of different kinds are typical results, and such models are categorized as *integrated assessment models* which we describe in the next section. Other examples of hybrid models are NEMS and CIMS.

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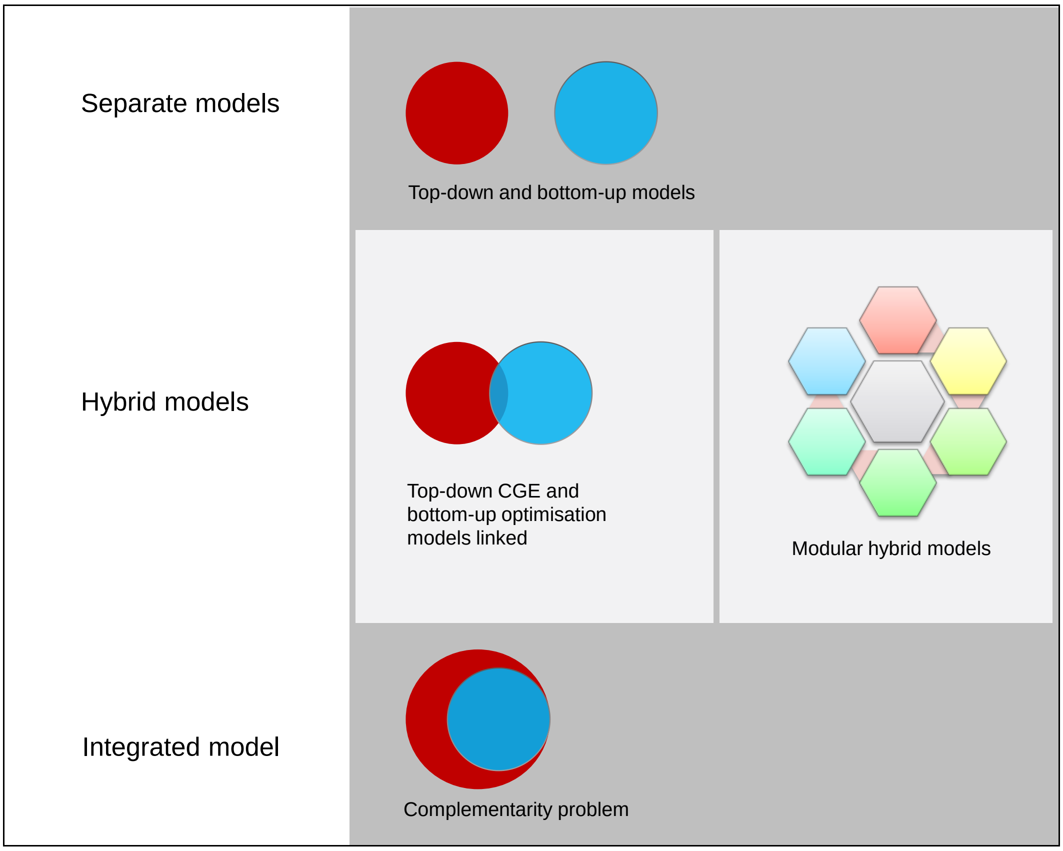

Figure 5 Hybrid models

NEMS – the National Energy Modeling System

NEMS is used by the US Department of Energy, Energy Information Administration. The primary use of the model is to generate the projections presented in the yearly Annual Energy Outlook publications. The first version of NEMS was completed in December 1993, and was used to develop projections presented in the Annual Energy Outlook 1994. Predecessors to NEMS are the PIES (Project Independence Evaluation System) and the IFFS (Intermediate Future Forecasting System) systems.

PIES was a combination of a linear programming model and econometric demand equations used to determine valid prices and quantities of fuels. PIES solved for a supply-demand equilibrium in energy markets by iterating between the linear program and a reduced-form representation of end-use demand models. Shadow prices for fuel were derived from the linear program and delivered to the end-users by sector and region. The reduced-form demand representation was evaluated at these prices, the new end-use demands entered into the linear program, and the program reoptimized. This process continued until the end-use prices and demands were not changing between iterations, within a specified tolerance.

The NEMS model is solved by iterating through different modules in order to reach an equilibrium. (Gabriel, Kydes et al. 2001) argues that the problem could be modelled as a complementarity problem, and thus implemented as an integrated model instead of a

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modular hybrid model. As such it could utilize more robust solution methods, as the NEMS model may encounter various problems when the model is solved today.

