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Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models

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ABSTRACT

Decarbonizing transport will be necessary to limit global warming below 2 °C. Due to persistent reliance on fossil fuels, it is posited that transport is more difficult to decarbonize than other sectors. To test this hypothesis, we compare long-term transport energy demand and emission projections for China, USA and the world from five large-scale energy-economy models. We diagnose the model's characteristics by subjecting them to three climate policies. We systematically analyze mitigation levers along the chain of causality from mobility to emissions, finding that some models lack relevant mitigation options. We partially confirm that transport is less reactive to a given carbon tax than the non-transport sectors: in the first half of the century, transport mitigation is delayed by 10–30 years compared to non-transport mitigation. At high carbon prices towards the end of the century, however, the three global models achieve deep transport emission reductions by >90% through the use of advanced vehicle technologies and low-carbon primary energy; especially biomass with CCS (carbon capture and sequestration) plays a crucial role. The extent to which earlier mitigation is possible strongly depends on implemented technologies and model structure. Compared to the global models, the two partial-equilibrium models are less flexible in their reaction to climate policies.

1. Introduction

To limit global warming to less than 2 °C above pre-industrial temperatures, greenhouse gas emissions have to be strongly reduced in the near term with long-term emissions close to or below zero [1]. Transport contributed 22% to global CO_2 emissions in 2010 [2], and transport CO_2 emissions are projected to double by 2050, reaching 14–18 Gt CO_2 (IEA 2009). Decarbonizing the transport sector is thus a fundamental challenge that needs to be tackled to limit global warming. The research community has consistently posited the hypothesis that the transport sector tends to react less and later to mitigation policies than other sectors, and that the transport sector is quite difficult to decarbonize due to a reliance on fossil fuels and persistent demand [3–7]. This study sets out to test this hypothesis and advance the understanding of possible decarbonization pathways in the transport sector through the use of large-scale energy-economy models with embedded transportation modules. The study also has a diagnostic focus, as it presents and compares the results from transport modules of several energy-economy models that are and have been used for research and policy advice. In doing so, we discuss the strengths and weaknesses of the different models.

Accurate short-term projections of transport for a city or region is best performed with detailed bottom-up models that include spatially explicit infrastructure modeling. In contrast, the analysis of long-term transformations to achieve climate targets requires large-scale energy-economy models that aggregate the detailed mitigation actions into general trends and that are able to represent the interactions between different sectors and regions via resource prices, capital flows and technology diffusion.

Decarbonization options for the transport sector exist on many different levels: Total demand for mobility can be reduced through increased travel costs, improved (urban) infrastructure, changes in consumer preferences and socio-cultural norms. Modal shift from travel modes with high carbon intensity such as aviation or private vehicles to ones with lower carbon intensity such as buses, trains or

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ships will reduce GHG (greenhouse gas) emissions. Within one travel mode, energy demand and thus emissions can be reduced through more efficient vehicles (either through technological change or smaller and lighter vehicles), as well as increased load factors. Switching to advanced vehicles like plug-in hybrids, battery electric vehicles or fuel cell vehicles not only increases efficiency, but can also open up new paths to low-carbon primary energies like renewable energies or nuclear. Finally, the Fischer–Tropsch process allows the production of liquid fuels from biomass, coal or natural gas, both with or without CCS (carbon capture and sequestration) [8–10].

Decarbonization options within the electricity sector have been focused on extensively within the modeling literature and are relatively well understood. Furthermore, the first comprehensive mitigation policy targeting the electricity sector has been in place for more than five years, as reflected in the establishment of the EU ETS (EU Emissions Trading System). In contrast, the systematic analysis of transport sector decarbonization is at a much earlier stage. Until the 2000s, large-scale transportation studies focused mostly on projections of global mobility and the implications for energy demand and emissions, while measures to reduce emissions were not analyzed [11,12].

