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Integrating the bottom-up and top-down approach to energy–economy modelling: the case of Denmark

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Abstract

This paper presents results from an integration project covering Danish models based on bottom-up and top-down approaches to energy–economy modelling. The purpose of the project was to identify theoretical and methodological problems for integrating existing models for Denmark and to implement an integration of the models. The integration was established through a number of links between energy bottom-up modules and a macroeconomic model. In this integrated model it is possible to analyse both top-down instruments, such as taxes along with bottom-up instruments, such as regulation of technology choices for power plants and energy standards for household electric appliances. It is shown that combining the two kinds of initiatives reduces the emission-reducing effect of each of the instruments remarkably.

JEL classifications: Q34; C60

Keywords: Energy–economy modelling; Integration; Bottom-up; Top-down; Denmark; Emission-reducing effect

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1. Introduction

Two different approaches to energy–economy modelling exist: top-down modelling based on macroeconomic modelling principles and techniques, and bottom-up modelling based on disaggregation and the inclusion of a large number of technical parameters. The different approaches have led to very different properties and model results which in recent years have been most widely noticed in the analyses of emissions and mitigation costs. Both older (Hoffman and Jorgenson, 1977) and

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more recent studies (Barker et al., 1995) have argued the need to integrate the approaches, as they are in many cases of a more complementary than substituting nature. Others have argued that the two approaches are incompatible. This is based on that the models are developed with different purposes and designed to permit the performing of different analyses for examining different questions. According to these differences they could not be expected to yield the same results.

Studies exist that integrate or link bottom-up and top-down approaches. These studies range from integrated models with so-called 'hard linking', defined as interactions in an iterative procedure, to models that calculate the energy consequences of different economic developments. Models vary between those that are global, regional and even very local. A common purpose for developing these recent examples of integrated models has been the need for analysing environmental issues related to greenhouse gas emissions.

In this study models representing the two approaches were integrated. The purpose of the study was to integrate a bottom-up simulation model with a Keynesian type macroeconometric model and to identify theoretical and methodological problems connected to the integration. Elements of the bottom-up simulation model BRUS[1] (Morthorst, 1993) were developed into new modules which fit the structure of a macroeconometric model. The Danish macroeconometric model ADAM[2] (Danmarks Statistik, 1996), which is the most commonly used macroeconomic model for economic analysis and forecasting in Denmark, was linked to the developed bottom-up energy modules. This combined model was called Hybris (Jacobsen et al., 1996).

There are important interactions between the energy system and the economy, which makes the integration of bottom-up and top-down approaches an important issue. Integration of the two approaches is also important to ensure that it is the same cost concept which is being used when evaluating bottom-up and top-down options for reducing emissions. The integrated model Hybris is capable of analysing traditional bottom-up and traditional top-down options for reducing CO_2 emissions in the same model. This makes it possible to analyse the dependence of different options or initiatives on each other. The effect of price incentives as fuel taxes depend on the technological options for substituting between fuels and the effect of standards for electric appliances depends on the sales of durable consumer goods. The dependence was quantified with Hybris by running scenarios for bottom-up and top-down initiatives separately and comparing them to scenarios with combinations of reduction initiatives. The effect of three different options for emission reduction was found to be highly dependent on each other.

This paper is divided into three parts: The first describes the different approaches to energy–economy modelling, the integration problems and relevant options for integrating. In the next part, the Danish model Hybris and the actual integration followed in this model exercise is described. In the third part of the

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[1] Brundtland Scenario model.

[2] Annual Danish Aggregated Model.

paper, model scenarios and calculations are presented to illustrate the properties of the model and the interaction between bottom-up and top-down oriented CO_2 reduction options.

2. Bottom-up and top-down modelling of energy–economy issues

Energy modelling has been undertaken by many different institutions and professions but the models in existence are dominated by two different approaches. Top-down modelling is based on macroeconomic modelling principles and techniques and is intended to include all important economic interactions of the society. Bottom-up modelling is based on disaggregation and technical parameters. The two modelling approaches have been designed with different purposes and with a different theoretical background. This is the main reason for the very different properties and results from using the models for analysing the same issues.

Bottom-up models have been widely used within energy analysis and planning. Models of this type have a lot of detail and describe a number of specific energy technologies with both technical and economic parameters. Both present and future technologies are often included, which means that these models include a description of the change in parameters as, e.g. fuel substitution options based on knowledge of the stage of development of new technologies. Bottom-up models in this indirectly way describe changes in parameters which in top-down models would be fuel substitution elasticities. Models based on the bottom-up approach can be either optimisation or simulation models.

Many bottom-up models include energy demand divided into end use demands, e.g. heating, lighting, ventilation, process, rather than divided into energy types. This reflects the view that developments in energy demand tend to depend more on the different purposes for which energy is made use of than on the specific energy type and the characteristics related to this type including the energy price.

