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Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model

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ABSTRACT

This paper proposes and discusses a soft-linking procedure between a Computable General Equilibrium (CGE) model and an energy system model with the aim to improve national energy policy decision-making. Significant positive and negative experiences are communicated. Specifically, the process of soft-linking the EMEC and TIMES-Sweden models is presented, and unlike previous work we rely on the use of multiple direction-specific connection points. Moreover, the proposed soft-linking methodology is applied in the context of a climate policy scenario for Sweden. The results display a partly new description of the Swedish economy, which when soft-linking, generates lower CO_2-emissions in the reference scenario due to a decline in industrial energy demand. These findings point at the importance of linking bottom-up and top-down models when assessing national energy and climate policies.

1. Introduction

The transition to a low carbon economy will take decades, have significant impacts on future energy systems and is likely to affect the entire economy. Low carbon development is also likely to affect the interactions between different sectors of the economy. Developments of the energy system can be analysed within so-called energy system optimization models (ESOMs), which provide a detailed representation of the energy system and capture important interactions within the energy system of technology–specific resource potentials, costs, and conversion efficiencies. These models are thus essentially simulation tools, often used to simulate the operation of given energy-system to supply a given set of demands, and can be referred to as bottom-up given their focus on analysing specific energy technologies and the associated investment options [8]. Developments of the entire economy are instead often assessed with computable general equilibrium (CGE) models, which provide a consistent representation of interactions of different economic sectors. CGE models are equilibrium tools that seek to explain the behaviour of supply, demand and relative prices in the whole economy with many markets; they are also top-down tools in that they use macroeconomic data to determine the development of energy prices and demands [8].

Both modelling approaches have been used for analysing costs of mitigating global warming (e.g. Refs. [14,44]). The difference between the two approaches was explored already two decades ago in Wilson and Swisher [51]. Since then, many models have incorporated features of both modelling approaches because they address different mechanisms of the economy-environment-energy interactions [15]. ESOMs are often better suited to identify technical options and the associated investments and fuel costs, but do not cover the impacts on the overall (macro) economy. On the other hand, CGE models are generally better suited to investigate overall economic impacts in terms of GDP growth rates, structural change etc. Due to these differences the two modelling approaches may generate diverging estimates of the economic impacts of climate policy [14,16,51] and of emission reduction potentials [48]. Therefore, and given the existence of strong interactions between the energy system and the rest of the economy, a combination of the two approaches has often been applied in climate mitigation analysis [15].

The models can be hard-linked or soft-linked [2]. In the case of

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soft-linking, the CGE model and the ESOM operate together in an iterative process until convergence in central parameters are achieved, e.g., prices and quantities [23]. A soft-linking approach takes advantage of the strengths of both models. In hard-linking, the two models are fully integrated and solved in a simultaneous optimization, unlike the iterative process, which characterises soft-linking. The hard-linking approach often implies a simplified description of either of the two models (e.g., [40]), such as introducing a simplified energy system model in a CGE model (e.g., [3,4]). Such combined approaches are typically referred to as hybrid models. Hard-linking can be useful when addressing the global picture for which the regional details are subordinate, while soft-linking typically is more useful at the national level when existing, highly detailed models can be – and need to be – kept more or less intact (e.g. Refs. [1,5]).

Wene [50] presents a generic soft-linking approach but he does not provide any details regarding the linking at the sector level. Labriet et al. [26] couple two global models. Their study indicates what kind of information that should be linked, but does not discuss the specific challenges that arise when two detailed national models are linked. Klinge Jacobsen [18] describes and discusses model integration problems, and then presents relevant options for soft-linking. His example, though, is based on a model set-up where the CGE model is in-between two energy system models, one energy demand sector model and one energy conversion model. Messner and Schrattenholzer [30] describe an automated soft-linking between an energy supply model (MESSAGE) and a macroeconomic model (MACRO). These authors provide an extensive description of the overall linkage, but they do not provide any details regarding the linking process between sectors even though this is likely to be very important at the national level. There has recently been a stronger focus on linking national models, examples are provided in Glynn et al. [12].

In national models, which are of particular importance from a policy perspective since most of the policy-making takes place at the national level, important features of several key sectors with respect to energy, environment and economy, are typically well-described. The availability of reliable and detailed data facilitates a more complex model representation (e.g., more detailed sector representations), and since the soft-linking approach can address more complexity it provides advantages in a national policy perspective. There are several examples of national studies on climate policy, and some of these apply soft-linking procedures, e.g. Martinsen [29] and Schäfer and Jacoby [42]. Common for these publications is that they focus on the model results rather than on the linking process itself, and the description of the actual soft-linking process is therefore limited or non-existent. One reason for this could be the uniqueness of each country's energy system and economic structure, thus implying difficulties in making generalisations.[1] Even though the specific information that is transferred across the models will be unique for each country, the challenges that arise and the steps needed are similar.

While Fortes et al. [11] describe an integrated technical-economic modelling platform for Portugal, providing insights on how national models (CGE and ESOM) can be soft-linked and a detailed description on how the CGE model can be modified in order to improve the linking, there is a lack of transparency with regards to the presentation and discussion of the soft-linking details and challenges. Thus, due to the strong current policy-driven interest in soft-linking of ESOMs and CGEs, as emphasized by Kragt et al. [19]; there is in the scientific literature a great demand for publications outlining the national scale soft-linking processes and its interlinked challenges in a transparent and detailed way. This is a key point of departure for the present paper.

In Sweden, as in many other countries, both modelling types are employed by the government and its agencies, and there information are often exchanged between the models (e.g. Swedish Energy Agency 2014). However, there is often a lack of explicit links between the models, and therefore also a lack of transparency. For this reason, it is of particular interest to evaluate the impacts of soft-linking (versus the case of running the models separately), as well as to discuss what can be gained in terms of transparency and policy learning.

In this study, we aim to explore how to capture the sector details when soft-linking a national ESOM model (TIMES-Sweden) with a national CGE model (EMEC) in order to improve the policy decision-making process at the national level. Some aspects of the way in which we perform the soft-linking, in particular the use of connection points that differ in each feedback direction, have not been reported before. Therefore, we communicate both the process of identifying and testing a soft-linking procedure as well as highlight important challenges, strengths and weaknesses of this procedure.

The underlying philosophy has been to develop and apply a soft-linking approach allowing the models to interact in a transparent manner while at the same time maintaining each model's strengths. The models selected for the study are good examples of their respective model type; they have both recently been updated, they have both been applied to study the impacts of low-carbon developments and policies, and they are both employed to provide decision support to the Swedish Energy Agency.

The paper is organized as follows. Section 2 focuses on outlining the main differences and similarities between the two models; this results in the identification of connection points, i.e., which point in one model that should be linked to which point in the other model. Section 3 presents our soft-linking procedure based on reflections upon *how* these connection points can be linked, i.e., the identification of so-called translation models. In Section 4, the soft-linking procedure is applied to a climate policy scenario analysis for the Swedish industrial sector where the outcomes from running the models stand-alone are compared with the outcomes from iterations between the models using our approach. Section 5 synthesizes and discusses the challenges and the positive and negative lessons learned, and Section 6 presents the conclusions.

2. Model similarities and differences: identifying what to link

One of the key steps in the soft-linking process is to identify what to link, i.e., the connection points. A connection point arises when an endogenous variable in one model is fed into the other model as an exogenous (fixed) variable. This must however first build on a clear understanding of the key differences and similarities between the two model approaches, and for this reason each model is introduced below.

2.1. The models

The Environmental Medium term Economic model (EMEC) is a one-step recursive dynamic CGE model of the Swedish economy

[1] Global and multi-country models, in general, do not have the same level of details as national models, and do thus not necessarily benefit from having a detailed soft-linking procedure. Even in cases when they have a high level of details (such as in the European TIMES model), the complexity could be enormous if including a detailed soft-linking using an ESOM and a CGE model. Thus, there is a clear trade-off between usefulness and complexity. Another aspect is the type of decision-making processes that the different model set ups should support; global and multi-country models generally set the broader policies (all details are not crucial for the analysis) while the nation-specific models typically focus on (and need to focus on) context-specific policy portfolios.

developed and maintained by the National Institute of Economic Research (NIER) for analysis of the interaction between the economy and the environment (e.g., [37]). This model addresses changes in sectoral-supply, demand, and relative prices in the Swedish economy due to policy changes. It also address the emissions connected to the respective economic activity. EMEC has played an important role in the Swedish government's climate policy decision-making process, involving economic (cost) assessments of various policy proposals. One example is Broberg et al. [7] in which the NIER analyses the proposals of the Parliamentary Climate Committee (M2007/03) for achieving Sweden's climate objectives. More recently EMEC has been used to examine the consequences of new climate and energy policy packages on the Swedish economy [34–36].

EMEC distinguishes between 26 production sectors and 33 composite commodities, including seven energy commodities. There is also a public sector producing one single commodity. Produced goods and services are exported and used together with imports to create composite commodities for domestic use. Composite commodities are used as inputs by the production sectors and for capital formation. Production requires primary factors (i.e., two kinds of labour and capital) as well as inputs in terms of materials, transports and energy. Households can consume 26 different composite commodities. Furthermore, households are assumed to maximize utility subject to an income restriction, firms maximize profits subject to resource restrictions, the provision of public services is subject to a budget constraint and the foreign sector's import and export activities are determined by an exogenously given trade balance.

The EMEC model differs from many other CGE models through its detailed description of the energy use, different environmental policy instruments as well as any resulting emissions. In the model, both household spending and production activities cause pollution. The model calculates emissions of carbon dioxide, sulphur dioxide, nitrogen oxides and particulate matter from stationary and mobile sources of emissions, but also emissions from different types of industrial processes. In Sweden, households' and industries' uses of energy are subject to energy and environmental taxes (e.g., a carbon dioxide tax and a sulphur tax). In EMEC the tax rates are calibrated to the base year, something which enables a correct representation of the different tax exemptions for various industries. The sectors that are included in the EU emissions trading system (EU ETS) buy carbon allowances at a given (exogenous) price. Further details about EMEC are presented in Table 1.

