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Published in:
Energy

Link to article, DOI:
10.1016/j.energy.2018.11.153

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

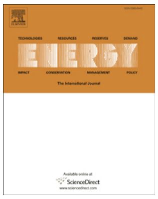
Citation (APA):
Andersen, K. S., Termansen, L. B., Gargiulo, M., & Ó Gallachóirc, B. P. (2019). Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models. Energy, 169, 277-293. DOI: 10.1016/j.energy.2018.11.153

Energy 169 (2019) 277–293

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models

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ARTICLE INFO

Article history:
Received 3 April 2018
Received in revised form
28 November 2018
Accepted 30 November 2018
Available online 6 December 2018

Keywords:
Bottom-up
Top-down
Hybrid modelling
Energy service demand
Mixed complementarity
Carbon capture and storage

ABSTRACT

Giving policy advice related to climate mitigation requires insights that take both sectoral and technology effects (and their interactions) into account. This paper develops a novel soft-linking method for bridging the gap between sectoral top-down and technology rich bottom-up models. A unique feature of the approach is the explicit modelling of energy service demand in the top-down model, which creates a direct correspondence to the energy service production in the bottom-up model. This correspondence allows us, unlike previous work, to capture the macroeconomic impact of energy system investment flows. The paper illustrates the full-scale application of the method in the Danish IntERACT model, considering the unilateral introduction of coal carbon capture and storage in the Danish concrete sector. The policy leads to a reduction in the Danish concrete production, and in turn, a carbon leakage effect of 88%. Results also underscores the importance of accounting for the macroeconomic impact of energy system investment flows, as this is the source of approximately half of the policy-induced reduction in macroeconomic activity.

1. Introduction

The global commitment to keep climate change well below 2° requires large-scale replacement of fossil-based technologies across all sectors. Energy intensive industries (e.g. cement production) will likely have to make costly investments in abatement technologies (e.g. carbon capture and storage (CCS)); while mitigation policies will likely affect other sectors (e.g. service industries) to a lesser degree. In turn, these adverse effects will reverberate through the economy, affecting energy use, capital demand, trade flows and economic activity. Decision makers, most of whom operate at a national level, need clear and consistent insight on these climate policy impacts [1]. Insight, that take both sectoral and technology effects (and their interactions) into account. This calls for the development of comprehensive modelling frameworks capable of bridging the gap between bottom-up and top-down modelling [2]. Bottom-up and top-down modelling being the two main approaches used for climate mitigation analysis [3].

The term bottom-up refer to the focus on the detailed analysis of energy technologies and the associated investment options [4]. Bottom-up models are typically casted as optimization problems [5], which define the cost minimizing set of technologies needed to satisfy a given demand for energy services.[1] This type of bottom-up approach is criticized for the lack of behavioural realism [6] as competing technologies are treated as perfect substitutes. This leads to the default property of "winner-takes-all", whereby the cheapest technology captures the whole market. Bottom-up models are generally also lacking in terms of endogenous market

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[1] An energy service is the combination of energy and other inputs (mainly capital, e.g. boiler technology and insulation) that produces a desired service (e.g. comfortable room temperature).

https://doi.org/10.1016/j.energy.2018.11.153

Nomenclature

Abbreviations

CGE	Computable General Equilibrium
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
GDP	Gross domestic product
KKT	Karush–Kuhn–Tucker
LP	Linear programming
MCP	Mixed complementarity problem

Stylised top-down variable

P_X	Price of other commodity (including fuels)
P_Y	Price of energy service
P_K	Price of capital
P_W	Price index for welfare
W	Utility level
X	Production level of other goods (including fuels) sector
Y	Production level of heat service sector
I	Income of representative household
K	Capital endowment
τ	Heat service price wedge

Stylised bottom-up indices

i	Technology
j	Season

Stylised bottom-up variables

$x_{i,j}$	Fuel input and energy service output from technology i in season j
k_i	Installed capacity of technology i
λ_i	Shadow price of seasonal demand of heat service
$\mu_{i,j}$	Shadow price of capacity of technology i in season j

Stylised bottom-up parameters

C_i^X	Cost of fuel input for heat service production
C_i^k	Cost of capacity of technology i
d_j^k	Capacity demand in season j
h_j	Hours per season j

Additional soft linking parameters

$\overline{Y}$	Production level of heat service sector from last top-down model iteration
$\overline{P}_X$	Price level of other commodities from last top-down model iteration
$\overline{P}_K$	Price level of capital from last top-down model iteration
$\overline{\lambda}_j$	Benchmark shadow price of seasonal demand of heat service
$\overline{\Lambda}$	Relative change in consumption weighted price of heat service from last bottom-up model iteration
$\overline{X_{BU}}$	Total quantity input (in monetary terms) of other commodity into heat service production from last bottom-up model iteration
$\overline{k_{BU}}$	Total quantity input (in monetary terms) of capital into heat service production from last bottom-up model iteration
$\overline{Cost_{BU}}$	Total cost of heat service production from last bottom-up model iteration

adjustments [5], e.g. due their deficiency in terms of demand response[2] and as they do not capture the macroeconomic effects of energy system investment demand. The latter is a major deficiency, if climate mitigation policies leads to substantial increases in investments across the energy system [7].

Top-down refers to models that use macroeconomic data to determine the development of energy prices and demands [4]. The top-down modelling of energy-economy policies has been dominated by computable general equilibrium (CGE) models [6]. CGE models represent the interactions of different economic sectors (e.g. firms, households and government) based on a consistent microeconomic behavioural framework. The aim of CGE models is to explain the behaviour of supply, demand and relative prices in the whole economy covering many markets (e.g., capital, labour, materials/services and energy). Nevertheless, the treatment of energy demand and supply is typically highly aggregated and lacks in technological details. The traditional CGE models have therefore proven ineffective in assessing technology policies [3]. A related barrier that reduces the usefulness of CGE models is the reliance on historic data to determine fuel use far into the future [6]. While another critique centres on the possible misspecification of the energy demand equations used in top-down models [8]. This misspecification arise as top-down models tend to neglect that fuel consumption is a derived demand, i.e. that fuels are not required for their own sake but for the energy services they produce (e.g. comfortable room temperature or high temperature process heat). An extension of this point relates to heterogeneity of energy service demand, which is difficult to capture within a top-down approach. Cement production, for example, requires a carbon based fuel to satisfy high temperature process energy service needs, whereas the sector's demand for room heat services could potentially be fully electrified (using heat pumps technology).

Recent decades has seen a diverse effort to combine elements of the top-down and bottom-up approach into so-called hybrid models [6]. Böhringer and Rutherford [5] divide this effort into three typologies: 1) Reduced form, focus either on the top-down or bottom-up model while using a simplified representations of the other; 2) Integrated, use mixed complementarity problem (MCP) format to integrate bottom-up technological details fully into the top-down approach, and; 3) Soft-link, link independent top-down and bottom-up models.

A common reduced form approach is to couple a bottom-up energy system model with an aggregate one-sector representation of macro-economic production and consumption in a single optimization framework [5]. Two examples are the ETA-Macro model and the MARKAL-Macro model [9]. The ETA-Macro models has been used to access the impact of banning additional nuclear power plants in USA [10]. Whereas the MARKAL-Macro model has been applied in a UK context to study long term carbon reduction scenarios [11]. Other reduced form approaches, such as the WITCH model [12], rely on a simplified energy system model representation within a top-down model to determine optimal regional long

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[2] A number of studies have incorporated demand responses into bottom-up models based on own-price elasticities of energy service demand (e.g., Ref. [1]). However, this type of demand response does not consistently capture complex sectoral effects (e.g. income and cross-sectoral effects).

term carbon reduction scenarios. Overall, reduced from approach is useful when addressing the global picture for which regional details are less important [2]. However, within a national policy setting, reduced form is less useful because it by default leaves out either sectoral or technological details.

The integrated MCP approach has been successfully applied to the study of renewable energy promotion in Europe [13]. To study the cost of limiting CO2 emissions through carbon taxes on electricity generation [14]. And to model intermittent renewable energy production in a general equilibrium model covering USA [15]. The focus on a single sector in these studies reflect that dimensionality may limit the scope for integrating more than one sector. In part because the MCP format typically leads to a doubling of the number of equations and thereby increases the scope for errors in model specification [16].

To address some of the limitations of the integrated approach, Böhringer and Rutherford [16] outline a soft linking approach based on the MCP format. This approach has been used to study the electricity generation decision (e.g., Ref. [17]). Soft linking involves exchanging data between independent top-down and bottom-up models, often in an iterative loop to ensure convergence between the models (e.g., Ref. [18]).[3] Soft linking has the advantage of offering transparency in the effect chain, as both models are kept complete, while complexity and running time are generally manageable [19]. Furthermore, from a national policy perspective, the advantage of soft linking is the potential for addressing complex energy and climate policy issues, within a detailed representation of both technical and sectoral effect [2].

A number of studies soft-link top-down and bottom-up models for climate policy analysis focus on linking a single sector. Martinsen [19] focuses on linking the electricity sector in Norway. Schäfer and Jacoby considers the transport sector in global context [20]. Drouet et al. [21] centres on the residential sector in Switzerland. However, in recent years a growing number of national soft-linking studies rely on what Fortes et al. [1] have termed a ‘full-link’ and ‘full-form’ approach. Full-link focuses on more than one economic sector, while full form combines extensive technology data and disaggregated economic structure.

Dai et al. [22] employ a full-form and full-link soft-linking strategy to determine a baseline for China's CO2 emissions for multiple sectors. Fortes et al. [1] demonstrate the ability of their ‘full-form’ ‘full link’ soft-linking strategy to evaluate climate mitigation policies for Portugal. While Krook-Riekkola et al. [2] discuss a full-form and full-link soft-linking approach for evaluating a climate policy scenario for Sweden. With minor variation, all these three studies use an energy system bottom-up model (based on the TIMES modelling framework [23]) to inform a national CGE model on how sectoral fuel mix and fuel efficiency changes over time, while the CGE model determines the sectoral energy service demands drivers used in the bottom-up energy system optimization.

Based on their high level of sectoral and technological detail and their focus on evaluating climate mitigation policy, Fortes et al. [1] and Krook-Riekkola et al. [2] represent current best practice in terms of applying soft-linking strategy within a national climate and energy policy context. Nonetheless, Krook-Riekkola et al. [2] identify two concerns, which apply equally well to both studies. First, neither study formally account for the macroeconomic impact of changes in investment demand associated with sectoral energy service demand (although Krook-Riekkola et al. [2] implicitly account for capital adjustment in the electricity generation sector in the CGE model). This omission creates uncertainty, as to whether the soft linking approach offers a complete picture of the cost of climate mitigation policy. The second concern relates to the overall consistency across models. Both studies rely on existing top-down and bottom-up models for their soft linking strategy. This is a source of inconsistency because sector definitions and energy supply/demand structure differ across models. This model heterogeneity complicates the linking and necessitates the use of translation modules between the top-down and bottom-up. For example, since the CGE models (in these studies) do not explicitly model energy services, an intermediate module translates sector production activity (from the CGE model) into the energy demand drivers (used in the bottom-up model). The lack of consistency is also reflected in that full convergence was not achieved by Krook-Riekkola et al. [2].