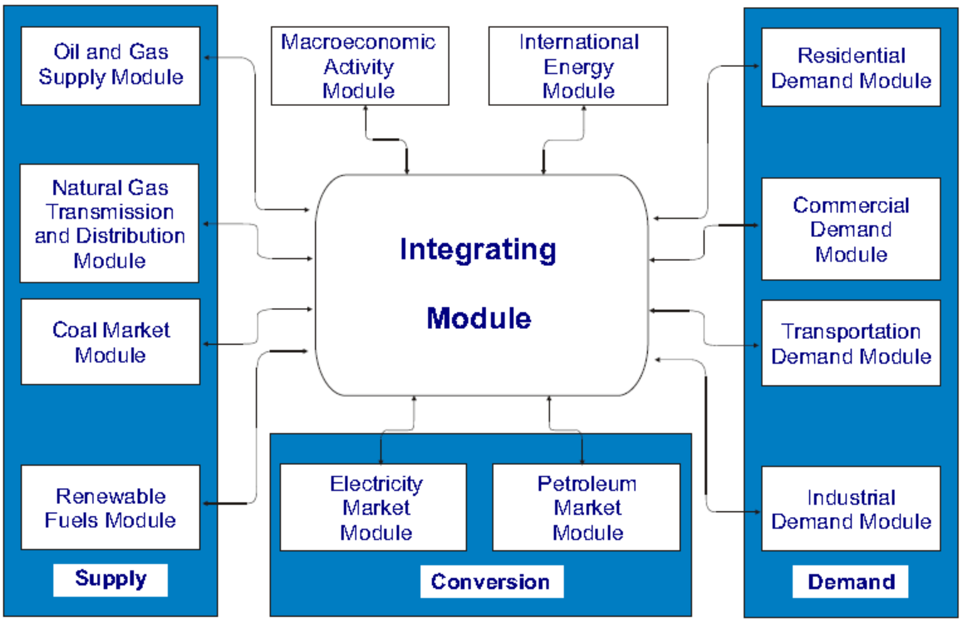

Figure 6 NEMS - National Energy Modelling System

CIMS – Canadian Integrated Modelling System

CIMS is another example of a modular hybrid model that is solved by an iterative process. CIMS projects energy consumption in order to forecast greenhouse gas emissions caused by the combustion of fossil fuel products.

CIMS combines the strengths of the top-down and bottom-up approaches in order to fulfill three key modelling criteria: technological explicitness, behavioural realism, and the ability to capture equilibrium feedbacks. CIMS has the technological richness of a bottom-up model, but simulates technology choices by firms and households using empirically estimated behavioural parameters instead of portraying these agents as financial cost optimizers. As such it can be categorized as a behavioural simulation model. Work is underway to soft- or hardlink CIMS to a CGE model.

CIMS' equilibrium solution is found by first iterating between energy supply and energy demand, and then between these components and the macroeconomic module. Changes in energy demand can result in changes in energy supply, and consequently adjustments to energy prices, which in turn require rerunning energy demand calculations. Once energy supply and demand have reached equilibrium, production cost changes may result in a further adjustment to demand for traded goods and services at the macroeconomic level, requiring further iteration using these new demands. Given this simulation protocol, as more linked systems are integrated in a model like CIMS it becomes more difficult to reach an equilibrium solution (Jaccard et al., 2003a). This situation is quite similar to NEMS.

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(Murphy, Rivers et al. 2007) states that alternative solving algorithms for CIMS will be explored when the model is expanded.

5.3 Integrated Assessment Models

Integrated assessment models integrate knowledge from two or more domains into a single framework. The typical goal is to analyse environmental problems, which crosses different academic disciplines. The activity aims to generate useful information for policy making rather than to advance knowledge for knowledge's sake, hence the term "assessment".

- World Energy Model (WEM), International Energy Agency (IEA), used for the yearly World Energy Outlook report
- Integrated Global System Model (IGSM), MIT Joint Program on the Science and Policy of Global Change (includes the EPPA model mentioned before)
- Global Change Assessment Model (GCAM), Joint Global Change Research Institute at the University of Maryland
- Integrated Assessment Modeling Framework (IAM) at IIASA
- Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) developed at Stanford University.

Some of the models described previously as bottom-up or top-down models are components of an integrated assessment model or framework. Figure 7 below shows the diverse set of inputs and outputs of integrated assessment models, using GCAM as an example.

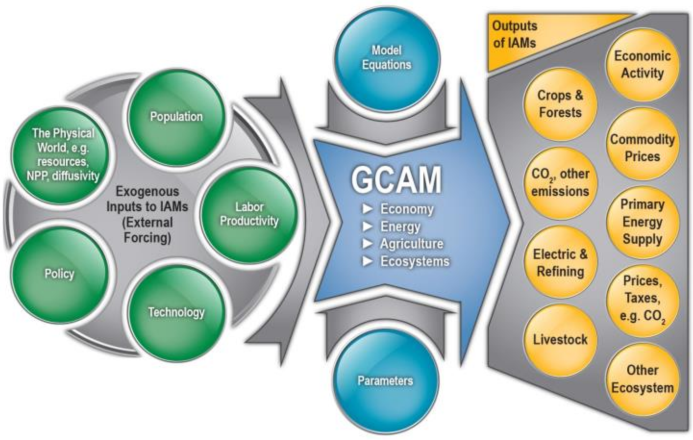

Figure 7 Integrated Assessment Model

5.4 Ongoing work comparing models

There is an ongoing project at the Energy Modeling Forum (EMF) at Stanford University, named the Global Model Comparison Exercise (EMF 27). This project should hopefully provide relevant information in the future.

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6 Examples of linked models

6.1 MARKAL-MACRO

The linkage between MARKAL and MACRO is an early example of linked energy-economy models. Both models are dynamic and solved under the assumption of perfect foresight. MACRO has a rather aggregate structure, the whole economy is aggregated in *one sector* in a *single region*, and there is only one representative producer and consumer. Basic input factors are capital, labour and energy in different forms – fed into an economy-wide production function. MACRO is solved by nonlinear optimization.

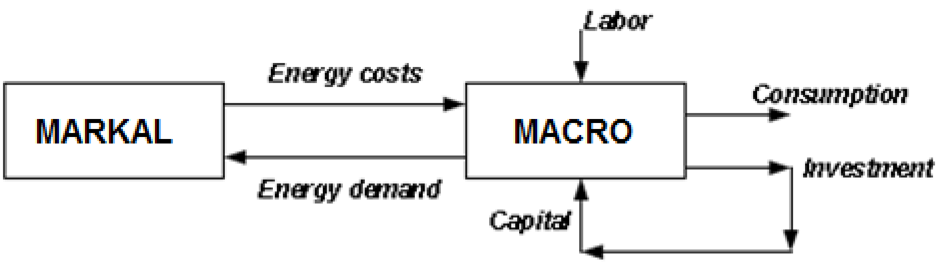

Figure 8 Linking MARKAL and MACRO

Figure 8 shows the linkage between MARKAL and MACRO. MARKAL calculates the physical flows of energy, and the costs of this energy supply are transferred from MARKAL to MACRO (calculated as shadow prices from MARKAL). MACRO then updates the energy demand which is fed back to MARKAL. The exchange of data is fully automated, so this is an example of hard-linked systems. In effect, MARKAL-MACRO includes a relation between demand growth and price changes.