In the last decade, some progress in the analysis of transport sector decarbonization has been achieved. There have been a number of transport studies with a strong mitigation focus at the level of nations or regions [13–17], but only a few utilize an integrated global approach. When studies have analyzed global mitigation, they often limit the analysis to the LDV (light duty vehicle) sector and its different technology options for mitigation [18–25]. Other studies model the full transport sector, but do not include direct feedbacks between the rest of the energy system and the transport sector [26]. This allows the use of a very detailed transport model, but prevents all interactions between the different sectors. As the transport sector is a main driver for the demand for liquid fuels, ignoring the feedback on oil and biomass prices is a strong limitation for such a study. Azar et al. developed a linear partial-equilibrium energy system model including a detailed transport sector at the global [27] and regional level [28]. In a comparison study they also tried to reconcile contrasting results from two different transport models about the use of biomass for transport [29].

Besides price signals on CO_2, various other policies can have a substantial influence on mobility demands, and thus CO_2 emission. Cuenot et al. use the IEA's mobility model to develop a passenger transport scenario in which a variety of measures including strong policy action result in strong modal shifts towards less energy-intensive modes, leading to a 20% decrease in CO_2 emissions compared to their reference scenario [30].

This study presents the analysis of transport decarbonization that was carried out within the Climate Policy Outreach project. It brings together a range of large-scale energy-economy models with dedicated transport modules, namely:

- CHN-TIMES, from Tsinghua University, based on the China MARKAL model [31–33]
- GCAM, from Pacific Northwest National Laboratory [22,34]
- PECE, from Renmin University of China [35,36]
- REMIND 1.4, from Potsdam Institute for Climate Impact Research [6,7,37,38]
- WITCH-T, a modification of the WITCH (World Induced Technical Change Hybrid) model with a transport module added, from Fondazione Eni Enrico Mattei [39–41]

Utilizing a variety of models means that we can diagnose how different model structures influence the projections for transport energy demand and the emission reductions achievable. We apply a consistent set of climate policies with varying stringency to all the models by implementing three different carbon tax regimes. These harmonized climate policies allow for a detailed comparison of the flexibility of different models and the analysis of robust of mitigations options.

We contribute to the existing literature by i) comparing transport mitigation efforts across five energy-economy models that were all subject to the same climate policies, ii) bridging the scales by discussing both world and country level results, with China and the US taken as examples for emerging and developed countries, iii) systematically analyzing the mitigation levers along the chain of causality from mobility to primary energy, and iv) discussing the structural differences between mitigation in the transport sector and the non-transport sectors.

The paper is structured as follows: Section 2 describes the key traits of the participating models and the climate policy scenarios applied to them, as well as presenting the chain of causality on which the later analysis is based. Section 3 presents the general results from the model runs: 3.1 reviews each of the model's final energy demand in the reference scenarios to gain an understanding of the different projections of the world without climate policy. Section 3.2 presents the emissions in the different policy scenarios. Section 4 develops the analysis: Section 4.1 focuses on the climate mitigation options that occur within the transport sector under the various mitigation policies. Section 4.2 contrasts the transport sector with the non-transport sectors. Section 5 concludes the paper with an overview of the robust characteristics of transport decarbonization emerging across the models and a discussion of caveats and future research needed.

2. Methodology

This study is based on the comparison and analysis of modeling results from large-scale energy-economy models. To be able to interpret the results and develop an understanding for the dynamics behind these results, one has to understand the basic model properties, which are discussed in this section.

2.1. Model description

All participating models include a detailed energy system that converts primary energy inputs into distinct final energies that are demanded for the production of energy services such as mobility.

Mobility demand and travel choices are influenced by a number of interdependent drivers, including income, fuel and technology costs, motorization rate, infrastructure, congestion, transport policies (such as tolls or licensing), and life style. Although it is very challenging to project exact travel numbers on a detailed local or national level, several stylized facts about transport have been identified that come to bear at large scales and help to make aggregated projections of transportation. A stylized fact implemented by Yacov Zahavi in his "Unified Mechanism of Travel" model [42] and later discussed and refined by others [12,43], states that across a wide variety of regions and cultures it is possible to find regularities about the amount of time (about 1.1 h per day) and the share of personal income (about 10–15% percent at high motorization rates) that people spend on mobility. These stylized facts allow for a linkage of broad mobility demands to personal income, as well as cost of travel. In addition, the observation of a travel time budget in combination with finite travel speeds leads to a saturation effect of total travel demand [12]. The limited speed of LDVs (which is even further reduced through congestion) is one factor that leads to saturation of demand for private motorized travel.

The models take into account these drivers for the parameterization of their mobility demand function either implicitly or