This paper describes a novel soft linking method for bridging the gap between top-down and bottom-up models. The method was developed as part of the IntERACT model, a comprehensive modelling framework for evaluating Danish energy and climate policies. The choice of a soft-link approach facilitates a detailed modelling of both sectoral and technology effects, while ensuring transparency in the effect chain. Unlike other national soft linking approaches, which typically rely on already existing top-down and bottom-up models, the top-down and bottom-up model (constituting the IntERACT model) was built from scratch. This has made it possible to create a highly consistent parallel structure between the top-down and a bottom-up model. A novel feature of the parallel structure is the explicit modelling of energy service demands in the top-down model. The consistency of the soft linking approach ensures full convergence between the top-down and bottom-up model, while it also avoids the need for intermediate translation modules. Finally, the soft linking method captures the macroeconomic impact of investment flows associated with the sectoral demand for energy services. Although the literature recognised the importance of this issue (e.g., Ref. [7]). The novelty of this paper is that it actually provides a comprehensive assessment of the macroeconomic impact of investment flows associated with a sector and technology specific climate mitigation policy. The remainder of this paper is organised as follows. Section 2 develops our soft linking method within a stylised setting. Section 3 discusses the full-scale implementation of the soft linking method in the IntERACT model. Section 4 considers a technology and sector-specific policy experiment using IntERACT - the mandated use of coal carbon capture and storage (CCS) technology in the Danish concrete sector. Section 5 concludes.

2. Materials and methods

A hybrid model should allow for the integration of bottom-up activity analysis into the top-down representation of the broader economy [5]; defining activity analysis as the modelling of alternative technologies producing one or more products subject to process-oriented capacity constraints. Hybrid modelling can be facilitated by formulating the top-down model as a mixed complementarity problem [24]. “Mixed” reflects the property that the problem consists of equations and inequalities, while “complementarity” mirrors the property that each equation/inequality is associated with a particular unknown. Say in the case where an inequality is in strict equilibrium (e.g. an unprofitable production technique) the associated complementary variable (production activity) will be zero.

Böhringer and Rutherford [5] highlight how it is possible to integrate the properties of a bottom-up approach fully into a top-down CGE model based on the MCP format. The method rely on

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[3] Studies that rely on a one-direction soft-link also exists (e.g., Ref. [35]). However, one-directional soft-link approaches may well be suffering from a degree of inconsistency, as this approach does not secure convergence between top-down and bottom-up model results.

the equivalence between the Karush–Kuhn–Tucker (KKT) conditions of a bottom-up linear programming (LP) problem and optimality conditions of a CGE model, i.e. an equivalence between the shadow prices of the LP constraints and market prices of the CGE model. However, large scale implementation of the integrated approach is limited by issues of dimensionality and complexity [16]. Dimensionality, related to the increase in number of equations in the top-down model, and complexity associated with the use of bounds on many decision variables in full-scale LP models. Bounds often introduced to avoid the "winner-takes-all" property of the optimization problem (see Section 2.4.2. for a detailed discussion).

Böhringer and Rutherford [16] suggest an alternative MCP approach, which overcomes the issues of complexity and dimensionality by soft linking a CGE model with a quadratic programming bottom-up model. However, their bottom-up model only covers a single sector (electricity generation sector) and hence does not provide guidance on soft linking multiple industry sectors consistently between a top-down and a bottom-up model. To provide such guidance, this section instead show how it is possible to decompose the integrated approach [5] into an equally consistent soft-linking strategy designed for full-scale implementation. The relevance of this strategy is underlined by its compatibility with existing bottom-up optimisation frameworks, such as the TIMES modelling framework used in more than 70 countries [25].

This section follows the approach taken in Böhringer and Rutherford [5], illustrating how it is possible to integrate a stylised bottom-up model into a stylised top-down model formulation. However, extending the scope relative to Böhringer and Rutherford [5] by dividing the year into time-slices; as this is an essential part of energy system modelling, needed to capture seasonal demand variation or the intermittency of renewable energy production. The section then decompose the integrated approach into equally consistent soft linking strategies (soft linking based on either full or partial information exchange). Finally, the section concludes that iterative soft linking using partial information exchange and average cost pricing is superior in terms of full-scale implementation.

2.1. Stylised top-down approach

The stylised top-down model is specified as a non-linear programming problem in terms of zero profit, market clearance and income constraints using common CGE MCP practice (e.g., Ref. [26]). The model describes a closed economy with two sectors, one factor input (capital) and one representative household. Each sector produces one good, heat service, and a good representing all other goods (including fuels used for heat service production). Table 1 provides stylised data on benchmark prices and the benchmark quantity flows used to calibrate the stylised top-down model. A positive record in the social accounting matrix part of Table 1 implies a sale in a particular market, while a negative record implies a purchase. The household receives income from their capital endowment and divides the income between the purchase of heat service and "other goods" to produce utility.

A Cobb-Douglas-function[4] describes both the production technology of the "other goods" sector and the household utility function. Whereas a Leontief function describes the production of heat service, i.e. heat service is produced using fixed relative proportions of capital and "other goods" commodity based on input shares from the social accounting matrix. The choice of Leontief function echoes the reliance of top-down models on historic data for determining production technology and input use. The ensuing paragraphs introduces the zero profit and market clearance conditions, focusing on the heat service supply and demand. This narrow focus reflects that the main contribution of this section is to show, how different hybrid modelling strategies changes the modelling of heat services in the stylised top-down model.

The market clearance conditions dictate that supply must be greater than or equal to market demand for each commodity. Only if demand equals supply does the commodity command a positive price (the complementary variable). Equation (1) describes the market clearance condition for heat service in the stylised top-down model. Derived from microeconomic theory, the two terms on the left hand side reflects respectively the Hicksian demand for heat service by the household and the conditional heat service demand by the "other goods" sector based on the Cobb-Douglas function. The stylised top-down model is calibrated to replicate the benchmark social accounting matrix (Table 1) using calibrated share form [26], which means that activity indices (W, X and Y) will be equal to unity in the benchmark solution.

$$\underbrace{5\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_Y}}_{\text{household demand for for heat service}} + \underbrace{5\cdot X\cdot\frac{P_K^{0.95}\cdot P_Y^{0.05}}{P_Y}}_{\text{other good sector demand for heat serivce}} \le \underbrace{10\cdot Y}_{\text{heat service supply}}, \quad \underbrace{P_Y}_{\text{complementary variable}} \qquad P_K, P_X, P_Y, W, X, Y \ge 0 \tag{1}$$

The zero profit conditions of top-down models dictate that unit cost of each sectoral production process must be at least as great as unit revenue. If unit cost exceeds unit revenue, then the activity level (the complementary variable) will be zero. Equation (2) displays the zero profit condition related to the Leontief heat service production of the stylised top-down model. The left hand side represents unit cost of production (weighted by benchmark input flows of capital and "other goods" commodity), whereas the right hand side represents unit revenue (weighted by benchmark production).

Table 1
Prices and quantities in the benchmark equilibrium.

Prices $P_X = P_Y = P_K = P_W = 1$			
Social accounting matrix (million euro)			
	Other goods, (X)	Heat service, (Y)	Household (RA)
Other goods (X)	100	−5	**−95**
Heat service (Y)	−5	10	**−5**
Capital (K)	−95	−5	**100**

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[4] Constant-elasticity-of-substitution (CES) function with a input substitution elasticity of one.

$$\underbrace{5\cdot P_K + 5\cdot P_X}_{heat\ \ service\ \ unit\ \ cost} \quad \geq \quad \underbrace{10\cdot P_{Y,}}_{heat\ \ service\ \ unit\ \ revenue} \quad \underbrace{Y}_{complementary\ \ variable} \tag{2}$$

See Appendix A for an overview of all equations and complementary variables describing the stylised top-down model. Appendix A also displays the complete top-down formulation for the three subsequent stylised hybrid-modelling strategies.

2.1.1. Stylised bottom-up approach

The stylised bottom-up model is a LP problem, which determines the least-cost solution to satisfy seasonal demands for heat service. The problem includes three technologies (i) and two seasons (j). Equations (3)–(5) describes the objective function and constraints:

$$minCost_{BU} = \underbrace{min\overline{P}_X\cdot\sum_i\sum_j c_i^x\cdot x_{i,j} + \overline{P}_K\cdot\sum_i c_i^k\cdot k_i}_{minimise\ \ total\ \ cost} \tag{3}$$

$$\underbrace{\sum_i x_{i,j} \geq d_j^k\cdot h_j\cdot\overline{Y}}_{seasonal\ \ demand\ \ constraint} \qquad \underbrace{\lambda_j}_{complementary\ \ variable:} \tag{4}$$

$$\underbrace{k_i\cdot h_j \geq x_{i,j}}_{seasonal\ \ technology\ \ capacity\ \ constraint} \qquad \underbrace{\mu_{i,j}}_{complementary\ \ variable} \tag{5}$$

$$x_{i,j}, k_i, \lambda_j, \mu_{i,j} \geq 0;$$
$$\forall\ i \in [Biomass\ boiler, Oil\ boiler, Heatpump];\ \forall j \in [summer, winter]$$

whereas Equations (6)–(8) describes the dual (surplus maximization) problem associated with the bottom-up model:

$$\underbrace{\max\sum_j \lambda_j\cdot d_j^k\cdot h_j\cdot\overline{Y},}_{\text{maximise surplus}} \tag{6}$$

$$\underbrace{\overline{P_X}\cdot c_i^x + \mu_{i,j} \geq \lambda_j}_{optimal\ fuel\ constraint} \qquad \underbrace{x_{i,j}}_{\text{complementary variable}} \tag{7}$$

$$\underbrace{\overline{P_K}\cdot c_i^k \geq \sum_j \mu_{i,j}\cdot h_j}_{optimal\ \ techology\ \ capacity\ \ constraint} \qquad \underbrace{k_i}_{\text{complementary variable}} \tag{8}$$

The upper bars over $\overline{Y}, \overline{P_X}$and $\overline{P_K}$indicate that these parameters are exogenous to the bottom-up model as they capture general equilibrium conditions related to demand for heat service and input price levels. Initially, these parameters are equal to one reflecting the benchmark activity and price levels in the top-down model. Derived from the four optimization constraints, equations (2), (3), (5) and (6), the four KKT conditions characterizing the optimality of this linear program are given by equations (9)–(12):

$$\sum_i \boldsymbol{x_{i,j}} \geq \mathbf{d_j^k}\cdot\mathbf{h_j}\cdot\overline{\mathbf{Y}}, \quad \lambda_j \geq 0, \quad \lambda_j\cdot\left(\sum_i \boldsymbol{x_{i,j}} \geq \mathbf{d_j^k}\cdot\mathbf{h_j}\cdot\overline{\mathbf{Y}}\right) = 0 \tag{9}$$

$$\boldsymbol{k_i}\cdot\mathbf{h_j} \geq \boldsymbol{x_{i,j}}, \quad \mu_{i,j} \geq 0, \quad \mu_{i,j}\cdot(\boldsymbol{k_i}\cdot\mathbf{h_j} \geq \boldsymbol{x_{i,j}}) = 0 \tag{10}$$

$$\overline{\mathbf{P_X}}\cdot\mathbf{c_i^x} + \mu_{i,j} \geq \lambda_j \quad \boldsymbol{x_{i,j}} \geq 0 \quad \boldsymbol{x_{i,j}}\cdot\left(\overline{\mathbf{P_X}}\cdot\mathbf{c_i^x} + \mu_{i,j} \geq \lambda_j\right) = 0 \tag{11}$$

$$\overline{\mathbf{P_K}}\cdot\mathbf{c_i^k} \geq \sum_j \mu_{i,j}\cdot\mathbf{h_j}, \quad \boldsymbol{k_i} \geq 0, \quad \boldsymbol{k_i}\cdot\left(\overline{\mathbf{P_K}}\cdot\mathbf{c_i^k} \geq \sum_j \mu_{i,j}\cdot\mathbf{h_j}\right) = 0 \tag{12}$$

Two additional steps ensure that the benchmark solution to the bottom-up model is consistent with the top-down model's benchmark solution. First step defines a correspondence between capacity cost in the bottom-up model and capital cost in the top-down model; and a correspondence between fuel cost in the bottom-up model and "other goods" cost in the top-down model. The second step specifies the demand and technology parameters (d_j^k, h_j, $c_j^x$and c_j^k) such that the benchmark solution to the LP problem match the benchmark monetary flows of energy service production in the top-down model, i.e. the social accounting matrix (Table 1).