MARKAL is driven by exogenously given energy demands, and these are independent of prices. The MARKAL-MACRO coupling introduces a demand-price interaction. Demands are calculated endogenously in the combined MARKAL-MACRO, but they depend upon the aggregate rate of economic growth, the autonomous energy efficiency increase (AEEI), the elasticity of price-induced energy substitution (ESUB) and changes in energy prices. The linking ensures consistency between energy supplies, demands and prices. This consistency cannot be expected in stand-alone MARKAL. Figure 9 from (Manne and Wene 1992) exemplifies this. The left graph (A) shows that price and demand are related when MARKAL and MACRO are linked, whereas the right graph (B) does not indicate such a relation when MARKAL is run stand-alone.

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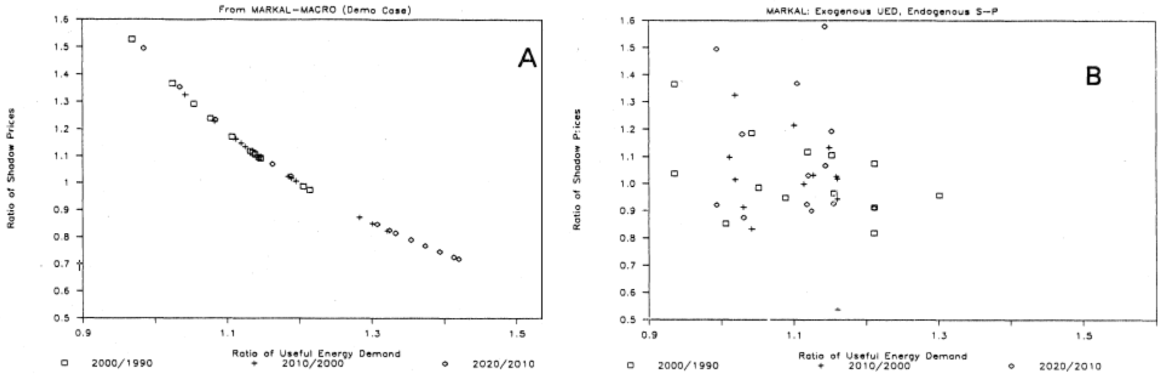

Figure 9 Correlations between prices and demand from linked model (A) and stand-alone model (B)

The MACRO model includes substitution possibilities between energy, labour and capital, so the solution space increases. The resulting energy prices decreases in MARKAL-MACRO compared to MARKAL stand-alone.

To calibrate the MACRO submodel, the following base year data are required: GDP, aggregate energy costs, demand and price for each category of useful energy. Furthermore, estimates must be provided for the capital-GDP ratio, the depreciation rate and capital's value share of GDP. Energy demands and prices can be taken from standalone MARKAL. Prices are found as shadow prices from MARKAL. Care must be taken on the base year calculations, because MARKAL does not have any investment decisions to make in this year. All investments are treated as sunk cost, and all existing capacity is represented as residual capacity that requires no investment. Thus, the total energy costs for the base year will contain virtually no capital charges. As a consequence, the shadow prices will not reflect long-term marginal costs (including capital charges) for some demand categories. Horizon effects may also create spurious results.

The MARKAL-MACRO and TIMES-MACRO coupling is maintained by IEA ETSAP, but it seems not to be in widespread use. Some recent articles using MARKAL-MACRO to analyse energy policies in China, Italy and United Kingdom are (Chen 2005, Contaldi, Gracceva et al. 2007, Strachan and Kannan 2008, Strachan, Pye et al. 2009). We are not aware of any published TIMES-MACRO applications. Enhancements to TIMES-MACRO has however been completed in December 2012, and new extensions are currently being implemented in the ANSWER front-end to TIMES in order to exploit these enhancements.

6.2 MARKAL-MSG

These are examples of soft-linked models, where the user is coordinating the models.

The following procedure was used in (Johnsen and Unander 1996):

1. Adjust the exogenous input assumptions in MARKAL so that they include income effects on the residential energy demand more coherently with the way it is modelled in MSG-EE

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2. Run MARKAL with the adjusted useful energy demand to calculate the composition of the energy system that minimizes the energy expenditure.
3. Adjust the distribution of energy use on different energy carriers in MSG-EE according to the results from the MARKAL calculations.

Johnsen and Unander demonstrate that separate model results get adjusted based on the feedback between models. Their paper does investigate the residential sector, and the feedback from MARKAL in this single sector had little impact on the general economy. The authors suggest that their procedure for an iterative link should be used on all energy using sectors, and repeated until convergence is reached.

In a more recent article MARKAL and MSG are softlinked in order to analyse technology learning (Martinsen 2011). Endogenous handling of technology learning is a standard option in MARKAL, and is modelled using technology learning curves (TLC). Martinsen takes boundary conditions and input to the TLC-curves in MARKAL from the IEA Energy Technology Perspectives (ETP) model (which is primarily based on MARKAL).

The softlinking process is accomplished through three steps.

1. Coherence – all three models are run independently, with coherent scenario assumptions across all models.
2. Calibration – Common measuring points (CMP): MARKAL should reproduce the electricity production estimated by MSG. Export and import of electricity is forced to zero in both models to eliminate this source of inconsistency.
3. Simulation and policy analysis. The bottom-up MARKAL Norway model is given control of the energy system, while the macroeconomic MSG model provides demand for energy services. The *electricity price* is taken from MARKAL.

In order to check that the models are linked, the long term marginal electricity price estimated by MSG is compared with the annual average electricity cost from MARKAL. The iteration procedure is repeated until these values converge.

