A three-model linkage for energy-economics-environmental analysis: TIMES, REMES and EXIOBASE

Discussion paper

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About the project

SET-Nav aims for supporting strategic decision making in Europe’s energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our first pillar. The EU’s energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.

Who we are?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.
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A three-model linkage for energy-economics-environmental analysis: TIMES, REMES and EXIOBASE

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Abstract

In this paper we present and discuss how an energy systems model for Norway, a regional economic model for Norway and an environmental and climate assessment tool will be linked to allow improved assessments of energy and climate policies. Since the implementation is not ready yet, we hypothesize how results from this linked framework would be different when analyzing a CO2 tax increase in Norway.

Keywords: model linking, energy-economic-environmental modeling, regional modeling, energy systems, footprints.

1 Introduction

November 24 and 25, 2016, the first workshop in the SET-Nav1 workshop series was held at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The workshop topic was Top-down bottom-up hybrid modelling. This discussion paper aims to take some of the concepts presented and discussed during the workshop, and take them one step further.

The three terms in the workshop title can be interpreted as follows:

Top-down (TD) models describe the economy as a whole and emphasize the possibilities to substitute different production factors in order to optimize social welfare. This is the traditional macroeconomic approach. Bottom-up (BU) models (in the context of energy systems modeling) is the sectoral, or engineering approach, which represents the energy system through relatively detailed descriptions of

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technologic characteristics. Hybrid modelling is used to describe modelling approaches which blend aspects of TD and BU perspectives.

Compared to TD approaches, BU approaches describe a smaller part of the world in more detail. This means that BU models will provide more detailed insight (on the energy system), but at the cost that they ignore any effects caused by the part of the world that is not represented (the broader economy). In contrast, TD models look at the big picture (of the broader economy), but do not give detailed insights that are relevant for the actors in the energy system. Due to their different identification and representation of the relevant system BU and TD models may produce different guidance for policymakers. However, when applied adequately, these modelling approaches can complement each other as tools to support decision making and policy development. Therefore, linking or integrating BU models with TD models can be an important contribution for designing energy systems compatible with, for instance, sustainable economic growth. The intention is that the hybrid result of the linking or integration will provide more or better insight than the individual models could on their own.

Most of the presentations in the workshop showed and discussed examples, both theoretical and practical, of how one TD and one BU model could be linked to arrive at hybrid modeling approaches. Some examples considered more than two models. Linking more than two models was also an aspect that came up during the panel discussion as an interesting direction for future research.

In this paper, we discuss an extension of the work presented by Per Ivar Helgesen and Gerardo Perez-Valdes at the workshop. Their presentations discussed the linking of BU model TIMES-Norway (hereafter simply TIMES, unless otherwise noted) and TD model CGE REMES Norway (hereafter simply REMES). Here, we discuss and present the steps to link these models with EXIOBASE\(^2\). EXIOBASE is a "detailed multi-regional environmentally extended supply and use / input output database".

As part of this work, we will extend the existing links from REMES to TIMES, and from TIMES to REMES. We create new links from TIMES to EXIOBASE and REMES to EXIOBASE, and develop functionality to modify values in EXIOBASE based on inputs from TIMES and REMES so that EXIOBASE represents a new consistent picture.

In essence, EXIOBASE is a backward-looking tool that shows how economic activities have affected a range of stressors and footprints concerning resource and energy usage, the environment, climate, employment, etc. The forward-looking version of EXIOBASE takes global macro-economic development as given from scenarios, such as the IEA Energy Technology Perspective scenarios. The intermediate input structure as well as final demand are changed to reflect the expected changes in energy and material consumption. All the changes in EXIOBASE are implemented exogenously, so no endogenous adjustment of the production function depending on behavioral parameters occurs.