Based on the parameter values in Tables 2 and 3 the solution to the LP problem involves a capacity of 2.5 MW of oil boiler and 2.5 MW of heat pumps. Oil boilers and heat pumps each deliver 12500 MW h in the winter, while heat pumps deliver additionally 7500 MW h in the summer. The total benchmark cost of heat service production in the bottom-up model will be €10 million divided between €5 million in fuel costs and €5 million in capacity costs.

2.2. Integrating stylised top-down and bottom-up model into one

The integrated model incorporates the four KKT conditions from the bottom-up model into the top-down model, i.e. adding seasonal and technology-specific market clearance conditions (equations 9 and 10) and zero profit conditions (equations 11 and 12) for fuel and capacity demand to the heat service sector.

The seasonal market clearance condition (equation (9)) requires that the seasonal supply of heat service (summing over technologies) is greater or equal to demand. Only if supply is equal to demand does a non-zero seasonal heat service price exist. Whereas the market clearance condition for technology-specific capacity (equation (10)) requires the seasonal supply of capacity to be equal to demand for capacity if the technology-specific capacity is to command a non-zero seasonal price.

The zero profit condition for fuel use (equation (11)) implies that the marginal cost of fuel input must be at least as great as the marginal revenue. When marginal cost exceeds marginal revenue then the activity level (the complementary variable) must be zero. The same interpretation applies to the zero profit condition for technology capacity (equation (12)), i.e. the marginal cost of heat

Table 2
Bottom-up demand profile.

Description	Parameter	Summer	Winter
Effect demanded (MW)	$\mathbf{d_j^k}$	2.5	5.0
Hours per season	$\mathbf{h_j}$	3000	5000
Total heat demand (MWh)	$(\mathbf{d_j^k}\cdot\mathbf{h_j})$	7500	25000

Table 3
Technology parameters.

Description	Parameter	Biomass boiler	Oil boiler	Heat pump
Capacity cost (€/MW)	$\mathbf{c_i^k}$	1200000	750000	1250000
Energy input cost (€/MWh)	$\mathbf{c_i^x}$	220	208	120

service production for a given technology must be equal to its marginal revenue if the technology activity is to be non-zero.

The integrated approach further requires the modification of the zero profit condition related to heat service production (equation (2)). Modifying Equation (2) ensures zero profit when transforming seasonal heat service production to an annual heat service demand commodity. The left hand side of equation (13) reflects annual consumption weighted heat service costs, whereas the right hand side reflects annual heat service revenue.

$$\sum_j \left[d_j^k \cdot h_j \cdot \lambda_j \right] \geq 10 \cdot P_Y, \qquad \underbrace{Y}_{\textbf{complementary variable}} \tag{13}$$

In addition, market clearance conditions for capital and "other goods" is updated to reflect input of these goods into heat service production. Appendix A gives a complete outline of the move from the stylised top-down approach to the integrated approach.

2.2.1. Policy experiment: banning oil boilers

Now consider the technology specific policy of banning oil boilers to achieve a climate policy target. Table 4 shows the solution to the bottom-up model and the integrated model when imposing such policy.

The bottom-up model lacks demand response, which means that banning oil boilers simply leads to a one-to-one replacement of oil boiler capacity with heat pump capacity. Total cost of heat service production increases by €0.2 million due to additional capital cost and the lower utilisation rate of heat pump capacity in the policy scenario. Consequently, the price of heat service increase from 307.7 €/MWh to 312.3 €/MWh.

Using the integrated approach, the increase in the price of heat service leads to a reduction in the demand for heat service by 2% (or 678 MW h). This demand-response moderates the increase in the price of heat service by 0.4 €/MWh compared to the bottom-up solution. The integrated approach also shows that banning oil boilers reduces household demand for other goods by 0.1% and household welfare by 0.15%.

This stylised experiment confirms the relevance of an integrated approach. In isolation, the top-down model cannot answer technology-specific policy questions, while using the bottom-up model alone ignores essential demand responses and adverse macroeconomic effects.

2.3. Soft linking using full information

A fully integrated hybrid model is difficult to implement in practice due to issues related to complexity and dimensionality. Instead, choosing a soft linking approach offers a way of avoid the need to represent technological and seasonal details in the top-down model. Tapia-Ahumada et al. [15] raises an equally important point, namely that top-down-modellers do not have the necessary information to build an integrated model without the assistance of bottom-up models. This suggests that keeping the bottom-up model intact is key for successful hybrid modelling. Hence, the next subsection decomposes the integrated approach into an equally consistent iterative soft linking strategy. To this end, the subsection discussed the introduction of connection points between the bottom-up and top-down model, i.e. the links introduced to exchange information between the models as part of the iterative soft linking process.

2.3.1. Connection points in the stylised bottom-up model

In the bottom-up model, the iterative soft linking strategy involves using the general equilibrium conditions related to heat service demand and input price levels ($\overline{Y}, \overline{P_X}$ and $\overline{P_K}$)as connection points to the top-down model. The value of $\overline{Y}, \overline{P_X}$and $\overline{P_K}$are updated based on the value of $Y, P_X$and $P_K$from the most recent top-down model iteration. In other words, consistent soft linking involves harmonising the price and demand changes in the bottom-up model to those of the top-down model.

2.3.2. Connection points in the stylised top-down model

In the top-down model, the goal is to emulate bottom-up heat service production. This requires two types of connection points. The first connection point fixes the price of heat service in the top-down model to match the relative change in heat service price from the bottom-up model. While the second connection point ensures that heat service production technology in the top-down model reflects the choice of technologies in the bottom-up model in terms of aggregate capital and fuel input.

Adding equation (14) fixes the heat service price in the stylised top-down model to the change in heat service price from the bottom-up model. Equation (14) relay the change in the annual consumption-weighted marginal price of heat service (relative to benchmark) from the bottom-up model. Using the annual consumption-weighted marginal price as a means of translating from the seasonal time slice level in the bottom-up model to the annual price level of the stylised top-down model. An endogenously determined price wedge (τ) is introduced as complementary variable to equation (14), to control the price of heat service exogenously in the top-down model.

Table 4
Comparing results from the bottom-up model and the integrated model.

	Benchmark		Banning oil boilers	
	Bottom-up	Integrated	Bottom-up	Integrated
Heat pump output (MWh)	20000	20000	32500	31822
Oil boiler output (MWh)	12500	12500	0	0
Annual heat service price (€/MWh)	307.7	307.7	312.3	311.9
Total cost of heat sector output (€ million)	10.0	10.0	10.2	9.9
Household demand, other goods		95		94.9
Household demand, heat service		5		4.9
Welfare change in percent		0		−0.15

Note: The GAMS-code used to derive these results accompanies this paper.

$$P_Y = \overline{\Lambda} = \sum_j \left[d_j^k \cdot h_j \cdot \lambda_j\right] \Big/ \sum_j \left[d_j^k \cdot h_j \cdot \overline{\lambda_j}\right], \qquad \underbrace{\tau}_{\substack{\textit{Complementary variable:} \\ \textit{price wedge}}} \tag{14}$$

The second connection point modifies the zero profit condition of the heat service sector to equation (15). In effect, re-calibrating the Leontief heat service production based on technology information from the latest bottom-up model iteration.
where: $\overline{x_{BU}} = \sum_{i,j} c^x_{i,j} \cdot x_{i,j}$ and $\overline{k_{BU}} = \sum_i c^k_i \cdot k_i$

$$\underbrace{\left(\frac{\overline{x_{BU}} + \overline{k_{BU}}}{10 \cdot \overline{Y}}\right)}_{\substack{\textit{Change in efficiency} \\ \textit{from bottom-up model}}} \cdot \underbrace{\left(\frac{\overline{x_{BU}}}{\left(\overline{x_{BU}} + \overline{k_{BU}}\right)} \cdot P_X + \frac{\overline{k_{BU}}}{\left(\overline{x_{BU}} + \overline{k_{BU}}\right)} \cdot P_K\right)}_{\substack{\textit{re-calibrated fixed shares} \\ \textit{based on bottom-up model}}} \geq (1-\tau) \cdot P_Y, \qquad \underbrace{Y}_{\substack{\textit{Complemary variable:} \\ \textit{heat service activity}}} \tag{15}$$

The first term on the left-hand-side of equation (15) is the ratio between the input quantities (measured in monetary units) relative to the output quantity in the bottom-up model ($\overline{Y}$ is the heat service activity index used in the most recent bottom-up model iteration). A decrease in this term implies that heat service production becomes more efficient. The second term represents the recalibration of the input shares in the Leontief production function, while the right-hand side of equation (15) expresses the producer's price of heat service net of the price wedge. Understood within the MCP framework, equation (15) states that the output of heat service (Y) will be positive if, and only if, the cost of producing heat service (based on technology information from the bottom-up model) is equal to the net producer price of heat service.

The iterative soft linking approach convergences fully to the solution provided by the integrated model within five iterations (see Section 2.5). A key feature of the convergence is that the price wedge becomes zero, as the stylised top-down model emulates the production technology from the bottom-up models, while the bottom-up model takes the general equilibrium feedback from the stylised top-down model fully into account.

$$\underbrace{100}_{\textbf{\textit{Capital supply}}} \geq \underbrace{95 \cdot \boldsymbol{X} \cdot \frac{\boldsymbol{P_K^{\alpha}} \cdot \boldsymbol{P_Y^{1-\alpha}}}{\boldsymbol{P_X}}}_{\substack{\textit{Other goods sector} \\ \textit{demand for capital}}} + \underbrace{5 \cdot \boldsymbol{Y}}_{\substack{\textit{Heat service sector} \\ \textit{demand for capital}}} + \underbrace{\frac{10 \cdot \boldsymbol{Y} \cdot \boldsymbol{\tau} \cdot \boldsymbol{P_Y}}{\boldsymbol{P_K}}}_{\substack{\textit{Capital demand} \\ \textit{from wedge rent}}} \tag{16}$$

2.4. Soft linking using partial information and average cost pricing

Soft linking using full information offers an increase in flexibility and transparency over the integrated approach. Flexibility since both the use and further development of the top-down and bottom-up model can take place independently. Transparency as the method provides insight into the effect chain between top-down and bottom-up model. Even so, soft linking using full information will likely prove difficult in a full-scale setting. As this approach does not address dimensional and conceptual differences related to capital demand and energy service prices. The next two subsections will address a solution to these issues in the form of a soft linking strategy using partial information exchange and average cost pricing.