TIMES-Sweden is a dynamic energy system model with a comprehensive coverage of the entire national energy system, including supply and demand. The model is based on the generic TIMES model structure, which has been developed within the ETSAP program.[2] TIMES is an energy-economic model generator for local, national or multi regional energy systems, and provides a technology-rich basis for calculating energy dynamics over a long-term, multi-period time horizon. The model optimization is achieved through minimization of the total system cost defined as the sum of the net present values of the technical energy system costs (i.e., the costs of technology investment, operation and maintenance, fuel inputs and distribution) over a given time horizon [27]. The model generates the cost-minimizing combination of different energy technologies and fuel uses in meeting the pre-specified demands subject to certain constraints. It includes a large number of current and future energy technologies, as well as their current and assumed future energy conversion efficiencies and costs. Most of the demands are specified as 'useful energy demand' (i.e. energy available to the consumers after having accounted for conversion losses), whereas some are specified as a service (e.g. personal-km) or in terms of the quantity of a physical commodity (e.g. ton steel).

TIMES-Sweden (see Ref. [22]) was initially developed as a part of the European TIMES model within two different EU projects, NEEDS[3] and RES2020,[4] and shares main structure with other European national TIMES models as well as with the European TIMES models, e.g. the JRC-EU-TIMES model documented in Simoes et al. [46]. It describes the Swedish energy system divided into five demand sectors (agriculture, services, residential, industry and transport) and two energy conversion sectors (fuel production and electricity & heat) in line with the structure of Eurostat's energy statistics [9].

Each sector is divided into different sub-sectors described with different technologies to meet a final demand of products and services. All demand segments are listed with units in Appendix A and are given exogenously to the model with quantified values for each time period, so-called demand projections. Energy-intensive industries are represented by detailed reference energy systems, including process steps and material flows. Unlike partial equilibrium models that only address one energy market, ESOMs like TIMES-Sweden calculates the equilibrium for all energy markets described in the model and calculates a shadow price for each energy carrier (see Section 3.2 in Ref. [27]). TIMES-Sweden has been used to analyse, for instance, the costs and the ancillary benefits of Swedish climate policy [20], and to compare impacts of climate policy instruments on the Swedish district heating sector [21]. Further details about TIMES-Sweden are provided in Table 1.

2.2. Similarities and differences in model structures

When identifying the key differences and similarities between EMEC and TIMES-Sweden, the steps outlined by Wene [50] are applied: i) identifying basic differences between the models; ii) identifying overlaps; and iii) identifying and deciding upon common exogenous variables.

The main differences between the two models are that i) EMEC is a general equilibrium model while TIMES-Sweden is a partial equilibrium model; and that ii) EMEC represents the flows of energy, materials, capital and labour in monetary terms while TIMES-Sweden is based on physical energy flows (in energy units) with a representation of materials (in mass or volume), renewable energy credits (in number) and taxes (in monetary terms). Emissions are expressed in metric tonnes in both models. Two other important differences with direct relevance for the soft-linking process are; i) while EMEC addresses the competition between the industry sectors with regards to labour, capital and other inputs, in TIMES-Sweden, the production of goods is exogenously provided for each industrial sector (see Appendix A); and ii) TIMES-Sweden, in contrast to EMEC, has an extensive representation of energy technologies and their current and assumed future energy conversion efficiencies and costs. Basic differences between EMEC and TIMES-Sweden are summarized in Table 1.

The main overlap between the models is that both simulate the

[2] The Energy Technology Systems Analysis Program (ETSAP) is an implementing agreement of the International Energy Agency (IEA), see also www.iea-etsap.org.

[3] "New Energy Externalities Development for Sustainability" (NEEDS) was a research project of the European Commission in the context of the 6th Framework Programme, Research Stream 2a "Modelling internalisation strategies, including scenario building". Webpage: www.needs-project.org.

[4] "Monitoring and evaluating of the RES directives implementation in EU27 and policy recommendation for 2020" (RES2020) was a research project of the European Commission Intelligent Energy – Europe program. Webpage: www.cres.gr/res2020.

Table 1
Basic differences and similarities between EMEC and TIMES-Sweden.

	EMEC	TIMES
Define the objective – Identify what determines the coefficients in the objective function:		
Overall objective and performance measure	Households maximize utility subject to an income constraint. Firms maximize profits. Public services face a budget constraint, and there is an exogenously given trade balance.	Cost-minimization of the total system cost to meet given demands of goods and services subject to technological, physical and environmental constraints.
General scope of the model	Support the policy-making process. Provide knowledge about the economic implications of different policy options.	Support the policy-making process. Provide knowledge about the energy system impacts of different policy options.
Geographic and sectoral scope	Sweden as one region, divided into 6 household groups, 26 production sectors and one public sector (see Table A1).	Sweden as one region divided into residential, services, agriculture, transport and industry. Each sector is sub-divided according to the complexity of the sector in terms of energy.
Identify the components of the analysed system, their activity and their performance measures:		
Time dimension	One-step recursive dynamic (solved one period at a time where the between-period component governs the dynamics of the model)	Dynamic (optimize over all time-slices and all years).
Time horizon and time resolution	Focus on the change between the base year and a final year (i.e., 2008 and 2035 in this study).	12 time periods each year (day/night/peak-hour and four seasons). Flexible time horizon (present study: every 5 year until 2050).
Demand for goods and services	33 different commodities and a public sector producing a single commodity.	58 different demand segments (see Table A1), belonging to five demand sectors (agriculture, services, residential, transport and industries).
Energy commodities and sectors.	Four energy sectors (i.e., electricity, district heating, natural gas, refined petroleum). Seven energy commodities (i.e., electricity, district heating, natural gas, coal, oil, petrol, biomass).	Over 200 different energy carriers. The generation of electricity, and production of district heating and biofuels are described in detail, while the descriptions of gas, crude oil, refined petroleum are less detailed. Biomass is divided into different types (waste, forestry, agriculture etc.).
How energy conversion technologies are described	Continuous production functions (i.e., CES specifications), where (e.g., fuel) substitution elasticities are key parameters.	Discrete processes/techniques with pre-defined technological (efficiency, availability etc.) and economic (capital, and operating costs etc.) parameters. These may vary over time to address technical progress.
Base-year calibration	Based on the Swedish National and Environmental Accounts.	Official energy statistics, e.g. Eurostat and Swedish Energy Agency, are used to calculate efficiencies, base-year load factors (which is 'released' the next year) and base-year energy balance for energy carrier and sector.
Emissions and tradable credits	Emissions: CO_2, NOX, N_2O, CO, CH_4, PM10, PM25, SO_2. EU ETS prices.	Emissions: CO_2, NOX, PM10, PM25, SO_2, VOC. The prices of tradable renewable energy credits and EU-ETS allowances.
Monetary flows – how prices are treated	Prices are normalized to one (1) in the base year. Only relative price changes are modelled.	Prices in the global markets (import/export) and extracted resources (e.g. biomass) are given exogenously. A shadow price for each delivered energy carrier (final energy demand) is calculated for each time step.
Taxes/subsidies included	Yes	Yes
Impact/ performance measures	Macroeconomic impacts such as GDP growth, consumption, import, export and investment; output, price and employment by sector, etc.	Total system cost, final energy use and prices, emissions by sector. Efficiency and activity by process, fuel mixes etc.
Define the problem's constraints – Identify the limitations and the boundary conditions:		
Resources	Total amount of hours worked in the economy, physical capital and trade balance restrictions.	Import and export of energy carriers, natural resources (biomass), existing power plants etc.
Policy goals	Emission targets, energy efficiency targets etc.	Emission targets, renewable energy targets, energy efficiency targets etc.

electricity generation mix and the derived energy demand for each sector in the economy, and these variables will in turn determine the resulting emissions. Since the level of detail is higher in ESOMs, TIMES-Sweden will govern these variables. Still, in the soft-linking procedure it is important to also capture the general equilibrium effects of policy interventions on energy demand patterns through changes in demand for energy related services, materials and transports. Such changes in demand could also be captured by using the demand-elasticity feature in TIMES [27]; chapter 4). This would allow the exogenously given output demand (e.g. the demand for steel) to change in response to changes in energy prices (e.g. coal or electricity) following a carbon tax. However, these general equilibrium effects are better described by CGE models. For this reason the EMEC model will be governing the development of energy related demands for services, materials and transports.

Finally, common exogenous scenario variables are identified. Since the baseline assumptions have a major impact on the results, it is important that the exogenous variables are harmonized between the two models, in particular since the two models are based on different statistic sources. Variables that are exogenously provided to both models and therefore possible to harmonize include import fuel prices and different energy, environmental and climate policy instruments. Variables that represent exogenous inputs to one of the models and outputs from the other model, e.g., the yearly steel demand from EMEC into TIMES-Sweden, will be soft-linked between the models. Some variables could however not be fully harmonized, the most important example being the biomass prices. EMEC contains a relatively limited description of biomass resources (it is described as one commodity available only for some sectors), while TIMES-Sweden has a much richer representation of different types of biomass.[5]

[5] The main use of biomass in Sweden represents by-products, e.g., waste or forestry residues, and there is still a large un-tapped potential of sustainable forestry residues. There is also a small potential for energy crops in the TIMES-Sweden model, this is agricultural land that has been put on 'hold' (i.e. it is not profitable to harvest food crops). Thus, it is not competing with food supplies.

2.3. Identifying the connection points

Wene [50] emphasizes the importance of finding common measuring points (CMP) at which the macroeconomic model and the energy system model can interact. He suggests that the reference energy system framework can be used to identify these CMPs. Specifically, an energy flow or technology belongs to the influence area of a CMP, if a change in the flow or technology produces a change in the energy flow measured at the CMP. Wene [50] acknowledges that there will still be overlaps between the models, between the different sector definition and between so-called influence areas, and this makes it practically impossible to identify independent CMPs.

