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Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport

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ABSTRACT

In this paper we have hard-linked a bottom-up energy system model (TIMES) and a top-down computable general equilibrium model (REMES) in order to analyze both the energy system impacts and the economic impacts of reducing greenhouse gas emissions from transport. We study a limitation of CO_2 emissions from transport in Norway in 2030 to 50% of CO_2 emissions in 1990. The linked approach gives new insight both in terms of the technology mix and the emissions from different transport segments, ripple effects through the economy and regional welfare effects. Furthermore, the convergence of our full-link full-form hybrid model is relevant for comparison with soft-linked approaches.

1. Introduction

The transition towards a sustainable energy system affect a number of other sectors in the economy. This has created a need to better integrate energy system models with economic modeling. We have hard-linked a bottom-up energy system model, TIMES, and a top-down computable general equilibrium (CGE) model, REMES, in order to analyze both the energy system impacts and the regional economic impacts of reducing greenhouse gas emissions from transport. In our case study from Norway, future CO_2 emissions from transport in 2030 are limited to 50% of CO_2 emissions in 1990. The first contribution of the paper is related to the policy insight which suggests how ambitious emission reductions can be achieved in the transport sector. The second contribution is on the linking methodology building a hybrid approach. Before going in detail on that, we review existing literature.

Top-down CGE models describe the whole economy, and emphasize the possibilities to substitute different production factors in order to maximize the profits of firms and satisfy market clearance conditions. The proof of existence of a general equilibrium was established in Arrow and Debreu [1]. The first successful implementation of an applied general equilibrium model without the assumption of fixed input-output coefficients was made in 1960 by Leif Johansen [2], as noted by Dixon and Jorgenson [3]. A survey of well-known CGE models for sustainability impact assessments is presented in Böhringer and Löschel [4]. The substitution possibilities between energy and other production factors are captured in production functions, which describe the changes in fuel mixes as the result of price changes under certain substitution elasticities. The smooth CGE production functions can result in violation of basic energy conservation principles. The widely used constant elasticity of substitution (CES) production function aggregates economic quantities in a nonlinear fashion, conserving value but not physical energy flows [5]. Top-down representations of technologies can also produce fuel substitution patterns that are inconsistent with bottom-up cost data [6].

Bottom-up engineering models describe energy supply from primary energy sources, via conversion and distribution processes to final energy use as well as interactions between these. In contrast to CGE models, they neglect the macroeconomic impact of energy policies, since they are partial equilibrium models and look only at

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the energy market. Another weakness is that bottom-up models are unable to capture the full economy-wide rebound effects. They can easily capture substitution of energy carriers or technologies, but cannot anticipate demand increase due to income effects [7]. Bottom-up technologies for CO_2 abatement and the use of bottom-up and top-down models is thoroughly discussed by Grubb et al. [8], and an overview of hybrid modeling to shift energy systems toward more environmentally desirable technology paths is given by Hourcade et al. [9].

Hybrid models aim to combine the technological explicitness of bottom-up models with the economic richness of top-down models [10]. This can be accomplished in different fashions. Wene classifies model linking as either (informal) soft-linking or (formal) hard-linking [11]. Böhringer and Rutherford [12] do not use the term "hard-linking", but define three categories: 1) Coupling of existing large-scale models, 2) having one main model complemented with a reduced form representation of the other, and 3) directly combining the models as mixed complementarity problems. In this paper we adopt the terms *soft-linking* and *hard-linking* as defined by Wene, where soft-linking is information transfer controlled by the user and hard-linking is formal links where information is transferred without any user judgment (usually by computer programs). Furthermore, we use the term *integrated* when the models are combined into one, instead of exchanging information between separate model runs. Thus, we classify hybrid models as shown in Fig. 1.

One early example of *soft-linking* full models is described by Hoffman and Jorgenson [13], who couple an econometric macroeconomic model with a process analysis model of the energy sector. Later studies have focused on certain sectors, such as soft-linking between ETEM and GEMINI-E3 focusing on residentials [14], and between MARKAL and EPPA focusing on transport [15]. Recent publications attempt to link all economic sectors, for example between TIMES and EMEC [16] and between TIMES and GEM-E3 [17].

Many earlier linking experiments have been able to *hard-link* the models by simplifying or narrowing the focus in one of the models to defined parts of the economy. Some well-known examples of this type are the ETA-Macro model [18], MARKAL-Macro [19], MESSAGE-Macro [20] and TIAM-MACRO [21]. These applications have simplified the top-down model, while WITCH [22] on the other hand, has a simplified energy system model. Duan et al. [23] also describe a hybrid top-down model of China, with a bottom-up technical sub-model.

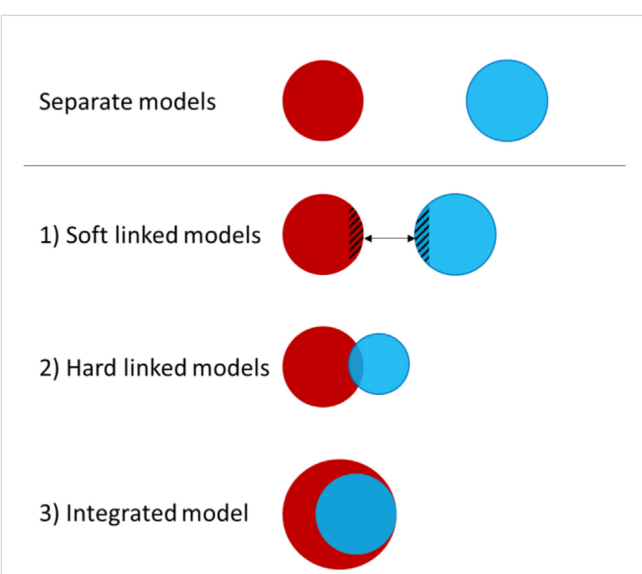

Fig. 1. Hybrid model variants.

Böhringer and Rutherford have been proponents for the *integrated* approach [10]. Böhringer [24] shows that bottom-up formulations of activity analysis can be integrated by formulating the general equilibrium problem as a complementarity problem. This type of approach was presented early by Scarf and Hansen [25], and further demonstrated by Mathiesen [26]. The approach is illustrated by Böhringer and Löschel [27], and Böhringer and Rutherford [12] present a decomposition procedure that also allows larger models to be solved. The integrated approach focuses on a selected sector in order to maintain tractability, and most contributions focus on electricity. Sue Wing [28] describes how to disaggregate the top-down representation into specific technologies in a manner consistent with the bottom-up characteristics. Proença and St. Aubyn [29] evaluate whether a feed-in tariff can be a cost-effective instrument to achieve a national target of renewable electricity generation, while Rausch and Mowers [30] examine the efficiency and distributional impacts of clean and renewable energy standards for electricity. Abrell and Rausch [31] study interactions between electricity transmission infrastructure, renewable energy penetration and environmental outcomes.

One argument for keeping the models intact instead of integrated is that top-down and bottom-up data are collected from different data sources and often with different product granulation and time resolutions. Bottom-up models focus on quantities and build on national energy balances, while top-down models deal with economic values and build on national accounts. In order to integrate models, data must be reconciled across models - which is highly advisable, but engineering and economic data are rarely consistent with each other [28]. By linking the models, we retain the consistency of each database. We keep the two models intact, and exchange relative information affecting demand, energy mix and capital growth.

Fortes et al. [17] use the terms "full-link" and "full-form" to characterize hybrid models. Full-link hybrid models cover all economic sectors, while full-form hybrid models combine detailed and extensive technology data with disaggregated economic structure. The state of the art in hybrid top-down bottom-up modeling reflected in the articles above is to use either soft-linked, full-link, full-form models, or integrated full-form models that focus on technical details in specific sectors. Our first contribution is to pursue a *hard-linked*, full-link, full-form approach, filling a knowledge gap between current state of the art practices.

In the literature above, the convergence of full-link full-form models is poorly investigated. Our approach eliminates two important drawbacks of soft-linked models: They are time and labour consuming to run, so convergence may not be tested stringently. Current state-of-the art articles have reported few iteration cycles and some observed convergence problems (see Krook-Riekkola et al. [16] section 4.1 and Fortes et al. [17] page 722, footnote 4). Whether full-link full-form models are able to reach convergence represents a knowledge gap. Our second contribution is therefore to utilize our hard-linked approach to check whether we are able to reach convergence using a full-link full-form approach.

Our third contribution is related to the case study, which is of high importance for Norwegian policy makers. While a 50% reduction of emissions from transport has been widely suggested by policy makers as a tool to meet Norwegian climate obligations [32], the feasibility and welfare effects has not been studied in the literature as far as we know. Our finding is that greenhouse gas emissions from transport may indeed be halved by transport technology investments, amounting to 6.5% reduction of income compared to a business-as-usual scenario. Regional utility reductions vary between 6.1% and 7.4% reduction of income.

As far as the authors are aware, our article represents the first hard-linking of large-scale stand-alone models employing a full-link with regional resolution and full-form bottom-up and top-down approach.

Our two models and their hard-linking is described in Section 2. Section 3 introduces the case study and presents results. We conclude in Section 4, where we also summarize the advantages of hard-linking.

2. The models and the linking

2.1. Description of the models

TIMES (**T**he **I**ntegrated **M**arkal **E**fom **S**ystem) is a bottom-up, techno-economic model generator for local, national or multi-regional energy systems [33]. A TIMES-model gives a detailed description of the entire energy system including all resources, energy production technologies, energy carriers, demand devices, and sectorial demand for energy services. The model assumes perfect competition and perfect foresight and is demand driven. The model aims to supply energy services at minimum total cost by making equipment decisions, as well as operating, primary energy supply and energy trade decisions.