2.4.1. Bridging the capital demand differences between bottom-up and top-down models

In practice, conceptual differences exist between capital demand in top-down and bottom-up models. Capital demand in top-down models is based on very aggregated national account statistics, while the capital demand in bottom-up models is based on investment costs related to specific energy services, traditionally sourced from detailed technology catalogues.

However, within the stylized soft linking framework it is possible to capture the macro economic impact of changes in capital demand implicitly without exchanging information on capital between the models. To see how, consider what happens in the stylised soft-linked model when $\overline{k_{BU}}$(in equation (15)) is fixed at its benchmark value of €5 million. In this case, the price wedge will no longer converge to zero. Instead, the rent generated by the price wedge (in the stylised top-down model) will reflect the now missing bottom-up capital cost component. This follows from the presence of a zero profit condition in stylised top-down model. It is hence possible to account for the macroeconomic impact of capital cost by adding the wedge rent divided by the price of capital to the market clearance equation for capital in the stylised top-down model, see equation (16).

2.4.2. Average versus marginal cost pricing

In the stylised bottom-up model, the shadow price of heat service demand is equal to the average cost of heat service production. This reflects that constant returns to scale prevail in the stylised setting, i.e. equivalence exists between using marginal and average cost pricing. However, this equivalence breaks down when introducing binding bounds on decision variables in the LP problem.

In full-scale energy system modelling, heterogeneity of energy service demand often dictates the introduction of bounds on decision variables. The heterogeneity reflects that energy services are produced and consumed within a particular firm (or household), at a particular site, at a particular time, using a particular technology,

Table 5
Comparing results from alternative scenario (banning oil boilers) integrated approach with soft linking iteration based on full and partial information.

Soft linking	Heat service: Fuel input cost (million €)		Heat service: Capital input cost (million €)		Heat service: wedge rent (million €)		Heat service: Capital input cost + wedge rent (million €)		Cost of heat service production (million €)		Welfare change (percent)	
	Full	Partial	Full	Partial	Full	Partial	Full	Partial	Full	Partial	Full	Partial
Iteration 1	3.9000	3.9000	6.2500	5.0000	0.0128	1.2311	6.2628	6.2311	10.1500	10.1500	−0.3909	−0.3722
Iteration 2	3.8035	3.8042	6.0904	4.9920	−0.0011	1.1023	6.0893	6.0942	9.8940	9.8958	−0.1126	−0.1175
Iteration 3	3.8174	3.8172	6.1130	4.9927	0.0001	1.1197	6.1131	6.1123	9.9303	9.9299	−0.1522	−0.1514
Iteration 4	3.8157	3.8157	6.1102	4.9926	0.0000	1.1177	6.1102	6.1103	9.9259	9.9260	−0.1474	−0.1475
Iteration 5	**3.8159**	**3.8159**	**6.1105**	**4.9926**	0.0000	1.1179	**6.1105**	**6.1105**	**9.9264**	**9.9264**	**−0.1479**	**−0.1479**
Integrated	**3.8159**		**6.1105**		-		**6.1105**		**9.9264**		**−0.1479**	

Note: Bold text indicates absolute converge between integrated approach and the soft linking strategies. The GAMS-code used to derive these results accompanies this paper.

for a particular process. One may, for example introduce lower bounds to capture that firms, within a specific geographical area, cannot readily substitute a specific energy service technology (e.g. oil-boilers). However, when introducing binding lower bounds on a technology, the technology can no longer serve as a marginal supplier of energy service demand. In this case, the shadow price of the energy service demand will not reflect the cost of bounded technology.

To summarise, in case the energy service commodity is very heterogeneous the shadow price of energy service demand is a poor measure of energy service cost (for use in a top-down model). Instead, average cost pricing provide a means of bridging the gap between the heterogeneity of energy services in the bottom-up model and the aggregated nature of energy services in the top-down model – aggregated in the sense that top-down models traditionally neglect geographical, temporal and technological details. Average cost pricing also ensures consistency with the zero profits assumption of the top-down model. In other words, the price of energy service in the top-down model is equal to the average cost of providing energy service in the bottom-up model. Without this consistency, firms would either operate at a loss or generate pure profit.

To go from marginal to average cost price equation (17) replaces equation (14) in the stylised soft-linked model. Equation (17) captures the average cost of energy service production as determined by the latest bottom-up model iteration. The nominator expresses the total cost of energy service production, while the denominator expresses the quantity of energy service produced.

$$\mathbf{P_Y} = \frac{\overline{\mathbf{Cost_{BU}}}}{10\cdot\overline{\mathbf{Y}}} = \frac{\overline{\mathbf{P_X}}\cdot\sum_i\sum_j \mathbf{c_i^x}\cdot \boldsymbol{x_{i,j}} + \overline{\mathbf{P_K}}\cdot\sum_i \mathbf{c_i^k}\cdot \boldsymbol{k_i}}{10\cdot\overline{\mathbf{Y}}}, \qquad \underbrace{\boldsymbol{\tau}}_{\textbf{complementary variable}} \tag{17}$$

2.5. Convergence of soft linking strategy using full and partial information

Table 5 show the convergence for key variables of the two soft linking strategies to the integrated model for the policy experiment (banning oil boilers). With iteration five, full convergence to the integrated approach is observable for both soft linking strategies. The convergence in the cost of fuel inputs for heat service is practically identical for the two soft linking strategies. However, using the soft linking strategy based on partial information exchange, the capital input cost of heat service production converges to €4.9926 million (not the €6.1105 million associated with the integrated approach). This reflects that the partial strategy does not directly capture the change in capital use associated with heat service production in the bottom-up model. Instead, the heat service wedge rent captures this missing capital component.

2.6. Method conclusion

This section has illustrated three different approaches for integrating the properties of a top-down and bottom-up model into a fully consistent hybrid model. Each approach facilitates the evaluation of the economy-wide effects of a technology-specific energy policy.

However, limitations apply to the full-scale implementation of the integrated approach as well as soft linking using full information. Complexity and dimensionality mean that the integrated approach is not practically feasible. Whereas, soft linking using full information will likely also prove difficult to implement in a full-scale setting due to conceptual differences between the top-down and bottom-up model related to capital demand and energy service prices.

In conclusion, soft linking using partial information while relying on average cost pricing provides a superior method for soft linking top-down and LP energy system models. This approach allows us to overcome both dimensional and conceptual differences related to capital demand, while the soft linking approach offers benefits in terms of transparency and flexibility.

3. Full-scale application of method

This section describes the implementation of the partial soft linking strategy in the Danish IntERACT model. The section starts by introducing the full scale top-down (CGE) model and full scale bottom-up model (TIMES-DK), which together form the IntERACT model. The section further discusses a number of important aspects of the full-scale implementation of soft linking strategy, including model harmonisation, the adaptation of the connection points from the stylised model, price harmonisation, calibration and the automated iterative soft linking routine. Focus is on the application of the soft linking strategy to 12 industry sectors.[5] The 12 sectors account for roughly 90% of final energy demand by industry and encompass primary, secondary and tertiary industry sectors.

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[5] The IntERACT model also soft-link the power and district heating supply sector, household heating and appliance demand in the IntERACT model, applying the same basic methodology. Future work will document these aspects of the model in detail.

3.1. Full scale bottom-up approach

TIMES-DK is a multi-regional model covering the entire Danish energy system from 2010 to 2050. TIMES-DK is based on the TIMES modelling framework [23] and minimises total discounted system costs, assuming perfect foresight. TIMES-DK has a detailed geographical representation, while it captures variability in electricity supply and demand by dividing the year into 32 time slices [27]. The model covers the supply sector (import/export of primary and secondary fuels, fuel extraction and refining of oil products), the power sector (including heat production and distribution through district heating network), residential sector (heating and appliance demand), transport and 12 industry sectors.

Each of the 12 industry sectors demand up to seven energy services including high and medium temperature process heat, room heating services, electric motors and cooling, fork lift services, lighting and appliances. Energy service demand in TIMES-DK is understood as the net energy demand associated with the particular type of energy service, i.e. energy available to the firms and consumers after having accounted for conversion losses. The calibration of TIMES-DK involves endowing the model with fuel-specific conversion capacities to ensure that the model matches historic fuel demand by energy service and sector. This endowment process treats existing energy service capacities as sunk costs. In future modelling years, TIMES-DK satisfies energy service demand in one of three ways: Using existing capacities, by investing in new fuel (and energy service) specific (conversion) capacity or by investing in energy service specific savings.

3.2. Full scale top-down approach

The CGE model is a single country multisector model formulated in the MCP format by using the mathematical programing system MPSGE [12]. The model consists of 20 economic sectors, a government and a representative household. The main data inputs are national accounts and energy account statistics for the Danish Economy for the year 2012 [13]. The trade balance is fixed. Armington specifications are used to model trade, i.e. foreign goods are imperfect substitutes [28]. The model consists of three factor markets: labour, machinery capital and building capital. Labour and capital markets are homogenous, which reflects the modelling of a long-run equilibrium.

The approach taken in IntERACT differs from the standard CGE modelling practice along two dimensions. First, the CGE model explicitly model demand for energy service for the 12 sectors (See Appendix B list of sectors in the CGE model). Second, the CGE model includes equations that make it possible to update both energy service prices and production technology based on information from TIMES-DK. Fig. 1 illustrates the generic structure of the 12 soft-linked sectors. Each node in the figure represents a constant elasticity of substitution function with a particular substitution elasticity. A separate study has guided the choice of nesting structure and substitution elasticities [29]. Except for the aggregated energy service nest (E), which assumes substitution elasticity of zero, reflecting the presumption that the share of different types of energy service within a sector remains fixed into the future.

CGE baseline calibration is done by matching a gross domestic product (GDP) projection from the Danish Ministry of Finance, using a Hicks-neutral technology innovation index [30]. The development in government consumption, investment, and net-export is also exogenous in the model, fixed using the same source as the GDP projection. Using the model for a policy experiment, involves fixing the Hicks-neutral technology index to its baseline calibration level, and thereby allowing GDP adjust endogenously in the policy scenario.

3.3. Model harmonisation

The main component of the model harmonisation is the parallel structure created between the two models, i.e. the energy service demand in the CGE model mirrors the structure of energy service supply in TIMES-DK for the 12 soft-linked industry sectors. Both models have been calibrated on the same energy account statistics and sectoral energy service mapping [31].