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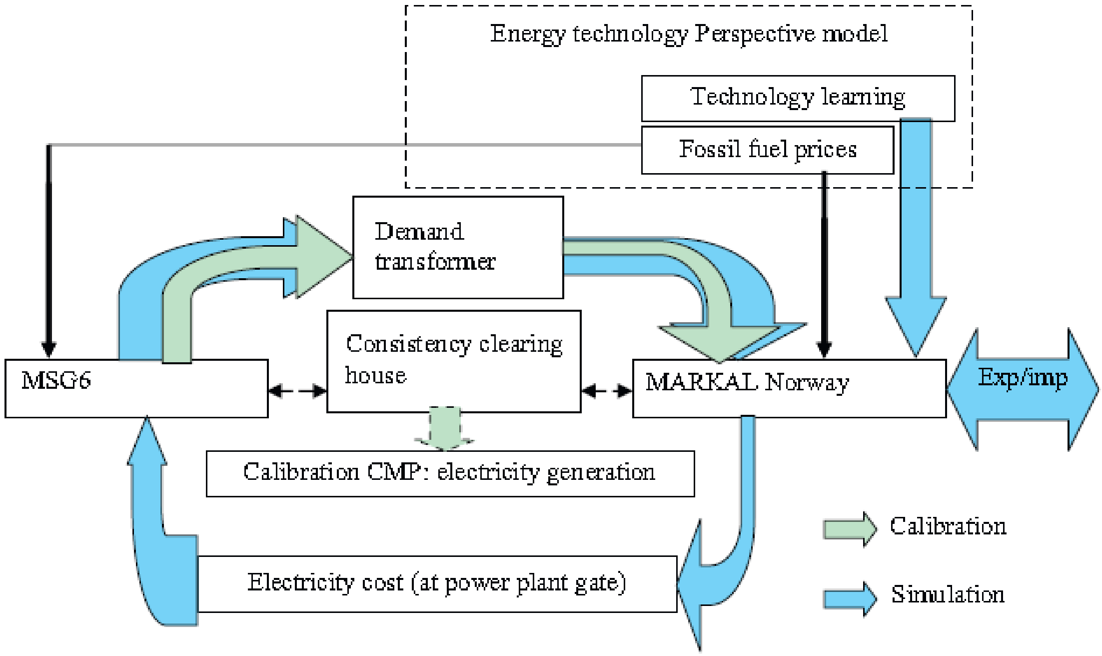

Figure 10 MARKAL and MSG softlinked

MARKAL and MSG have also been linked in a recent discussion paper (Bjertnæs, Tsygankova et al. 2012). They describe the following steps:

1. Coherent reference scenarios are established in both MSG and MARKAL. The MSG scenario is based on assumptions from the Long Term Program (LTP) for Norway from the Norwegian Ministry of Finance. Production and consumption quantities from MSG are implemented as exogenous inputs into the MARKAL reference scenario. MARKAL determines the technology choices.
2. The CO2 tax is increased in MARKAL, with all other exogenous variables unchanged. The MARKAL model calculates an overall present value of costs (net of taxes). *The increase in present value cost is transformed into infinite annuities and allocated to sectors in MSG*. New technologies are more costly, but reduce the emissions.
3. Different scenarios of national CO2 tax and international CO2 quota prices are calculated and compared, focusing on welfare costs.

6.3 MESSAGE-MACRO

Wene describes softlinking between MESSAGE and MACRO[7] (Wene 1996). The MACRO model receives prices related to the total and marginal costs of energy supply from the MESSAGE model. From these it supplies the quadratic demand functions for MACRO so that the overall energy demand can be adjusted. MESSAGE is then rerun with these

[7] The top down macroeconomic system is referred to as MACRO in the abstract and introduction, and 11R in the following sections of the article. Apparently 11R means a global MACRO model with 11 regions.

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adjusted demands to give adjusted prices. This cycle is repeated until prices and energy demands stabilize.

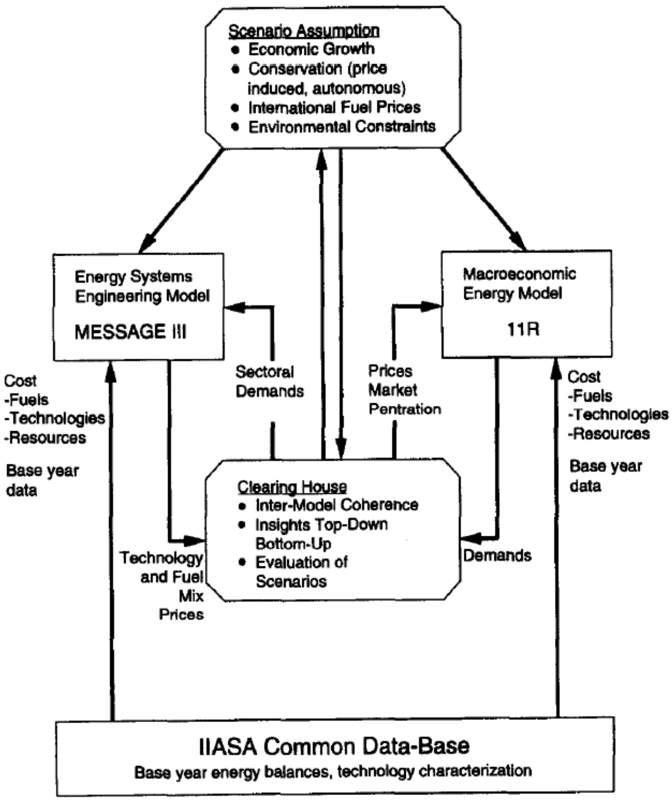

Figure 11 Linking MESSAGE and MACRO

Three sets of CMPs are defined: two for the linking of the master model and the 11R and MESSAGE models (respectively), and one for the linking of 11R and MESSAGE. The CMP for the master and 11R models is the total primary energy demand, the CMPs for the master and MESSAGE III models it is the useful energy demands, and for the 11R and MESSAGE III the primary energy demands by source. The master model ensures coherence between regions and also reduces the softlinking noise between the 11R and MESSAGE III models at the individual regional levels. The price is that the regional models lose autonomy and some of their ability “to go out and find solutions for themselves”. However, the reduced autonomy is consistent with the view from the scenario level of softlinked energy-economy models as tools for checking the feasibility of scenarios.