A modified version [34] of TIMES-Norway [35] is used in the current work. The demand for various energy services, the techno-economic characteristics of energy technologies and resource costs and availability are given exogenously to the model. On the energy supply side, the following power production technologies are included: Hydropower (5 technologies), wind power (3 technologies), gas power with/without CCS (2 technologies), CHP plants (3 technologies) and waste heat recovery in industry (1 technology). Additionally, district heat may be generated by several different technologies (12 in total), such as oil, LPG and electric boilers. Transmission and distribution include high and low voltage grids, as well as district heating grids. The model has a wide range of demand sectors, including industry (11–14 sub-sectors per region), residentials (5 sub-sectors), services (8 sub-sectors), agriculture and transport (9 sub-sectors). The base year of the model is 2010 and the model horizon is to 2030. The time resolution covers all weeks during each year with five time-slices per week, giving 260 time-slices annually. Geographically the model covers Norway, and is divided into 5 model regions based on the pricing areas in the Nordic spot market for electricity [36]. There is exchange of electricity between regions and neighbouring countries, and the transmission capacity within and outside the model regions is given exogenously and is based on the current capacity. An overview of all energy commodities in TIMES-Norway is given in Table 8 in the Appendix.

Generally, the projected energy demand has to be given exogenously to the model [37], but due to the hard-linking of the two model approaches, the energy demand is now determined endogenously by REMES. The energy service demands of residential, service, industry and transportation are used as input to the TIMES-Norway model. The top-down model REMES is a **R**egional **E**quilibrium **M**odel with focus on the **E**nergy **S**ystem. REMES is a spatial CGE model. Consumers are demanding goods in order to maximize utility, and producers are supplying goods in order to maximize profits. A social accounting matrix (SAM) defines a benchmark equilibrium for the model. All the economic agents and goods are represented with accounts for all the economic transactions in a base year. Knowing this reference equilibrium, the model is able to adapt to shocks or policy changes like taxes, subsidies or endowment changes.

REMES focuses on the multiregional aspects, and works on the basis of fully balanced interregional SAMs with detailed interregional trade flows and transport margins. The model implementation allows for a flexible nesting structure. The nesting structure and substitution elasticities used in this study are presented in Appendix 7.2. We refer to the REMES model description in Ref. [38] for further details. The work has been inspired from several spatial CGE models such as PINGO [39], RAEM [40] and RHOMOLO [41]. Each agent in REMES is represented on the regional level, and comprise a representative household, a representative producer in each sector, a trader for each good acting according to the Armington assumption [42], a local government and a local investment sector.

We define production functions of the form ((KL)E)M in REMES (see Appendix 7.2 for further descriptions). We use elasticities as reported in Koesler and Schymura [43], but we assume a Leontief nesting of the energy goods. We refer to section 2.4, where we describe how we update the Leontief coefficients.

2.2. Design of the hard linking

Both the top-down and the bottom-up models have their own detailed databases. We keep both models intact, but have expanded them by accepting input from the other model (see Fig. 2). The exception is the adjustment of capital growth, which mandates homogenizing the absolute levels between model.

We do not attempt to define or restrict prices in REMES based on TIMES results, as done in Krook-Riekkola et al. [16] and Fortes et al. [17]. TIMES results should adjust technical aspects of REMES only.

One challenge is to define a data granulation that preserves the individual model strengths but allows an overlap enabling the linking between the models. The TIMES model gains from highly granulated data. In contrast, REMES is designed to work with aggregated data. The SAM describes an economic equilibrium where the use of production factors and available technologies are optimized simultaneously by different agents.

Preparations to accommodate hard-linking are:

1) Define data granularity for regions, sectors and commodities suitable for linking the top-down and the bottom-up model.
2) Define mappings between the model data structures (depending on step 1).
3) Describe nesting structure and substitution elasticities in top-down model (depending on step 1).
4) Preprocess top-down national accounts data to the data granularity defined in step 1.
5) Preprocess bottom-up national energy balance data to the data granularity defined in step 1.

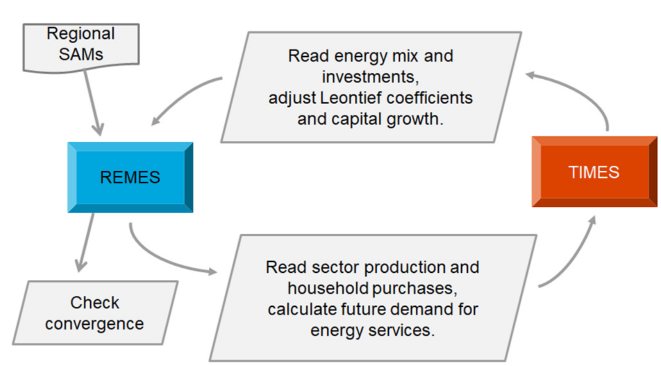

Fig. 2. Hardlinked models and mappings.

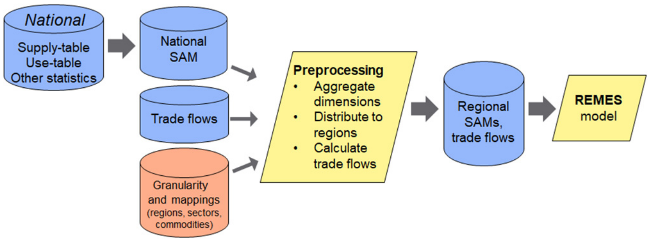

Fig. 3. Illustration of data input and preprocessing for the top-down model.

The preparation process for the top-down model is illustrated in Fig. 3.

We have defined four mappings, in order to couple the data dimensions: commodity (1 mapping), sector (2 mappings) and geographic region (1 mapping). Instructive examples of the data mappings are provided in Table 7 in the Appendix. The regions in the models are the same in our application, so the regional mapping is only necessary to link the different regional codes. Sector mappings are directional, as in Krook-Riekkola et al. [16], see Fig. 4 below.

In order to achieve a full-link, full-form and hard-linked approach, we have simplified the time dimension. We run a static version of the REMES model and assume a linear development of demand for energy services from base year to horizon year in TIMES. We harmonize time assumptions in the setup of the models, such that growth assumptions in REMES match the planning horizon in TIMES. Let us exemplify: In TIMES we have used a base year of 2010 and a horizon year of 2030, see Fig. 5. We calculate an economic shock in REMES based on yearly growth rates for capital and labour growth, provided in national projections. Let γ represent the yearly capital growth and let λ represent the yearly labour growth. In REMES we assume a capital growth equal to $(1+\gamma)^{(2030-2010)}$ and a labour growth equal to $(1+\lambda)^{(2030-2010)}$. The REMES solution for 2030 determines the demand for energy services in TIMES throughout the model period, and the TIMES solution for 2030 then determines the energy mix in REMES in 2030.

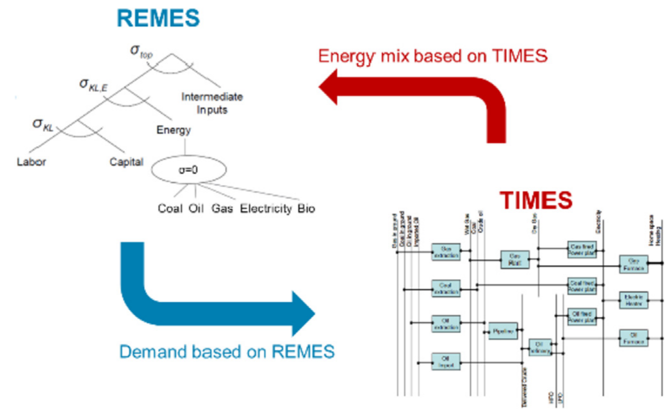

Fig. 4. Directional sector mappings.

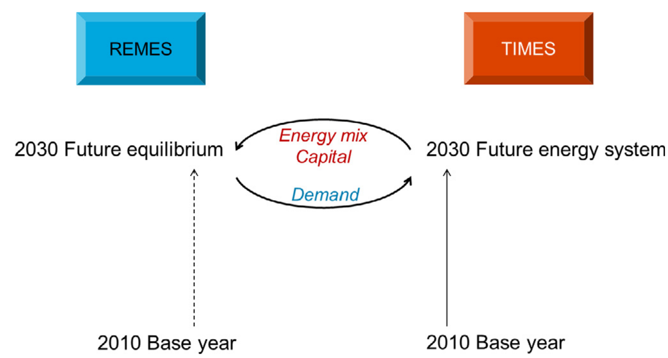

Fig. 5. Time dimension, linking the static REMES model with the dynamic TIMES model.

When a sector produces more, we assume that demand for energy services increase proportionally, keeping the same energy intensity. Assumptions about decreasing or increasing energy intensities can easily be implemented as well.

Sets	
R	regions in top-down model, indexed by r, mapped by subsets R'_r
R'	regions in bottom-up model, indexed by r', mapped by subsets R'_r
C	energy commodities in top-down model, indexed by c, mapped by subsets $C_{c'}$
C'	energy commodities in bottom-up model, indexed by c' mapped by subsets C'_c
S	sectors in top-down model, indexed by s, mapped by subsets $S_{s'}$
S'	energy service demand sectors in bottom-up model, indexed by s', enumerates relevant energy services[1]
P'	processes in bottom-up model providing energy service, indexed by p', mapped by subsets P'_s
T'	time periods in bottom-up model, indexed by t'
TS'	time-slices in bottom-up model, indexed by τ'
Mapping parameters	
$k_{s,s'}$	demand factor mapping top-down sector activity to bottom-up energy service demand
$\mu_{p',s}$	distribution of bottom-up energy use in process p' towards top-down sector s

Examples of the four mappings are provided in Section 7.5 in the Appendix.

