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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.

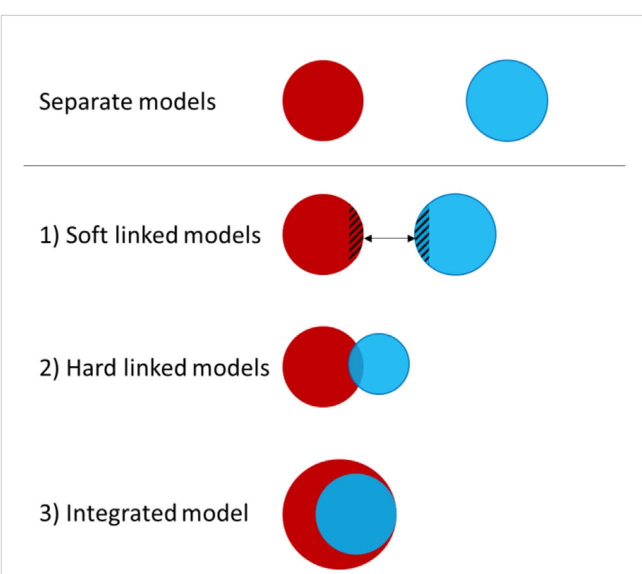

Fig. 1. Hybrid model variants.

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