While Wene [50] and other soft-linking approaches that we have identified apply the same set of CMP regardless of direction, we introduce direction-specific connection points (DSCPs). The argument is that since the models' analytical concepts represent different aspects of sector development (e.g., energy composition versus economic growth), and since they are typically based on different statistical sources (e.g., energy statistics versus the national accounts), what appears as the same thing in the two models may often describe different kinds of development. To identify the connection points, we focus on *how the results generated by one model can improve the assumptions required by the other model*. Thus, rather than using CMPs we identify DSCPs in order to describe the interaction between the results from one model and the different assumptions required by the other model.

By ‘direction-specific’ we mean that each direction is addressed separately, i.e., one direction when transferring information from EMEC to TIMES-Sweden (see Table A1 in Appendix A) and another when transferring information from TIMES-Sweden to EMEC (see Table A2 in Appendix A). In identifying the connection points it is important to answer the following two questions: i) what does it mean that a sector is growing in one model compared with the corresponding sector growth in the other model?; and ii) how should one solve the problem of non-matching sector classifications? In order to illustrate the identification approach performed and the need for DSCPs, two examples will be useful.

The *first* example concerns the pharmaceutical industry, which accounts for 25–30% of the total chemical industry production value [45]. Due to its economic importance it is treated as a separate sector in EMEC while in TIMES-Sweden, due to its small energy use, it is aggregated with the sector ‘other chemicals’. The energy-intensive chemical sectors are likely to react differently compared to the pharmaceutical industry with respect to changes in energy prices, i.e., the own-price elasticities of energy demand differ across the two sectors. When soft-linking the aggregated chemical sector, i.e. the energy-intensive chemical sector and the pharmaceutical industry, biased information would thus be transferred from the CGE model to the energy system model in terms of changes in the activity of the pharmaceutical industry. Consequently, it is important not to aggregate these sectors when soft-linking the two models. For further details of how the chemical industries are soft-linked, see Tables A1 and A2 (in Appendix A).

The *second* example concerns the treatment of the transport sector and its energy use. This is the sector with the most profound differences across the two models. Transportation in TIMES-Sweden is gathered into one sector, which is then split into different segments based on both the type of transport (e.g., freight or passenger) and the type of vehicle (e.g., air, train, bus etc.). In EMEC, most of the transport services are gathered into dedicated transportation sectors, but transports are also parts of other sectors and part of the household consumption, e.g., company cars and private cars, represented by the demand for fuels. Consequently, full consistency between the models was difficult to achieve, and the focus was instead to – for each direction – identify which result in one model that could describe a specific input assumption in the other model. Thus, for each demand segment in TIMES, we identified which sector/sectors in EMEC that could describe the demand projections required by TIMES-Sweden. Thereafter, we identify which results from TIMES-Sweden that could improve the assumptions required by EMEC. Table 2 summarizes the outcomes of this exercise.

3. The soft-linking procedure: identifying how to link

In this section the soft-linking procedure is presented, i.e., how information at each of the identified connection points has been transferred. Each direction will be addressed separately since there are direction-specific issues. EMEC has an impact on the demand projections into TIMES-Sweden (i.e. the model itself is not changed), while the results from TIMES-Sweden will change depending on how energy is represented in EMEC. For each direction, the weaknesses of the receiving model were first identified in order to define what type of information the other model could provide in order to improve the overall policy analysis. These findings were then used to develop a method to translate simulation results between EMEC and TIMES-Sweden, resulting in two intermediate ‘translation models’.

The first translation model generates the demand projections that should be fed into TIMES-Sweden (specified in Table A1) based on results derived from EMEC, while the second translation model provides energy system feedback to EMEC based on the results derived from TIMES-Sweden. Fig. 1 provides a conceptual visual presentation of the soft-linking procedure between EMEC and TIMES-Sweden. Specifically, the starting common scenario definition and the main parameters transferred in each step are introduced in this figure.

The soft-linking procedure has been inspired by Labriet et al. [26] and Fortes et al. [10]; but emphasizes the need for different approaches at different connection points. This is motivated due to the differences in sectoral breakdown of the two models and in the relationship between the energy demand and economic development across different commodities.

3.1. Translation model – EMEC to TIMES-Sweden

In order to identify an applicable translation between overall economic development (derived from EMEC) and demand of energy intensive goods and services (in TIMES-Sweden), we have investigated the literature focusing on the specificities of soft-linking processes and on how to generate demand projections for energy system models. The aim is to further position our choice of soft-linking approach in the existing literature.

Manne and Wene [28] calculate the demand for useful energy endogenously within MARKAL-MACRO based on four factors: the aggregate rate of economic growth, the autonomous energy efficiency improvement (AEEI), the price elasticity of energy substitution, and the change in energy prices. Messner and Schrattenholzer [30] soft-link the models MESSAGE and MACRO and base their method on pre-defined translations in a so-called ‘scenario generator’ (see also [13], either as a one-way feedback into MESSAGE when running the model stand-alone or in an iteration loop. Kypreos and Van Regemorter [24] use the GEM-E3 (a recursive dynamic European CGE model) to generate exogenous demand projections to a European TIMES model. In their analysis, the energy demand projections per region and sector depend on the change of a pre-specified demand driver (either population, GDP or a combination of the two), the change in prices and the AEEI. Kypreos and Van Regemorter argue that much of what is

Table 2
Mapping of transport-related sectors/segments, one direction at a time.

The following results from EMEC …	… impact the following assumption in TIMES-Sweden
Economic development of "Aviation transports" from EMEC	Demand for Aviation International/Generic (PJ)
Economic development of "Navigation freight transports" from EMEC	Demand for Navigation Generic/Generic Bunker (PJ)
Economic development of the "Public Transportation sector" from EMEC (when buses are mainly found in this sector)	Demand for Road Bus Intercity/Urban (Million Person km)
Aggregate household consumption/disposable income from EMEC (even though a substantial share of cars also are owned by companies, utilities etc.)[a]	Demand for Road Car Long/Short Distance (Million Person km) Demand for Road Motorcycle (Million Person km)
Economic development of "Road Freight transports" from EMEC	Demand for Road Freight (Million Tonne km)
Economic development of "Rail transports" from EMEC	Demand for Rail Freight (Million Tonne km) Demand for Rail Passengers Light/Heavy (Million Persson km)
The following results from TIMES-Sweden …	**… impact the following assumptions in EMEC**
Energy demand and mix in the sum of Rail transports from TIMES-Sweden	Energy efficiency and energy mix in Rail road transports
Energy demand and mix in the sum of Road freight transports from TIMES-Sweden	Energy efficiency and energy mix in Road goods transports
Energy demand and mix in the sum of Bus transport from TIMES-Sweden	Energy efficiency and energy mix in Road passenger transports
Energy demand and mix in the sum of Navigations from TIMES-Sweden	Energy efficiency and energy mix in Sea transports
Energy demand and mix in the sum of Aviation from TIMES-Sweden	Energy efficiency and energy mix in Air transports
Energy demand and mix in the sum energy mix from Commercial sector (including the public sector) from TIMES-Sweden	Energy efficiency and energy mix in Other transports
Sum of transport fuels to passenger cars and motorcycles from TIMES-Sweden	Energy efficiency and energy mix in Households fuels for vehicles

[a] According to the Swedish Government Agency for Transport Policy Analysis, in 2012 Swedish households owned 75% of all cars in the country and these cars in turn accounted for 72% of the total kilometers driven [47]. Thus, even though a non-negligible share of all cars are not owned by households, the disposable income of households will also influence the extent to which cars are used in other sectors, e.g., carpenters and carrier transports.

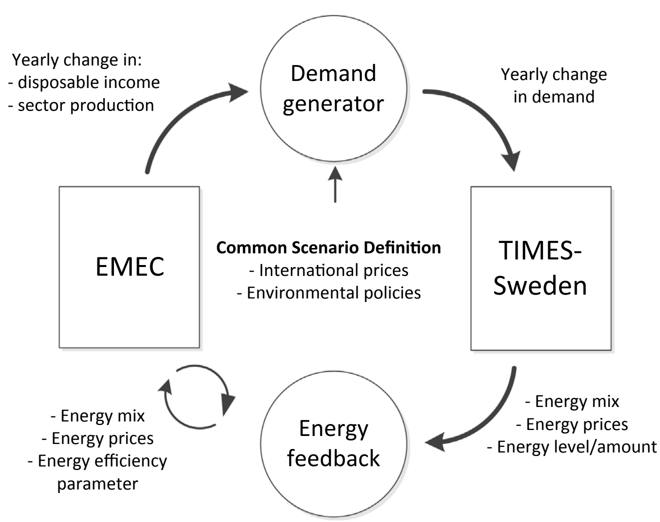

Fig. 1. Identified soft-linking procedure between EMEC and TIMES-Sweden.

normally incorporated into the AEEI is already included for most of the sectors in the European TIMES model (which shares the structure of TIMES-Sweden). In the model, higher energy prices will result in more energy-efficient technologies being chosen, using an AEEI factor can therefore lead to double-counting. Still, Kypreos and Van Regemorter [24] argue that AEEI factor is relevant to use for sectors that are described with aggregate energy conversion technologies and where one can assume structural changes over time, like the agriculture sector in TIMES-Sweden. They also emphasize that the AEEI can capture lifestyle changes that are independent of energy prices, e.g., a shift from cars to public transportation following altered preferences and attitudes.