In contrast, REMES determines intermediate and final demand for goods endogenously. REMES uses nonlinear relations in its functions for production and other sectors to reflect the complexity of input factor and consumption goods substitution while maintaining tractability. By coupling REMES and EXIOBASE, we provide EXIOBASE with the impact of substitution effects in the broader economy, effectively changing the fixed coefficients in EXIOBASE to reflect the changed economic structure. The coupling between TIMES and REMES lets REMES reflect the changes in the energy system in more detail (specifically concerning the generation technologies and fuel mix), while REMES provides TIMES with changes in prices and demand for individual energy carriers (gas, oil, and electricity.)

\(^2\) [http://www.exiobase.eu/](http://www.exiobase.eu/)
1.1 Contribution of linking the models

The main contributions by the linking the three models TIMES, REMES and EXIOBASE are:

- Compared to the state-of-the-art models for energy-economy-environmental analysis, we represent and analyze the problem is more detail, using the strengths of all three modeling approaches.
- Compared to EXIOBASE, the TIMES/REMES framework considers and analyses the feedback and substitution effects in and between the economy and the energy systems. This will make the representation of the economic system in EXIOBASE more accurate, and thereby the stressors and footprints.
- Compared to the linked TIMES / REMES framework, EXIOBASE can provide more accurate and more detailed climate, environmental and resource stressors and footprints. This will provide more accurate information to analyse consequences of energy, climate and other policies to support policy development.
- Solving the three models separately allows for maintaining the relative strengths of each of the models, while the combination of the three provides both a broader and a more detailed perspective and allows for a deeper level of insight than could be obtained otherwise.

This result of this three-way linkage has some similarities with so-called Integrated Assessment Models (IAMs), which are often used for analyzing climate scenarios. However, our perspective and approach are fundamentally different, not so much driven by climate policy but by the energy system and broader economy and allowing for regional detail of a single country.

The remainder of this paper is organized as follows. Section 2 discusses a selection of relevant literature, as well as an introduction of TIMES, REMES and EXIOBASE. Section 3 presents the linking methodology. Section 4 discusses how the analysis and results from a hypothetical case study will be different using the three linked models compared to using EXIOBASE stand-alone. Section 5 concludes and presents directions for future work.

2 Literature review

Since we are linking three fundamentally different types of models, and the resulting multi-disciplinary approach has similarities with IAMs, there is a potentially large body of literature that can be considered relevant for this research. We have chosen to limit ourselves to a selection of the relevant literature that illustrates the different concepts and approaches so that the reader has a good starting point to understand our contribution.

2.1 Economic top-down models

Computable General Equilibrium (CGE) are macroeconomic models, although they are in fact based on microeconomic assumptions. In CGE models, consumers demand goods in order to maximize utility, and producers supply goods for maximizing profit. The work by Leif Johansen is considered to be the first implementation of a CGE. The MSG model (Multi Sectoral Growth, see Johansen, 1960; Jorgenson, 1982) is still operational and currently maintained by Statistics Norway.

There is a wide body of literature on CGE models. CGE models vary in many ways, including scope (e.g., a single country, several countries, global), level of detail (e.g., number of sectors, representative households, governments), representation of time (static vs. multi-period), and functional forms used to represent economic agents, their behavior, and the flows of money among them. (CGE consider monetary flows, not physical goods.)
One of the most well-known CGE models and databases is developed and maintained in the Global Trade Analysis Project (GTAP). The multi-regional GTAP model assumes perfect competition and constant returns to scale (Hertel 2013). Other well-known global CGE models are WorldScan and GEM-E3.

WorldScan\(^3\) is developed to analyse international issues and policy analysis in the global economy. Examples of issues that can be analysed are aging, the increasing role of emerging countries, GHG emissions or fossil fuel resources depletion (Lejour et al. 2006). Emissions Prediction and Policy Analysis (EPPA)\(^4\) has been developed to analyse human-activity induced GHG and other emissions (Paltsev et al. 2005).

GEM-E3\(^5\) has been developed to analyse the effects of climate and energy policies and represents interactions between the energy system, the economy and the environment in Europe (Capros et al. 2013). These are the same three areas we aim to cover. However, beside our focus on Norway in this initial development stage, differences with GEM-E3 and our approach lie in the level of detail wherein the energy system and the environment are represented. Because we link different models, we account for more detail albeit at the cost of increased computation time.