The linkage between MESSAGE and MACRO is brought one step further in (Messner and Schrattenholzer 2000). They demonstrate a fully automated link, improving the earlier soft-linked versions. We will categorize this as hardlinking, although the authors do not use the term. They do however indicate that the other links are still softlinks.

"The link is fully *automated*, but involves running the two parts in a stand-alone mode. In comparison with fully *integrated* models such as MARKAL–MACRO, our approach lacks

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the elegance of a single black box but it has, perhaps, more transparency. We are also convinced that it is more versatile and faster than a fully integrated model. In any case, and under the given circumstances, it was the most straightforward tool to produce for the purpose.

- MESSAGE-MACRO is a highly flexible model, as both constituent models are kept intact for independent runs, making further model development easier.
- The model's most important driving input variables are the projected growth rates of total labor.
- A key part of the dual model framework describes the interaction between macroeconomic production, energy demand and supply, and pollutant emissions."

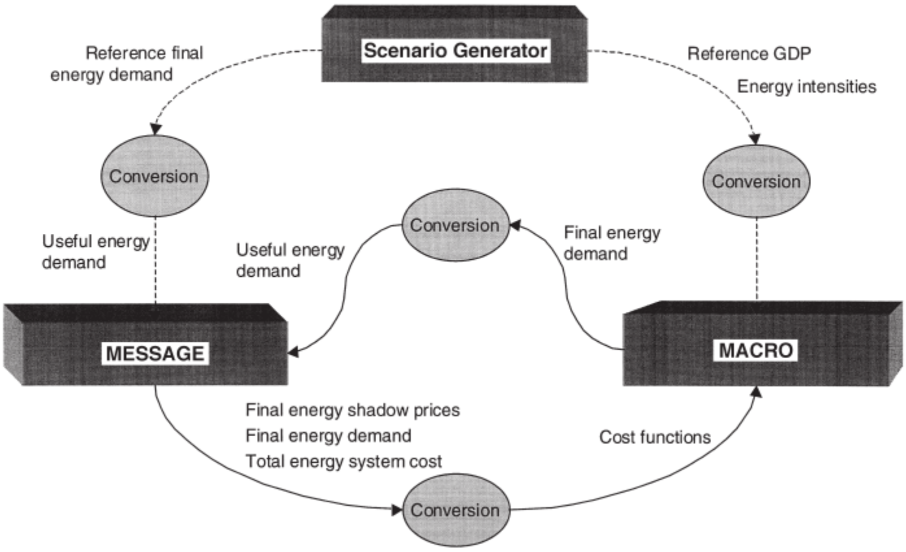

Figure 12 Hard-linking MESSAGE and MACRO

MACRO internally defines an inter-temporal utility function for a single representative producer-consumer in each of the model’s world regions, which is maximized. The main variables in this module are production factors such as capital stock, available labor, and energy inputs, which together determine the total output of an economy. The optimal quantities of the production factors are determined by their relative prices.

Energy demand curves are given in two categories, electric and non-electric energy, for all time periods. Actual demands are determined by MACRO in a way that is consistent with projected GDP. MACRO also disaggregates total production into macroeconomic investment, overall consumption, and energy costs.

A more recent example is (Klaassen and Riahi 2007).

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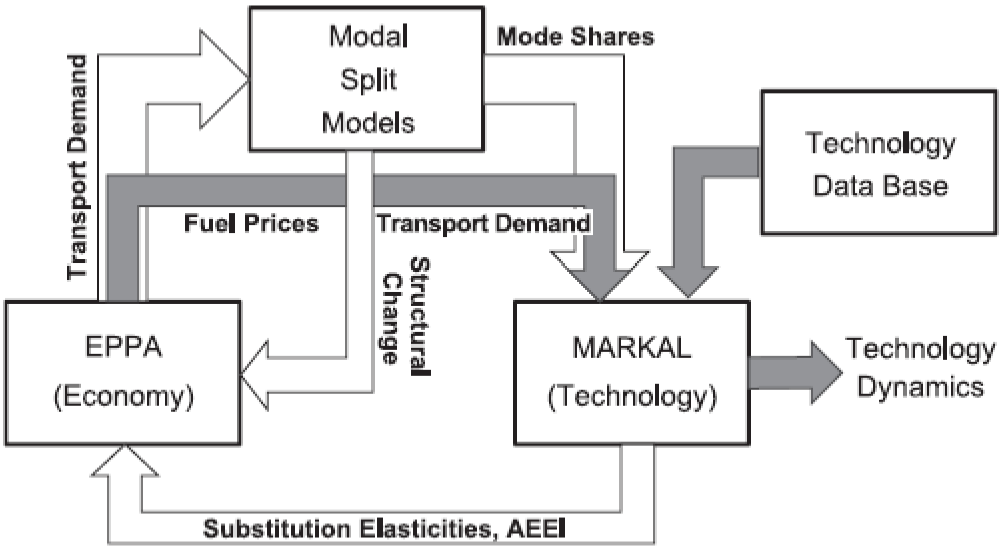
6.4 MARKAL-EPPA

Schäfer and Jacoby have experimented with a hybrid CGE-MARKAL model, focusing on transport (Schafer and Jacoby 2005, Schafer and Jacoby 2006). The CGE model is the Emission Prediction and Policy Analysis (EPPA) model. These models are quite different, and the coupling is loose. EPPA works on a macro scale, with a rougher sector classification than the micro details of MARKAL. EPPA is constructed on a social accounting matrix stated in value terms, while MARKAL is built up from physical flows. A third model of modal splits in transportation is applied to connect the aggregate transport sector of the EPPA model to the technology detail in MARKAL.