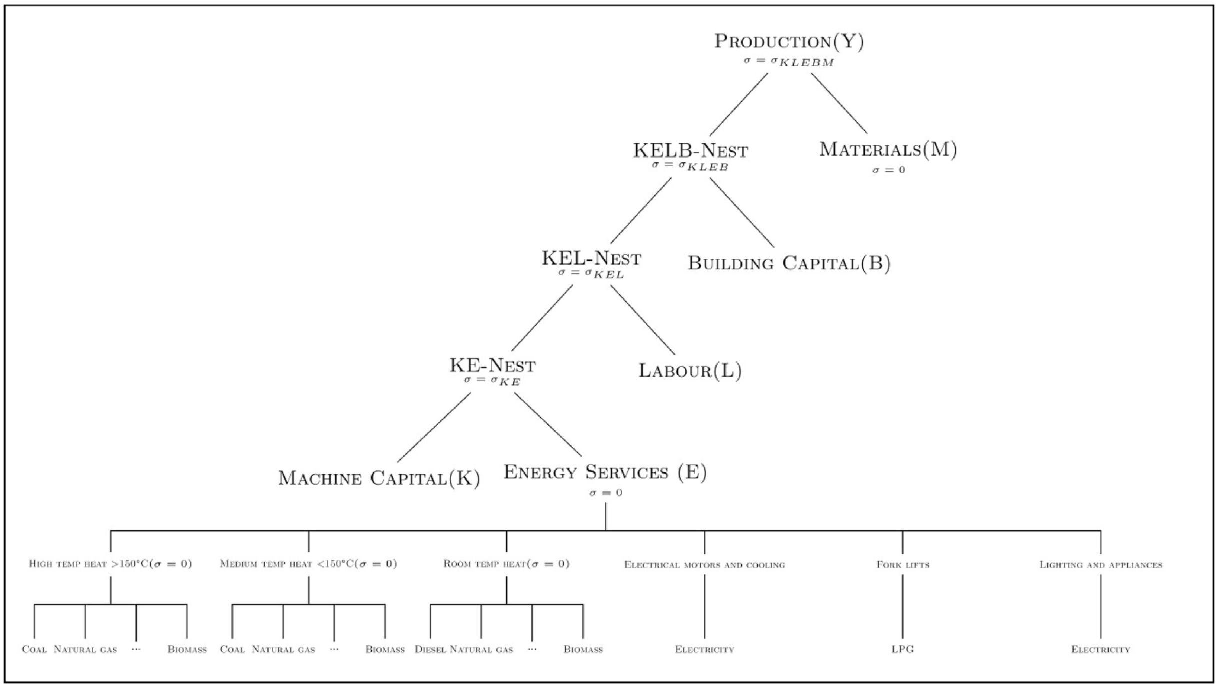

Fig. 1. Generic nesting tree for the 12 energy-service-demanding sectors in the CGE model.

3.4. Connection points in full scale bottom-up model

TIMES-DK contains two connection points. These connection points allows for the updating of sectoral energy service demands and fuel prices directly based on the CGE model. Thereby harmonising fuel prices and demand changes in the bottom-up model to those of the top-down model. Future research will explore the introduction of a connection point in TIMES-DK to facilitate the harmonisation of the price of capital across models.

3.5. Connection points in full scale top-down model

Box 1 contains the nomenclature and equations (18) and (19), describing the two connections points introduced in CGE model. The first connection point relays information from TIMES-DK on the change in the average price for each sectoral energy service (relative to the benchmark year). In effect, transforming equation (17) into equation (18) by adding dimensions that reflect the sector, energy service and year. The complementary variables are the endogenous price wedges needed in the CGE model to match the change in the average price of energy service from TIMES-DK. The average price of energy service is defined as total cost of providing the energy service in TIMES-DK, i.e. fuel costs, fuel taxes, fixed, variable and investment costs, divided by the quantity of energy service produced.

$$\boldsymbol{pes_{n,s,year}} = \frac{\frac{\sum_z\left(\boldsymbol{Cost_{n,s,z,year}}\right)}{\overline{\boldsymbol{es}}_{\boldsymbol{n,s,year}}}}{\frac{\sum_z\left(\boldsymbol{Cost_{n,s,z,2012}}\right)}{\overline{\boldsymbol{es}}_{\boldsymbol{n,s},2012}}}, \qquad \underbrace{\boldsymbol{\tau_{n,s,year}}}_{\textbf{\textit{complementary variable}}} \tag{18}$$

$$\underbrace{\left[\frac{\frac{\sum_f \mathbf{x}^{\mathbf{TIMES-DK}}_{\mathbf{n,s,f,year}}}{\sum_f \mathbf{x}^{\mathbf{CGE}}_{\mathbf{n,s,f},2012}}}{\frac{\overline{\mathbf{es}}_{\mathbf{n,s,year}}}{\overline{\mathbf{es}}_{\mathbf{n,s},2012}}}\right]}_{\substack{\textit{Change in fuel efficiency}\\ \textit{relative to benchmark}}} \cdot \underbrace{\sum_{\boldsymbol{f}}\left[\underbrace{\frac{\mathbf{x}^{\mathbf{TIMES-DK}}_{\mathbf{n,s,f,year}}}{\sum_f \mathbf{x}^{\mathbf{TIMES-DK}}_{\mathbf{n,s,f,year}}}}_{\substack{\textit{update relative fuel (quantity)shares}\\ \textit{in future linking years}}} \cdot \boldsymbol{pf_{f,year}} \cdot \left(1 + \mathbf{tax_{n,s,f,year}}\right)\right]}_{\substack{\textit{re-calibrated fixed shares}\\ \textit{based on TIMES-DK model}}} \geq \left(1 + \tau_{n,s,year}\right) \cdot pes_{n,s,year}, \qquad \underbrace{es_{n,s,year}}_{\textit{Complementary variable}} \tag{19}$$

The second connection point, equation (19), re-calibrates the production technology of energy services in the CGE model according to the production technology used in TIMES-DK. The left hand side of equation (19) consists of two terms; the first term is a measure of the change in conversion efficiency (measured in monetary terms) between fuels and energy service relative the benchmark year. Whereas the second term, on the left hand side, updates fuel quantity shares in the energy service production functions in the CGE model. The right hand side of equation (19) captures the net producer price of the energy service.

Equation (19) has the same basic components as the zero profit condition of heat service in the stylized model (equation (15)) except for the absence of capital demand and inclusion of fuel tax rates. The absence of capital demand from equation (19) is fundamentally due to the lack of national account statistics on capital demand associated with specific energy services; cf. the discussion in Section 2.4.1. Including taxes, captures the significance of fuel taxes on energy service costs. Future tax rates in the CGE model are calculated based on fuel costs and fuel revenues from TIMES-DK (by sector, service and fuel). Updating tax rate in this manner ensures convergence across models in terms of fuel tax revenues.

3.6. Interpretation of a price change relative to the benchmark year

This subsection conceptualise how IntERACT overcomes key soft linking consistency issues, related to prices and costs. Fig. 2 illustrates the different cost components in the CGE and TIMES-DK models associated with a representative energy service in 2012 (benchmark year) and 2035. Assuming that the demand for energy service is the same in 2012 and 2035 enables the interpretation of a relative change in the total costs of energy service as corresponding to the relative change in the price of the energy service.

In the benchmark year, only fuel cost and fuel taxes determine energy services production cost in the CGE model and in TIMES-DK. However, in future modelling years investment (as well as fixed and variable) costs play an important part in determining the total cost of energy service production in TIMES-DK. This occurs as new conversion technologies replace existing (sunk cost) technologies in the TIMES-DK model.

Equation (19) ensures convergence between TIMES-DK and the CGE model in terms of fuel costs and fuel tax revenues. Nonetheless, without additional price information from TIMES-DK, the price of energy service in the CGE model will only reflects the change in fuel cost and taxes; corresponding to a 20% reduction in relative price of energy service in Fig. 2. The price wedge in Equation (18) provide the additional price information, allowing the CGE model to capture the “actual” 40% increase in the energy service cost. Just as in the stylised approach, the rent generated by the price wedge in the CGE model reflects the missing bottom-up cost component (i.e. the missing variable, fixed and investment costs), as illustrated in Fig. 2. Based on the assumption that the wedge rent mainly reflects capital demand associated with energy services, the rent from the wedge is used to buy capital in the CGE model. By doing so, the method captures the general equilibrium impact of energy service capital in terms of its crowding-out effect on alternative capital uses in the economy.

3.7. Full scale iteration routine

The iterative routine starts by runing TIMES-DK to inform the CGE-model on future energy service prices, energy service production technologies and fuel taxes. Based on this information, the CGE-model determines new energy service demands and prices. TIMES-DK uses these new demands and prices in the second

Box 1
IntERACT nomenclature and CGE model connection points

Indices

n	Economic sector
s	Energy service
f	Fuel
z	Energy service cost components (fuel, taxes, variable, fixed and investment)

Variables

$pes_{i,s,year}$	Energy service price (CGE-model)
$es_{n,s,year}$	CGE energy service activity/demand
$\tau_{n,s,year}$	Sector and energy service specific price wedge
$pf_{f,year}$	Fuel price (CGE model)

Parameters

$\mathrm{Cost}_{n,s,z,year}$	Energy service cost (TIMES-DK)
$\overline{\mathrm{es}}_{n,s,year}$	Energy service demand used in previous TIMES-DK iteration
$\overline{\mathrm{x}^{CGE}_{n,s,f,2012}}$	CGE benchmark fuel input quantity (measured in monetary units, real 2012 prices)
$\mathrm{x}^{TIMES-DK}_{n,s,f,year}$	TIMES-DK fuel input quantities (measured in monetary units, real 2012 prices)
$\mathrm{tax}_{n,s,f,year}$	CGE fuel tax rate calculated based on output from TIMES-DK

iteration to project a new set of energy service prices, energy service production technologies and fuel taxes. This iterative proces continues until fuel cost and fuel tax revenues (by sector, service and fuel) have converged fully. This happens within 5 iterations. The choice of fuel costs and fuel tax revenues as convergence criterion reflects that these components are equally and well defined in both TIMES-DK and the CGE model. The coherence of the TIMES-DK and the CGE model avoids the need for intermediate translation modules, as used by other national soft linking studies. The iteration routine is fully automated and takes approximately 15 minuttes to complete on a standard office laptop. This is approximately five times longer than it takes to run a stand-a-lone version of TIMES-DK. The results are, however, qualitative very different because running TIMES-DK alone neglects important behavioural demand feedbacks and key macroeconomic consequences.

4. Results and discussion

This section demonstrates the potential of the soft linking strategy by considering a narrow yet radical policy: Unilateral implementation of coal CCS-technology in the Danish *concrete, brick, glass and ceramic* sectors (henceforth the concrete sector). This CCS policy is by no means cost effective in terms of CO_2 abatement as it violates basic textbook recommendations, most notably that the marginal abatement cost should be equal across sectors and countries [32]. Still, given the proposed role of CCS technology in limiting global temperature increase to below 2 °C [33], it is crucial to have modelling tools that can evaluate both the energy system and economy-wide effect of introducing CCS technology.

Two assumptions in particular drive the results. First, the cost and technical properties of the coal CCS technology (Appendix C) and, second, the minimum share of coal-based technologies to satisfy the demand for medium and high temperature energy service in the concrete sector, set at 30% for 2035. Both of these assumptions are debatable. However, an important rationale for using a hybrid model, such as IntERACT, is that it offers transparency and flexibility to adjust these technical assumptions based on a dialogue with technical experts and stakeholders [34].