Kypreos and Van Regemorter [24] conclude that additional research is needed on the country-specific correlation between economic growth and useful energy demand. In the Swedish case this was confirmed through communication with representatives of the Swedish Energy Agency. An applicable relation between economic development and energy demand can also be retrieved through econometric analysis, which however requires long time-series that are not publicly available. We have therefore chosen to initially keep the equations simple, and to focus on identifying the most important variables. The relationship between the yearly change of each demand segment and the yearly change in gross production in monetary terms of the corresponding sector in EMEC was defined by Equation (1). Here the TIMES commodity $TC_{t,i,j}$ is the exogenous demand for a specific commodity or product in physical terms in TIMES-Sweden (e.g., tons of steel), in year t, iteration i and demand segment j. Moreover, $drgr_{t,i,j}$ represents the annual change in gross production in monetary terms of iteration i and commodity j, from the EMEC model.

$$TC_{t,i,j} = TC_{0,i,j} \cdot \left(\prod_{\tau=1}^{\tau=t} \left(\beta_j \cdot drgr_{t,i,j} \right) \right) \tag{1}$$

The conversion parameters β_j, all of them presented in Table 3, are based on the historical correlation between the demand of a commodity j in physical units as described in TIMES-Sweden ($TC_{t,j}$) and the corresponding sector growth in monetary units according to the national accounts ($drgr_{t,j}$). Thus, in this way a historical relationship between gross production in monetary terms from the national accounts and production of the corresponding commodity in mass or volume gathered from the branch associations was identified for each demand segment. This is based on regression analysis using data on value added over the period 1984–2008.[6]

The above approach was found to be applicable only in the demand segments where useful energy is a result from TIMES-Sweden, i.e. when the final demand can be met by technology options with different characteristics. In the cases where the demand in TIMES instead is specified as 'useful energy demand' (i.e. demands specified with 'PJ' in Table A1, Appendix A) and the demand segments are represented by one or two aggregate

[6] For the future, one should aim at a more elaborate regression analysis. This would improve the result both when running the models in a soft-linking mode and when running TIMES-Sweden stand-alone based on demand calculated from EMEC.

Table 3
Conversion parameters representing the change in demand in relation to economic growth based on historical data.

Segment in TIMES	Identified sector in EMEC	Physical commodity (j)	Conversion parameter
Steel (IIS)	Iron and Steel industry	Steel production	1.002
Aluminium (IAL)	Metal industry	Alluminium production	0.996
Copper (ICU)	Metal industry	Copper production	1.047[a]
Cement (ICM)	Mineral industry	Cement production	1.000
Paper (IPH, IPL)	Pulp and paper industry	Paper production	1.007
Freight transport road (TFR)	Road freight transport	Freight transport road	0.995
Freight transport train (TTF)	Rail transport	Freight transport train	1.020
Navigation (TNA)	Sea transport	Navigation	0.983
Passenger City Busses (TBU)	Passenger road transport	Passenger Busses	0.979
Passenger Intercity Busses (TBI)	Passenger road transport	Passenger Busses	0.979
Passengers City Train (TTL)	Rail transport	Passengers Train	1.008
Passengers Train (TTP)	Rail transport	Passengers Train	1.008

[a] The copper demand is assumed to follow the growth of the iron- and steel industry due to distraction in the data-set. Swedish copper production capacity increased significantly during the sample period (1998–2010), which made it difficult to identify which changes in production that were related to GDP growth and which were related to the construction and expansion work.

production functions, the demand projections in the reference scenario are based on the historical relationship between total energy use and gross production in monetary terms. In the alternative scenarios, changes in energy demand projections in TIMES for these demand segments are only adjusted with respect to the changes in aggregate energy demand in EMEC.

There are also demand segments that in TIMES-Sweden are described by several technology options, but for which no direct relationship between economic growth and demand could be identified from the available statistical sources (e.g. the transport demand based on household car use). In EMEC, household car transport demand is modelled as demand for petrol and diesel, while TIMES-Sweden instead calculates the demand for energy subject to a certain demand for travelled distance in passenger kilometres. 'Road transport by cars' is in TIMES-Sweden split into long and short distances. In order to estimate the change in demand for this demand segment ($TC_{t,j}$), the income change ($igr_{r,j}$) and the change in the price of petrol ($pgr_{r,j}$) from EMEC were used and calculated with the help of Equation (2).

$$TC_{t,j} = TC_{0,j} \cdot \left(\prod_{\tau=1}^{\tau=t} (1 + igr_{r,j}) \right)^{\mu_j} \cdot \left(\prod_{\tau=1}^{\tau=t} (1 + pgr_{r,j}) \right)^{\varepsilon_j} \tag{2}$$

The assumed price elasticity (ε_j) and the income elasticity (μ_j) are based on information from VTI [49] and SIKA [43].

Finally, we assumed some of the demands to be decoupled from changes in the economy. One example of this is the demand for space heating that to some extent depends on the income, but to a larger extent is influenced by demographical changes (e.g., population growth, how and where people chose to live, etc.). In addition, an increase in income can both increase and decrease the demand for space heating, increasing through the enabling of larger living space and decreasing by providing households with the necessary means for energy insulation investments. We have therefore assumed that the demands for space heating and hot water depend on population growth and on changes in the number of persons per household. Thus, this is not affected by the soft-linking procedure and is instead harmonized between the models.

From the above two different kinds of approaches can be distinguished when translating the results from EMEC into demand projection as required by TIMES-Sweden: a direct approach where a relationship between economic growth (from EMEC) and energy demand (into TIMES-Sweden) can be identified, and an indirect approach for the remaining cases. The chosen approaches for each demand segment are listed in Table A1 (Appendix A).

3.2. Translation model – TIMES-Sweden to EMEC

CGE models are often unable to explicitly address the following three aspects of the energy system: i) changes in energy intensity due to the introduction of new technologies; ii) changes in the energy-mix following changes in energy demand; and iii) changes in electricity and heating prices due to the competition for limited energy commodities between and within sectors. For these reasons information from TIMES-Sweden will be transferred to EMEC.

The change in energy intensity (from TIMES-Sweden) is incorporated into EMEC so that the general equilibrium effects of the policy change are not modified. The technical efficiency parameter, which is normally exogenously given in the EMEC model, is now endogenously changed until the ratio between total energy use and total production equals the ratio given by the TIMES model. This restriction is specified in Equation (3). By introducing this restriction in the EMEC model, the resulting technical improvement found in the TIMES model can be included in EMEC without making total energy use exogenous.

$$EE_{i,n} / YE_{i,n} = ET_{i,n-1} / YT_{i,n-1} \tag{3}$$

where $EE_{i,n}$ is total energy used in sector i, iteration n, in EMEC; $YE_{i,n}$ is the gross production in sector i, iteration n, in EMEC; $ET_{i,n-1}$ is the total energy used in segment i, iteration $n-1$, in TIMES-Sweden; and $YT_{i,n-1}$ is total production in segment i, iteration $n-1$, in TIMES-Sweden (which in turn equals $YE_{i,1}$).

In EMEC the energy use mix (i.e., the shares of different energy carriers) for each sector will be completely determined by the results from TIMES-Sweden. In order to facilitate this transformation of results from TIMES to EMEC, the production function in the soft-linked version of EMEC has been changed so that the substitution elasticity between the different energy inputs in each sector is set to equal zero, i.e., the energy branch is assumed to be represented by a so-called Leontief (fixed coefficient) structure.

Electricity and heat prices are endogenously determined in both models. EMEC describes the electricity and heat production with two aggregated production functions, but the model is not able to describe the changes in the technology mix arising in different scenarios. TIMES-Sweden, on the other hand, describes the power generation and district heating sector in detail, and generates shadow prices for each time-slice (within and over the years) for each energy commodity. This shadow price also includes the investment costs incurred when installing new capacity. The electricity and heat prices in EMEC are therefore assumed to rely on the results generated in TIMES-Sweden. In order to implement these price changes in EMEC, the price of capital in the power-generating sector is changed endogenously by a 'mark-up'; this makes capital more or less expensive than in other sectors. This mark-up is adjusted (within EMEC) until the electricity price change is equal to the price change in TIMES-Sweden. With the exception of diesel and gasoline prices, fossil fuel prices are exogenously given to both models and are not assumed to be affected by the soft-linking.

3.3. Deciding where to start and when to stop

In the above-presented soft-linking process, both models are dependent on inputs from the other model. Still, one model has to start the iteration. In order to run the EMEC model, it is not necessary to include information from an energy system model, while the TIMES model needs demand assumptions from a macroeconomic model like EMEC. It is therefore useful to start the iteration with EMEC.

In the case of hard-linking two models, some kind of stop parameters is required in order for the algorithm to cease the iteration. Stop parameters, or convergence criteria, are pre-defined criteria for how much the two models' results can differ. Stop parameters may also be introduced in the case of soft-linking two models, see e.g. Wene [50]. As discussed in Section 2.3, the difference between Wene's [50] and our approach is that the connection points in Wene's study represent the same kind of value in both models, while a connection set in our approach represent a value in one of the models that influence a certain point in the other model (i.e. it will not necessary be the same set in both directions). Thus, we have not ex ante specified any convergence criteria since our approach includes a large set of connection points. Instead, we review the change in each connection node after each iteration.

4. Applying the identified soft-linking procedure: a climate policy scenario illustration

This section presents results from a policy scenario analysis applying the developed soft-linking approach. Specifically, we compare the outcomes of a reference scenario with a climate policy scenario in which higher prices of carbon dioxide have been implemented, with and without the soft-linking method. The reference scenario describes a possible outcome for the Swedish economy, and the long-run energy demand is based on NIER [33]; apart from the energy efficiency parameters in EMEC that have been determined through the soft-linking. For more details on the data input assumptions in the respective models, see Krook-Riekkola [22] and NIER [33]. The iteration between the two models in this policy scenario exercise is described in Fig. 2.

In the policy scenario we devote specific attention to the prospects for CO_2 reduction and energy use changes in the Swedish industrial sectors. The Swedish power generation and district heating sectors are virtually carbon-free, but the industry sector is overall more carbon- and energy-intensive (e.g. pulp and paper, iron and steel, mining). It therefore needs to confront further measures to cut CO_2 emissions and lower energy requirements. So far the policy incentives have been modest with low allowance prices in EU ETS for the energy-intensive sectors, and several CO_2 and energy tax exemptions for many of the remaining industries. The current climate debate in Sweden has therefore several times raised the question of how more stringent policies would affect the industry's carbon and energy performance.

For this reason, our climate policy scenario involves increases in both the domestic carbon tax and in the European-wide EU ETS price. The CO_2 tax in the sectors not included in EU ETS is assumed to increase by 50%, and the CO_2 allowance price within EU ETS is assumed to increase to 30 €/tonne. The focus on the industry sector is motivated by the fact that the derived demand for industrial products depends on production (input) costs (the substitution between goods/services is captured in EMEC). At the same time, production costs partly depend on the energy cost and taxes (substitution between energy carriers is better captured in the TIMES model). Energy demand has also been presented as an important – and complicated – aspect of the soft-linking process in Labriet et al. [26].