The parameters that determine substitution possibilities within the EPPA CGE-structure are set at *levels consistent with an engineering-process representation of transport technology*, and a further calibration procedure is used to ensure consistency between the two models. It thus becomes possible to identify a set of specific technologies within the transport sector that are consistent with a particular general equilibrium simulation of climate policy.



The needed intermodel calibration is essentially *one way*. The idea is that the more detailed MARKAL model and the model of modal splits contain the correct representation of transport technology, its change over time and its response to various incentives. *EPPA parameters are adjusted* so that its transport sector mimics the subscale behavior from the model split and the MARKAL models. The sector "own transport" needs inputs from vehicle manufacture and services and fuel. Normally the substitution elasticity between these inputs is held constant in the EPPA model, but according to the MARKAL results the CES elasticity is adjusted and made increasing over time. A similar calibration is done for production of transport services, where the substitution between energy and value added (labor and capital) is adjusted over time. In addition to these adjustments, *modal splits* are imposed from the specific model and there is an overall calibration of the autonomous energy efficiency variable (AEEI) in EPPA from MARKAL. The AEEI parameter for household personal transport is calibrated to yield a rate of efficiency gain that is consistent

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with the more detailed MARKAL representation. Thus an AEEI trajectory is calculated, and this trajectory is reused in the different scenarios.

Simulation results from EPPA are fed to the MARKAL model. These data includes prices, taxes and transportation demand.

Convergence between the models is defined in terms of the total energy use in the transport sector. The result is best seen as producing a set of scenarios *at different levels of details* that are consistent with one another. The CES-function parameters are adjusted by curve-fitting the CES through the data points for each of the future years calculated in MARKAL. The estimated elasticities are dynamic, increasing throughout the period. The time profile of the resulting elasticity is fitted by a logistic curve. One result was that the substitution elasticities in the EPPA model had to be substantially tightened, in order to achieve a representation of the transport sector that was consistent with MARKAL.

6.5 TIMES-EMEC

EMEC[8] is a static CGE model, which has been developed and maintained at the Swedish National Institute of Economic Research (NIER) for over 10 years. A one-year project has been completed where EMEC and TIMES-Sweden have been softlinked. A report describes quite detailed how this has been achieved (Berg, Krook-Riekkola et al. 2012).

Some changes have been necessary to the EMEC model, in order to make the softlink possible. The production functions are changed in regard of the energy use: the energy mix is modeled with Leontief functions instead of CES functions, fixing the proportions of energy based on the results from TIMES. Also the household utility from energy to heating is changed to Leontief functions. The mix is adjusted during the iterations, based on TIMES results.

The easiest conclusion when we are linking top-down and bottom-up models, is probably that the bottom-up model should get the demand from the top-down model. The bottom-up demand is exogenous in the first hand, so it should obviously be transferred from the top-down model. There are some important differences though. The economic model calculates *values*, while the engineering model calculates material and energy *flows*. While the values and prices are *relative* in the economic model, the engineering model calculates absolute prices. Thus the demand in the economic model is calculated in relative monetary units, and must be translated to physical units in the engineering model. This is implemented by transferring the *rates* of change between the models, instead of the *levels*.

This difference between the models also appears from the data sources. Data input to EMEC are primarily collected from the national accounts (monetary units) while data input to TIMES-Sweden are primarily collected from the national energy balance (physical units).

[8] Environmental Medium term EConomic Model

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When data are transferred from the dynamic model TIMES to the static model EMEC, the point in time has to be decided. One important variable for calibrating the models to the same reference scenario is the electricity price. The autumn price between year 2010 and 2035 is chosen for price conversion from TIMES to EMEC. The price in EMEC is affected by adjusting the capital rate of return from electricity production. The change in marginal cost of electricity production should equal the price-change in TIMES.

The calculation of relative change is used as a general principle for transferring data from TIMES to EMEC. The relative change is transferred, and this is automated so that no user judgment is needed. Each sector has been evaluated individually, to decide which model is dominant. When EMEC is the dominant model, the calculation depends on the sector and possibly also whether it is a reference scenario or a policy-scenario that is calculated. Typically there is an estimated conversion parameter for each different sector from EMEC to TIMES.

The mix is decided by TIMES-Sweden, and the total demand is decided by EMEC.

6.6 Summary of examples

Table 3 below summarizes the investigated linked models, and the data transferred between them.

Linked models	From macroeconomic model	From energy systems model	Link type
MARKAL-MACRO (1992)	Energy demand	Energy costs	Hard
MARKAL-MSG (1996)	Useful energy demand	Energy mix	Soft
MARKAL-MSG (2011)	Demand for energy services. Initial electricity production.	Energy mix. Electricity price.	Soft
MARKAL-MSG (2012)	Production and consumption quantities	Technology choices. Tax increase giving higher present value of cost is transformed and allocated to sectors in MSG.	Soft
MESSAGE-MACRO (1996)	Energy demand	Prices (total and marginal) -> quadratic demand functions	Soft
MESSAGE-MACRO (2000)	Demand curves for electric and non-electric energy	Energy shadow prices Energy demand Total energy system cost	Hard
MARKAL-EPPA (2005)	Prices, taxes and transport demand	Adjustment of CES elasticities and AEEI	Soft
TIMES-EMEC (2012)	Energy demand (converted from monetary units)	Energy mix (to Leontief functions)	Soft

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Table 3 Examples of linked models

6.7 Other projects with work in progress

- The HybCO2 project is linking a TIMES model of Portugal to a GEM-E3 CGE model of Portugal.
- The IntERACT project is linking TIMES-Denmark to a CGE model of Denmark.