4.1. Climate mitigation in the concrete sector

The policy forces the adoption of coal CCS technologies in 2035 by banning traditional coal-based technologies in the concrete sector. Fig. 3 and Fig. 4 show the concrete sector's CO_2 emissions

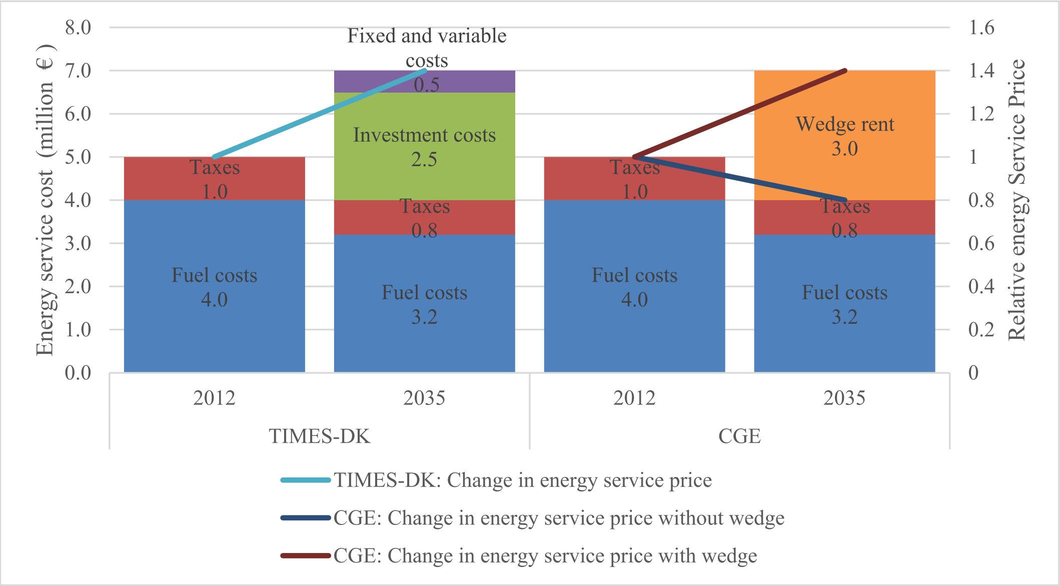

Fig. 2. **Stylised illustration of cost components and price change for a representative energy service in TIMES-DK and CGE model in 2012 and 2035.** Note: Assuming the same energy service demand in 2012 and 2035.

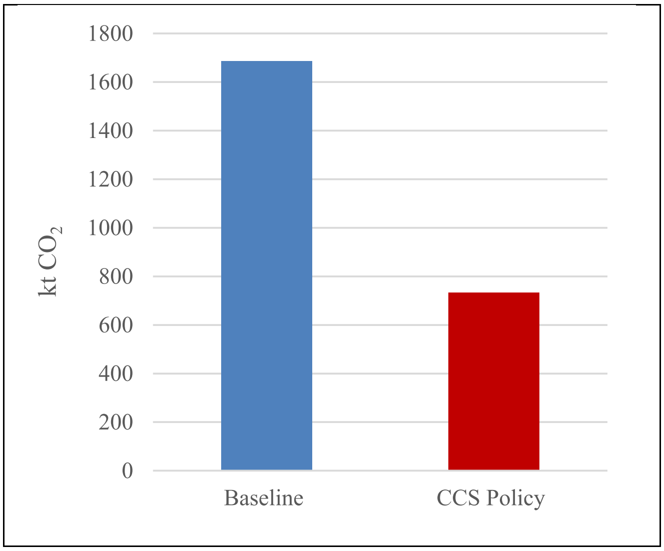

Fig. 3. CO2 emissions in 2035 from the concrete sector in baseline and policy scenario (iteration 5).

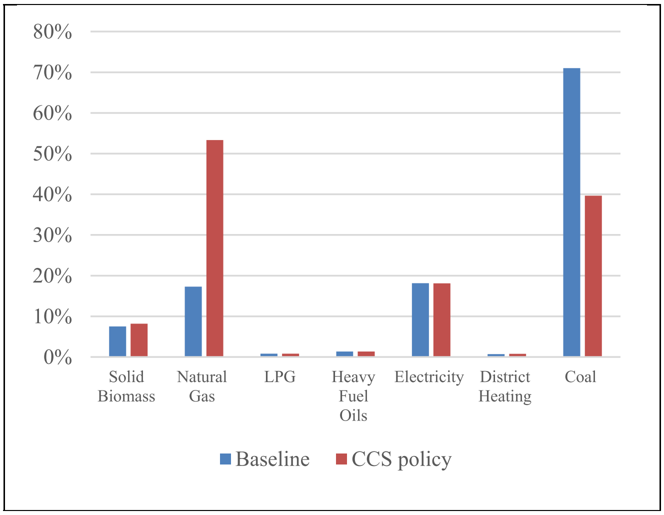

Fig. 4. Share of total fuel input in the concrete sector by energy content in 2035 in baseline and policy scenario (iteration 5).

and the fuel input shares in 2035 for the baseline and policy scenario respectively.

The baseline scenario is associated with continuous growth in CO_2 emissions and fuel consumption up to 2035. The CCS policy leads to a 56% reduction in CO_2 emissions relative to the baseline. The high share of coal in the fuel mix increases in 2035, which reflects that coal-based technologies are competitive (based on fuel and CO_2 price assumptions). In the policy scenario, the high costs of coal CCS technologies leads to the substitution of coal for natural gas in the fuel mix. The remaining, significant share of coal in the policy scenario is due to the lower efficiency of coal CCS technologies and due to the critical assumption that coal-based technologies have to satisfy close to a third of energy service demand for high and medium temperature process heat in 2035.

4.2. Forced adaptation of expensive climate mitigation technologies leads to higher energy service prices and lower demand

Fig. 5 depicts the effect of the coal CCS policy on the energy service prices in the concrete sector in 2035. The coal CCS policy leads to a doubling of the price of both medium and high temperature heat services compared to the baseline, while the price of other energy services are unaffected. The change in the price of high and medium temperature increases the price of the aggregated energy service nest for the concrete sector in the CGE-model by seven percent. This change in the aggregated energy service price reduces the overall energy service demand from the concrete sector by close to 8% in 2035 relative to the baseline.

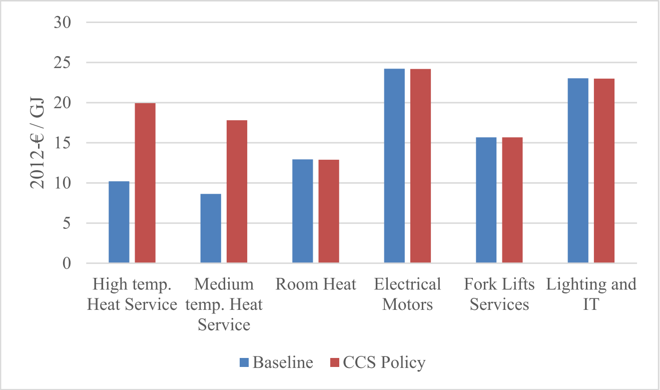

Fig. 5. Average price of energy services in concrete sector in 2035 Baseline and CCS Policy scenario (iteration 5).

4.3. Convergence in fuel and investment costs

Fig. 6illustrates the convergence in fuel costs and fuel tax revenue across TIMES-DK and the CGE model for the concrete sector. Parallel to the stylised model, full convergence in fuel and tax cost can be observed after five iterations.

Fig. 7 highlights the different cost components of energy service production for the concrete sector in year 2035 across models and scenarios for iteration 5. Fig. 7 confirms that wedge rent is capable of approximating investment, variable and fixed cost from TIMES-DK. In particular, the change in wedge rent between baseline and policy (€107 million) compares well with change in investment, fixed and variable costs from TIMES-DK (totalling €121 million).

4.4. Economy-wide effect

Fig. 8 shows the change in sectoral activity. The CCS policy reduces the activity of the domestic concrete sector by nine percent relative to the baseline. One could, in principle, capture the isolated effect on the concrete sector by using the TIMES demand elasticities feature [23] in a standalone version of TIMES-DK. However, the benefit of a hybrid model, such as IntERACT, is that it captures the complex sectoral effect of the policy, which includes both upstream effects (increase in gas distribution sector) and downstream effects (reduction in construction sector). However, it also includes effects that follow from changes in the relative price of capital and labour (decrease in chemical sector) and effects related to changes in households' disposable income (reduction in the activity of the wholesale and retail sector). The overall policy impact is a reduction in gross domestic product (GDP) of 0.05% in 2035.

4.5. Carbon leakage

A key consideration for any climate mitigation policy is carbon leakage. Carbon leakage occurs as climate mitigation in a country increases CO_2 emissions in other countries. Using CGE part of the

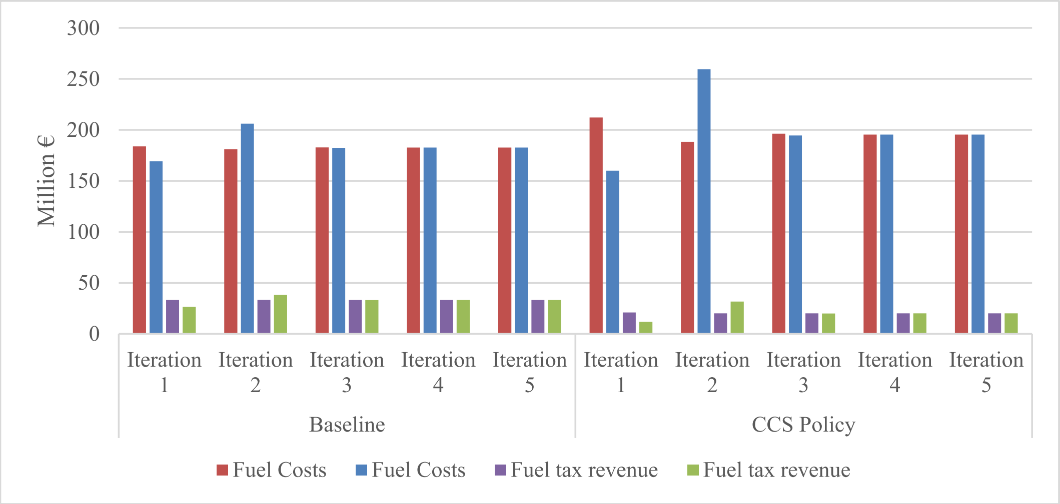

Fig. 6. Convergence in total fuel costs and tax revenue between TIMES-DK and CGE for concrete sector in 2035.