2.3. From REMES to TIMES: energy service demand

REMES provides input about total energy demand to TIMES. We assume there are specific energy intensities for each industry in each region, measuring input of energy service per production quantity. Energy services consists of heating, cooling, electricity specific, transport and energy in the form of raw materials.

We define the following notation:

$TDem_{r',t^{base},s'}$	base year demand for energy service in bottom-up model for sector s' and region r'
$XD_{r,s}$	sector production from top-down model in region r and sector s
$HOUS_{EXP_r}$	household expenditure from top-down model in region r
$\alpha_{r',s'}$	demand growth factor based on top-down model
$TDem_{r',t',s'}$	calculated demand in bottom-up model region r', period t', energy service demand sector s'

The demand in TIMES is calculated as:

$$TDem_{r',t',s'} = TDem_{r',t^{base},s'} + TDem_{r',t^{base},s'} \cdot \alpha_{r',s'} \cdot \frac{\left(t' - t^{base}\right)}{\left(t^{future} - t^{base}\right)}$$

The demand growth factor is based on REMES:

$$\alpha_{r',s'} = \sum_{r \in R_{r'}, s \in S_{s'}} \frac{\left(XD_{r,s}^{future} - XD_{r,s}^{base}\right)}{XD_{r,s}^{base}} k_{s,s'}$$

Most TIMES demands are mapped from one relevant REMES sector acting as demand driver, and a natural default value for the mapping factor $k_{s,s'}$ is 1, retaining the same energy intensity in the future as in the base year.

In the tertiary sector we assume that new buildings in education, health and social services, hotel and restaurant, offices, wholesale and retail are expected to have lower energy demands, and these growth factors are scaled down based on regulations on technical requirements for building works. We assume that new requirements will lead to lower energy services demand, but that some buildings will also lag behind due to lack of refurbishment.

The factor $k_{s,s'}$ allows to make demand growth dependant of more than one REMES sector, and pooling these together. Values of $k_{s,s'}$ must then be scaled accordingly.

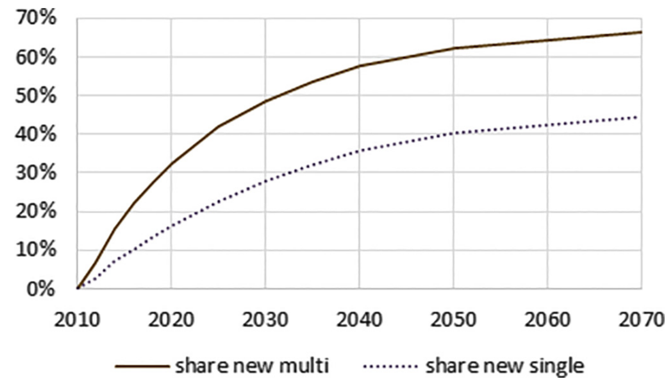

Fig. 6. Share of new buildings in building stock.

For new houses,[2] we calculate demand for heating as

$$TDem_{r',t',s'} = \left(TDem_{r',t^{base},s'} + TDem_{r',t^{base},s'} \cdot \alpha_{r',s'} \cdot \frac{\left(t' - t^{base}\right)}{\left(t^{future} - t^{base}\right)}\right) \psi_{t,s'} \phi_{s'}, \quad s' \in S'$$

For existing houses,[3] we calculate demand for heating as

$$TDem_{r',t',s'} = \left(TDem_{r',t^{base},s'} + TDem_{r',t^{base},s'} \cdot \alpha_{r',s'} \cdot \frac{\left(t' - t^{base}\right)}{\left(t^{future} - t^{base}\right)}\right) (1 - \psi_t), \quad s' \in S^{household' heating}$$

2.3.1. Households

For households we assume specific energy service intensities for each region, measuring input of energy service per household expenditure. Energy services consists of heating and electricity specific energy demand.

Household expenditure from REMES is used as driver for energy services demand in TIMES. We calculate alpha coefficients for single-family houses, multi-family houses and cottages:

$$\alpha_{r',s'} = \sum_{r \in R_{r'}} \frac{\left(HOUS\_EXP_r^{future} - HOUS\_EXP_r^{base}\right)}{HOUS\_EXP_r^{base}} k_{HOUS,s'}$$

The factor $k_{HOUS,s'}$ acts as an income elasticity. We assume heating to be a normal and necessity good with income elasticity between 0 and 1, while electricity is assumed to be a luxury good with income elasticity above 1. In this study we have assumed income elasticities of 0.99 for heating and 1.01 for electricity in existing single-family and multi-family houses.

Energy demand for heating is expected to decrease more sharply in new buildings, due to strengthened regulations and improved building techniques. We assume that heating demand decrease by 23% in new single-family houses and by 25% in new multi-family houses, captured by the two factors $\phi_{single-family} = 0.77$, and. $\phi_{multi-family} = 0.75$.

Furthermore, we assume certain shares $\psi_{t,s'}$ of new single-family and multi-family houses per year during the planning period, see Fig. 6.

Electricity-specific demand in households is calculated accordingly, only without the use of the heat specific factor ϕ.

2.3.2. Transport

TIMES focuses on transport demand groups with exogenous demand, and associated transport technologies. Demand for transport services in REMES is determined by the amount of inter-regional trade multiplied with inter-regional transport and trade margins and direct consumption of transport services by households and firms.

Demand growth factor $\alpha_{r',s'}$ is based on REMES:

$$\alpha_{r',s'} = \sum_{r \in R_{r'}, s \in S_{s'}} \frac{\left(XD_{r,s}^{future} - XD_{r,s}^{base}\right)}{XD_{r,s}^{base}} k_{s,s'} + \sum_{r \in R_{r'}} \frac{\left(HOUS\_EXP_r^{future} - HOUS\_EXP_r^{base}\right)}{HOUS\_EXP_r^{base}} k_{HOUS,s'}, \quad s' \in S^{transport'}$$

[1] H = heat, E = electricity specific, M = materials, C = cooling, T = transport.

[2] The s'index used in TIMES enumerates both energy service (heating versus electricity specific) and household type (single-family versus mult-family).

[3] We assume that refineries transform crude oil into heavy, medium and light distillates in fixed proportions.

Table 1
Transport linking demand factors from REMES to TIMES.

REMES (s)	TIMES (s')	$k_{s,s'}$ coefficient	TIMES unit
Air transport (TAIR)	Air transport (TAIRT)	1	GWh
Railway transport (TRAI)	Train transport (TPUTT)	1	GWh
Sea transport (TSEA)	Sea transport (TSEAT)	1	GWh
Agriculture (AAGR)	Other transport (TOTHT)	1	GWh
Construction (CCON)	Other transport (TOTHT)	1	GWh
Land transport (TLND)	Bus transport (TPUBT)	0.5	Mv-km [a]
Households (HOUS)	Long distance cars (TCART-L)	1.416	Mv-km
Households (HOUS)	Short distance cars (TCART-S)	1.231	Mv-km
Land transport (TLND)	Short distance cars (TCART-S)	0.05	Mv-km
Land transport (TLND)	Heavy duty freight (TFRET-H)	2	Mv-km
Land transport (TLND)	Light duty freight (TFRET-L)	2	Mv-km

[a] Million-vehicle-kilometers.

The transport linking demand factors $k_{s,s'}$ are provided in Table 1.

$$\lambda_{r,c,\mathrm{HOUS}} = \frac{\sum_{r'\in R_r, p'\in P'_{HOUS}, c'\in C_c, \tau'\in T}\left(Flo_{r',t_{future},p',c',\tau'}\cdot\mu_{p',s}\right)}{\sum_{r'\in R_r, p'\in P'_{HOUS}, c'\in C_c, \tau'\in T}\left(Flo_{r',t_{base},p',c',\tau'}\cdot\mu_{p',s}\right)}\cdot\frac{HOUS\_EXP_r^{base}}{HOUS\_EXP_r^{future}}$$

2.4. From TIMES to REMES: energy mix

We assume Leontief production technology with fixed input factors for energy inputs in the spatial CGE model. Leontief coefficients of the production functions are calibrated on the data from inter-regional SAMs.

We adjust Leontief coefficients of energy inputs in REMES, based on TIMES quantities. This adjustment constitutes a different shock to REMES (additional to growth in labour and capital). Factors for relative development of energy carriers as input to REMES production sectors and end use per region are calculated by comparing TIMES's flows of energy carriers in the future year against the base year. However, we do not adjust Leontief coefficients of the energy production sectors in the top-down model. This choice is due to the unique structure of the Norwegian SAM. We consider the various petroleum products as a cluster in the SAM.[3] Then there are few intermediate energy goods flowing between energy producing sectors. For example, electricity production in Norway is approximately 100% renewable, for the most based on hydropower. Electricity supply is independent of coal, oil and gas. This makes the Norwegian power sector independent of the rest of the energy production sectors. However, if such substitution effects are important in an economy, an update scheme for these Leontief factors may need to be implemented.

We define the following notation:

$Flo_{r',t',p',c',\tau'}$	flow of energy in bottom-up model of energy commodity c' in process p' in region r' during time period t' and time-slice τ'
$\lambda_{r,c,s}$	Leontief adjustment factor changing use of energy commodity c in sector s in region r based on bottom-up model
$cost_{adj_{r,s}}$	cost adjustment factor in top-down model, rescaling Leontief factor in order to isolate substitution effect from energy commodities
$leontief^{base}_{r,c,s}$	Leontief factor in top-down model base year SAM
$Leontief_{r,c,s}$	calculated Leontief factor in top-down model in region r of energy commodity c in sector s

Leontief adjustment factors for top-down sectors are calculated as:

$$\lambda_{r,c,s} = \frac{\sum_{r'\in R'_r, p'\in P_s, c'\in C_c, \tau'\in T}\left(Flo_{r',t_{future},p',c',\tau'}\cdot\mu_{p',s}\right)}{\sum_{r'\in R'_r, p'\in P_s, c'\in C'_c, \tau'\in T}\left(Flo_{r',t_{base},p',c',\tau'}\cdot\mu_{p',s}\right)}\cdot\frac{XD^{base}_{r,s}}{XD^{future}_{r,s}}$$

The last fraction adjusts for growth in the sector as a whole. If the use of oil in the construction sector increase by 10%, but the construction sector also grows by 10%, then the relative use of oil remains unchanged. The corresponding formula for households is shown below.