Bottom-up models of household energy demand are typically based on vintage models of a large number of end use technologies. Penetration rates for each technology, e.g. electric appliances, are described as following a time profile with saturation levels. Sometimes penetration rates are just projected exogenously. Energy demand relations for bottom-up models of electricity demand in households could, e.g. be specified as

$$E = \sum_{s=1}^{n} \eta_s \sum_{i=t_0}^{t} B_{i,s}\, e_{i,s} \tag{1}$$

$B_{i,s}$, stock of appliance s, vintage i;

$e_{i,s}$, electricity consumption by each unit of appliance s, vintage i per unit of use; and

η_s, intensity of use for appliance s.

The stock of appliance s of vintage i at a given time t is given by

$$B_{i,s} = S_{i,s}(1 - a_{i,s})^{(t-i)} \tag{2}$$

where $1/a_{i,s}$ is average lifetime for the vintage of appliance s; and $S_{i,s}$ is the size (sales) of vintage i of appliance s. The development in the stock of appliances is assumed to be determined by penetration ratios for households (share of households which have a specific appliance). Penetration ratios could be specified to follow logistic functions, and in some cases parameters of these functions are estimated for each type of appliance. The logistic function implies that saturation levels exist. For example, it is natural to assume that a household would never have more than one washing machine. Normally assumptions about the development of penetration ratios exclude income and price effects on the stock of appliances. This may be modified by letting sales depend on income or prices. However, saturation levels would often be exogenous. Such modifications will be characterised as incorporating top-down elements into bottom-up models.

Top-down models are characterised by behavioural relations at an aggregated level with parameters estimated based on historical relationships. Both models are used that are developed specifically for analysing energy issues and models of a more general macroeconomic type. The models used for energy–economy modelling are based on different economic traditions and theories, both models with neo-classical and Keynesian origin exist. Also, there is a difference in the time spans covered by the models. The type of macroeconomic model used has a significant influence on the properties of the model including the results of analysing energy issues as, for example the costs of greenhouse gas mitigation.

Top-down specifications of energy demand in households could, for example be

$$E_j = e(p_i, p_j, aeei, C) \tag{3}$$

p_j, price of different energy types, electricity, district heating, natural gas, etc.;
p_i, price of other consumer goods or services;
aeei, autonomous energy efficiency improvement (indexed); and
C, total private consumption.

The different approaches reflected in the specifications of energy demand above are a consequence of different theoretical backgrounds and modelling practices. Bottom-up and top-down approaches are complementary in some respects. The autonomous energy efficiency improvement *aeei* is exogenous to the top-down model. When forecasting, the energy efficiency is projected to rise by an exogenous rate each year, which in different model studies range from a yearly efficiency improvement of 0.5 to 1.5%. In the bottom-up model the vintage effect through technology improvement for each new vintage of appliances could give a better description of energy efficiency developments. The longer the horizon the more inaccurate will be the estimate from the bottom-up model.

With regard to the effect of energy price changes, the two approaches are fundamentally different. The macroeconometric approach is based on estimation of historical relations between energy prices and energy demand and assumes that the behaviour reflected in the estimated elasticities is constant. The elasticities imply that to some extent electricity could be substituted by other energy forms and that an energy service to some extent could be substituted by other consumer goods or services. On the other hand, many bottom-up models of household energy demand do not include any response to fuel price changes at all. In bottom-up models it is, for example assumed that electricity cannot be substituted by other types of energy. For household heat demand it is assumed that consumers do not respond to higher energy prices by saving energy for heating. Savings depend instead on the public programmes for improving housing standards and the insulation standards for new dwellings.

For disaggregated studies of household energy demand, the macroeconometric approach leads to practical problems that arise in estimating fuel price elasticities. The estimation requires that time series of some length for energy prices and demands are available. These empirical data are not always at hand. For example, in the Danish case when natural gas was introduced for use in households, empirical data for estimating elasticities between natural gas and other types of energy were not present. Due to this lack of data the share of natural gas out of household energy demand will have to be put as an exogenous variable in the macroeconometric model. Furthermore, household energy demand is often regulated and dependent on public policies especially for natural gas and district heating. For example, the penetration of natural gas in households depends on public long-term decisions about expanding networks and making compulsory connections. The bottom-up model could be complementary in this case and used for describing the development of natural gas penetration.

There is a fundamental difference in the way household energy demand responds to income developments. Bottom-up models in general have no response to income developments; e.g. they consider housing area to be an exogenous explanation for heat service demand. For electricity, the penetration ratio for each appliance is assumed to follow a logistic function in time and thus there is no connection from income to the stock of each appliance. Top-down models include income effects measured by the total consumption C in Eq. (3) and often the long-term effect from income increases is to increase energy demand proportionally.

