

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 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.

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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 CO₂ emissions in 2010 [2], and transport CO₂ emissions are projected to double by 2050, reaching 14-18 GtCO₂ (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 ships will reduce GHG 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 carbon capture and sequestration (CCS) [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. 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 light duty vehicle (LDV) 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 CO₂, various other policies can have a substantial influence on mobility demands, and thus CO₂ 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 CO₂ 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 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 1.1h 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 explicitly. The specifics of the transport modeling that are important for the further analysis are briefly presented in the following paragraphs, including references for more explicit documentation and previous use of the models.

Table 1: Overview of basic model properties

	Objective function	Dynamics	Runs until	Reg. coverage	Mobility demands	Technology choice by	Endogenous learning
CHN-TIMES	min. energy system costs	recursive-dynamic	2050	China	Exogenous projection	linear least-cost	No
GCAM	Min. social costs	recursive-dynamic	2100	Global	Endogenous with fixed price and income elasticity	logit-shares based on cost	No
PECE	min. energy system costs	recursive-dynamic	2050	China	Exogenous projection	linear least-cost	Yes
REMIND	maximize welfare	Inter-temporal opt.	2100	Global	endogenous CES production function	intertemporal cost minimization	Yes
WITCH-T	maximize welfare	Inter-temporal opt.	2100	Global	Exogenous projection (all other FE: endog. CES function)	Transport: linear least-cost. Other: intertemp. cost minimization	Yes

China TIMES (CHN-T): For the CHN-T model, mobility demands for all transport modes (see Table 2) are projected exogenously based on regressions on GDP/cap (for passenger transport) or GDP (for freight transport), as well as assumptions about vehicle ownership (with saturation level considered) and expected modal shift. To fulfill the projected price-independent mobility demands, the model then chooses investments into different vehicle technologies according to investment-time fuel prices and technology investment costs. Investment costs for advanced light duty vehicles, such as hybrids, battery-electric vehicles (BEV) or fuel cell vehicles (FCV), decrease exogenously over time. Modal shift is not endogenously modeled. The model has a scenario-independent lower limit of 2% annual growth rate for BEV, while not limits were set for FCV.

GCAM: In summary, the transportation services modeled include passenger transport, freight transport, and international shipping, with the demand for each service driven by per-capita GDP and population. Each type of service demand is met by a range of competing modes. Changes in modal shares in future periods depend on the relative costs of the different options, modeled using a logit choice formulation. Costs in the passenger sector include time value of transportation, which tends to drive a shift towards faster modes of transport (light duty vehicles, aviation) as incomes increase. Many of the modes (including light-duty vehicles) include competition between different vehicle

types, which also uses a logit choice mechanism that is calibrated to base-year shares. For new or emerging technologies (e.g. electric or hydrogen vehicles), costs also consider infrastructural constraints, non-economic consumer preferences, and as such are especially high in the near-term future time periods. No upper limits of BEV or FCV use are implemented.

PECE: For the PECE model, mobility demands for all transport modes are exogenously projected based on regressions on GDP/cap and vehicle ownership (with saturation level considered) as well as expected modal shift. To fulfill these price-independent mobility demands, the model chooses investments into different vehicle technologies according to investment-time fuel prices and technology costs. Investment costs for advanced vehicles (hybrids, BEV, FCV) decrease endogenously through learning-by-doing. Modal shift is not endogenously modeled. The model has a scenario-independent upper limit of 25% to BEV usage.

REMIND: In REMIND 1.4, mobility demands are endogenously determined through a nested CES production function, with CES efficiency parameters chosen such that the Reference scenario follows a region-specific exogenous projection based on GDP and population. In the LDV sector, the model can choose between different vehicle technologies based on a minimization of the intertemporal costs (fuel prices at each time step and investment costs). Investment costs for advanced vehicles (BEV, FCV) are endogenously reduced through learning-by-doing. Modal shift between LDVs and the other transport sectors is possible via a CES substitution elasticity of 1.5. The model has scenario-independent upper limits to BEV/FCV usage: at all times, the maximum share of BEV is 60%, of FCV is 80%.

WITCH-T: For the WITCH-T model, mobility demand for all transport modes are exogenously projected based on regional GDP/cap and vehicle ownership per capita. To determine the price dependent final energy demands arising from the mobility demand, the model chooses investments in different vehicle technologies according to lifecycle costs, consisting of vehicle investment costs plus O&M and fuel expenditure for each time step. Investment costs for advanced vehicles (hybrids, BEV) decrease endogenously through learning-by-searching. Modal shift is not endogenously modeled. The model constrains BEV usage through cost alone.