As we prefer to keep each model with data intact, we do not attempt to harmonize the data. If TIMES has zero energy flow in the base year, we still calculate a growth factor from the first intermediate year where TIMES calculates a flow. If TIMES does have energy flow in the base year but zero energy flow in the horizon year, we calculate a zero factor as input to REMES – as opposed to the situation where TIMES does not use the energy carrier and we do not use an adjustment factor in REMES (a zero value operates differently from no value.) If TIMES does not have a flow in either the base year or the future/horizon year, we do not consider flows in intermediate years and avoid any adjustment on the corresponding Leontief-factor that might exist in REMES.[4] If TIMES utilizes an energy flow in the horizon year only, we assume a λ growth factor value of 2.

Energy flows in TIMES may evolve from a marginal level, and produce high λ growth factor values, which may cause problems in REMES. If the shock is too severe, REMES may fail to find a solution. We limit the λ growth factor to a value of 400.

The calculations described thus far will adjust the regional

[4] We have experienced cycling behavior during iterations when we adjust Leontief factors in such situations.

Table 2
Mapping energy use from transport processees in TIMES to REMES sectors.($\mu_{p',s}$).

TIMES process	REMES sectors			
Bus transport (TPUB*)	100%	Land transport (TLND)	–	(n.a.)
Train transport (TPUT*)	100%	Land transport (TLND)	–	(n.a.)
Sea transport (TSEA*)	100%	Sea transport (TSEA)	–	(n.a.)
Other mobile combustion (TOTH*)	67%	Agriculture (AAGR)	33%	Construction (CCON)
Air transport (TAIRT*)	99%	Air transport (TAIR)	1%	Households (HOUS)
Heavy freight (TFRET*-H)	100%	Land transport (TLND)	0%	Households (HOUS)
Light freight (TFRET*-L)	99%	Land transport (TLND)	1%	Households (HOUS)
Short distance cars (TCART*-S)	15%	Land transport (TLND)	85%	Households (HOUS)
Long distance cars (TCART*-L)	1%	Land transport (TLND)	99%	Households (HOUS)

energy mix for each sector, and produce both substitution effects and income effects. Our primary aim is to capture the changed energy mixtures. We rescale the costs of the adjusted energy mix to become equal to the costs of the original energy mix, in order to isolate the substitution effects.

$$cost\_adj_{r,s} = \frac{\sum_{c\in C}\left(leontief^{base}_{r,c,s}\right)}{\sum_{c\in C}\left(leontief^{base}_{r,c,s}\cdot\lambda_{r,c,s}\right)}$$

$$Leontief_{r,c,s} = cost\_adj_{r,s}\cdot\lambda_{r,c,s}\cdot leontief^{base}_{r,c,s}$$

Regarding autonomous energy efficiency improvements (AEEI), REMES rely on TIMES data input on expected new future technologies and exploit TIMES results to capture future relative use of energy carriers. In this study we focus on substitution effects, and employing income effects from the adjusted energy mix is left for future research.

Transport in REMES is modelled differently from TIMES. REMES focuses on commercial transport, while household own production of transport is not captured by any other value transfer than fuel demand. Some energy flows in TIMES serves processes (for example transport technologies) which naturally belong to multiple sectors in REMES. We assume for example that most long-distance car transport (99% of the kilometres) in TIMES are demanded by households in REMES, while 15% of short distance car kilometres are driven as part of land-based commercial transport in REMES. Table 2 shows mapping of transport related energy flows from TIMES processes to REMES sectors.

In this study we put the policy goal[5] into TIMES as a restriction, which triggers higher investments. We assume that the investment increase reduces capital growth in REMES accordingly.

We define the following notation:

$KS^{base}_{r,s}$	capital income in top-down model in region r and sector s in base year
$ncapcost_{r',t',p'}$	capacity investment cost in bottom-up model for process p' in time period t' and region r'
$CapitalRemes_r$	estimated capital value in bottom-up model in region r
$NCAP_{r',t',p'}$	capacity investments in bottom-up model region r' time period t' process p'
$shockadj^{CO2K}_r$	calculated capital growth adjustment factor in top-down model for region r

Our social accounting matrix (SAM) holds capital income by region and sector in the base year ($KS^{base}_{r,s}$). The perpetuity value of the capital income would overestimate the capital value, and we add a factor κ to adjust for capital depreciation:

$$CapitalRemes_r = \frac{\sum_s KS^{base}_{r,s}}{df\cdot\kappa}$$

where df is the real discount factor used in TIMES. We assume $df = 4\%$ and $\kappa = 2$, these values produce a coarse capital estimate which corresponds with national estimates of real capital and net national wealth per capita.[6] For a discussion of discount rates in energy system models, see Garcia et al. [44].

We calculate adjustment factors for capital shocks in REMES based on TIMES investments like this[7]:

$$shockadj^{CO2K}_r = \frac{CapitalRemes_r - \sum_{r'\in R_r, t'\in T, p'\in P} ncapcost_{r',t',p'}\left(NCAP^{CO2K}_{r',t',p'} - NCAP^{BAU}_{r',t',p'}\right)}{CapitalRemes_r}$$

2.5. Linking capital from TIMES to REMES

Changes in Leontief coefficients are typically favourable, meaning that less energy input is required to achieve the same production as before due to expected technological progress. These improvements require investments into capital stocks of the production sectors. Linking TIMES investments and REMES capital stocks requires absolute instead of relative levels. We must establish a harmonized baseline of capital stocks between the models, and we make the assumption that the scale of investments in a business as usual (bau) scenario is compatible with the capital stocks growth of REMES.

2.6. Convergence

We calculate the relative change of variable values between iterations, and compares it against a chosen tolerance. If all changes are below the tolerance, the iterations have converged. Examples for commodity prices and sectoral output are shown below (where

[5] Reducing CO_2 emissions from transport.
[6] Long-term Perspectives on the Norwegian Economy 2013, white paper from Norwegian Ministry of Finance.
[7] For simplicity, we have not displayed currency indexes in the formula, as we only use one currency in this study.

index i indicates iteration number).

$$\text{Commodity prices: } \max_{r,c}\left(\frac{\left|P^{i}_{r,c}-P^{i-1}_{r,c}\right|}{\left(P^{i-1}_{r,c}\right)}\right) \leq \text{tolerance.}$$

$$\text{Sectoral output: } \max_{r,s}\left(\frac{\left|XD^{i}_{r,s}-XD^{i-1}_{r,s}\right|}{\left(XD^{i-1}_{r,s}\right)}\right) \leq \text{tolerance.}$$

We calculate the relative change of the following variables, to assess whether iterations have converged with tolerance 10^{-5} (see Fig. 14): Commodity prices, sectoral output, household consumption, sectoral labour use, price of labour, price of capital, total energy system cost, consumer welfare, public welfare, investor welfare as well as hicksian prices of consumer welfare, public welfare and investor welfare.

3. Analysis and results

3.1. Scenarios and data

In our analysis we restrict emissions of CO_2 from transport in 2030 to 50% of CO_2 emissions in 1990, corresponding to suggestions by National transport agencies [32].

The CO_2-restriction is imposed in TIMES, and mandates the use of new technologies and energy carriers. We run a business-as-usual scenario (*bau*) without the CO_2-restriction, and a CO_2-reduction scenario (*co2*) with the naïve assumption that TIMES investments do not affect available capital growth in REMES. We run a third scenario (*co2k*) where we restrict CO_2 emissions and make the assumption that TIMES investments exceeding those in the *bau* scenario will reduce available capital growth in REMES.

The *co2k* scenario resembles a techno-optimistic policy where national authorities finance technological shifts to reach the common target of the society, while societal actors can behave as before. These technological investments demand capital, which could have served society better if used alternatively. In the *co2k* scenario we calculate Hicksian compensating variation per region, to quantify the amount of additional income households would mandate to compensate for their utility loss compared to the *bau* scenario.

The current policy for zero emission vehicles in Norway shares important characteristics of the *co2k* scenario. Government has provided powerful financial incentives: Battery electric vehicles and fuel cell electric vehicles are exempt from registration tax, value added tax and road tolls, pay a lower annual fee, are allowed to drive in the bus lane, enjoy free parking in municipal car parks and run free on ferries [45]. A thorough review of Norwegian incentives is provided by Figenbaum et al. [46].

We also compare stand-alone TIMES solutions based on exogenous demand with the hard-linked iterative TIMES solutions. Exogenous demand for energy services are taken from the CenSES national energy demand projection (see Ref. [47]).

3.1.1. Growth assumptions

We have used expected yearly growth rates for capital and labour from the government white paper “Long-term Perspectives on the Norwegian Economy 2013”, and regionalized these according to Statistics Norway's official population projection (MMMM).

3.1.2. The continental shelf

Norway has an extensive production of oil and gas from the continental shelf, with high production, no households and highly specialized transportation needs. We have chosen to attach the continental shelf to the northern region of Norway, as this is the outermost region with the lowest population. Our results are presented without this combined region, but full results are available in a downloadable Appendix.