Bottom-up models calculate the costs of operating the energy system including discounting with a social discount rate. Changes of operating costs caused by alternations in the configuration of the energy system, for example with the purpose of reducing emissions, are included but the effects on the economy are not included. In contrast to this the top-down model would calculate the cost of emission reduction from the long-term loss in GDP or a change in welfare. This includes the indirect effects on the economy from alternations in the configuration of the energy system. The measures in the bottom-up and top-down approaches are based on different cost concepts, but they are often compared and this explains some of the controversies over cost of greenhouse gas mitigation.

The different approach includes other issues as whether knowledge of economical energy-saving options in industry can exist without implementation taking place (the so-called 'no regret options'). The difference often includes both divergent assumptions about behaviour in response to price changes and different assumptions about efficiency developments.

The differences described above have led to very different results for costs of reducing emissions. In IPCC (1996) the difference between the approaches and the consequences for costs has been treated in depth. As argued by Hourcade and Robinson (1996), both top-down and bottom-up models can be optimistic or pessimistic on costs. Bottom-up models tend to be optimistic on the technical cost, while top-down models are often more negative on this issue. Top-down models can be either optimistic or pessimistic regarding the existence of double dividends. The effect of double dividend in a top-down model could produce costs that are negative and in this way the top-down model could be more optimistic than some bottom-up models. The relative advantages of the two approaches for analyses in different fields could be summarised as:

Bottom-up

- regulation and detailed energy planning;
- restructuring of energy supply sector;
- using standards for housing insulation or electric appliances; and
- project the technological development in order to quantify the aggregated development in energy efficiency.

Top-down

- energy taxes;
- effect of different economic scenarios on energy and environment;
- macroeconomic consequences of changes in the energy system; and
- general equilibrium effects.

3. Integration principles

Integration implies choosing from a number of alternative integration principles which have both practical and theoretical implications for the properties of the integrated model. The options for integration can be grouped as:

- top-down;
- bottom-up; and
- mixed integration principle.

A top-down-based principle implies that energy demand is determined by relative prices, income or production and an exogenous energy efficiency. This energy efficiency is quantified from bottom-up calculations that are aggregated to the level of the macroeconomic model. This aggregate describes only the autonomous energy efficiency development. In this way the bottom-up principle applies only to quantifying an exogenous component in the macroeconomic relation. On integrating according to this principle no conflict appears with the top-down modelling approach. On the other hand, the controversy between bottom-up and top-down approaches over macroeconomic effects or costs of reducing greenhouse gases is not dealt with. Integration based on top-down principles with an exogenous energy efficiency ensures that the same basic assumptions regarding technological improvement are used in both model approaches. If the bottom-up energy efficiency is considered to be not only autonomous but a function of investments in production capacity or energy-saving equipment, problems of consistency will arise. How should investments from the bottom-up part be linked to the top-down specification of factor-inputs? The technological improvements in energy efficiency in bottom-up models could, for example initiate from a higher capital intensity and this could not be transferred to the macro model setup through exogenous efficiency parameters because it involves a re-specification of important relations in the macroeconomic model.

Bottom-up principles[3] used for integration mean that the macroeconomic specification of energy demand is replaced. The importance and possibility of doing this depend very much on the macroeconomic specification used. Replacing energy demand relations is likely to influence relations for total factor demand in producing sectors. Thus, in most macroeconomic specifications the relations for all factor-demand components must be revised and re-estimated. Apart from the practical problems connected to this re-specification and re-estimation, the link to the theoretical basis for the factor-demand specification might be weakened. Fig. 1 illustrates the aggregation problems for integrating according to bottom-up principles. The nested levels of determination in macroeconomic top-down models, where for example the factor inputs of energy, capital and labour are determined dependent on each other at an upper level, could imply problems for integrating a bottom-up determined energy input directly. According to a top-down principle the input of different types of energy is found by splitting the total energy input in a relation at a lower level.

Different aggregation levels of the basic relation that determines energy demand in the two approaches lead to problems in integrating the bottom-up modules of energy in the macroeconomic model. Bottom-up determined energy demand is seen as independent of other factor inputs and there is no simple way of adjusting these other factor inputs if the bottom-up relation yields a result other than the top-down relation. Bottom-up models could implicitly include a different substitution between electricity against capital and fuels for process against capital and this would be inconsistent with the assumption of the top-down relation.

The link to economic theory for the factor-demand relation is weakened if other factor inputs are merely adjusted in proportion to the adjustment in energy input. Another solution is to characterise the difference in energy input demand between

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[3] See Chandler (1994), for examples of links from economic variables to bottom-up models.