These three examples as well as many other models are dynamic recursive, multiflows computable general equilibrium models of the world economy. All of them use the GTAP database (for more details and references, see, e.g., Bohringer and Loschel 2006, Wolfgang 2006, Balabanov 2011).

A model for the Norwegian economy with focus on the transport sector is PINGO\(^6\). It is a spatial CGE model, which means that it distinguishes regions within Norway so as to allow analyses on domestic transportation and the transport sector (Ivanova et al. 2002). The spatial structure and the representation of trade in PINGO was the starting point for the development of the REMES model.

### 2.2 Sectoral, bottom-up models

Bottom-up (BU) models for the energy sector can consider a single or multiple fuels and energy carriers. Here we consider BU models that represent the most relevant energy carriers, so at least oil, coal, gas and electricity.

MultiMod is an energy sector model model capturing all relevant energy market interactions in a single model, including fuel substitution in power generation and demand sectors, infrastructure development and capacity expansion in production, generation, storage, transmission as well as market power aspects in the upstream fossil fuel markets (Huppmann and Egging 2014). MultiMod has a rather elaborate representation of agent behavior and explicitly considers market power exertion in the upstream fossil fuel markets. In contrast, most BU models cannot represent such behavior. Additionally, MultiMod allows for nonlinear functions, which most other BU models do not. A consequence is that MultiMod represents technologies and sectors at a more aggregate level than other models, so as to allow solving the model in an acceptable amount of time.

Two linear energy systems models, developed by IIASA and under the IEA ETSAP agreement respectively, are MESSAGE and TIMES/MARKAL.

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\(^3\) http://en.openei.org/wiki/WorldScan  
\(^4\) http://en.openei.org/wiki/MIT_Emissions_Prediction_and_Policy_Analysis_(EPPA)_Model  
\(^6\) Prediction of regional and INterreGiOnal freight transport
The MESSAGE model is a BU model for the energy system (Schrattenholzer 1981). MESSAGE is a linear model that optimizes the usage of fuels and energy carriers to satisfy final demand. MESSAGE represents the most relevant energy carriers and conversion technologies. Final energy demand is assumed fixed and exogenous to the model.

TIMES is a detailed model for the energy sector (Loulou and Labriet 2008). TIMES can be customized to represent a specific region, which can be rather small, e.g., a single city to the global scale. The planning period is usually 20 to 50 years into the future. The predecessor of TIMES is MARKAL (Fishbone and Abilock 1981). MARKAL is used for the IEA’s Energy Technology Perspectives reports (ETP) – published every second year. Much of the model structure is similar between MARKAL and TIMES, but TIMES allows the user more flexibility when defining time periods.

2.3 TIMES NORWAY

TIMES is a least-cost optimization, bottom up model. The Norwegian implementation covers the country’s entire energy system, including resources, production, carriers and demands (Rosenberg et al. 2013). It is a perfect competition and perfect foresight model, that is, it cannot say much about market forces or uncertainty in the future of the system. The model’s strength is its comprehensive modelling of energy drives, sources, consumption sectors and technologies, and high time resolution.

The model’s planning horizon is between 2006 and 2050, and its time resolution is 260 periods per year. The regions in the model are modelled according to the Nordic power market model EMPS (Wolfgang et al. 2009), to allow the TIMES models to run based on EMPS input for the electricity system. TIMES does not need EMPS and can run independently as well.

TIMES-Norway is demand-driven: Given an exogenous demand for the system among the various sectors, the model determines an optimal energy and technology mix to satisfy the demand in every period. Other important input data are energy prices and taxes, the availability of energy resources, and international trade possibilities. The model output covers roughly the energy production in each period, sector and region, the final consumption and end-use by consumer and energy carrier, emissions related to energy production technologies, and total system cost.