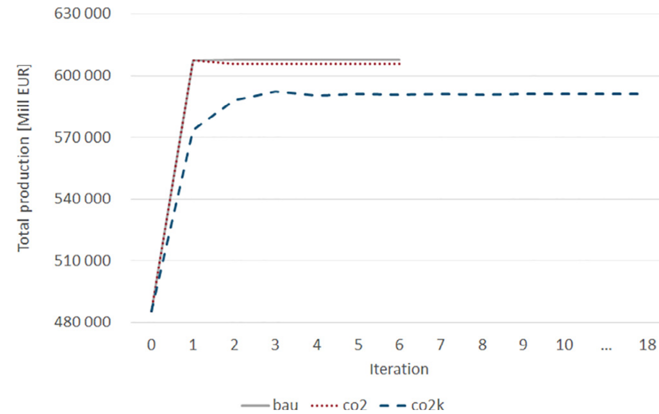

Fig. 7. Value of total production in 2030 in REMES by scenario per iteration (iteration 0 shows production in base year 2010 for comparison).

3.2. Results

Fig. 7 shows that changes in energy mix from scenario *bau* to *co2* has a small impact in the REMES model, and that few iterations are needed to reach convergence. Linking capital investments in scenario *co2k* has larger impacts, and more iterations (18 compared to 6) are required to achieve convergence. REMES calculates a significant growth in total yearly production from the base year (represented by iteration 0) to iteration 1, reflecting the changes between year 2010 and 2030. The production growth in our scenarios *bau* and *co2* are quite similar. The only difference in REMES between these scenarios is the energy mix feedback from TIMES. In scenario *co2k* investments in TIMES reduce available capital growth in REMES. Having less available resources reduces production potential, household income and demand for goods and services, and the value of total production decreases by 2.8% compared to *bau*. This reduction influences the demand for energy services in TIMES and the total energy system costs, which Figs. 7 and 8 show.

Fig. 8 shows total system costs in TIMES, which grows considerably from the *bau* to the *co2* scenario while the *co2k* scenario ends somewhere in between. The constraint on CO_2 emissions from transport leads to higher investments in new technologies in TIMES. In scenario *co2k* these investments reduce production in REMES. Then demand for energy services decreases, and energy system costs in scenario *co2k* decrease compared to *co2*.

The capital linking provides important feedback and causes oscillations between the models. Total production in REMES (Fig. 7) and energy system costs in TIMES (Fig. 8) appear to be inversely correlated in scenario *co2k*, because increased costs in TIMES limit the growth in REMES.

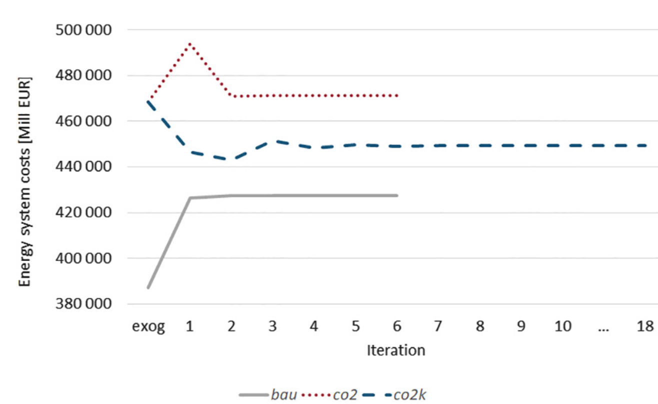

Fig. 8. Total aggregated energy system costs in TIMES by scenario per iteration (the first iteration is based on exogenously given demand).

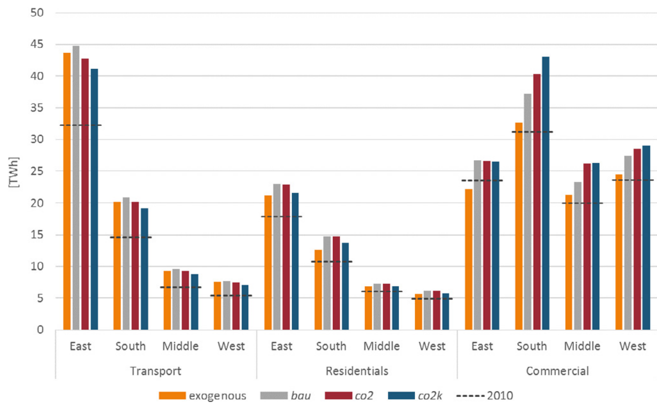

Fig. 9. Projected demand for energy services in 2030 per scenario, region and aggregated sector, compared to 2010 (TWh).

In the first iteration (exog), energy service demand is given exogenously to TIMES from a national projection. We see that energy system costs increase significantly in iteration 1 in both *bau* and *co2*. The reason is that demands derived from REMES are higher than the exogenous demand in these scenarios, as we will see in Fig. 9.

System costs in the *co2* scenario bounce back in iteration 2, due to changes in energy mix that REMES recognizes at this point. Further iterations appear to produce small movements after iteration 2 in scenarios *bau* and *co2*. This shows that energy mix feedback from TIMES to REMES has effects, but they are minor compared to the effects from the capital linkage. Keep in mind that we rescale Leontief coefficients to avoid income effects from the revised energy mix. We have seen that introducing such income effects have greater impacts than the isolated substitution effects of energy carriers.

3.2.1. *Energy service demand*

Fig. 9 illustrates the demand in 2030 for the three main scenarios as well as the exogenous projection, divided into transport, residential and commercial (consisting of primary sector, manufacturing and services). In the *bau* scenario, the demand is higher than the exogenous projection in all sectors and all regions. In the *co2* scenario, the transport demand is reduced compared to *bau*, and the demand is reduced even further in the *co2k* scenario. For the residential sector, the demand in the converged solution is more or less identical in the *bau* and *co2* scenarios, which is higher than the exogenous projection. The *co2k* scenario experiences a slight increase in all regions for the residential sector compared to the exogenous projection.

For the primary sector, manufacturing and services (labelled "commercial" in Fig. 9), the demand increases in all the scenarios compared to the exogenous projection. This can especially be seen in region South, but the increase is also significant in the other regions.

One might ask how demand for energy services in the commercial sector can increase going from *bau* to *co2* and *co2k*? CGE models are highly nonlinear, and our application includes many adjustments happening jointly. These adjustments lead to diverse effects across sectors and regions. The demand for energy services does not follow directly the aggregated production in REMES, since 1) activity levels and prices in disaggregated sectors shift differently and 2) sectors have different energy intensities. Total demand for energy services in fact increases from *bau* to *co2*, even though production decreases. One reason is that the price of several energy carriers decreases.

Table 3
Regional growth rates for labour and captial.

Region	2010 population	2030 projection	Labour growth 2010–2030	Capital growth 2010–2030
East	2 000 176	2 560 530	18%	53%
South	1 181 781	1 489 341	16%	50%
Middle	670 073	814 900	12%	45%
West	530 408	658 994	15%	48%
North	445 333	486 861	1%	30%
Total	**4 827 771**	**6 010 626**	**15%**	**49%**

Since CO_2 emissions from transport are constrained in the *co2* and *co2k* scenarios, the transport sector has to invest in new technologies. The transport energy mix shifts to new and more expensive energy carriers without emissions. Fossil energy carriers on the other hand get cheaper, creating growth opportunities in other sectors.

As shown in Table 3, we assume a higher capital growth than labour growth. The price of capital decreases, while the price of labour increase. Capital intensive manufacturing sectors are able to grow more than labour intensive service sectors. The commercial sectors with highest growth are aluminium, chemicals and metals. These sectors are also energy intensive, and are the main reasons that demand for energy services increases.

Furthermore, we assume that the capital growth is given per region, and transport investments hit different regions with different strength (see Table 5 in the Appendix).

Table 5 in the Appendix shows that the South region is the relatively least affected by the investments in transport technologies, and thus has relatively more capital growth left to spend in the economy. Region South increases activity in energy intensive sectors, and this leads to the significant increase in energy demand in Fig. 9.

This kind of response may at first be considered counter-intuitive. In our opinion these results are a good example that a hybrid top-down and bottom-up approach may provide new knowledge.

3.2.2. CO_2 *emissions*

Fig. 10 shows the CO_2 emissions in 2030 from the transport sector in the three scenarios. Emissions based on exogenous demand and the converged solution as well as the first three iterations are included. As seen, the emissions in 2030 are restricted in

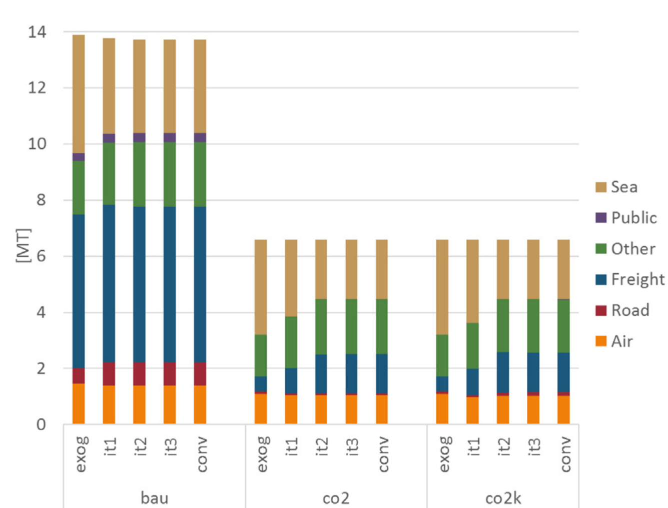

Fig. 10. CO_2 emissions from transport in 2030.