Table 2 presents the detail at which the transport sector is represented in the models, breaking down the sector by Passenger and Freight, as well as the sub-categories LDVs, Truck, Rail, Bus, Aviation and Navigation. Table 3 focuses on the transport fuels included in the model and adds to the description contained within Table 2 by reviewing the coverage of these fuels across models and type of vehicle. As the dominant energy carrier type for the transport sector in all models is liquid fuels, Table 4 focuses on which primary energies are used for the production of liquid fuels in the different models. Extraction/production costs for these primary energy resources (crude oil, coal, gas, biomass) rise over time and deployment, with some models representing broad world markets based on detailed resource extraction cost curves (GCAM, REMIND, WITCH), while others assume independent

production cost curves for each region. The importance of the fuel coverage within the models will become evident upon reviewing the decarbonization scenarios contained in section three.

Table 2: Overview of transportation sector representation in the different models

	Transport Sector							
	Passenger				Freight			
	LDV	Rail	Bus	Aviation	Truck	Rail	Aviation	Navigation
CHN-T	Y	Y	Y	Y	Y	Y	Y	Y
GCAM	Y	Y	Y	Y	Y	Y	Y	Y
PECE	Y	Y	Y	Y	Y	Y	Y	Y
REMIND	Y	Y	aggregated		aggregated			
WITCH-T	Y	Y	n	n	Y	Y	n	n

Table 3: Mapping of Energy Carriers to Transport sectors

		CHN-T	GCAM	PECE	REMIND	WITCH-T
LDVs use	Liquids	Y	Y	Y	Y	Y
	Liquids (efficient)	Y	n	Y	n	Y
	Gas	Y	Y	Y	n	n
	Power	Y	Y	Y	Y	Y
	H2	Y	Y	Y	Y	n
Fuels used for freight	Liquids	Y	Y	Y	Y	Y
	Gas	Y	n	n	n	Y
	Power	Y	n	Y	n	Y
	H2	n	n	n	n	n
Fuels used for aviation	Liquids	Y	Y	Y	Y	N/A
	Gas	n	n	n	n	
	Power	n	n	n	n	
	H2	n	n	n	n	

Table 4: Primary Energy types usable for liquid transport fuels

		CHN-T	GCAM	PECE	REMIND	WITCH-T
PE usable for liquid transport fuels	Crude Oil	Y	Y	Y	Y	Y
	Biofuel	Y	Y	Y	Y	Y
	Bio+CCS	n	Y	Y	Y	n
	Coal	Y	Y	Y	Y	N
	Coal+CCS	Y	Y	Y	Y	N
	Gas	Y	Y	Y	n	N

Vehicle ownership:

One crucial parameter influencing modal shares for passenger transport is the motorization rate, usually measured as the number of LDVs per thousand people. The motorization rate is both a driver and a consequence of transport choices in that it is influenced by per-capita income, population density inside cities, infrastructure, availability of other transport modes, lifestyles, and geographic parameters, while at the same time, motorization also influences travel choices, transport policies and infrastructure development. Historic motorization rates at certain per-capita income levels have varied by a factor of three in different regions (see Figure 1), so the projection of motorization in a certain country will depend substantially on how one expects the life style and infrastructure of this region to develop.

Figure 1 shows the range of values projected by the different models. All of the models forecast that China will have lower motorization levels than the US had historically, although the models diverge on whether it will move closer to the EU's or Japan's path. As China's cities have grown substantially over the last decades without being planned for large numbers of LDVs, it seems plausible that China will stay at much lower motorization rates than those within the US, where suburban structures co-evolved with the spread of automobiles. For a comparison, [44] develop a detailed stratified rural/urban model to project Chinese vehicle numbers out to 2050 and arrive at 400 cars per 1000 persons at a per-capita income of ~35,000 US\$ which coincides closely to estimates of the WITCH-T and REMIND models.