Both these projects report that they take prices from the TIMES model as input to the CGE-model.

The IEA Implementing Agreement ETSAP has recently decided to initiate an ETSAP project: "Linking TIMES and CGE models – Moving towards best practice", based on a project proposal from Brian O Gallachoir at University College Cork.

7 Conclusions

Softlinking is a necessary starting point, in order to test different modelling approaches. When the linking concepts have proved to work (proof-of-concept), further implementation to reach hardlinking is desirable because the results from the linked model should preferably not depend on the user judgment. The judgment should rather be built into the linking procedures.

An integrated model could be a next step, but integration of the models is not so obviously a step in the right direction. There are substantial benefits from keeping the existing models as stand-alone, for example regarding development and maintenance.

- An integrated model will probably have to simplify one or both of the "original" models considerably.
- Top-down and bottom-up models operate
  - on different time scales
  - with different detail levels and
  - possibly with different regions
- The models have different data sources. Top-down macroeconomic models use a social accounting matrix based on national accounts. Bottom-up engineering models use the national energy balance.

The granularity of the time dimension will probably be hard to integrate. The bottom-up models benefit from having finer timesteps, providing more information about seasons and peakloads versus baseloads. The top-down models often assume that economic markets are in equilibrium, and need longer timesteps and markets of a certain size for this assumption to be plausible.

In order to

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- utilise the different data sources and
- model both intra year time-patterns and large-scale economic yearly values

linking two fairly accurate models that complement each other seems preferable to integrating them into one model where one probably has to make bigger modelling compromises.

Data transfer

The following information could be transferred between the top-down macroeconomic and the bottom-up engineering models:

- Energy demands from SCGE to TIMES
  - Conversion/recalculation is needed
  - It would be preferable to gather information about demand elasticity from SCGE, and include the information as elastic demand in TIMES.

- Energy mix from TIMES to SCGE
  - The energy use could be described by Leontief functions with fixed proportions
  - Substitution elasticities could also be decreased gradually towards zero during iterations

- Energy prices from TIMES to SCGE
  - The SCGE model should keep some freedom to alter energy prices. Fixing prices in the SCGE model could be done gradually during iterations (or they could be left to converge).

Acknowledgements

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8 References

- Algehed, J., S. Wirsenius and J. Jönsson (2009). Modelling energy effi ciency and carbon dioxide emissions in energy-intensive industry under stringent CO2 policies: comparison of top-down and bottom-up approaches and evaluation of usefulness to policy makers. ECEEE 2009 Summer Study. La Colle sur Loup, France**:** 11.
- Arrow, K. J. and G. Debreu (1954). "EXISTENCE OF AN EQUILIBRIUM FOR A COMPETITIVE ECONOMY." Econometrica **22**(3): 265-290.
- Balabanov, T. (2011). Overview and evaluation of models in use for M/A policy portfolios and selection the relevant for Promitheas-4. http://www.fim.edu.al/promitheas-4/pdf/Climate_Mitigation_Adaptation_4_Zgjedhja_e_Modelit.pdf.

Corresponding author: Telephone +47 953 07 720, per.i.helgesen@iot.ntnu.no

- Berg, C., A. Krook-Riekkola, E. Ahlgren and P. Söderholm (2012). Mjuklänkning mellan EMEC och TIMES-Sweden - en metod för att förbättra energipolitiska underlag. Specialstudier. Sweden, Konjunkturinstitutet/National Institute of Economic Research**:** 73.
- Bjertnæs, G., M. Tsygankova and T. Martinsen (2012) "The double dividend in the presence of abatement technologies and local external effects."
- Bohringer, C. (1998). "The synthesis of bottom-up and top-down in energy policy modeling." Energy Economics **20**(3): 233-248.
- Bohringer, C. and A. Loschel (2006). "Computable general equilibrium models for sustainability impact assessment: Status quo and prospects." Ecological Economics **60**(1): 49-64.
- Bohringer, C. and T. F. Rutherford (2008). "Combining bottom-up and top-down." Energy Economics **30**(2): 574-596.
- Bohringer, C. and T. F. Rutherford (2009). "Integrated assessment of energy policies: Decomposing top-down and bottom-up." Journal of Economic Dynamics & Control **33**(9): 1648-1661.
- Bos, F. (2011) "Three centuries of macro-economic statistics." 87.
- Brandsma, A., O. Ivanova and D. Kancs (2011). RHOMOLO - A Dynamic Spatial General Equilibrium Model. 19th International Input-Output Conference. Alexandria, USA**:** 22.
- Brocker, J. (1998). "Operational spatial computable general equilibrium modeling." Annals of Regional Science **32**(3): 367-387.
- Brocker, J. and A. Korzhenevych (2013). "Forward looking dynamics in spatial CGE modelling." Economic Modelling **31**: 389-400.
- Chen, W. Y. (2005). "The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling." Energy Policy **33**(7): 885-896.
- Connolly, D., H. Lund, B. V. Mathiesen and M. Leahy (2010). "A review of computer tools for analysing the integration of renewable energy into various energy systems." Applied Energy **87**(4): 1059-1082.
- Contaldi, M., F. Gracceva and G. Tosato (2007). "Evaluation of green-certificates policies using the MARKAL-MACRO-Italy model." Energy Policy **35**(2): 797-808.
- Dils, E., A. Van der Linder, T. Geerken, M. Christis and A. Vercalsteren (2013). Feasibility of integrating data from Multi-regional IO models in the Flemish EE-IO model. Heverlee, Policy Research Centre for Sustainable Materials**:** 55.
- Facchinei, F. and J. Pang (2003). Finite-Dimensional Variational Inequalities and Complementarity Problems, Springer.
- Fleiter, T., E. Worrell and W. Eichhammer (2011). "Barriers to energy efficiency in industrial bottom-up energy demand models-A review." Renewable & Sustainable Energy Reviews **15**(6): 3099-3111.
- Gaasland, I. (2008). En modell for norske matsektorer (FOOD.CGE.MOD04) - Dokumentasjon og analyser, Institute for Research in Economics and Business Administration / SNF**:** 143.
- Gaasland, I. (2013). Regionale virkninger av økonomisk politikk - et makroperspektiv, Institute for Research in Economics and Business Administration / SNF**:** 91.
- Gaasland, I., K. L. Rødseth and E. Vårdal (2013) "Efficient Supply of Cultural Landscape in a CGE Framework." 16.
- Gabriel, S. A., A. J. Conejo, J. D. Fuller, B. F. Hobbs and C. Ruiz (2012). Complementarity Modeling in Energy Markets, Springer.
- Gabriel, S. A., A. S. Kydes and P. Whitman (2001). "The National Energy Modeling System: A large-scale energy-economic equilibrium model." Operations Research **49**(1): 14-25.
- Herbst, A., F. Reitze, F. A. Toro and E. Jochem (2012). Bridging macroeconomic and bottom up energy models - the case of efficiency in industry. ECEEE 2012 Industrial Summer Study. Arnhem, The Netherlands, The European Council for an Energy Efficient Economy.
- Hertel, T. (2013). Chapter 12 - Global Applied General Equilibrium Analysis Using the Global Trade Analysis Project Framework. Handbook of Computable General Equilibrium Modeling. B. D. Peter and W. J. Dale, Elsevier. Volume **1:** 815-876.
- Hoffman, K. C. and D. W. Jorgenson (1977). "ECONOMIC AND TECHNOLOGICAL MODELS FOR EVALUATION OF ENERGY-POLICY." Bell Journal of Economics **8**(2): 444-466.
- Hourcade, J. C., M. Jaccard, C. Bataille and F. Ghersi (2006). "Hybrid modeling: New answers to old challenges - Introduction to the special issue of The Energy Journal." Energy Journal: 1-11.