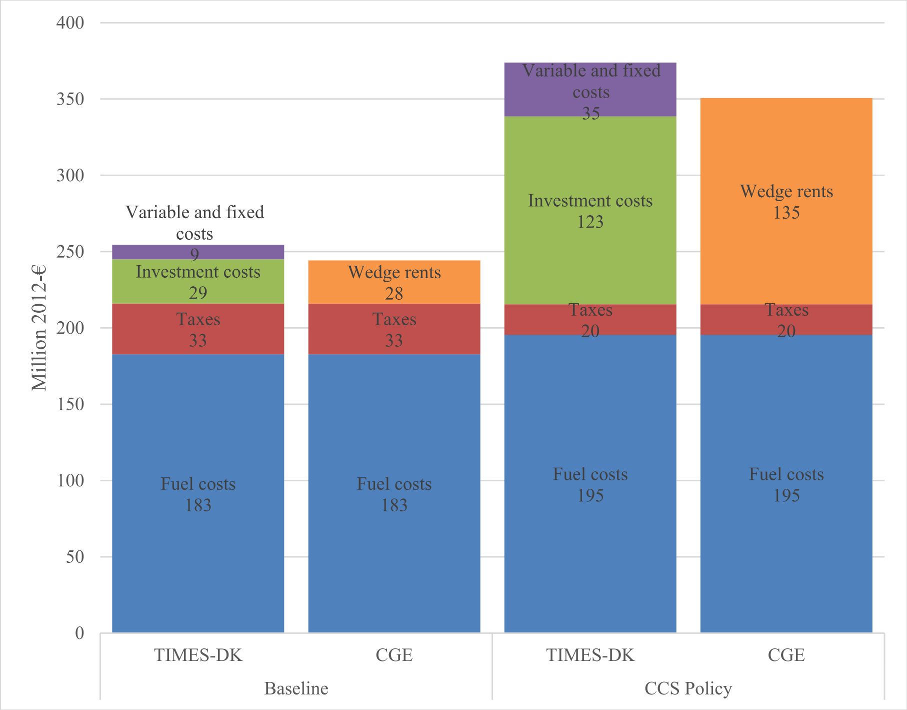

Fig. 7. Decomposition of energy service cost in the concrete sector in 2035 for baseline and CCS policy (iteration 5).

IntERACT model, carbon leakage is estimated as the change in net-import of the concrete commodity (change in import minus change in export) divided by the change in the domestic concrete production. The CCS policy increases net import of concrete by €316 million and reduces domestic production by €357 million in 2035, suggesting a carbon leakage of around 88%. This results is, however, highly sensitive to the assumed CO2-intensity of foreign concrete production. The extent of the carbon leakage effect underscores that the policy, as expected, does little or nothing in terms of mitigating global climate change.

5. Macroeconomic impact of energy service investment flows

This section provides an assessment of the macroeconomic impact of investment demand associated with coal CCS technology. Two effect dominates the sectoral capital demand in IntERACT model, an activity and a technical effect. The activity effect is a pure CGE model effect, which captures the relationship between sectoral activity and capital demand. While the technical effect rely on the wedge rent to capture investment flows associate with sectoral energy service demand in TIMES-DK.

The activity effect, of the coal CCS policy, reduces the concrete sector's capital demand by 9% (€250 million) in 2035 relative to the baseline. Thereby, matching the decrease in the activity of the concrete sector closely (cf., Fig. 8). The technical effect increases the concrete sector's demand for capital by €107 million, following the adoption of coal CCS technology. The net effect is a reduction in the capital demand by the concrete sector of 5% (€143 million).

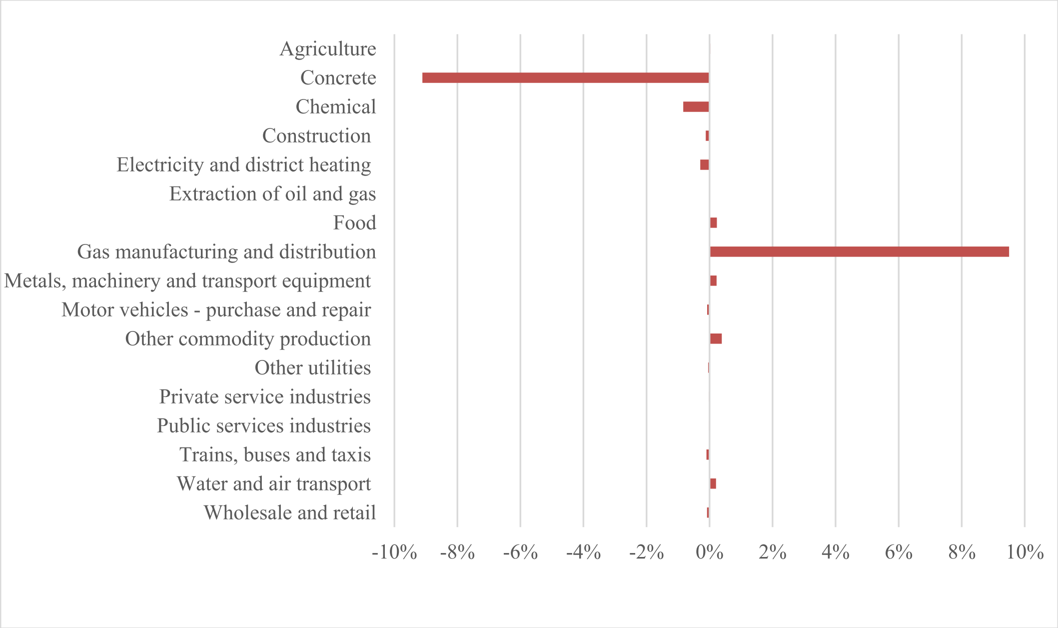

Fig. 8. Relative change in sectoral activity relative to baseline across the 20 sectors in the CGE model (iteration 5).

Resulting in an increase in the capital intensity of the concrete sector (as sectoral activity is reduced relatively more than capital demand). The higher capital intensity of concrete sector increases the user cost of capital throughout the economy by 0.2% in 2035 (relative to the baseline).

Using IntERACT, it is possible to estimate the significance of the energy service investment flows for the macroeconomic impact assessment, and in so doing provide an indication of what might be missing in studies that do not consider the energy system investment flows. The estimation compares the 0.05% reduction in GDP from the coal CCS policy with the decrease in GDP that follows from simply reducing capital endowment in the baseline scenario by an amount corresponding to the wedge rent in the policy scenario, while compensating households for their loss of capital income. This crude estimate suggests that approximately half of GDP effect associated with the coal CCS policy is a consequence of additional investment flows related to the energy service demand of the concrete sector. This result emphasises the importance of accounting for the macroeconomic impact of changes in investment flows in the energy system, when studying climate mitigation strategies.

6. Conclusion

This paper has presented an improved soft linking method capable of accessing detailed technical and sectoral climate and energy policy question. Compared with existing studies the method offers a solution to the consistency issues typically associated with the soft linking of bottom-up and top-down models. The paper, also adds to the literature by providing a means of accounting for the macroeconomic impact of energy system investment flows.

Derived from a fully consistent integrated approach, the proposed soft linking method overcomes issues of complexity and dimensionality by relying on partial information exchange and average cost pricing. The paper further illustrated how modelling energy service demand explicitly in a top-down model, allows for the creation of a parallel structure between a top-down and a bottom-up model. The parallel structure reinforces consistency as it supports the clear division of labour between the top-down model and the bottom-up model. The bottom-up model determines the relative price of energy services and the associated production technology, while the top-down model determines energy service demands.

Finally, the paper has illustrated the potential of the method for capturing both energy system and economic wide effects, by considering the mandatory adoption of coal CCS technology by the Danish concrete sector. This sector and technology specific policy leads to a large contraction in the Danish concrete production, and in turn, to a carbon leakage effect of upwards of 88%. The policy experiment further shows that half of the policy-induced decline in GDP follows from additional capital demand associated with coal CCS technology. Underscoring the necessity of capturing the macroeconomic effects of investment flows associated with the energy system when modelling climate and energy policy questions. Owing to the importance of capital demand for the policy conclusion, future research will explore the linking methodology related to the price of capital and capital accumulation. A key part of this will be to improve the dynamic properties of the CGE model, i.e. by introducing endogenous investment and capital accumulation decisions.

Acknowledgements

Financial support from the Danish Energy Agency is gratefully acknowledged, as are contributions from Mikkel Kromann to an earlier version of the stylised model. Any remaining errors reside solely with the authors.

Appendix A

Table 1A.
Stylised top-down model under different linking assumptions

Inequality	Stylised top-down formulation		Integrated top-down formulation		Soft-link top-down formulation		Partial soft linking using average cost pricing top-down formulation	
	Equation	Complementary variable	Equation	Complementary variable	Equation	Complementary variable	Equation	Complementary variable
I. Non-positive profits for sector X (other goods sector)	$100\cdot P_K^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_X$	X	$100\cdot P_K^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_X$	X	$100\cdot P_K^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_X$	X	$100\cdot P_K^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_X$	X
II. Non-Positive profits for sector Y (heat service sector)	$5\cdot P_K + 5\cdot P_X \geq 10\cdot P_Y$	Y	$\Sigma_{\mathrm{j}}[d_j^k\cdot h_j\cdot \lambda_j] \geq 10\cdot P_Y$ $P_K\cdot c_i^k \geq \Sigma_{\mathrm{j}}\ (\mu_{i,j}\cdot h_j)$ (optimal capacity) $P_X\cdot c_i^x + \mu_{i,j} \geq \lambda_j$(optimal demand)	Y $\mu_{i,j}$ k_i	$\left(\frac{\overline{x_{BU}}+\overline{k_{BU}}}{10\cdot \overline{\mathrm{Y}}}\right)\cdot\left(\frac{\overline{x_{BU}}\cdot P_X+\overline{k_{BU}}\cdot P_K}{\overline{x_{BU}}+\overline{k_{BU}}}\right) \geq (1-\tau)\cdot PY$	Y	$\left(\frac{\overline{x_{BU}}+5}{10\cdot \overline{\mathrm{Y}}}\right)\cdot\left(\frac{\overline{x_{BU}}\cdot P_X+5\cdot P_K}{\overline{x_{BU}}+5}\right) \geq (1-\tau)\cdot PY$	Y
III. Non-positive profits for W (utility sector)	$100\cdot P_X^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_W$	W	$100\bullet P_X^{0.95}\bullet P_Y^{0.05} \geq 100\bullet P_W$	W	$100\cdot P_X^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_W$	W	$100\cdot P_X^{0.95}\cdot P_Y^{0.05} \geq 100\cdot P_W$	W
IV. Supply ≥ Demand for sector X (other goods sector)	$100\cdot X \geq 95\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_X} + 5\bullet Y$	P_X	$100\bullet X \geq 95\bullet W\bullet\frac{P_X^{0.95}\bullet P_Y^{0.05}}{P_X} + \Sigma_{i,j}(c_i^x\cdot x_{i,j})$	P_X	$100\cdot X \geq 95\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_X} + \overline{x_{BU}}$	P_X	$100\cdot X \geq 95\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_X} + \overline{x_{BU}}$	P_X
V. Supply ≥ Demand for sector Y (heat service sector)	$10\cdot Y \geq 5\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_Y} + 5\cdot X\cdot\frac{P_K^{0.95}\cdot P_Y^{0.05}}{P_Y}$	P_Y	$10\cdot Y \geq 5\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_Y} + 5\cdot X\cdot\frac{P_K^{0.95}\cdot P_Y^{0.05}}{P_Y}$ $\Sigma_i(x_{i,j}) \geq h_j\cdot d_j^k\cdot Y$(seasonal demand clearance) $k_i\cdot h_j \geq x_{i,j}$(seasonal capacity clearance)	P_Y λ_j $x_{i,j}$	$10\cdot Y \geq 5\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_Y} + 5\cdot X\cdot\frac{P_K^{0.95}\cdot P_Y^{0.05}}{P_Y}$	P_Y	$10\cdot Y \geq 5\cdot W\cdot\frac{P_X^{0.95}\cdot P_Y^{0.05}}{P_Y} + 5\cdot X\cdot\frac{P_K^{0.95}\cdot P_Y^{0.05}}{P_Y}$	P_Y
VI. Supply ≥ Demand for sector W (utility sector)	$100\bullet W = \frac{I}{PW}$	PW	$100\cdot W = \frac{I}{PW}$	PW	$100\cdot W = \frac{I}{PW}$	PW	$100\cdot W = \frac{I}{PW}$	PW
VII. Supply ≥ Demand for sector K	$100 \geq 95\cdot X\cdot\frac{P_Y^{0.05}\cdot P_X^{0.95}}{P_X} + 5\cdot Y$	P_K	$100 \geq 95\cdot X\cdot\frac{P_Y^{0.05}\cdot P_X^{0.95}}{P_X} + \Sigma_{\mathrm{i}}(c_i^k\cdot k_i)$	P_K	$100 \geq 95\cdot X\cdot\frac{P_Y^{0.05}\cdot P_X^{0.95}}{P_X} + \overline{\mathrm{k_{BU}}}$	P_K	$100 \geq 95\cdot X\cdot\frac{P_K^{\alpha}\cdot P_Y^{1-\alpha}}{P_X} + 5\cdot \mathrm{Y} + \frac{10\cdot\tau\cdot P_Y\cdot Y}{P_K}$	P_K
VIII. Income balance	$I = 100\cdot P_K$	I	$I = 100\cdot P_K$	I	$I = 100\cdot P_K$	I	$I = 100\cdot P_K$	I
IX. Additional soft linking constraint					$PY = \overline{\Lambda}$	τ	$PY = \frac{Cost_{BU}}{10\cdot \overline{Y}}$	τ