The main purpose of this study has been to develop and discuss an operative procedure rather than to produce scenario results per se. For this reason, the results presented below should primarily be seen as an illustration of the dynamics of the soft-linking methodology and to assess how each model's results are affected in this process. Thus, the focus lies on the differences in results with or without the soft-linking.

4.1. Output from the translation models: demand and energy mixes

The energy representation in EMEC is based on the resulting final energy use from TIMES-Sweden specified individually for each industrial sector (e.g., iron and steel, pulp and paper etc.) and for each transportation segment (e.g., freight, public, private etc.). Electricity and district heating are reported separately. The remaining sectors are grouped into households, the commercial and service sector, and agriculture-fishery-forestry. The EMEC results are in turn fed into the translation models, resulting in a set of demand projections (i.e. demand specified for each year) that are used as inputs to TIMES-Sweden.

Fig. 3a shows how the resulting demand (in million tonnes) in 2035 for six different energy-intensive industrial sectors changes with the soft-linking iterations for the reference scenario. In general, the first iteration resulted in a significant change in the structure of the economy, which in turn affected output demand and energy use. The most profound change is seen in the demand for high and low-quality paper, which is reduced by 9.60% between the first and the second iteration. Overall the two models adjust quickly to one another already in the second reference iteration (R-2 iteration); thereafter only smaller changes are made. However, full convergence was not achieved.

The lower demand in the energy-intensive industries after the iteration process, can be explained by: i) a higher electricity price from the TIMES-Sweden model compared with running the EMEC model alone; in combination with ii) TIMES-Sweden assuming more technology options in the energy-intensive industries to shift to less expensive energy options compared to the possibilities set by EMEC substitution elasticities. In EMEC higher electricity prices and lower substitution possibilities imply increased production costs, and a decreased demand for energy-intensive goods as their relative price increases.

It can also be noted that the soft-linking procedure reinforces the trend towards increased demand for transport and services. As production moves from capital- and energy-intensive industries with relatively high labor productivity towards transport and service with lower productivity levels, total energy demand decreases. This structural change also leads to lower GDP growth but this change, on an aggregate macroeconomic level, is not significantly different from the corresponding growth rate in the case without soft-linking.

The energy mix also changes during the iteration process despite the fact that it is determined by the results from the TIMES-Sweden model. This is partly due to the decrease in overall energy demand (see Fig. 4). The decrease in overall energy demand

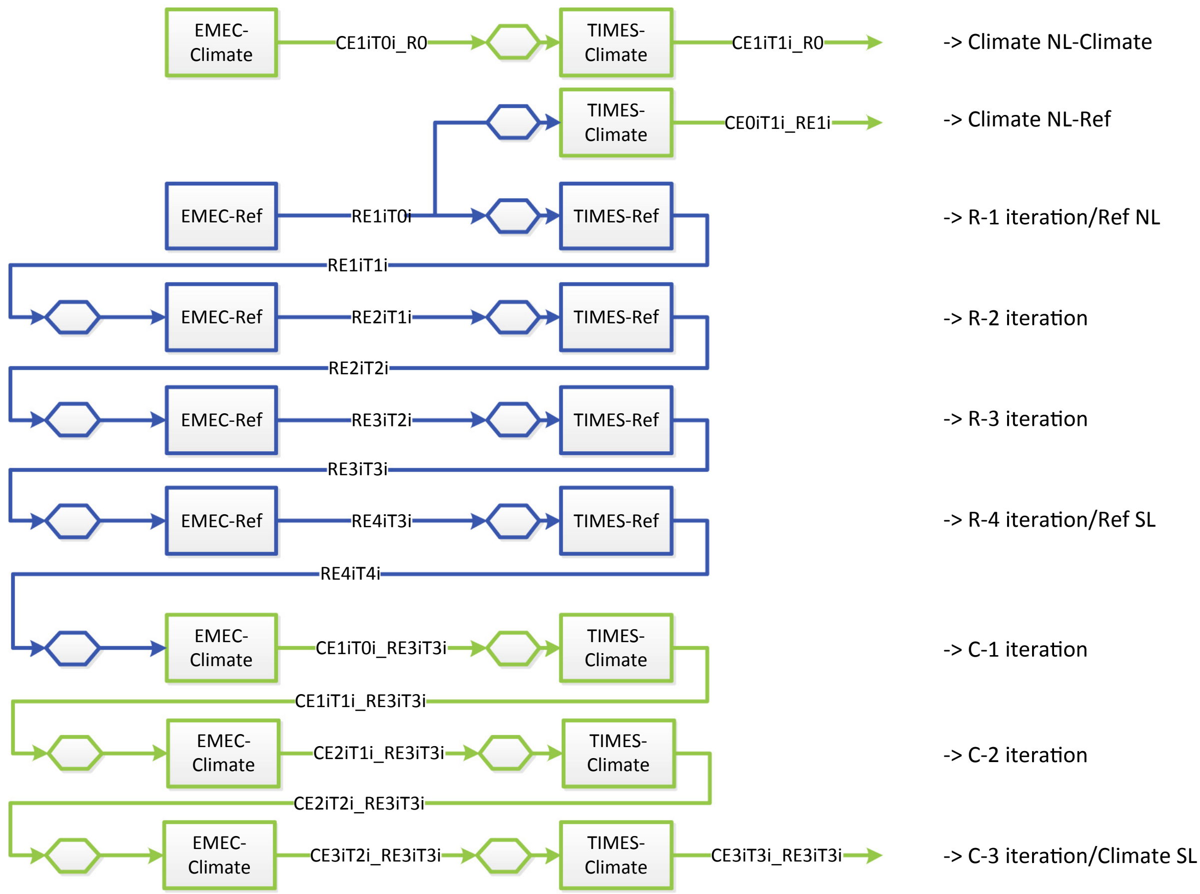

Fig. 2. Iteration Scheme between EMEC and TIMES-Sweden. Note: The rectangular boxes illustrate the models (TIMES versus EMEC). The notations within these boxes describe the applied scenario (Ref or Climate). Hexagon boxes illustrate translation models. The colours illustrate different soft-linking paths; blue paths generate reference scenario outputs, while green paths generate climate scenario outputs. The name of the resulting scenario outcome is written to the right. Scenario results in between models are described by a set of letters, in which; the first letter indicates the set of scenario assumption used, i.e., reference scenario or climate scenario; the second letter indicates the model (EMEC or TIMES-Sweden), followed by the number of iterations (xi is iteration No. x). NL indicates No Linking, whereas SL indicates Soft-Linking.

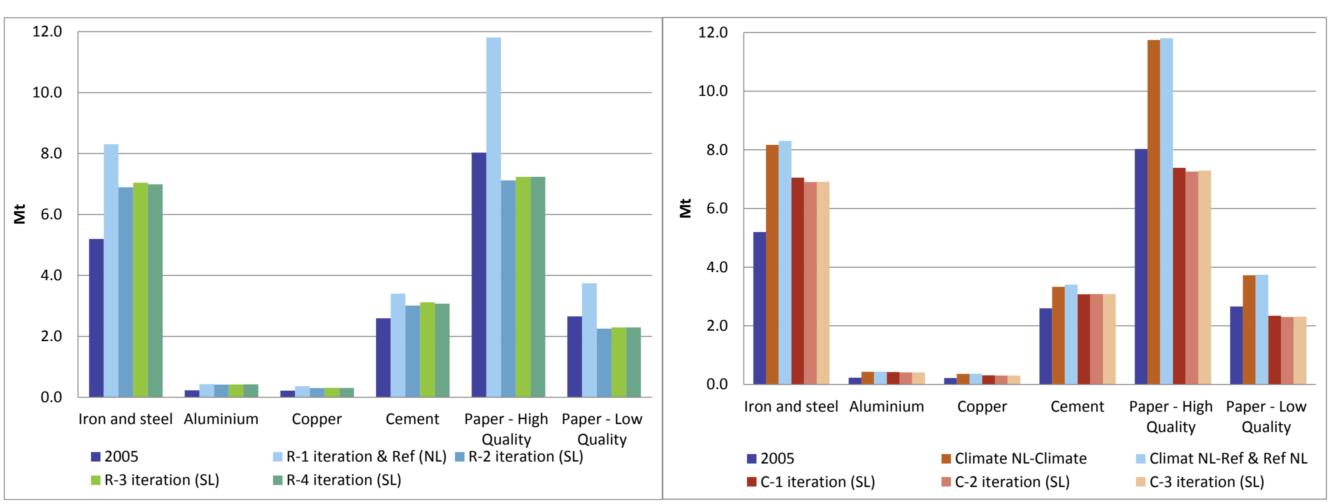

Fig. 3. a–b: Output demand projections for the year 2035 from the translation model (transferred to TIMES-Sweden) for six different energy-intensive goods in million tonnes (Mt). a) Reference scenario (left figure); and b) Climate scenario (right figure). Note: Demand projections are based on the results from EMEC. As a comparison, the demand patterns in 2005 are included. NL = no linking, SL = soft-linking, R = reference scenario, C = climate scenario. For further clarifications, see Fig. 2.

following the soft-linking iteration results in a corresponding decrease in the final energy use (in PJ) of electricity, gas and coal, while we observe only marginal changes in the use of other energy commodities. When investigating the relative differences between iterations in the reference scenario, aggregate final energy consumption decreases by 14% between the first and the second

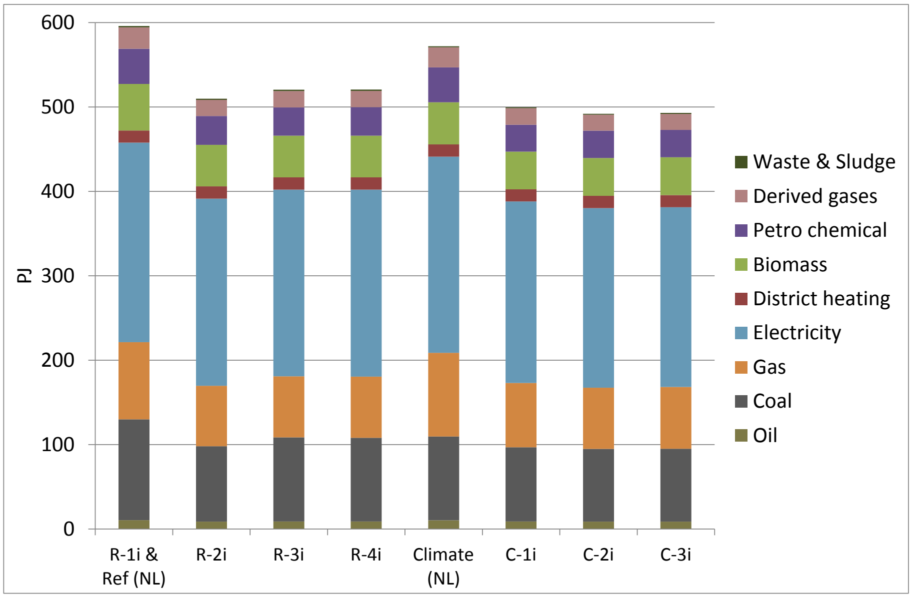

Fig. 4. Aggregate final energy use for six different energy-intensive goods in the year 2035 (results derived from TIMES-Sweden). Note: R represents iteration with the reference scenario, C the iteration with the climate scenario, and the numbers indicate which iteration. For further clarifications, see Fig. 2.

iteration, and then changes only marginally in the remaining iterations.