2.4 REMES-Norway

REMES Norway is a Regional Computable General Equilibrium (CGE) model developed by SINTEF Technology and Society (SINTEF, 2016). It follows the neo-classical macroeconomics modelling of the Arrow-Debreu family of equilibrium models, in which aggregated supplies equal aggregated demands for all goods in an economy.

REMES uses as input two main data-sets:

- a Social Accounting Matrix (or SAM), which represents an economic system through a matrix with the cash-flows between generally each and every actor in that system; and
- the structure and values of the elasticities of substitution (and transformation) for each producer. They determine to which extent a production agent can use or substitute one input commodity with another.

REMES is coded in the GAMS MPSGE subsystem, which simplifies the implementation of Arrow-Debreu CGE models. It distinguishes four main modelling elements:

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7 [http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html](http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html)
Commodities, which are subject to market clearing constraints; REMES Norway, in particular, includes intermediate commodities, final consumption commodities, imported commodities, regional labor, regional capital flows, and welfare commodities for consumers, among others;

- Production activities, which are subject to zero-profit conditions. REMES Norway includes domestic producers, local exporters and traders, transport services, and welfare production for consumers as production agents, which use the SAMs entries as reference volumes for the production structures;

- Demand activities, subject to budget balance conditions; consumers form a budget with endowment and tax earnings and use this to purchase welfare commodities. REMES Norway includes one household, one government, and one investment estate per region.

- Auxiliary equations, which are custom-defined and form additional complimentary conditions to taxes and endowment levels. REMES Norway uses these to regulate the consumer, government, and investment price indexes.

REMES typically works by calculating a calibrated basis equilibrium based on the SAM figures. Any policy shock causing a change in this calibrated equilibrium, such as the increase of an endowment quantity, a change in a tax, or changing a production parameter will change the basis condition, and a new equilibrium state of the economy, if existing, is calculated.

## 2.5 EXIOBASE

EXIOBASE is a global multi-regional input-output (MRIO) database covering 44 countries and five rest of the world regions at a resolution of 200 products and 163 industries per country/region for the years 1995 – 2012 (with estimates until 2016, Stadler et al under review). The database contains symmetric industry-by-industry and product-by-product input-output tables as well as product-by-industry supply-and-use tables. Final demand is broken down into final consumption of households, government and non-profit organizations serving households, gross fixed capital formation and changes in inventories and valuables. The system furthermore contains data on taxes and subsidies on products purchased, other net-taxes on production, compensation of employees; wages, salaries, and employers' social contributions (according to three skill levels), and operating surplus (consumption of fixed capital, rents on land, royalties on resources, remaining net operating surplus). For each country/region and industry/product, EXIOBASE has detailed data on environmental impact categories, such as energy, air emissions, water use, land use, material extraction and biodiversity (Wood et al. 2015).

Global MRIO databases, such as EXIOBASE, allow for a linking of economic activities along global production chains to their upstream environmental and socio-economic impacts. These databases combine information on inter-industry trade within and across countries with final consumption, thus allowing for environmental footprint calculations. EXIOBASE is among those databases with the highest product/industry resolutions and the most detailed environmental impact categories. Other similar databases are EORA (Lenzen, Moran, Kanemoto, & Geschke, 2013), GRAM (Wiebe, Bruckner, Giljum, & Lutz, 2012), the OECD-ICIO (Nakano et al., 2009; Wiebe & Yamano, 2015) and WIOD (Timmer, Dietzenbacher, Los, Stehrer, & de Vries, 2015).

Figure 1 and Figure 2 show where in the world CO2 was emitted while producing products that have eventually been consumed in Norway. The figures show a clear shift from Russia (in 1995) to China and India (in 2011).
Figure 1  Norway’s CO2 footprint 1995

Figure 2  Norway’s CO2 footprint 2011
3 Methodology

In this section we discuss the methodological and functional enhancements needed to implement the three-way linkage.