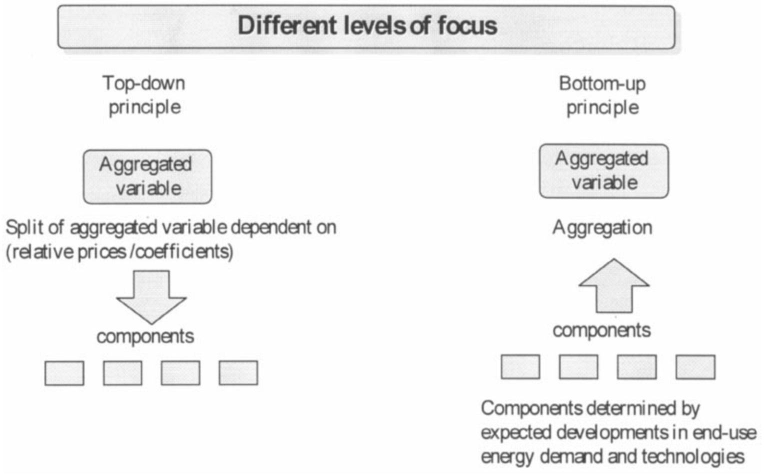

Fig. 1. Aggregation level for relations determining, e.g. energy demand.

the top-down and bottom-up models as an efficiency development. The top-down model determines the demand for input of energy services and the actual energy demand is found by adjusting for the development in energy efficiency.

A mixed principle for integration implies that:

- the theoretical basis for the macroeconomic structure and economic behavioural relations will be unaffected;
- adjustments in the macroeconomic setup can be limited to a few relations with energy content;
- price and production effects in energy demand will still be present though of reduced importance relative to a top-down based integration; and
- aggregation will differ even in the description of energy.

A combined model integrating the two approaches with both price and income effects in a bottom-up model and with linking of the energy supply sector to the rest of the economy will provide a better description of energy issues, policies and their consequences for the overall economy. Thus, a combined model will be able to analyse more complex issues incorporating both regulation of the energy supply sector and households along with energy tax policies including the interdependencies between the energy system and the economy.

Some studies have worked along this idea and integrated the approaches by linking bottom-up and top-down models. A widely used model of this kind is MARKAL-MACRO (Manne and Wene, 1992). This model is an integration of the bottom-up optimisation energy model MARKAL, which has been used for several years, and a specially designed MACRO model. Other integrated approaches for the energy supply sector include GLOBAL 2100 (Manne and Richels, 1992); in a long-term growth model this incorporates an optimisation between energy technologies, which are to be made available at some time in the future. The model for Denmark described below lies within this integration approach but involves other types of top-down and bottom-up models than the integrated models mentioned above.

Integration according to a mixed principle is used here as it creates the most flexible model structure and can be designed to minimise the re-specification and re-estimation work. Flexibility arises from the possibility of including bottom-up modules or excluding them, whereby the different effects from using bottom-up modelling or top-down modelling for elements of energy demand and supply can be examined. Different types of bottom-up modules linked to the top-down model can be compared as well. A mixed principle also allows concentrating on the important parts of energy demand and supply without having to change the top-down model specification in many areas, which could have made necessary a huge amount of re-estimation and reformulation work.

An important reason for choosing a mixed principle is that bottom-up modelling of energy demand is seen to be much more important and relevant for some parts of energy demand than for others. Top-down specifications are more inaccurate for sectors where technical energy parameters are very important for determining energy consumption and these parameters change at uneven rates, for example where the change occurs only by replacing long-lived production capacity or by adding new vintages of electric appliances.

4. Model description

The integrated model called Hybris[4] consists of the macroeconomic top-down model ADAM and three bottom-up energy modules. Integration of bottom-up and top-down elements is the result of a mixed principle. Links between the bottom-up modules and ADAM have been established and the system is run in an iterative procedure (Fig. 2).

Integration of the energy modules and ADAM was established through a number of links. Links have been identified from the top-down model, which means that the bottom-up modules have to aggregate or disaggregate variables to fit the specification of the macro model. The structure of the macroeconomic model ADAM was kept unchanged.

Bottom-up principles were applied to three specific bottom-up modules

- energy supply (electricity and heat);
- electricity demand in households; and
- heat demand in households.

The energy supply sector was chosen to follow bottom-up modelling practices

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[4] *Hyb*rid *I*ntegration *S*imulation model.