Corresponding author: Telephone +47 953 07 720, per.i.helgesen@iot.ntnu.no

- Ivanova, O., C. Heyndrickx, K. Spitaels, L. Tavasszy, W. Manshanden, M. Snelder and O. Koops (2007). RAEM: version 3.0, Transport & Mobility Leuven**:** 77.
- Ivanova, O., A. Vold and V. Jean-Hansen (2002). PINGO - A model for prediction of regional- and interregional freight transport, Institute of Transport Economics (TØI)**:** 48.
- Johansen, L. (1960). A Multi-Sector Study of Economic Growth, North-Holland Publishing Company, Amsterdam, Netherlands.
- Johnsen, T. A. and F. F. Unander (1996). "Norwegian residential energy demand: Coordinated use of a system engineering and a macroeconomic model." Modeling Identification and Control **17**(3): 183-192.
- Jorgenson, D. W. (1982). An Econometric Approach to General Equilibrium Analysis. Current Developments in the Interface: Economics, Econometrics, Mathematics. M. Hazewinkel and A. H. G. Rinnooy Kan, Springer Netherlands**:** 125-155.
- Klaassen, G. and K. Riahi (2007). "Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO." Energy Policy **35**(2): 815-827.
- Krugman, P. (1998). "What's new about the new economic geography?" Oxford Review of Economic Policy **14**(2): 7-17.
- Lucas, R. E. (1976). "ECONOMETRIC POLICY EVALUATION - CRITIQUE." Carnegie-Rochester Conference Series on Public Policy **1**: 19-46.
- Manne, A. and C.-O. Wene (1992). MARKAL-Macro: A linked model for energy-economy analysis. Report BNL-47161, Brookhaven National Laboratory.
- Marín Quemada, J. M. a., J. García-Verdugo and G. Escribano (2012). Energy security for the EU in the 21st century : markets, geopolitics and corridors. London ; New York, Routledge.
- Martinsen, T. (2011). "Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models." Energy Policy **39**(6): 3327-3336.
- Messner, S. and L. Schrattenholzer (2000). "MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively." Energy **25**(3): 267-282.
- Murphy, R., N. Rivers and M. Jaccard (2007). "Hybrid modeling of industrial energy consumption and greenhouse gas emissions with an application to Canada." Energy Economics **29**(4): 826-846.
- Oosterhaven, J., T. Knaap, C. Ruijgrok and L. Tavasszy (2001). On the development of RAEM: The Dutch Spatial General Equilibrium Model and its First Application to a New Railway Link. 41th Congress of the European Regional Science Association. Zagreb.
- Schafer, A. and H. D. Jacoby (2005). "Technology detail in a multisector CGE model: transport under climate policy." Energy Economics **27**(1): 1-24.
- Schafer, A. and H. D. Jacoby (2006). "Experiments with a hybrid CGE-MARKAL model." Energy Journal: 171-177.
- Strachan, N. and R. Kannan (2008). "Hybrid modelling of long-term carbon reduction scenarios for the UK." Energy Economics **30**(6): 2947-2963.
- Strachan, N., S. Pye and R. Kannan (2009). "The iterative contribution and relevance of modelling to UK energy policy." Energy Policy **37**(3): 850-860.
- Wene, C. O. (1996). "Energy-economy analysis: Linking the macroeconomic and systems engineering approaches." Energy **21**(9): 809-824.
- Wolfgang, O. (2006). Modeller for CO2 systemanalyse, SINTEF Energiforskning AS**:** 27.

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