3.1 General approach

Each of the three models have their own strengths and capabilities, which we aim to capitalize. The strength of TIMES is to optimize the energy system and technologies; that is to find the least-cost solution to satisfy future demand for energy carriers. The strength of REMES is to determine the usage and consumption of energy and other commodities in the production of goods, services and social welfare in the context of the broader economy. The strength of EXIOBASE is to determine environmental and socio-economic footprints of production and consumption activities. Note that in this first development step we will ignore the feedback loop from EXIOBASE to the other models concerning how restrictions on other emissions than CO2 might in turn affect the economy and the energy system.

Note that both REMES and TIMES determine prices. These prices are not exchanged between the models, but are used to determine if the models have converged, i.e., the values of some main prices and indicators are the same as those in the former iteration. This is important as TIMES uses absolute values for physical flows, while REMES models the economy in relative terms of monetary values.

Figure 3 below shows the linkages between the models and indicates the information flow.

![Linkages and data exchange between models](image)

**Step one** of the sequence is from EXIOBASE to REMES. EXIOBASE provides a national social accounting matrix (SAM) for Norway. A SAM is the major input source for any CGE. It reflects the current state of the broader economy to which the CGE is calibrated. As a pre-processing step, the national SAM is disaggregated to the regional level used in REMES and TIMES. REMES is calibrated to reflect the equilibrium SAM. Next, some kind of policy shock is implemented in REMES. This can be, for instance, a CO2 tax at a certain level different than the prevailing tax level.

Since REMES does work in monetary units, does not represent CO2 emissions directly, and has an aggregated electricity generation sector, CO2 tax values in USD or NOK per ton emitted must be
transformed based on the fuel and technology mix to product and / or commodity taxes. EXIOBASE provides data on CO2 emissions in physical units by industry, which will be used as a base for calculating the CO2 tax base in monetary terms.

In Step two, REMES sends demand for different fuels and energy carriers to TIMES. These demands are transformed from monetary to physical units, and TIMES will find the least cost solution to meet these demands. Part of the solution found by TIMES is capital requirements, the electricity generation technology mix, and a CO2 factor: the amount of CO2 per produced kWh. In Step three, these are sent to REMES. REMES transforms the results into monetary units and also recalculates the CO2 taxes. REMES and TIMES will iterate until the results of the models have converged. When this is the case, the information exchange to EXIOBASE is done. Steps two and three will generally happen multiple times.

Step four contains a part 4a. by REMES, where the updated structure of the economy is translated in Leontief coefficients which are sent to EXIOBASE. In Step 4b, TIMES sends the final technology and fuel mix to EXIOBASE. EXIOBASE performs an internal update to revise the Input-Output tables, and determines the new stressors and footprints of the entire domestic Norwegian economy and energy system.

Eventually, we have found a new electricity generation technology mix, impacts on the entire economy, production sectors and final demand (increases and decreases), and a detailed overview of the stressors and footprints. These can then be analyzed to find the consequences of the implemented policy shock.

3.2 REMES-TIMES linkage

The flow of data from REMES into TIMES is limited to consumption figures, i.e., expected demands in future times from industries and household consumers. TIMES can provide an optimal energy mix for a given demand situation, but contains no underlying or assumed demographic model, so it cannot create demand projections. REMES, while not a demographic model either, can take urban growth assumptions in the form of labor force endowment increases. Running REMES once per period (e.g., yearly) in the 2015 - 2030 time horizon of TIMES allows to estimate energy demand values for every production sector and the consumers for each period.

In general, the models will run over several iterations, with TIMES running once and REMES once per TIMES-period in each iteration. Convergence is achieved when both TIMES’s and REMES’s main indicator parameters do not change from one iteration to another. This means TIMES that calculates the same (within a tolerance) technology mix over its horizon than it did in the past iteration and that REMES provides activity levels and commodity prices for each of its periodical runs which are equal (also within tolerance) to the corresponding run of the previous iteration.

3.3 TIMES-REMES linkage

By introducing shocks to the economy, REMES Norway calculates new equilibrium states. The linkage between the models allows REMES to generate output data to be send to TIMES Norway. For this to work, both REMES and TIMES need to map the energy and transport commodities, i.e., transform the units of measurements of the values such that changes in one model can be accurately used in the other one.