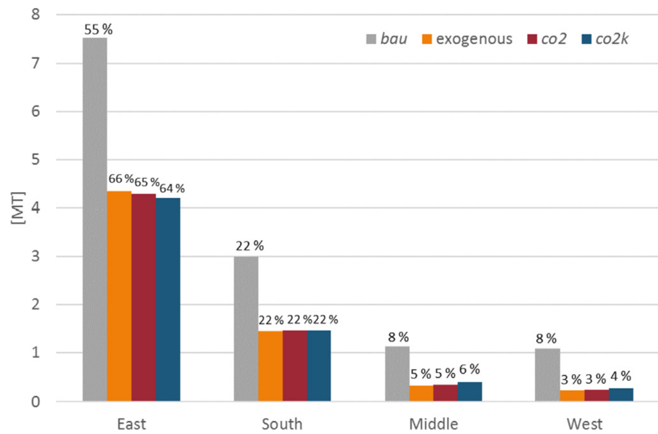

Fig. 11. CO_2 emissions from transport in 2030 by region (converged solution). Relative figures (above bars) indicate regional contribution for the respective scenario.

both of the CO_2 reduction scenarios. The total national emissions related to transport are reduced to 6.6 Mt in 2030.

For both of the CO_2 reduction scenarios, the same trend is observed during the iterations. In the exogenous demand solution, emissions from sea transport account for approximately 50% of the total emissions. In the linked approach, emissions from other transport modes are highest, followed by sea transport. As seen, CO_2 emissions from freight transport increase during the iterations. There are relatively small differences between the *co2* and the *co2k* scenario. The former has slightly higher emissions from air and other, whereas the *co2k* scenario has higher emissions from road transport (i.e. cars).

In the *bau* scenario, the total national emissions decrease slowly from 15.6 Mt to 13.7 Mt in 2030. The reason for this reduction is that several new transport technologies are being used in the *bau* scenario, reducing the use of e.g. conventional diesel and gasoline engines.

Regional CO_2 emissions in 2030 from the transport sector are illustrated in Fig. 11. 55% of the emissions in the *bau* scenario are related to transport activity in the east region, followed by 22% in region south. The solution based on exogenous demand allows region East to emit more CO_2 than the two hard-linked solutions, while the other regions show an opposite pattern.

3.2.3. *Energy system investments*

Fig. 12 illustrates energy system investments in transport technologies in the planning period. The upper part shows investments that only occur in the CO_2-constrained scenarios, while the lower part shows the largest investments in *bau* as well. It is evident that

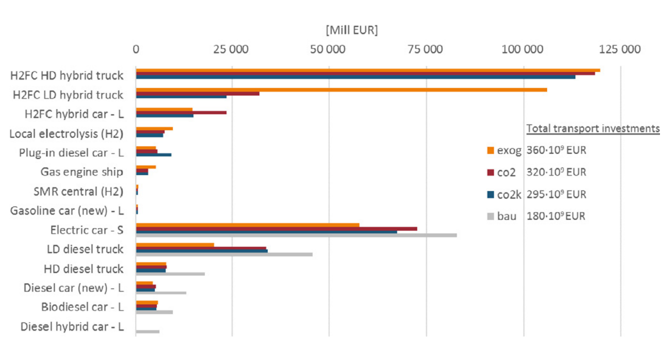

Fig. 12. Total transport investments comparing the CO_2 constrained scenarios with the bau scenario (H2FC = hydrogen fuel cell, HD = heavy duty, LD = light duty, L = long distance and S = short distance).

the CO_2-constraint triggers large investments.

In the CO_2-constrained scenarios, a massive increase in the use of hydrogen based light (LD) and heavy duty (HD) trucks are experienced. At the same time, the use of conventional diesel trucks is reduced. For heavy duty freight transport, massive investments in hydrogen vehicles occur in 2030, whereas for light duty trucks, the investments include a combination of gasoline, diesel and hydrogen vehicles. Another main difference between *bau* and the CO_2 constrained scenarios is the reduced use of diesel for long distance car travels. The majority of the traditional diesel cars are replaced by investing in either plug-in hybrid diesel cars or hydrogen fuel cell cars. As seen in Fig. 12, increased investments are also experienced in various hydrogen production technologies like electrolysis (mostly) and steam reformation of natural gas. In the *co2k* scenario, all hydrogen investments are made in 2030, whereas *co2* and *exog* starts in 2020 with hydrogen long distance cars and reformation of natural gas. A reduction in investments in electric vehicles for short distance travels is seen in the CO_2 constrained scenarios. This is due to reduced demand for short distance travels, and not because other technologies are being used.

Fig. 12 shows that in the CO_2-constrained solution based on exogenous demand (*exog*), hydrogen based light duty trucks are used heavily. Transport investments in *exog* are 65 000 million Euro higher than in *co2k*. This is an indication that estimated investment costs based on inflexible exogenously given demand projections could vary greatly.

3.2.4. *Regional welfare analysis*

Our models do not directly calculate environmental benefits from reaching the policy goal of reduced CO_2 emissions, they only assess economic costs of such policies. This means that we would need to compare the economic costs with the environmental benefits for full societal cost-benefit analysis of the policy scenarios. Here we use the Hicksian compensating variation (CV) [48] as a monetary measure of welfare loss. The CV takes the *co2k* equilibrium incomes and prices, and calculates how much income must be added in order to keep households at their *bau* utility level. Because our utility function is linear homogenous, the Hicksian compensating variation is computed as

$$CV_r = \frac{\left(U_r^{bau} - U_r^{co2k}\right)}{U_r^{co2k}} I_r^{co2k}$$

Table 4 shows that the East region has the highest compensating variation, but its welfare loss as a percent of income is lowest of all. Regions South and West experience the highest welfare losses, compared to the *bau* scenario. Interestingly, the Middle region that loses the highest share of its capital growth still suffers less than the South and West regions.

We are able to track the CV during iterations, as shown in Fig. 13.

Welfare losses are substantially higher during the first iterations. Eventually the hard-linked models converge to an equilibrium, where region South in particular has reduced its welfare loss compared to the initial iterations.

Welfare losses in the *co2k* scenario are corresponding to 6.5% of the household income in the *bau* scenario. These figures may seem high. One reason is our conservative choice regarding the costs of the adjusted energy mix. In this study we rescaled the costs of the adjusted energy mix to become equal to the costs of the original energy mix, in order to isolate the substitution effects and neglect uncertain income effects from autonomous energy efficiency improvements (AEEI).

Comparing scenarios *co2* and *co2k* suggests however that income effects provide greater impacts than substitution effects. We

Table 4
Hicksian compensating variation (CV) per region.

Region:	East	South	Middle	West	Total
Household utility					
Bau	1.514	1.629	1.434	1.490	(n.a)
co2k	1.421	1.507	1.341	1.380	(n.a)
Price of utility					
Bau	1.032	1.037	1.020	1.025	(n.a)
co2k	1.023	1.027	1.010	1.015	(n.a)
Income [*mill EUR*]					
bau	94 295	27 892	22 450	21 290	165 928
co2k	87 739	25 544	20 788	19 523	153 594
Hicksian Compensating Variation [*mill EUR*]	5 750	2 066	1 442	1 569	10 826
Hicksian CV as share of *bau* income	6.1%	7.4%	6.4%	7.4%	6.5%

suggest that AEEI improvements in the top-down model could be assessed based on results from the technologically more detailed bottom-up model. Preliminary experiments have indicated that income effects from energy efficiency improvements in the bottom-up model are significant, but these results require further investigations which fall outside the scope of this study and is left for future research.

3.2.5. Convergence

Fig. 14 shows convergence results from the three scenarios. Each scenario run reaches the chosen tolerance set at 10^{-5} as the largest relative variable deviation between iterations.

The *bau* and *co2* scenarios reach convergence faster than the *co2k* scenario, which also links capital growth. The first two scenarios reach convergence after 6 iterations, whereas *co2k* needs 18 iterations. Computer running times are provided in Appendix 7.4.

We have observed situations where convergence was not reached because of cycling due to two different reasons:

- Macro level: The top-down model found different equilibria, and alternated between these in different iterations. Convergence could be reached or not, depending on starting points and how the solutions progressed during iterations. We were able to avoid this behavior by removing one unintended degree of freedom to the model and narrow down the solution space to one unique equilibrium. Still, the general problem class does not rule out the possibility of non-uniqueness, in which case the top-down model might find alternative equilibria.
- Micro level: Leontief coefficients could alternate between iterations, creating oscillation. This phenomenon was avoided by generalizing the Leontief adjustment calculation, capturing situations where an energy carrier went out of the energy mix, and then returned into the mix due to an undefined Leontief adjustment factor.

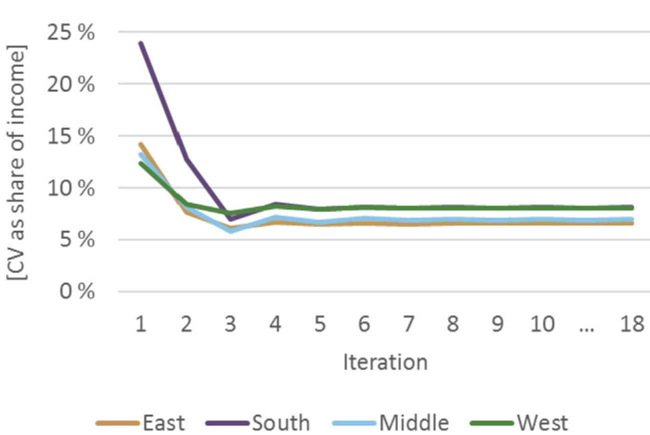

Fig. 13. Compensating variation per region and iteration.

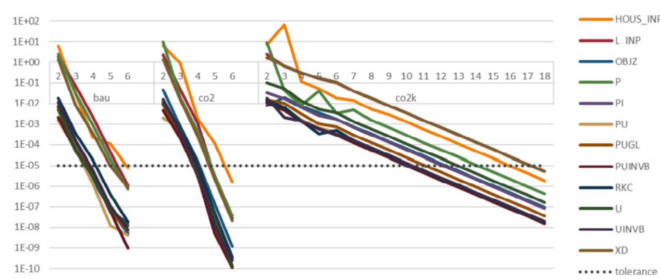

Fig. 14. Largest relative variable deviations per scenario until convergence.