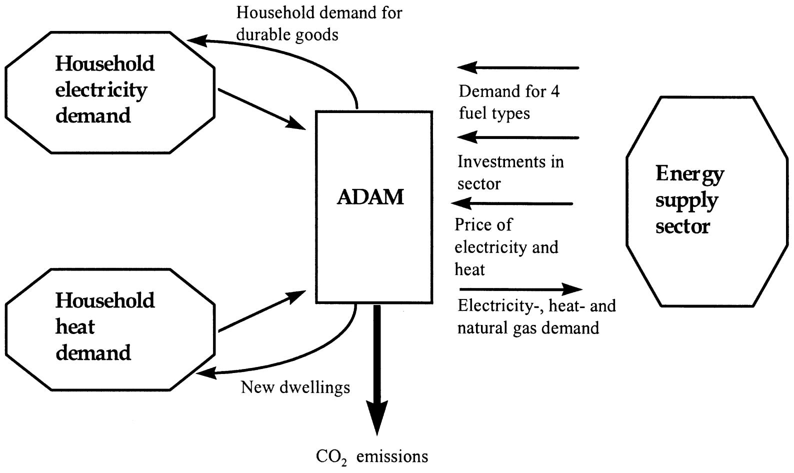

Fig. 2. Model structure in Hybris.

based on the importance of this sector for fuel demand and emissions in Denmark. More than 50% of CO_2 emissions in Denmark can be attributed to this sector. The long-term investment horizon, the detailed regulation and the limited number of production units also make this sector relevant for a bottom-up description. At the same time top-down modelling of the sector is very crude. In ADAM the sector is modelled with constant shares of two fuels: coal and fluid oil products that include natural gas. Thus, there is no fuel substitution in the energy supply sector in the basic ADAM model. In the bottom-up module price induced fuel substitution among four fuels: coal; fuel oil; natural gas; and biomass is very important and can create substantial changes in CO_2 emissions.

Electricity demand in households was chosen because it is one area of modelling where bottom-up modelling does not incorporate price or income effects. Price and income effects could be very interesting to incorporate in some of the exogenous developments of, e.g. appliance stocks. Household heat demand was found interesting for the same reasons as for electricity demand and because it constitutes the other part of the relevant consumption group in ADAM. Household heat demand is regulated in Denmark and related to the expansion of networks for district heating and natural gas. The household energy demand modules are also areas where bottom-up modules have a long tradition in Denmark and have been extensively used for energy planning.

The modules include economic behaviour, which is an important factor in determining the fuel demand in the module for electricity and heat but is much less important in the household modules. Household modules are linked to economic variables driving the sales of appliances and the total heated area. Integrating the bottom-up modules with ADAM was established by creating a number of approx. 100 linking variables and running ADAM and the modules in an iterative procedure. Linking variables include: energy demand; fuel prices; input coefficients; investments; tax revenues; stock variables; etc. Some of these are important variables determined in either the bottom-up modules or in ADAM, but others are chosen merely to ensure consistency between exogenous assumptions. The important links in Hybris are:

- electricity and heat prices;
- fuel demand in the energy supply sector;
- electricity and heat demands in households;
- electricity, heat and natural gas demands in the economy; and
- investments in electricity production capacity.

Electricity and heat prices are the most important for the effect of linking from the energy system to macroeconomic variables. Higher prices lead to increasing production costs for industry and a deteriorating competitive position in foreign markets. The major parts of macroeconomic consequences from changes in the energy system or energy prices can be referred to this link. Fuel demand influences the trade balance, but the size of fuel consumption changes in the energy supply sector is relatively small compared to other factors that influence the trade balance.

The energy supply sector in ADAM is replaced by the developed bottom-up module by transferring ADAM variables from the bottom-up module to exogenous variables in ADAM. This is possible, due to the flexible possibilities for exogenising relations in ADAM. In Fig. 3, links between ADAM and the energy supply sector are illustrated. Demands for electricity and heat are determined in ADAM, where household demand is indirectly determined in the two other energy modules.

It is the energy supply sector which is the most obvious sector to describe with a bottom-up model without constant fuel price elasticities. At the same time, it is relevant to include some fuel demand responses to fuel price changes. Short-term responses (within 1 year) will depend on the technology used in the production capacity at the time of price change, which could be very well-described in a bottom-up model that includes cost minimisation. Long-term fuel price effects depend both on the organisational structure of the energy supply sector as well as on vintage effects of existing capacity. Direct regulation of the sector could be the driving force for long-term fuel changes, but if the sector is moving towards deregulation the fuel price will become a more important parameter for long-term fuel demand changes.

The module developed for Hybris covering the energy supply sector is a bottom-up module as it includes a very detailed description of the major plants in Denmark with technical parameters for energy conversion efficiency, fuel substitution limits on individual plants, plant capacity, lifetime and co-generation parameters. Top-down elements represented by prices are also very important in determining fuel demand in this module. The energy supply module is in itself an example of integration of bottom-up and top-down approaches to energy–economy modelling.