Because TIMES Norway is a multi-period model, and REMES Norway is used in its single-period, non-dynamic version, some adjustments are needed:

- REMES runs once per TIMES period; changes for each period in TIMES are input to independently-calculated runs of REMES
• Each iteration of REMES receives a new technological configuration for energy commodity usage in five categories: agricultural, industrial, service, and transport sectors; and the consumer welfare production.

In the context of studies aiming at decarbonizing the energy system, each time step 3 (see Figure 3 above) is performed and REMES receives a new technological configuration from TIMES, the production functions generally tend to become less dependent in fossil energy commodities. This induces an increase in the equilibrium activity levels for the cleaner energy sources and those industries related to them, and it decreases the activity levels of non-clean energy production sectors. Because the available amount of capital and labor is limited, these changes impact the whole economy in different manners, which are usually specified by the elasticities of substitution and of input transformation.

By changing the technology mix, the initially calculated value of CO2 emissions per unit produced or consumed in a sector used in REMES is no longer valid. REMES will therefore re-calculate the emissions corresponding to each industry based on their new technological energy mix, and use these values as part of the shock to calculate each run's equilibrium.

3.4 REMES - EXIOBASE

EXIOBASE is used for the subsequent environmental footprint analysis considering changes in Norwegian consumption and production patterns as determined by REMES. As EXIOBASE in itself is a static system, the changes of the REMES projections up to 2030 are implemented in EXIOBASE. These changes include intermediate demand relations including energy technologies, final demand, imports and exports, energy use and associated emissions. This is possible as REMES is based on the EXIOBASE tables for Norway, thus making sure that both models are using a consistent database.

The global economic development, including changes in demand, technology and trade (among the other countries), is modelled based on data from the IEA Energy Technology Perspective scenarios (IEA 2015). Projecting MRIO systems such as EXIOBASE is an involving task, but researchers from NTNU Industrial Ecology (Wood and Hertwich 2010, Gibon et al. 2015, Wiebe 2016) are among the few (maybe the only ones) who have succeeded in this task (see for another example of simplified regional models of de Koning et al (2016).

In a first step, the changes in Norway's environmental footprints due to different policies regarding the CO2 price of production in Norway are analyzed. The environmental footprints change with changing final demand in Norway, changing production structure and energy use within and outside Norway and changing imports from outside Norway. A production-side CO2 tax is expected to shift energy use within Norway away from carbon-intense energy carriers towards low-carbon and carbon-free energy and possibly substitute carbon-intensive production by imports. The footprint analysis with EXIOBASE will clearly show where in the world the CO2 embodied in the final goods consumed in Norway is emitted. This shows both industries and countries/regions of origin of the emission, thus allowing policy makers to estimate not only the direct but also the indirect impact of carbon-pricing policies in Norway.

In a second step, the consumption-based carbon footprints of Norway can be used to estimate the effects of implementing a demand-side CO2 tax instead of or in addition to the production-side CO2 tax. This would require to implement one additional loop in the linked model systems. EXIOBASE would not be used for a subsequent analysis, but, in every iteration of the REMES-TIMES model, provide information on the global CO2 footprint of consumption, which is then used to recalculate the associated taxes. These taxes then would cause a change in behavior, changing demand and production structure in REMES and TIMES.
4 Hypothetical analysis

The development of the linkage framework is still underway, therefore actual results are not yet available. However, we have ideas of how results of the linked models will be different from running the models stand-alone.

Let’s consider an analysis of an increasingly stringent CO2-tax in Norway. Here we hypothesize how the results of the linked framework will differ from results by obtained from the decoupled models.

4.1 Imposing a CO2 tax in REMES

Taxes in REMES are divided into three main categories: 1. consumption taxes, paid by all consumers and producers on their inputs; 2. production taxes, paid by producers on their outputs, and capital and 3. labor taxes, paid by the household sector directly to the government.

Imposing a CO2 tax in REMES is achieved by increasing the taxed amount on consumption to some or all consumers. Initially, the exact tax amount should be directly proportional to the CO2 emissions generated during the production of each particular commodity. Selected production and consumption sectors could be exempt from this tax if such would be a policy requirement.