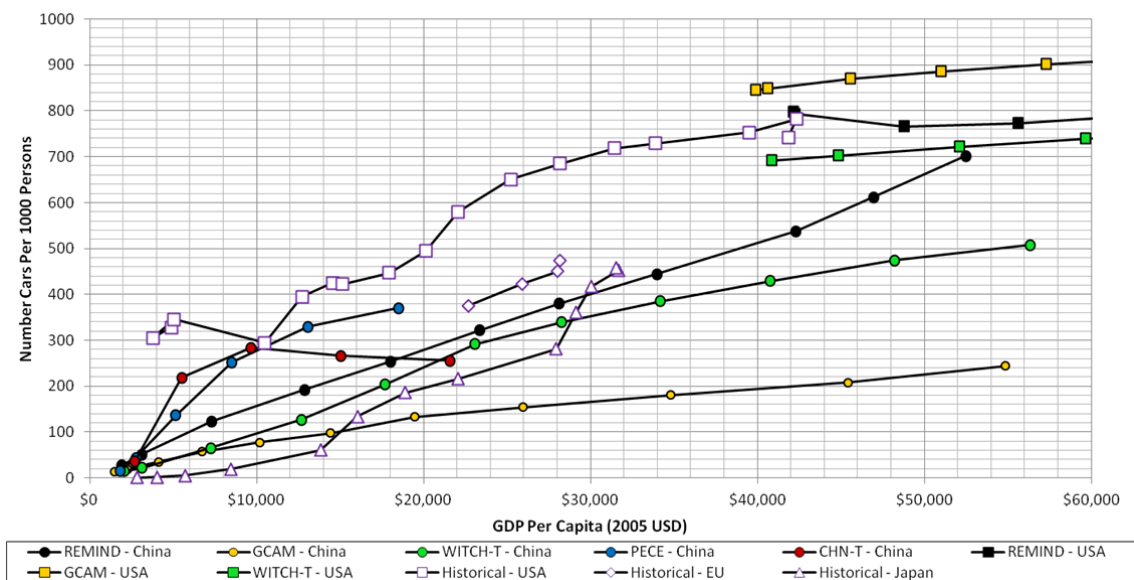


Figure 1: Projected motorization rates for China and the US from 2010 to 2100 in 10 year time steps, as well as historic values for US (1930 – 2010), EU (1990 – 2010) and Japan (1950-2010). Numbers based on [18], [45]–[50].

PECE and CHN-T see the fastest rise over the next two decades with up to 300 cars per capita at per-capita incomes below \$10,000 (a six-fold increase over 2010), but then show notable saturation effects, with CHN-T projecting an actual decline in motorization rates. The global models see a slower, more linear growth: WITCH-T and REMIND project that China reaches a level of vehicle ownership similar to Japan and the EU in the late 1990s, while GCAM projects much lower motorization rates that remain below the values seen in Japan for similar per capita incomes.

2.2 Policy Scenarios

To compare the reaction of the different models to climate policy, three global economy-wide carbon tax paths starting in 2015 and rising by 5% per year were imposed on the models (Table 5), thus following the design of the Asian Modeling Exercise [51] scenarios. Using globally uniform taxes instead of CO₂ concentration targets allows for a direct comparison between global and national models, while the flexibility of the models can be explored with the three different tax levels.

Table 5: Description of Scenarios, all values in US\$(2005)/t CO₂

<i>Brief Description</i>	<i>Policy Scenario Name</i>	<i>Tax level 2020</i>	<i>Tax level 2050</i>	<i>Tax level 2100</i>
No carbon policy	REF	0	0	0
Global economy-wide carbon tax in all sectors	TAX10	10	43	496
	TAX30	30	130	1487
	TAX50	50	216	2478

2.3 Following the chain of causality

To better understand and interpret the behaviors of the transport sector in the different models, it is useful to follow the “chain of causality” implemented in the models (refer to Figure 2). Each model includes a demand for energy services (for the transport sector: mobility), measured in passenger km for passenger transport and ton km for freight transport. This mobility demand can either be exogenously prescribed or can result from a simple economical demand model (refer to Table 1 for an overview of which model uses what approach), and it can be specified for each individual transport mode or aggregated across several modes. The mobility demand is translated into final energy (FE) demand by different vehicles, with vehicle types determining the energy carrier type (liquid, gas, electricity, hydrogen) and amount of FE demanded (efficient vs. less efficient vehicles, refer to Table 3). These FE demands are then fulfilled by the energy systems of the models, with different primary energy (PE) types usable for different FE types. The type of PE used determines the total well-to-wheel CO₂ emissions for the FE provision, with some conversion routes allowing the use of CCS to decrease emissions from this PE (refer to Table 4). Along each step, mitigation options exist that influence the amount and type of the drivers; as displayed in Figure 2. Some models implement more and some less of these mitigation options.

When discussing CO₂ emissions, this study always uses well-to-wheel emissions, thus including end-of-pipe emissions (e.g., from burning gasoline in a car engine) as well as the emissions from

the energy transformation process (e.g., emissions from a coal power plant for the production of electricity used in an electric car).