An important strength of our hard-linked approach is the ability to detect such situations. First, whether most CGE models possess a unique equilibrium or whether multiplicity usually simply goes undetected is an open question [49]. Second, iteratively updating the models may lead to unanticipated responses with unrealistic effects, which are desirable to detect and prevent.

4. Conclusions

We have implemented hard-linking between a computable general equilibrium complementarity model (REMES) and an energy systems model (TIMES). This enables us to define sectoral energy policy measures and investigate ripple effects through the economy and regional welfare effects. The methodology developed in this paper represents a general and robust linking between top-down and bottom-up models using a full-link full-form approach.

Soft-linking will often lead to lower data granularity, and manual procedures will typically limit the number of iterations, resulting in less rigid convergence criteria. In this study using hard-linking, we were able to achieve stable convergence with a low tolerance of 10^{-5}. Earlier soft-linked full-link contributions have reported partial lack of convergence. Our hard-linking approach also exposed many convergence challenges. Initially we observed situations with multiple equilibria in the REMES model. These situations exposed model errors, which could otherwise easily go undetected. We have observed different kinds of cycling behavior during iterations, which we have been able to avoid by adjusting the model and the linking calculations. Our full-link full-form hard-linking avoids human judgment and error, ensures replicability and speeds up scenario testing tremendously. It also exposes iterative challenges like cycling behavior, permits stringent convergence requirements, and increases the likelihood of detecting any multiple equilibria.

We have demonstrated this methodology on a study of the relations between the transport sector, the energy system and the regional economy using the models REMES and TIMES, with a target of decreasing climate gas emissions by 50% from the Norwegian transport sector compared to 1990. The target is reached by making technology investments in hydrogen vehicles. The considerable technology investments consume capital and limit the capital stock growth, decreasing the value of total production in 2030 by 2.8%. The decrease in household welfare corresponds to a 6.5% salary reduction.

The linking provides model harmonization, producing results that are consistent across both the bottom-up and top-down model.[8] The linking is also essential for levelling out regional welfare reductions. There are large regional welfare differences during the first iterations, and it takes several linking iterations before the regional effects stabilize.

The energy system costs from technology investments depend heavily on the demand differences in the various scenarios. This observation indicates that it would be relevant to extend the analysis with alternative policy options directly affecting demand, for example transport taxes or fuel taxes.

A promising area for further research is to assess autonomous energy efficiency improvements in the top-down model based on results from the technology rich bottom-up model in the linking procedures. Changes in the energy mix may then lead to important income effects as well as substitution effects in the top-down model. Integration of these effects provide an interesting area for future research, and availability of hard-linked models will greatly improve our ability to do so.

Acknowledgements

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Appendix

7.1. E3 and integrated assessment models

Top-down and bottom-up models in general belong to the broader class of energy-economy-environment (E3) models [17,50], together with integrated assessment models (IAM) [51] which also should be mentioned here as a hybrid model approach. A broad definition is that IAMs integrate knowledge from two or more domains into a single framework [52], but the typical aim is to combine the scientific and economic aspects of climate change in order to assess policy options for climate change [53]. IAMs usually consists of many hard-linked modules [54], not only bottom-up and top-down.

7.2. Nesting structure

Nesting structures are commonly grouped into KLEM branches, where KLEM stands for Capital, Labour, Energy and Materials [55]. The two major forms of substitution structures are the ((KE)L)M and the ((KL)E)M forms [56], see Fig. 15.

The nesting variants (KE)L, (KL)E and (EL)K are compared for the German industry in Kemfert [57] and Kemfert and Welsch [58]. The (KE)L nesting is chosen for the entire German industry, while (KL)E nesting is more realistic for most individual industrial sectors. All nesting structures are also systematically compared in van der Werf [55], who concludes that the (KL)E nesting structure fits the data best. The same (KL)E nesting structure is used in Koesler and Schymura [43]. Data from the World-Input-Output-Database (WIOD) is utilized to estimate a consistent dataset of substitution elasticities for the three-level nested KLEM production structure covering 35 industries. The elasticities are estimated by nonlinear estimation techniques. Relevant elasticities are compared with elasticities from van der Werf [55], Okagawa and Ban [56] and Kemfert [57].

We use elasticities reported in Koesler and Schymura [43], but we assume a Leontief nesting of the energy goods (substitution elasticities are assumed to be zero). Both the top-down and the bottom-up model assume a region- and sector specific production structure. The regional Leontief coefficients for energy goods are adjusted on the basis of regional energy quantities calculated in the bottom-up model TIMES.

7.3. Effect of capital linking in co2k

Energy system investments in TIMES are significantly higher in the CO_2 reduction scenarios than the *bau* scenario, as shown in Table 5. Total investment costs are EUR 177 million in the *bau* scenario, while investments increase to EUR 296 million in the *co2* scenario. This bottom-up increase in investments affects capital growth in the top-down model. REMES decreases demand and investments revert to EUR 275 million in the *co2k* scenario.

The regions have different base year levels of capital, and the investment needs from the bottom-up model shown in Fig. 16 have different regional damping effects on capital growth.

Fig. 17 shows regional capital growth adjustments in REMES due to investments in TIMES.

The East region has the largest capital base, and region South has the lowest growth of TIMES investments. Both regions have smaller decreases in capital growth than the other regions, as Fig. 17 shows. Regions Middle and West have similar capital bases, but TIMES investments are larger in the Middle region. This region has the largest drop in capital growth. We also see in Fig. 17 that this region has the largest fluctuations during the model linking iterations. Fig. 18 shows how the cost of capital depends on the capital stock growth adjustments. The cost of capital is low during the *bau* iterations, since the full capital stock growth is available in REMES. When capital is consumed for technical investments in TIMES, the cost of capital is affected inversely. In the next section we look at the regional welfare consequences.

7.4. Computer runtime

Computer runtime on a Dell Precision T7600 with two Intel Xeon CPU E5-2650 2 GHz processors are shown in Table 6.

7.5. Data mappings

Table 7 shows instructive examples of the data mappings.

Table 8 show complete mapping between energy commodities in TIMES and REMES.

Table 9 lists the sectors in REMES.

Table 10 lists the commodities in REMES.

[8] The supply of energy services from the bottom-up model is consistent with the demand in the top-down model, and the energy mix in the top-down model is consistent with the supply in the bottom-up model.

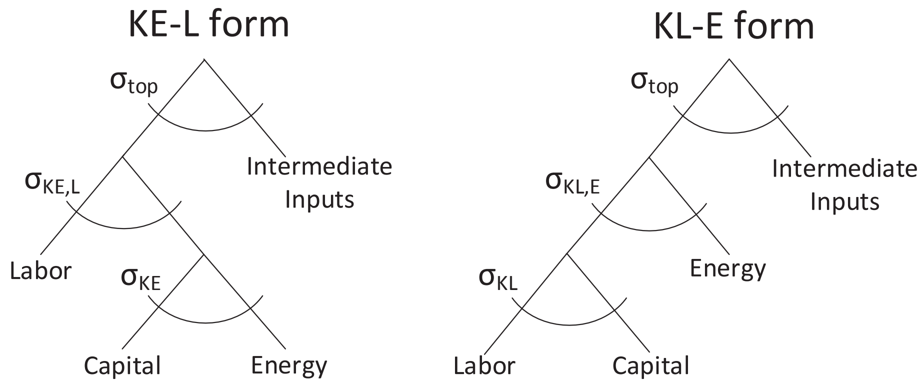

Fig. 15. Two major forms of substitution structures (see Okagawa and Ban [56] Fig. 2).

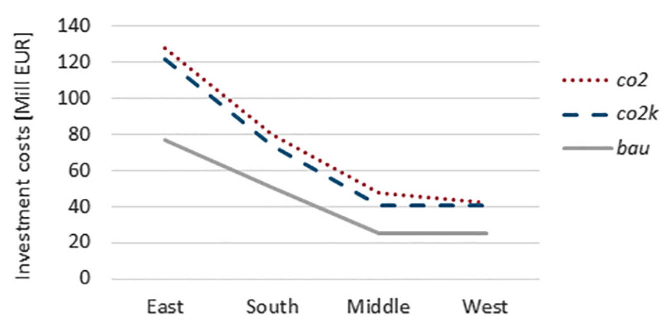

Fig. 16. Regional bottom-up investment costs per region by scenario.

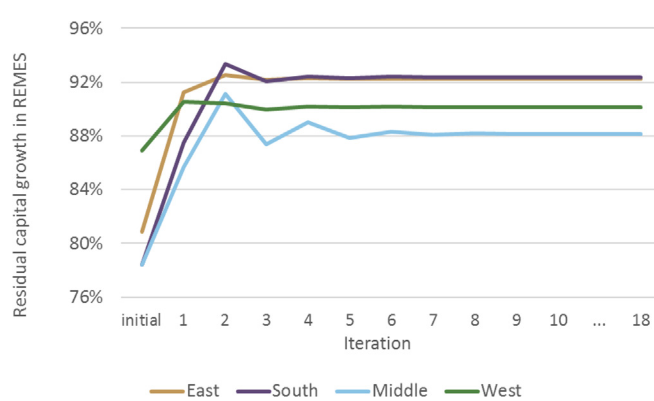

Fig. 17. Regional capital growth adjustments in REMES due to investments in TIMES (*co2k* scenario).

Fig. 18. Cost of capital per region for *bau* and *co2k* scenario.