As a result of an imposed or increased CO2 tax, the input cost of commodities heavily contributing to CO2 emissions will increase more markedly than of other commodities. Production and consumption sectors in REMES will then try to substitute CO2-intensive commodities with cleaner sources. Energy from fossil fuels will be substituted for energy from low-carbon sources, such as hydropower electricity. More capital and labor will be routed to these production activities and away from CO2-heavy activities. This will change demand and supply of energy and other goods in REMES. Depending on the substitution levels and amount of capital and labor "locked in" each sector, the new equilibrium activity level of CO2-intensive sectors will provide the government with a higher income from taxes in early periods, but as the economy re-adjusts itself, the government income will again go down as CO2 heavy industries operate at lower activity levels.

4.2 Imposing a CO2 tax in TIMES

Since TIMES is a cost-minimizing model, the immediate effect of a CO2 tax imposed on CO2 heavy commodities will be a drift away from these commodities into low-carbon ones. Changes in TIMES, however, do not take into account market forces, but rather current and future investment on infrastructure. Within existing electricity generation portfolios the merit order will change in favor of low and no-carbon technologies, and new investment will favor low-carbon technologies so that their share in the generation mix will increase over time.

4.3 Imposing a CO2 tax in EXIOBASE

Imposing a production-based CO2 tax on production reflects in increased prices of products. Using the Leontief price model, we can estimate the effect that this price increase has on the price level of the products. Using household expenditure data from EUROSTAT and World Bank by income quantile, Tisserant et al (under review) have estimated Engel curves for the 200 products in EXIOBASE. These estimations give income elasticities for each country and each product. Interpreting the increase in prices as a reduction in disposable income, the elasticities can be used to re-estimate final demand spending of households by product.
4.4  Imposing a CO2 tax in the linked models.

Linking models allows for more “maneuvering” space to find least-cost or otherwise optimal solutions. The so-called “feasible region” of the combined models is larger and will therefore allow for better solutions than if the models would not be linked.

TIMES itself does not account for changes in intermediate and final demand due to an increased CO2 tax. A CO2 tax changes the costs for non-renewable energy goods, which changes the costs of meeting the demand. REMES, however, will reflect how the intermediate and final goods consumption is affected by price changes induced by CO2 tax increases. CO2 intensive goods get higher prices, which makes consumers shift away from them in favor of low-carbon goods. Making these adjusted demand levels available in TIMES means that also TIMES should meet lower demands for CO2-intensive goods and higher demands for low-CO2 goods. Meeting these adjusted demand level will be cheaper and allow TIMES to find a lower cost solution than previously. However, TIMES might opt for quite radical adjustments of the structure of the energy sector, which would not always be reasonable. In turn, REMES reflects inertia in the economy as sectors are generally unable to shift overnight from one energy source to another. Both models combined, the costs and demand changes will gradually be adjusted in TIMES. Through the iterations with REMES, both models will eventually “agree” on a demand and price for every period in TIMES’s running horizon.

Step-wise increasing the CO2 tax would push any of the individual models quicker into more expensive solutions. That TIMES optimizes the energy system and that REMES considers substitution effects in the economy will allow for lower cost solutions than would be the case otherwise.

However, all this only considers CO2 tax and good production and consumption in Norway. The link with EXIOBASE allows to capture the global impact of the Norwegian CO2 taxation, including the impact of carbon leakage.

5  Summary / Conclusions & Future work

We have discussed how three models, an energy systems model, an economic model, and an extended emissions and footprint model can be linked to provide a hybrid assessment tool for broad and deep analyses concerning, for instance, energy and climate policy.

In the coming months, we aim to finalize the implementation of the linkages and run and analyze the case study for increasing CO2 taxes in Norway that was hypothesized in this paper.

In future, we will extend this framework to include feedback from EXIOBASE into REMES and TIMES and a broader geographical scope.

6  Bibliography


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