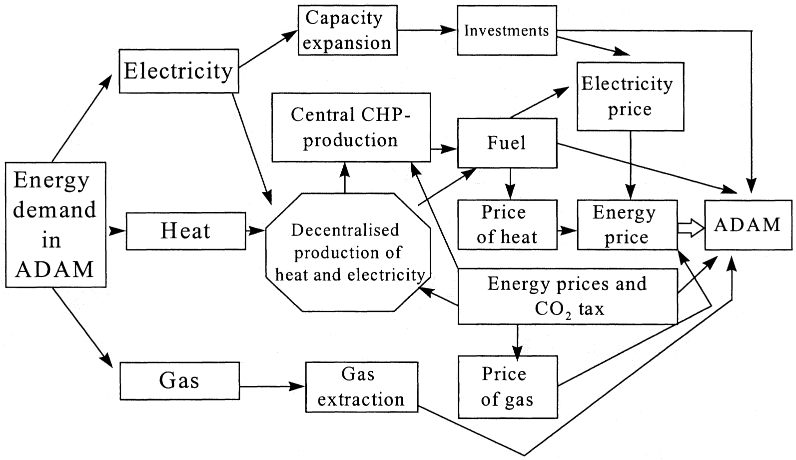

Fig. 3. Links between the economy and the energy supply sector.

Fuel input for electricity and heat production by the major combined heat and power plants in Denmark is found by minimising total fuel cost for these plants. Substitution between fuels within boundaries specified for each plant is allowed in minimising production cost. Fuel input to electricity and heat production is found by minimising total fuel cost for the joint production of electricity and heat by the 50 major power plants of Denmark, which are mainly combined heat and power plants. Substitution between fuels within technical constraints specified for each plant is allowed in minimising production cost. Fuel demand from each plant is found based on a duration curve for electricity demand. The duration curve for electricity is based on the assumption of 365 identical 24-h periods and use of a linear approximation. The duration curve illustrates the time in which electricity demand is at a certain level. Heat is assumed to be storable within the 24-h period to the extent necessary, and no duration curve for heat is applied here.

Plants are sorted according to marginal costs given the cost-minimising fuel mix on each plant. Thus, substitution between plants with different production cost takes place within limits given by the duration curve. The plants with the high marginal costs (fuel costs) will produce relatively less, but as long as the peak demand includes their capacity they will produce. Secondary units that are nearly 20% of production at present are treated as exogenous. An exogenous capacity projection and exogenous number of full load hours are used to calculate production. Expansion technologies for these plants are handled as exogenous but technical parameters change over time and the endogenous expansion of production capacity in large plants acquires the technical parameters given by the year they are built.

A detailed description of the electricity-pricing policy formation is included following the official guidelines given by Danish legislation. In principle, prices are given by average cost as the utilities are not allowed to generate surplus. Important and fluctuating parts of the cost determination for electricity prices are fuel costs and especially allowances on production capacity under construction. Fuel costs change as a consequence of substitution induced by fuel taxes and as new capacity includes options for using different fuels. The total investment cost of large power plants can be written off in only 5 years during construction where the physical lifetime tends to be 25–30 years. By this legislation Danish consumers directly and immediately pay for construction of new plants. This creates fluctuations in electricity prices with rising energy prices in the years prior to the introduction of new power plants and falling electricity prices following the introduction. The module includes an option to change the price relation towards short-term marginal cost pricing. Investments in electricity production capacity are calculated from the expansion of capacity and are linked to the investments of the energy supply sector of ADAM. Substitution possibilities are present in the existing Danish capacity primarily as an option for switching between coal and fuel oil and to some extent natural gas. The scenarios and their results reported later in this paper assume that future production capacity expansion is dominated by multi-fuel combined heat and power plants. This implies the possibility of substituting between using as much as 50% biomass in each new plant or almost 100% coal or fuel oil.

Household heat demand is described from a net heat demand per square meter heated area and new dwellings from ADAM increase the heated area. Thus, the income effect on household heat demand arises indirectly through the demand for new dwellings. The shares of heating technologies are projected according to official energy plans. Projected are the local efficiencies of different heating technologies, both technologies, such as natural gas and district heating as well as individual heating technologies, such as those based on electricity, biomass, coal and oil. In the module for household electricity demand a number of electrical appliances are described regarding electricity consumption and the coverage percentage (penetration ratio) in households of each appliance. The stock of appliances is derived from a proposed pattern of coverage development. The speed at which this development takes place is dependent on the activity of households in buying consumer durables, which is the important link to the economy in this bottom-up module.

5. Properties of the integrated model relative to bottom-up and top-down models

The properties of hybris are different compared to the bottom-up modules and ADAM, because Hybris includes the interactions between the models. This is especially seen for the strength of energy and emissions response to emission-reducing initiatives. Another result of integrating is that the effects of initiatives depend on which other initiatives are carried out at the same time. In many cases of experiments with Hybris this leads to less reduction than anticipated by analyses carried out with separate models and for separate initiatives. The most important properties originating from integration of top-down and bottom-up in Hybris include:

- The effect on electricity prices and electricity demand as a consequence of regulating fuel mix and capacity expansion technologies spill over to the energy demand in top-down relations.
- Changing macroeconomic conditions affect the energy system structure and feed back to the economy through changing energy prices and investments.
- Energy price elasticities are relatively low in top-down relations for industrial energy demand, very low in household energy demand and at some points very high for the energy supply sector.
- Economic costs of emission-reduction initiatives arise through price effects which are scarcely more than marginal when analysing taxes imposed on all energy use. Macroeconomic costs seem very moderate for all kinds of reduction initiatives.