The climate policy scenario is analysed based on three different starting points (see also Fig. 2): a non-linked reference scenario (Climate NL-Ref), a non-linked climate scenario (Climate NL-Climate) and a soft-linked scenario (C-* iteration). In the last case, the number of iterations does not affect the production level transferred from EMEC to any greater extent. Hence, the differences between C-1 and C-3 reported in Fig. 3b are small compared to the differences found between R-1 and R-2. The EMEC model has already adjusted to mimic TIMES-Sweden's behaviour in the reference scenario. Since the increases in the CO_2 tax and the EU ETS price, respectively, only have modest impacts on the electricity price in TIMES-Sweden, the differences between the two methods regarding the economic development are modest.

When comparing the energy mix generated by TIMES-Sweden with and without soft-linking in the climate scenario, this changes only marginally in the iron and steel and the chemical industries, while the changes in the other industries are similar to the ones in the reference scenario. Like in the reference case, the lower final energy demand in the soft-linking case results in a lower use of gas and coal; the decrease in coal is much smaller. An important reason is that the total use of coal is lower in the climate scenario compared to the reference scenario without linking; thus, there are fewer possibilities for coal use reduction.

4.2. Policy impacts — the resulting CO_2 emissions

In order to test if the changes in the results from introducing the soft-linking process have a decisive policy impact, we investigated the resulting CO_2 emissions from TIMES-Sweden in the year 2035 (see Table 4). These results show that the CO_2 emissions are significantly lower in the case involving soft-linking than in the case without soft-linking (i.e., Ref NL vs. Ref SL, Climate NL vs. Climate SL). This is mainly a result of lower demand for energy intensive goods in the soft-linked case. The change in CO_2 emissions between the reference scenario and the climate scenarios is almost the same with and without linking when starting from a non-linked climate scenario in EMEC (i.e., Climate NL-climate' compared with 'Climate-SL' in Table 4), while the absolute difference is greater in the absence of linking.

If demand projections to TIMES-Sweden instead are based on EMEC's reference scenario, the relative difference is greater — i.e., 'Climate NL-ref' compared to the 'Climate SL' — while the absolute difference is almost the same. The main difference between soft-linking the two models and running them separately are in the EU-ETS sectors. While these sectors include both energy intensive industries and energy conversion sectors, the main difference between the two approaches seen in Table 4 (Ref NL-Climate NL and Ref SL —Climate SL) is in the energy intensive industries, as a direct effect of the lower demand when iterating the two models.

Table 4
Resulting Carbon Dioxide Emissions from each scenario in 2035 in quantities and relation to the compared reference scenario. Scenarios are described in Fig. 2.

	Carbon Dioxide Emissions (million tonnes)			Reduction in the Climate scenario relative to the Reference scenario	
	EU-ETS sectors	Non-EU-ETS sectors	total	Absolute difference (million tonnes)	Relative change
Ref NL (Reference No-Linking)	30.87	25.62	56.50		
Climate NL- Ref	24.53	25.08	49.62	6.88	12%
Climate NL- Climate	24.03	24.96	48.99	7.51	13%
Ref SL (Reference Soft-Linking)	27.36	24.53	51.89		
Climate SL	21.41	23.69	45.10	6.79	13%

5. Discussion and lessons learned

In this section we discuss how – and to what extent – the proposed soft-linking procedure contributes to an improved and transparent national energy, environmental and climate policy decision process. We also share some positive and negative experiences of the soft-linking procedure. Specifically, we first discuss a number of challenges associated with the new soft-linking procedure, including the issue of flexible connection points. Thereafter we highlight the role of the applied soft-linking in comprehending the Swedish energy system (and in particular industrial energy demand behaviour), and discuss important lessons based on a comparison of the results from soft-linking versus stand-alone model use.

5.1. The soft-linking procedure – what and how to link

The soft-linking approach employed in this paper has permitted us to preserve – and benefit from – each model's strengths, e.g., providing technological detail in the case of TIMES and providing a consistent description of the interaction between all sectors of the economy in the case of EMEC. We have aimed for a detailed soft-linking, i.e. linking more details than has been common practise in previous research. A simplified soft-linking approach would have been more straightforward and easier to automatize, but would not be sufficient to fully address the sector level changes.

Critics have raised concerns about difficulties in achieving consistency between the two modelling approaches, CGE and ESOM, since differences in terms of structure and methodology sometimes can be significant [5]. Fortes et al. [10] came to a similar conclusion, but at the same time emphasize on the importance of having both approaches in the climate policy analysis at the national level. In this study we did not aim at getting consistency, but instead to take the advantage in each approach when identifying what and how to link.

When soft-linking a national CGE and energy system model it is important to treat each connection point individually. Different translation methods may be needed at different connection points when generating demand projections. While this is also applied in other studies (e.g. Kypreos and Van Regemorter [24]), the use of independent and direction-specific connection points has, to our knowledge, not been reported before.

There is also the option to adjust (tailor) one of the models to the structure of the other to facilitate direct feedback links between the models, see e.g. Karlsson et al. [17]. However, this would make it more difficult to use the underlying statistics needed to build a robust model, and this underlying statistics are structured accordingly to its focus area (energy or economy). Consequently, there are benefits and drawbacks with both approaches – soft-linking existing models versus linking an existing energy system model (or CGE model) with a tailored CGE model (or energy system model). The use of DSCPs avoids compromising with the respective models' strengths, and instead largely retains the underlying model structures in the soft-linking process.

We have chosen to not introduce predefined iteration criteria, but instead manual reviews of the changes in each connection node have been conducted. The original argument was that the connection point often does not represent the same value in both models. When applying such a manual review, we also identified model improvements and learned about the studied system.

The conversion between rates of change in the overall economy and actual levels of demand proved challenging in our case. This is in part due to the differences in scope of the two models, where EMEC considers monetary units and has a wider economic scope while TIMES-Sweden mostly covers physical units and describes energy conversion processes. The price elasticities feature in the TIMES model, not applied in this exercise, could have made the two models' energy use converge quicker. However, such an approach implies a risk for double counting in the growth feed-back from the CGE model and could therefore make the soft-linking process less transparent. We therefore mainly see the price elasticity option as a tool when running the TIMES-model stand-alone.

When providing energy feedback from the energy system model to the CGE model, the biggest challenge was the price information. EMEC considers relative prices while TIMES-Sweden's prices are provided in terms of absolute levels. We found the price change between the base year (2008) and end year (2035) to be exaggerated. The standard use of TIMES-Sweden is to compare the results from different scenarios for a specific year. In contrast, in the soft-linking procedure the price difference between two years within one scenario is compared. The reason why this is problematic is that the calculated price in the first modelling year does not address all generation costs. The optimization solves for the lowest total cost, but when the base years are fixed there is no need to include these cost figures as the model is used for scenario analysis. Moreover, which price to pick from the TIMES model is not obvious, e.g. in the case of electricity; TIMES-Sweden calculates a shadow price for each time step, sector and each commodity, while EMEC only has one annual electricity price (but different taxes and tax levels depending on the sector). The price issue was not fully resolved during this exercise, and needs further investigation.

Changes in investment flows, e.g., due to large structural changes in the energy system, are also issues that cannot always be captured in a satisfactory way in the proposed soft-linking methodology. In the presence of a major restructuring of the economy, e.g., caused by a radical reduction in the use of fossil fuels, investment flows would most likely change substantially, and in turn give rise to significant general equilibrium effects. The resulting investments from the energy system model might therefore not be feasible since there is no link between investment demand and the rest of the economy.

Macroeconomic models, on the other hand, face difficulties in capturing the diffusion of new technologies and fuels. By adjusting the electricity and heat prices some of the changes in investments flows are captured in the presented soft-linking methodology. Labriet et al. [26] have introduced additional energy commodities into their CGE model (GEMINI-E3) in order to address the fact that energy conversion is associated with different uses of capital, energy and non-energy materials. The shares of the different energy commodities are in their case derived from an energy system model. However, also with such an approach it is important to take into account that investment costs are usually not included in the base-years in energy system models, whereas they always are included in CGE models.

Labriet et al. [26] conclude that soft-linking CGE and energy system models requires “a meticulous examination and understanding of both models in order to design the appropriate correspondence between energy commodities, regions, economy sectors, as well as the data exchanges at the heart of the coupling,” (p. 16). There are fundamental differences between the two models that should not be underestimated in the linking process. Nevertheless, our emphasis on a thorough comparison and understanding of both models and the importance of addressing each direction separately can be generally applicable to most soft-linking approaches.