Grey shading signifies no change relative to the stand-a-lone CGE formulation.

Appendix B

Table B.1
Sectors in IntERACT/CGE model and status in terms of linking with IntERACT/TIMES-DK

	Energy service demand	Soft-linket between CGE and TIMES-DK	Same exogenous driver in CGE and TIMES-DK
Agriculture, forestry, fishing, gravel & stone	X	X	
Food, beverages, tobacco industry	X	X	
Chemical industry (excl manufacture of basic metals)	X	X	
Metals, machinery and transport equipment industry	X	X	
Concrete and bricks, glass and ceramics	X	X	
Other commodity production	X	X	
Wholesale and retail trade	X	X	
Private service industries	X	X	
Public services industries	X	X	
Construction	X	X	
Dwelllings			X
Extraction of oil and gas (North Sea oil and gas production)			X
Oil refinery & manufacture of basic chemicals			
Electricity, steam and hot water production and distribution		X	
Gas manufacturing & distribution			
Other utilities	X	X	
Motor vehicles - purchase and repair	X	X	
Trains, buses, taxis			
Freight by road & pipeline, support for transportation and postal activities			
Water and air transport (mainly transport services delivered outside Denmark)			

Appendix C. CO2-capture-07 CO_2 Capture and Storage

Technology	CO2 capture (post-combustion),					
	2010	2020	2030	2050	Note	Ref
Energy/technical data						
Generating capacity for one unit (MW)		503–740				1 + 2+3 + 4
Capture efficiency (%)	90	90	90	90	A	1
Generation efficiency decrease (%-points)	8–10%	8–10%	8–10%	8–10%	B	1 + 2+3
Financial data						
Capture, post-combustion						
Nomina1 investment (M€/MW)	2.3–4.3	3.07	3.OD	2.86	C	1 + 2+3 + 4; 2;2; 2
Fixed O&M (€/MW/year)	72000–87000	72000–87000	72000–87000	72030–87000	D	1 + 2
Variable O&M (€/MWh)	3.4–4.1	3.4–4.1	3.4–4.1	3.4–4.1	D	1 + 2

Sources:
1 “The Costs of CO2 Capture, Transport and Storage”, Zero Emissions Platform (ZEP), July 2011.
2 “UK Electricity Generation Costs Update”, Mott MacDonald, June 2010.
3 “Energy Technology Perspectives”, IEA 2010.
4 ″ProjectCosts of generating Electricity”, IEA & NEA, 2010.

Notes:
A The non-captured CO2 is released into the atmosphere.
B Some of the electricity consumption may be regained as useful heat. The displayed efficiency decreases do most probably
C The nominal investment is per regenerating capacity, i.e. after deducting the power consumed for CO2 capture. If you
D The O&M costs are per net generating capacity and net generation, i.e. after deducting the power consumer for CO2 capture.

References

[1] Fortes P, Pereira R, Pereira A, Seixas J. Integrated technological-economic modeling platform for energy and climate policy analysis. Energy 2014;73:716–30. https://doi.org/10.1016/j.energy.2014.06.075.

[2] Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: lessons from linking a Swedish energy system model with a CGE model. Energy 2017;141:803–17. https://doi.org/10.1016/J.ENERGY.2017.09.107.

[3] Hourcade J-C, Jaccard M, Bataille C, Ghersi F. Hybrid modeling: new answers to old challenges introduction to the special issue of the energy journal. Energy J 2006;SI2006:1–11. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-1.

[4] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/J.APENERGY.2009.09.026.

[5] Böhringer C, Rutherford TF. Combining bottom-up and top-down. Energy Econ 2008;30:574–96. https://doi.org/10.1016/j.eneco.2007.03.004.

[6] Hourcade J-C, Jaccard M, Bataille C, Ghersi F. Hybrid modeling: new answers to old challenges introduction to the special issue of the energy journal. Energy J 2006;SI2006:1–11. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-1.

[7] Glynn J, Fortes P, Krook-Riekkola A, Labriet M, Vielle M, Kypreos S, et al. Economic impacts of future changes in the energy system—national perspectives. In: Giannakidis G, Labriet M, O Gallachóir B, Tosato G, editors.

Informing energy clim. Policies using energy syst. Model.; 2015. p. 359–88.

[8] Hunt LC, Ryan DL. Economic modelling of energy services: rectifying misspecified energy demand functions. Energy Econ 2015;50:273–85. https://doi.org/10.1016/j.eneco.2015.05.006.

[9] Manne AS, Wene C-O. MARKAL-MACRO: a linked model for energy-economy analysis. 1992. New York.

[10] Manne AS. ETA-MACRO : a model of energy-economy interactions/. Palo Alto, Calif. : Electric Power Research Institute; 1977.

[11] Strachan N, Kannan R. Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Econ 2008;30:2947–63. https://doi.org/10.1016/J.ENECO.2008.04.009.

[12] Bosetti V, Carraro C, Galeotti M, Massetti E, Carrarof C, Tavoni M. WITCH a world induced technical change hybrid model, vol. 27; 2006.

[13] Böhringer C, Löschel A. Promoting renewable energy in Europe: a hybrid CGE approach. Energy J Hybrid Model New Answers to Old Challenges 2006: 123–38. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-7.

[14] Sue Wing I. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. Energy Econ 2008;30:547–73. https://doi.org/10.1016/j.eneco.2006.06.004.

[15] Tapia-Ahumada K, Octaviano C, Rausch S, Pérez-Arriaga I. Modeling intermittent renewable electricity technologies in general equilibrium models. Econ Modell 2015;51. https://doi.org/10.1016/j.econmod.2015.08.004.

[16] Böhringer C, Rutherford TF. Integrated assessment of energy policies: decomposing top-down and bottom-up. J Econ Dynam Contr 2009;33: 1648–61. https://doi.org/10.1016/j.jedc.2008.12.007.

[17] d'Aertrycke G de M, Durand-Lasserve O, Schudel M. Integration of power generation capacity expansion in an applied general equilibrium model. Fondazione Eni Enrico Mattei (FEEM); 2014. https://doi.org/10.2307/resrep01082.

[18] Hoffman KC, Jorgenson DW. Economic and technological models for evaluation of energy policy. Bell J Econ 1977;8:444. https://doi.org/10.2307/3003296.

[19] Martinsen T. Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models. Energy Pol 2011;39:3327–36. https://doi.org/10.1016/j.enpol.2011.03.025.

[20] Schäfer A, Jacoby HD. Technology detail in a multisector CGE model: transport under climate policy. Energy Econ 2005;27:1–24. https://doi.org/10.1016/J.ENECO.2004.10.005.

[21] Labriet M, Drouet L, Vielle M, Haurie A, Kanudia A, Loulou R. Coupled bottom-up and top-down modelling Policies, to investigate cooperative climate. 2010.

[22] Dai H, Mischke P, Xie X, Xie Y, Masui T. Closing the gap? Top-down versus bottom-up projections of China's regional energy use and CO2 emissions. Appl Energy 2016;162:1355–73. https://doi.org/10.1016/j.apenergy.2015.06.069.

[23] Loulou R, Goldstein G, Kanudia A, Lehtila A, Remne U. Documentation for the TIMES model- Part 1 2016. http://iea-etsap.org/index.php/documentation.

[24] Böhringer C. The synthesis of bottom-up and top-down in energy policy modeling. Energy Econ 1998;20:233–48.

[25] ETSAP. Homepage 2017. http://www.iea-etsap.org.

[26] Böhringer C, Rutherford TF, Wiegard W. Computable general equilibrium analysis: opening a black box. 2003.

[27] Petrović SN, Karlsson KB. Residential heat pumps in the future Danish energy system. Energy 2016;114:787–97. https://doi.org/10.1016/j.energy.2016.08.007.

[28] Armington PS. A theory of demand for products distinguished by place of production. Int Monetary Fund Staff Pap 1969;XVI:159–78.

[29] Thomsen T. KLEM-estimationer. 2015 (in Danish). Copenhagen.

[30] Barro RJ, Sala-I-Martin X. Economic growth. Interation. McGraw-Hill Book Co.; 1995.

[31] Hedelund Sørensen L, Petersen PM, Draborg S, Christensen K, Mortensen K, Pedersen J. Kortlægning af energiforbrug i virksomheder. 2015 (in Danish). Copenhagen.

[32] Baumol WJ, Oates WE. The theory of environmental policy. second ed. Cambridge University Press; 1988.

[33] International Energy Agency. 20 Years of carbon capture and storage - accelerating future deployment. Paris: International Energy Agency; 2016.

[34] Fortes P, Alvarenga A, Seixas J, Rodrigues S. Long-term energy scenarios: bridging the gap between socio-economic storylines and energy modeling. Technol Forecast Soc Change 2015;91:161–78. https://doi.org/10.1016/j.techfore.2014.02.006.

[35] Hartwig J, Kockat J, Schade W, Braungardt S. The macroeconomic effects of ambitious energy efficiency policy in Germany – combining bottom-up energy modelling with a non-equilibrium macroeconomic model. Energy 2017;124:510–20. https://doi.org/10.1016/j.energy.2017.02.077.