Fuel price effects are more important in Hybris than in both the macroeconomic model ADAM itself and particularly in traditional bottom-up models, where price effects play a minor role. The increased price effect originates from the high degree of fuel substitutability in the energy supply module and is primarily connected to the choice of fuel inputs in electricity generation. The fuel price elasticity in this module is far from constant as is often the case in macroeconomic models. It is very hard to find econometrically reliable relations for fuel demands in the energy supply sector, which sometimes force macoeconomic models to exempt fuel substitution in the sector by distributing total fuel demand on fuel types by coefficients.

Economic growth is still the driving force behind the energy demand growth. An integrated model, such as Hybris could be expected to show that economic growth and energy consumption are only slightly connected. The actual interdependence between these variables in Hybris is very high as energy demand is growing roughly in line with the economy. Both household demand for electricity through the buying of durable consumer goods and household heat demand through the investment in housing area respond to changes in income.

Hybris is capable of analysing a long range of traditional bottom-up and top-down energy options in the same setup. The possibilities include:

Top-down

- effect of taxation on fuel inputs in the energy supply sector with constraints originating from the changing production structure; and
- the effect of economic growth on energy demand and the capacity structure of the energy supply sector.

Bottom-up

- regulation of fuel mix and capacity expansion in the energy supply sector; and
- effect of regulating energy use in new household appliances.

Hybris does not include substitution between different fuels in industrial demand. This reduces the effect on emission from CO_2 taxes compared to other top-down models. Fuel substitution in industry has been covered by a parallel project reported in Møller Andersen and Trier (1995). The transport energy demand has not been handled separately in Hybris, which means that it is the top-down description from ADAM that is included in Hybris. Obviously, a bottom-up approach with some saturation effect in the private car intensity of the population would yield different results. In Møller Andersen and Trier (1995) a thorough treatment of transport energy demand from both households and industry is carried out and top-down satellite models to ADAM are constructed but without feedback to the macroeconomy.

Emissions in Hybris are calculated from the macro model aggregation level with only three fuel types, which contributes to some inaccuracy in the calculation of total CO_2 emissions. This is a consequence of the different aggregation of energy demand in different parts of Hybris, which is caused by the mixed integration principle. Calculations of emissions have to be performed at the least disaggregated level for fuels that is found in Hybris. The model setup is designed to be run with or without the bottom-up modules for electricity and heat demand in households. In this way different properties of the bottom-up descriptions of households and the corresponding description in the top-down specification can be analysed. The main results from including the bottom-up modules for household electricity and heat demand are:

- CO_2 tax effects on emissions are moderated when bottom-up modules which have very low price elasticity are included; and
- the high income elasticity in the top-down specification of household energy demand is moderated as bottom-up modules describe how coverage of electricity-intensive appliances reach saturation.

6. Combining initiatives to reduce CO_2 emission

An integrated model, such as Hybris takes explicit account of the interactions between regulations of the energy supply sector, e.g. restricting new capacity to a specific fuel mix and the related change in demand for electricity due to the resulting price changes. Combined initiatives were analysed using Hybris, and the effect on energy demand was less than the effect that was found by adding up emission effects from the respective initiatives and models. A CO_2 tax, regulation of fuel demand in the energy supply sector and regulations of household and industry energy demand were analysed in a combined scenario using the Hybris model. Results from Hybris of separate initiatives to reduce emissions and the combined initiatives are shown in Table 1.

Some characteristics of the interactions in the combined scenario were:

- energy taxes had the full effect in industry energy demand, but the substitution

Table 1
CO_2 emission reduction from different initiatives

Analysed initiative	5 years (%)	10 years (%)	15 years (%)	25 years (%)
(a) CO_2 tax	7.3	3.8	8.9	13.9
(b) Regulation of electricity production	1.3	1.5	2.6	7.6
(c) Demand side regulation	5.3	7.6	10.3	15.9
(a) and (b)	8.2	5.6	10.9	15.6
(a), (b) and (c)	11.9	12.5	17.7	27.4

effect in the energy supply sector was less than if there had been no regulation on fuel mix; and

- the effect of reducing household energy demand if electricity and heat production were already cleaner was less than in the base case for electricity and heat production.