5.2. Impact of soft-linking on the scenario results

The soft-linking methodology led to a new picture of the economy's energy use. The first iteration resulted in a significant change in the structure of the economy, which in turn affected the energy use. The subsequent iterations only resulted in minor changes before (incomplete) convergence occurred. The change in demand assumptions, due to the iteration with the EMEC model, affected both the resulting energy mix and the quantity of final energy demand in each of the sectors of TIMES-Sweden. This indicates that it is essential that the impacts of the analysed policy on the economy are consistently reflected in the demand assumptions used by TIMES. When running TIMES-Sweden stand-alone, the demand assumptions are generally from a variety of official sources for which the underlying assumptions are usually difficult to assess. By instead using the economic output from EMEC directly into the translation model, scenario analyses become more transparent and consistent. The model results also become easier to replicate, and the approach facilitates the understanding of the underlying drivers of the results.

The changes in assumed demand to TIMES-Sweden, when soft-linking the two models, do not seem to have any significant impact on the resulting power price. This is likely due to several factors; i) in the industry the power price is relatively low compared to other energy commodities, thus the main change in demand is in sectors with large share of fossil fuels; ii) in TIMES-Sweden, there are possibilities to import/export electricity (different prices in different time-slices, each price is based on a certain ‘marginal’ technology with techno-economic parameters in line with the remaining modelling assumptions); and iii) Sweden has a large potential of renewables with low operating cost, thus resulting in low power prices also when electricity demand and/or the EU ETS price increase. For these reasons, the change in demand is not so much an electricity price effect and can rather be attributed to other energy carriers and price increases in these following higher EU ETS prices.

There are not many studies revealing the details of their soft-linking experiences, especially not at the country level, so opportunities to compare our results with other work have been limited. From what we can assess, Fortes et al. [10] did a similar soft-linking between the GEM-ES_PT and TIMES_PT models.[7] From what one can identify, an important difference is that they get a larger variation in final energy consumption (from the TIMES model) between the iterations than we did. Their soft-linking was repeated until the differences in “energy consumption per energy carrier and calibrated sector” were less than 10% [10]. In a similar study [11], the difference between iteration 0 and 3 was −1 to 9%. We attained this already after the first iteration. This could suggest that our detailed representation of the energy intensive industries in the feed-back between the two models helps the models to converge faster.

One disadvantage of our soft-linking approach is that the process is relatively time-consuming. Although we introduced intermediate translation models, each of the iterations required a certain amount of manual check. For example, the results from TIMES-Sweden must be checked for new fuels and new technologies. This is a challenge since EMEC does not include all future energy options (e.g. hydrogen, advanced biofuels etc.), and also because the link between the models is based on relative changes from base year values (the relative change from zero will be infinite). Nevertheless, the extra amount of time required for the soft-linking also give a certain amount of manual quality control. The analysis of each iteration step also provides an opportunity to learn about the interactions between the development of the entire economy and the development of the energy system.

6. Conclusions

Important similarities and differences between a domestic CGE model and an energy system model have been identified. These findings were used to develop a robust and transparent method to translate simulation results between the two models, resulting in intermediate ‘translation models’. Soft-linking the energy parameters for each sector in EMEC and synchronizing them to TIMES-Sweden's results has been done by altering: i) the energy efficiency parameters in each sector; ii) the energy mix in each sector; and iii) the price of electricity and heat. The change in energy efficiency and the price of electricity proved to be relatively more important for the economic outcomes (e.g., in terms of GDP) than changes in the energy mix and the price of heat. Finally, the proposed soft-linking process was tested and evaluated in the context of a simple climate policy scenario for Sweden.

During the work, some important future improvements of the models were identified. For example, a development of EMEC into a hybrid model would enhance the soft-link to describe the investment demand in the economy more accurately, since a disaggregation of the power sector will indicate the link between different power technologies and the demand for capital investments. The proposed change in EMEC would imply that the electricity sector from the national accounts is divided into two main sectors: one power-generating sector to which the cost for electricity and heat production is allocated and one transformation and distribution sector to which transformation and distribution of electric power as well as the overhead costs and sales organizations are allocated. Electricity and heat production would then be described by the various available technologies for heat and power generation, e.g., hydro, nuclear, wind, biomass, natural gas. This would improve the analysis both when running the model stand-alone and when transforming information from TIMES-Sweden to EMEC. In a similar way, TIMES-Sweden could be improved to better facilitate the soft-linking procedure by redefining the operating and maintenance costs in the model from a definition based on a single economic cost to one based on number of working hours required and wages per hour. In this way, the possible competition for labour is captured and wage changes resulting from EMEC could be linked to increased maintenance costs.

Finally, the work process of developing the soft-linking methodology has been characterized by integrity, trust, and mutual respect between team members − all three identified by Parker et al. [39] and McIntosh et al. [31] as important factors in interdisciplinary projects to achieve successful integration and communication. By working closely together with the soft-linking method, a mutual understanding of the respective scientific approaches has arisen. These insights are useful when soft-linking the models, in the analysis of the results and in the future separate use of the two models.

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[7] Fortes et al. [10] soft-link the models in their baseline "calibration process", but do not provide an extensive description of their approach. It is therefore difficult to make a fair comparison between our and their approaches. Nevertheless, some differences in methodologies can be identified. The main difference appears to be the representation of the energy intensive industries in the CGE models, which in EMEC is divided into several sectors while GEM-E3_PT treats this as one production sector. This has implications on how sectors are linked (compare, for instance, Table A1 in Ref. [10] versus Table A2 in our paper).

Appendix A

Table A1
Identified connection points – direction EMEC to TIMES-Sweden. EMEC results are first translated into yearly percentage changes. These values are then used together with external input to calculated yearly demand which is used by TIMES-Sweden. Three different translation methods are used: i) a direct approach based on the specific sector commodity (Dir-A), ii) an indirect approach based on other economic variables (InDir-A), and iii) assume no connections (N-C). In some cases the translation method differs depending on iteration in the reference (ref) or the alternative (alt) scenario.

TIMES Demand segment	Projection is based on the following EMEC variables	Translation method		Unit
Some include several segments, those are separated with "/"	*Yearly percentage change.*	*Ref. Scen*	*Alt. Scen*	
Commercial Sector (COM)				
Both Public and Private				
Refrigeration (COM)	hours worked in the service and public sectors	InDir-A		PJ
Cooking (COM)		InDir-A		PJ
Lighting (COM)		InDir-A		PJ
Public Lighting (COM)		InDir-A		PJ
Space Cooling Small/Large (COM)		InDir-A		PJ
Space Heating Small/Large (COM)		InDir-A		PJ
Warm Water Small/Large (COM)		InDir-A		PJ
Other Electric (COM)		InDir-A		PJ
Other Energy (COM)	–	N-C		PJ
Industry Sector (IND)*				
Aluminium Demand	Production level in the Non-iron metal industries	Dir-A		Mton
Copper Demand		Dir-A		Mton
Iron Demand	Production level in the Iron and steel industry	Dir-A		Mton
Steel Demand		Dir-A		Mton
Other Non-Ferrous Metals Demand	Production level in Non-Ferrous metal industries	N-C	InDir-A	PJ
Ammonia Demand	Production level in Chemistry	InDir-A		Mton
Chlorine Demand		InDir-A		Mton
Other Chemicals Demand	Weighted value between production level in Chemistry and Pharmaceutical industries	N-C	InDir-A	PJ
Mineral products: Cement/Lime/Glass-Hollow/Glass –flat	Production level in the sector of Mineral products	InDir-A		Mton
Other non-metallic mineral products		N-C	InDir-A	PJ
High/Low Quality Paper Demand	Production level in Pulp, paper and printing sector	Dir-A		Mton
Other Industries	Average value between production level in the sectors of Mining, Other industries, Engineering, Water and sewage and Construction	N-C	InDir-A	PJ
Non Energy Consumption – Chemicals	Weighted value between production level in Chemistry and Pharmaceutical industries	N-C	InDir-A	PJ
Non Energy Consumption – Others	–	N-C		PJ
Residential Sector (RSD)				
Cloth Drying (RSD)	Household electricity	InDir-A		PJ
Cloth Washing (RSD)	Household electricity	InDir-A		PJ
Dish Washing (RSD)	Household electricity	InDir-A		PJ
Refrigeration (RSD)	Household electricity	InDir-A		PJ
Lighting (RSD)	Household electricity	InDir-A		PJ
Other Electric (RSD)	Household electricity	InDir-A		PJ
Cooking	Household electricity	InDir-A		PJ
Space Heating – Multifamily/Single-family-rural/Single-family-urban and Existing/New (RSD)	(need further analysis, for now not connected with the results from EMEC)	N-C		PJ
Warm Water Heating – Multifamily/Single-family-rural/Single-family-urban and Existing/New (RSD)	–	N-C		PJ
Other Energy (RSD)	–	N-C		PJ
Transport Sector (TRA)*				
Aviation International/Generic	Production level of aviation transports	Dir-A		PJ
Navigation Generic/Generic Bunker	Production level of navigation freight transport	Dir-A		PJ
Road Bus Intercity/Urban	Production level of public transportation	Dir-A		Million Pkm
Road Car Long/Short Distance	Household disposable income and fuel-price	InDir-A		Million Pkm
Road Motorcycle		InDir-A		Million Pkm
Road Freight	Production level of road freight transport	Dir-A		Million Tkm
Rail Freight	Production level of Rail transport	Dir-A		Million Tkm
Rail Passengers Light/Heavy		Dir-A		Million Pkm
Other Segments				
Agriculture, Fishery and Forestry (AGR)	Average value between production level of Agriculture, Fishery and Forestry	N-C	InDir-A	PJ
Non specified (according to Eurostat)	–	N-C		PJ

* EMEC variables are adjusted according to Table 3.

Table A2
Identified connection points – direction TIMES-Sweden to EMEC. When transferring information about energy use and energy prices from TIMES-Sweden to EMEC, the TIMES-Sweden results are translated into EMEC as yearly percentage change.