Table 5
Regional investment costs in bottom-up model [million Euro].

	bau	*co2*	*co2k*	Increase from *bau* to *co2k*
East	76.6	127.4	121.1	58%
South	50.5	79.4	73.3	45%
Middle	25.0	47.2	40.4	62%
West	25.2	41.9	40.3	60%
Grand Total	**177.3**	**296.0**	**275.1**	**55%**

Table 6
Computer running times.

Scenario	Total run time	Top-down run time	Bottom-up run time	Top-down share	Bottom-up share	Iterations	Minutes per iteration
bau	2 h 52 m	0 h 06 m	2 h 46 m	3.5%	96.5%	6	29
co2	3 h 05 m	0 h 06 m	2 h 59 m	3.2%	96.8%	6	31
co2k	8 h 53 m	0 h 19 m	8 h 34 m	3.6%	96.4%	18	30

Table 7
Mapping of data structures.

id	Mapping	TIMES bottom-up (example)	REMES top-down (example)	Coef-ficient
a)	Regions $R_{r'}$ and R'_r TIMES regions towards REMES regions (5 mappings in total)	NO1	R1	n/a
		NO2	R2	n/a
		…	…	
b)	Energy commodities $C_{c'}$ and C'_c TIMES energy commodities mapped towards energy commodities in REMES. (50 mappings)	NG-L	c_NG	n/a
		NG-LPG	c_NG	n/a
		…	…	n/a
		BIO-PEL	c_BIO	
c)	Sectors TIMES→REMES $\mu_{p',s}$ TIMES processes (demand devices) mapped towards REMES sectors. (519 mappings)	CEDUH001 (oil boiler, education)	i-CEDU	100%
		CEDUH002 (natural gas boiler, education)	″	100%
		…	HOUS	85%
		TCART401-S (Gasoline car short distance) "… TOTHT400 (Fuels for transport use - other mobile combustion)"	i-TLND	15%
			i-AAGR	67%
			i-CCON	33%
d)	Sectors REMES→TIMES $k_{s,s'}$ TIMES energy services in demand sectors mapped towards REMES sectors (83 mappings)	COFFE (electricity demand in commercial offices)	i-COFF	0.703
		COFFH (heating demand in commercial offices)	″	0.535
		…	HOUS	1.231
		TCART-S (Personal Cars Short Distance)	i-TLND	0.05
		"… TOTHT (Other mobile combustion)"	i-AAGR	1.0
			i-CCON	1.0

Table 8
Mapping of energy commodities.

TIMES commodity	TIMES description	REMES commodity	REMES description
ELC-HP	Electricity High Voltage: From unregulated hydro	c_POW	Electricity
ELC-HV	Electricty High Voltage	c_POW	Electricity
ELC-LV	Electricty Low Voltage	c_POW	Electricity
ELC-LV-LOSS	Electricity Low Voltage: Losses in grid	c_POW	Electricity
ELC-LV-LOSS-DEMAND	Demand for LV-losses in grid (dummy)	c_POW	Electricity
ELC-WP	Electricity High Voltage: From wind power	c_POW	Electricity
BIO-BAR	Bark	c_BIO	Bio-energy
BIO-BLI	Black liqour	c_BIO	Bio-energy
BIO-COAL	Bio-Coal	c_BIO	Bio-energy
BIO-COKE	Bio-Coke	c_BIO	Bio-energy
BIO-DSL	Biodiesel (2. gen)	c_BIO	Bio-energy
BIO-ETN	Ethanol (E85)	c_BIO	Bio-energy
BIO-FOR	Biomass from forrestry	c_BIO	Bio-energy
BIO-MWS	Municipal waste	c_BIO	Bio-energy
BIO-OILI	Syntetic biomass oil, industrial use	c_BIO	Bio-energy
BIO-OILS	Syntetic biomass oil, stationary use	c_BIO	Bio-energy
BIO-PEL	Pellets	c_BIO	Bio-energy
BIO-SAW	Biomass saw	c_BIO	Bio-energy
BIO-WDO	Wood	c_BIO	Bio-energy
COAL	Coal (COAL-HC & BIO-COAL)	c_COAL	Coal
COAL-COKE	Coke	c_COAL	Coal

(*continued on next page*)

Table 8 (*continued*)

TIMES commodity	TIMES description	REMES commodity	REMES description
COAL-HC	Hard coal	c_COAL	Coal
OIL-CRUDE	Crude oil	c_COIL_	Crude oil
LTH	District heating	c_LTH	District heating
LTH1	District heating to grid	c_LTH	District heating
LTH-ALA	LTH Aluminium A	c_LTH	District heating
LTH-ALR	LTH Aluminium R	c_LTH	District heating
LTH-EDU	LTH Education	c_LTH	District heating
LTH-HEA	LTH Health and social services	c_LTH	District heating
LTH-HOT	LTH Hotel and restaurant	c_LTH	District heating
LTH-MEA	LTH Metal industry A	c_LTH	District heating
LTH-MER	LTH Metal industry Rest	c_LTH	District heating
LTH-MUN	LTH Multi-family houses, new	c_LTH	District heating
LTH-MUO	LTH Multi-family houses, old	c_LTH	District heating
LTH-OFF	LTH Office buildings	c_LTH	District heating
LTH-OTH	LTH Service sector other	c_LTH	District heating
LTH-PPA	LTH Pulp and paper A	c_LTH	District heating
LTH-PPR	LTH Pulp and paper R	c_LTH	District heating
LTH-RES	LTH Rest industry	c_LTH	District heating
LTH-SIN	LTH Single family houses, new	c_LTH	District heating
LTH-SIO	LTH Single family houses- old	c_LTH	District heating
LTH-ST-RES	LTH Steam Turbine Rest industry	c_LTH	District heating
LTH-WSR	LTH Wholesale and Retail	c_LTH	District heating
LTH-ALB	LTH Aluminium B	c_LTH	District heating
LTH-ALC	LTH Aluminium C	c_LTH	District heating
NG-CNG	Compressed Natural Gas (CNG)	c_NG	Natural gas
NG-L	Natural gas before pipeline distribution (for indu	c_NG	Natural gas
NG-LPG	Liquid Petroleum Gas	c_NG	Natural gas
NG-PL	Natural gas after pipeline distribution (local)	c_NG	Natural gas
OIL-DSL	Diesel	c_OIL-DSL	Diesel
OIL-GSL	Gasoline	c_OIL-GSL	Gasoline
OIL-HDI	Heavy distillate for industry	c_OIL-HD	Heavy distillate
OIL-HDT	Heavy distillate for transport	c_OIL-HD	Heavy distillate
OIL-JET	Jet fuel	c_OIL-JET	Jet fuel
OIL-KER	Kerosene	c_OIL-KER	Kerosene
OIL-LDI	Light distillate, industrial use	c_OIL-LD	Light distillate
OIL-LDIF	Light distillate, industrial use (fossil)	c_OIL-LD	Light distillate
OIL-LDS	Light distillate, stationary use	c_OIL-LD	Light distillate
OIL-LDSF	Light distillate, stationary use (fossil)	c_OIL-LD	Light distillate
OIL-LDT	Light distillate for transport (marine diesel)	c_OIL-LD	Light distillate

Table 9
List of REMES sectors.

Sector	REMES description	Sector	REMES description
i-AAGR	Agriculture, forestry and fishing	i_COAL	Mining of coal and lignite
i-IMIN	Mining and oil exploitation	i_COIL	Extraction of crude oil
i-IRES	Rest industry	i_NG-GASE	Extraction of natural gas
i-IPPA	Paper and paper products	i_NG-GASL	Natural gas liquids
i-IMEA	Iron, steel and other metals	i_OIL-GSL	Gasoline
i-IREF	Refinery	i_OIL-JET	Jet fuel
i-ICHA	Chemicals	i_OIL-KER	Kerosene
i-IALA	Aluminium	i_OIL-DSL	Diesel
i-CCON	Construction and building	i_OIL-HD	Heavy distillate
i-CWSR	Wholesale and retail	i_NG	Refinery gas
i-CHOT	Hotel and restaurant	i_CRUDE-OIL	Refinery feedstocks
i-COFF	Office buildings	i_OIL-LD	Light distillate
i-CEDU	Education	i_POW	Electricity
i-CHEA	Health services	i_POWTD	Electricity transmission and distribution
i-COTH	Other commercial	i_LTH	Steam and hot water supply
i-TRAI	Transport via railways		
i-TLND	Other land transport		
i-TPIP	Transport via pipelines		
i-TSEA	Sea transport		
i-TAIR	Air transport		
i-Waste	Waste treatment		

Table 10
List of REMES commodities.

Commodity	REMES description	Commodity	REMES description
c-AAGR	Agriculture, forestry and fishing	c_BIO	Bio energy and hydrogen
c-IMIN	Mining and oil exploitation	c_COAL	Coal
c-IRES	Rest industry	c_COIL_	Crude oil
c-IPPA	Paper and paper products	c_NG	Natural gas
c-IMEA	Iron, steel and other metals	c_OIL-GSL	Gasoline
c-ICHA	Chemicals	c_OIL-JET	Jet fuel
c-COTH	Other commercial	c_OIL-KER	Kerosene
c-CCON	Construction and building	c_OIL-DSL	Diesel
c-CWSR	Wholesale and retail	c_OIL-HD	Heavy distillate
c-CHOT	Hotel and restaurant	c_OIL-LD	Light distillate
c-COFF	Office	c_POW	Electricity
c-CEDU	Education	c_POWTD	Electricity distribution
c-CHEA	Health services	c_LTH	Steam and hot water
c-TRAI	Transport via railways		
c-TLND	Other land transport		
c-TPIP	Transport via pipelines		
c-TSEA	Sea transport		
c-TAIR	Air transport		
c-Waste	Waste		

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