The different categories of reduction initiatives represented in Table 1 are very dependent on each other. A CO_2 tax incentive in (a) is the typical option analysed in a top-down model setup, where (b) and (c) are options which are analysed in bottom-up energy models. The initiatives examined in Table 1 are:

(a) A CO_2 tax on all applications rising from 200 DKK/ton of CO_2 initially to approx. 400 DKK/ton in 25 years.
(b) The electricity production sector was restricted to using biomass and natural gas on the production plants that were technically able to substitute. Wind energy was expanded further.
(c) Demand side regulation including norms for the maximum electricity consumption of household appliances for sale.

The combined effect of (a) and (b) is only slightly smaller than the sum of (a) and (b) up to 15 years. At 25 years horizon the marginal effect of (b) is less than one-quarter. As option (c) is added to the calculation of a combined initiative the marginal reduction effect is less than three-quarters of the effect of option (c) alone. CO_2 reduction initiatives should not be analysed without considering other reduction policies, as the interdependencies between policies are quite significant as seen in Table 1. It is noticeable that traditional top-down and bottom-up initiatives in this integrated model are dependent on each other, but they do not fully offset the effect of one upon the other.

In Fig. 4 the emission effect of the combined initiative (a), (b) and (c) is shown. The peculiar time profile is caused by the technical constraints in the electricity production system and substitution between fuels on existing capacity. The fuel substitution possibilities are increased as old electricity and heat production

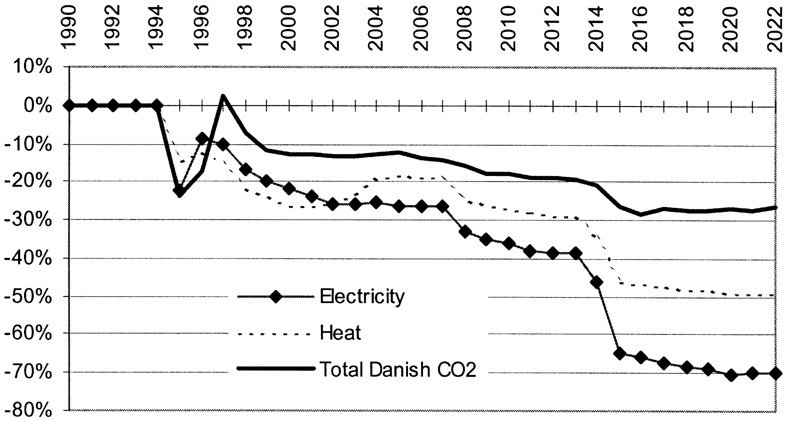

Fig. 4. CO_2 emission reduction by a combined initiative.

capacity is replaced with flexible multi-fuel plants. The first reduction in emission to be seen in the graph occurred when coal was replaced by fuel oil and natural gas. A few years later the relative fuel price movements induced a shift back to coal from fuel oil. In the long run the CO_2 tax and restriction on technology for new production capacity led to a shift towards renewable energy sources especially biomass. The reduction in emissions from end use energy demand was much more stable than the emission effect from electricity and heat production.

In the Hybris model the emission reduction possibilities in the energy supply sector are very great seen from the point of the present situation in the sector. With the given development in world fuel prices the emission reduction in the sector could be reached with a moderate CO_2 tax and regulation of the technologies with which the production capacity is expanded. Further reduction in this sector is not possible without expanding renewable technologies even further or replacing plants within their remaining physical lifetime. This conclusion is based on the technologies available in this scenario which consisted only of proven electricity production technologies with a constant yearly improvement in technological parameters.

7. Concluding remarks

The purpose of this study was to integrate bottom-up and top-down approaches to energy–economy modelling by linking models for Denmark based on these approaches. This study shows that a model integration is possible where most of the characteristics and possibilities of bottom-up and top-down models are included. A mixed principle for integration which was used here could lead to a weakening of the degree to which relations are theoretically founded. However, with the macroeconomic model used in our case (ADAM) the linking and replacement by bottom-up specifications influenced the macroeconomic theoretical basis only slightly.

The properties of the linked model include wide possibilities for analysing very different options for reducing energy consumption and emissions. Options included in traditional bottom-up and top-down models could be analysed in our linked model taking into account the interactions between energy and economy and the different initiatives. The most important links between the energy supply sector and the macroeconomy were found to be the price of electricity and heat, and to some extent the investments in the energy supply sector.

The relative unproblematic integration of top-down and bottom-up models in our case relies on both the integration principle chosen and the respective models which have been integrated. It was chosen to integrate approaches in the most unproblematic fields by introducing bottom-up modelling of energy demand for: the energy supply sector, household heat demand and household demand for electricity. Furthermore, it is worth noting that the different reduction initiatives analysed here do not seem to be complementary between bottom-up and top-down initiatives but there exist important interdependencies between them leading to lower marginal effects of the initiatives if combined. At the same time, the emission reduction effect of individual initiatives evaluated in an integrated model, such as Hybris are larger than the effect found in separate top-down and bottom-up models.

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