EMEC sector	Projections on energy use is based on TIMES Demand segment
Agriculture	Agriculture, Fishery and Forestry
Fishery	Agriculture, Fishery and Forestry
Forestry	Agriculture, Fishery and Forestry
Mining	Other Industries
Other industries	Other Industries
Mineral products	Sum of Cement, Lime, Glass hollow, Glass flat and Other non-metallic mineral products.
Pulp and paper mills	Sum of Pulp and paper industry
Drug industries	Sum of Ammonia, Chlorine and Other Chemicals
Other chemical industries	Sum of Ammonia, Chlorine and Other Chemicals
Iron & steel industries	Iron and Steel industry
Non-iron metal industries	Sum of Aluminium, Copper and Other Non-Ferrous Metals
Engineering	Other Industries
Petroleum refineries	No Connection
Electricity supply	Electrical generation
Hot water supply	District heat production
Gas distribution	No Connection
Water and sewage	'Other Industries'
Construction	'Other Industries'
Rail road transports	Sum of Rail transports
Road goods transports	Sum of Road freight transports
Road passenger transports	Sum of Bus transport
Sea transports	Sum of Navigations
Air transports	Sum of Aviation
Other transports	Commercial sector (includes also public)
Services	Commercial sector (includes also public)
Real estate	Commercial sector (includes also public)
Public sector	Commercial sector (includes also public)
Households	Residential sector and Transport fuels from passenger cars and motorcycles

References

[1] Bauer N, Edenhofer O, Kypreos S. Linking energy system and macroeconomic growth models. Comput Manag Sci 2007;5(1):95–117.
[2] Böhringer C. The synthesis of bottom-up and top-down in energy policy modelling. Energy Econ 1998;20:233–48.
[3] Böhringer C, Rutherford TF. Integrating bottom-up into top-down: a mixed complementarity approach. Discussion Paper No. Centre for European Economic Research; 2005. p. 05–28.
[4] Böhringer C, Rutherford TF. Combining bottom-up and tow-down. Energy Econ 2008;30:574–96.
[5] Böhringer C, Rutherford TF. Integrated assessment of energy policies: decomposing top-down and bottom-up. J Econ Dyn Control 2009;33:1648–61.
[7] Broberg T, Samakovlis E, Sjöström M, Östblom G. Economic assessment of the climate Committee's action plan for Swedish climate policy. Special Study No. 18. Stockholm: The National Institute of Economic Research; 2008.
[8] Connolly D, Lund H, Mathiesen BV, Lehay M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82.
[9] Eurostat. Energy balance sheets 2009-2010. Eurostat statistical books. 2012 edition. ISSN1830-7558, vol. 2012. Publications Office of the European Union; 2012.
[10] Fortes P, Simões S, Seixas J, Van Regemorter D, Ferreira F. Top-down and bottom-up modelling to support low-carbon scenarios: climate policy implications. Clim Policy 2013;13(3):285–304.
[11] Fortes P, Pereira R, Pereira A, Seixas J. Integrated technological-economic modeling platform for energy and climate policy analysis. Energy 2014;73:716–30.
[12] Glynn J, Fortes P, Krook-Riekkola A, Labriet M, Vielle M, Kypreos S, et al. Impacts of future changes in the energy system: national perspectives. In: Giannakidis G, Labriet M, Ó Gallachóir B, Tosato G, editors. Informing energy and climate policies using energy systems models : insights from scenario analysis increasing the evidence base. Springer; 2015. s. 359–38729 s. (Lecture notes in Energy; Nr 30).
[13] Gritsevskii A. Scenario generator. Internal Report. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA); 1996.
[14] Grubb M, Edmonds J, Brink P, Morrison M. The costs of limiting fossil-fuel CO2 emissions: a survey and analysis. Annu Rev Energy Environ 1993;18:397–478.
[15] Hourcade J-C, Jaccard M, Bataille C, Gershi F. Hybrid modeling: new answers to old challenges. Energy J 2006;(2):1–12 (Hybrid Modeling).
[16] IPCC. Climate Change 1995, economic and social dimensions of climate change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Published for the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press; 1996.
[17] Karlsson K, Larsen H, Petrovic S, Balyk O, Gargiulo M, De Miglio R. IntERACT TIMES-DK phase I. Working Paper No. 03. Copenhagen: Danish Energy Agency; 2014. Downloaded from, https://ens.dk/sites/ens.dk/files/Analyser/wp03_-_interact_times-dk_phase_1.pdf.
[18] Klinge Jacobsen H. Integrating the bottom-up and top-down approach to energy. Energy Econ 1998;20:443–61.
[19] Kragt ME, Robson BJ, Macleo CJA. Modellers' roles in structuring integrative research projects. Environ Model Softw 2013;22(5):640–8.
[20] Krook Riekkola A, Ahlgren EO, Söderholm P. Ancillary benefits of climate policy in a small open economy: the case of Sweden. Energy Policy 2011;39(9):4985–98.
[21] Krook Riekkola A, Söderholm P. Fjärrvärmen och de långsiktiga klimatmålen (Policy Instruments for a resource-efficient and low carbon heating: a scenario-based analysis). Fjärrsyn Rapportvol. 2013. Stockholm: Swedish District Heating Association; 2013. p. 10 [In Swedish].
[22] Krook Riekkola. National energy system modelling for supporting energy and climate policy decision-making: the case of Sweden. Ph.D. thesis. Sweden: Department of Energy and Environment, Chalmers University of Technology; 2015.
[23] Kumbaroğlu G, Madlener R. Energy and climate policy analysis with the hybrid bottom-up computable general equilibrium model SCREEN: the case of the Swiss CO_2 act. Ann Oper Res 2003;121:181–203.
[24] Kypreos S, Van Regemorter D. Key drivers for energy trends in EU: specification of the baseline and policy scenarios. Working paper RS2, WP2.3, NEEDS (new energy Externalities developments for sustainability) project. 2006. Downloaded from, http://www.needs-project.org/RS2a/Baseline%20Scenario_12_1_2006.pdf.
[26] Labriet M, Drouet L, Vielle M, Haurie A, Kanudia A, Loulou R. Coupled bottom-up and top-down modelling to investigate cooperative climate policies. Montreal: Les Cahiers du GERAD; 2010. Downloaded from, http://www.gerad.ca/fichiers/cahiers/G-2010-30.pdf.
[27] Loulou R, Goldstein G, Kanudia A, Lehtila A, Remne U. Documentation for the TIMES Model-Part 1. 2016. Downloaded from, http://iea-etsap.org/index.php/documentation.
[28] Manne AS, Wene CO. Markal-Macro: a linked model for energy-economy analysis. Brookhaven National Laboratory; 1992. BNL-47161. Downloaded from, http://www.osti.gov/bridge/product.biblio.jsp?osti_id=10131857.
[29] Martinsen T. Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models. Energy Policy 2011;39:3327–36.

[30] Messner S, Schrattenholzer L. MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 2000;25:267–82.
[31] McIntosh BS, Seaton RAF, Jeffrey P. Tools to think with? Towards understanding the use of computer-based support tools in policy relevant research. Environ Model Softw 2007;22(5):640–8.
[33] NIER. Svensk ekonomi – ett långsiktsscenario fram till år 2035 (Swedish economy – a long-term scenario to 2035). Special study Nr. 30. Stockholm, Sweden: National Institute of Economic Research (NIER); 2012 [In Swedish].
[34] NIER. Från vision till verklighet – en samhällsekonomisk analys av Färdplan 2050. Special study Nr. 34. Stockholm, Sweden: National Institute of Economic Research (NIER); 2013 [In Swedish].
[35] NIER. Samhällsekonomiska konsekvenser av olika bördefördelning av ett europeiskt klimatmål. PM Nr. 26. Stockholm, Sweden: National Institute of Economic Research (NIER); 2014a [In Swedish].
[36] NIER. Energieffektivisering som en del av ett 2030-ramverk. PM Nr. 27. Stockholm, Sweden: National Institute of Economic Research (NIER); 2014b [In Swedish].
[37] Östblom G, Berg C. The EMEC model: version 2.0. Working Paper No. 96. National Institute of Economic Research; 2006.
[39] Parker P, Letcher R, Jakeman A, Beck MB, Harris G, Argent RM, et al. Progress in integrated assessment and modelling. Environ Model Softw 2002;17(3): 209–17.
[40] Remme U, Blesl M. Documentation of the TIMES-MACRO model. Energy Technology Systems Analysis Programme (ETSAP); 2006. Downloaded from, www.etsap.org.
[42] Schäfer A, Jacoby HD. Experiments with a hybrid CGE-MARKAL model. Energy J 2006;(2):171–7 (Hybrid Modeling).
[43] SIKA. Metoder och riktlinjer för att förbättra samhällsekonomiskt Beslutsunderlag (Methods and guidelines for improving socio-economic basis for decision). SIKA Rapport 2002:19. The Swedish Transport Administration (Trafikverket); 2002 [In Swedish].
[44] Söderholm P. Modelling the economic costs of climate policy: an overview. Am J Clim Change 2012;1:14–32.
[45] Statistics Sweden. GDP quarterly 1993-2014:2. 2014 (publ: 2014-09-18). Corrected 2014-09-24. Downloaded from, www.scb.se.
[46] Simoes S, Nijs W, Ruiz P, Sgobbi A, Radu D, Bolat P, et al. The JRC-EU-TIMES model – assessing the long-term role of the SET Plan Energy technologies. JRC scientific and policy reports. JRC85804, EUR 26292 EN. 2013.
[47] Transport Analysis. Statistik över körsträckor 2012 (statistic on vehicle kilometers 2012). 2013. Excel spreadsheet. Downloaded from, www.trafa.se/Statistik/Vagtrafik/Korstrackor [In Swedish].
[48] van Vuuren DP, Hoogwijk M, Barker T, Riahi K, Boeters S, et al. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. Energy Policy 2009;37(12):5125–39.
[49] VTI. Hur hushållen anpassar sig till ändrade kostnader för bilinnehav och bilanvändning (Households adaption to changes in the cost of car ownership and car use). VTI rapport 545. The Swedish National Road and Transport Research Institute (VTI); 2006 [In Swedish].
[50] Wene C-O. Energy-economy analysis: linking the macroeconomic and systems engineering approaches. Energy 1996;21:809–24.
[51] Wilson D, Swisher J. Top-down versus bottom-up analyses of the cost of mitigating global warming. Energy Policy 1993;21:249–63.