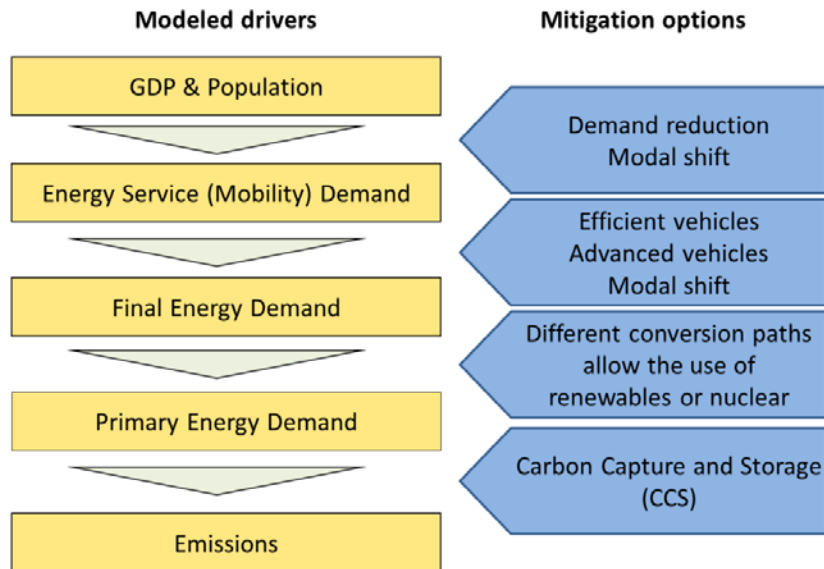


Figure 2: Chain of Causality in the Transport Sector

The data and figures used in the following sections tend to be split between the transport sector and all other sectors (aggregated under the name “non-transport sectors”) as this facilitates the analysis of fundamental differences between mitigation in the transport sector compared to the non-transport sectors.

3. General Scenario Results

3.1 Transport Final Energy Demand in the Reference Scenario

This section reviews each of the model’s reference scenarios to compare the different projections of the state of the world without climate policy. In doing so, it also reviews the different model attributes and formulations that have contributed to establishing these results. Figure 3 shows the Reference final energy projections for the overall economy, the transport sector, and light duty vehicles.

With respect to the final energy use in the overall economy, differences across models occur based on different base years, differing national data used for calibration, and differences in model assumptions about population growth, economic growth and autonomous energy intensity reductions.

All models project a strong increase of final energy use in China and for the whole world, while seeing only marginal growth in the US (Figure 3 a-c). For China, the models see strong growth in the first half of the century, from 62-75 EJ/yr in 2010 to 134-194 EJ/yr in 2050. After this doubling/tripling, the final energy increase slows (WITCH-T, GCAM) or even turns negative (REMIND), leading to a large range of 2100 values from 115-215 EJ/yr. For globally aggregated final

energy demand, the three global models are much more similar in their projections, showing an almost linear increase from 368-401 EJ/yr in 2010 to 943-1000 EJ/yr in 2100.

For China, final energy demand from the transportation sector shows an even larger variation (Figure 3 d-f). Both national models show an almost linear increase, leading to a four-fold increase within 40 years, from 9 EJ/yr in 2010 to 41 EJ/yr in 2050. GCAM also shows an almost linear increase, but with a much lower slope, reaching only 31 EJ/yr in 2100. Both REMIND and WITCH-T express a different behavior: after an initial increase, both models peak and decrease due to fuel switching towards electricity. REMIND projects a strong initial growth, leading to a 2100 value of 38 EJ/yr. WITCH-T already starts with a low growth, so that the peak-and-decline results in a very low demand of 9 EJ/yr in 2100. Note that the WITCH-T transport final energy demands reviewed in Figure 3 and onwards do not include energy for air travel or international navigation – for modeling reasons, these energy demands remain in an aggregated non-electricity sector.

For the US and the world aggregate, the three global models produce more similar transport energy demands than for China. Still, they each display their characteristic pattern: GCAM sees a relatively linear increase, REMIND shows a faster increase with a slight decline in the last third of the century, and WITCH-T shows a strong decrease in the last decades. The strong decrease in WITCH-T can be traced back to the possibility of also electrifying freight transport, which is not included in the other global models. This strong electrification of transport (not including air travel or international navigation) in WITCH-T and the partial electrification in REMIND already in the reference scenario is driven by the endogenous increase in oil prices – in WITCH-T, oil prices increase 5-fold until 2100, in REMIND 3-fold, while in GCAM they increase only by 50% compared to 2005.

Focusing on light duty vehicles, the models again show quite some differences for China. PECE, CHN-T and REMIND show strong initial increases of LDV energy demand leading to a 4-fold increase from 2010 to 2030. CHN-T then decreases LDV energy demand down to 6 EJ/yr in 2050, while PECE shows a leveling-off around 2050 at 10 EJ/yr, and REMIND increases until it shows the “electromobility kink” after 2080. GCAM follows a different storyline with a very slow linear increase of final energy demand for LDVs, reaching only 4 EJ/yr in 2100. WITCH-T sees an initially stronger increase halfway between GCAM and the other models, followed by a very strong downturn after 2070, so that it also reaches 4 EJ/yr in 2100. Again, the downturn within WITCH-T results from a leveling-off of passenger mobility demand combined with strong electrification of LDVs.

US and global values are much more similar between the models, with all models projecting a doubling of World LDV energy demand from 37-41 EJ/yr in 2010 to 82-88 EJ/yr in 2100. Again, WITCH-T and REMIND show a strong ramp-up of electric vehicles, leading to a noticeable reduction in energy demand at the end of the century.

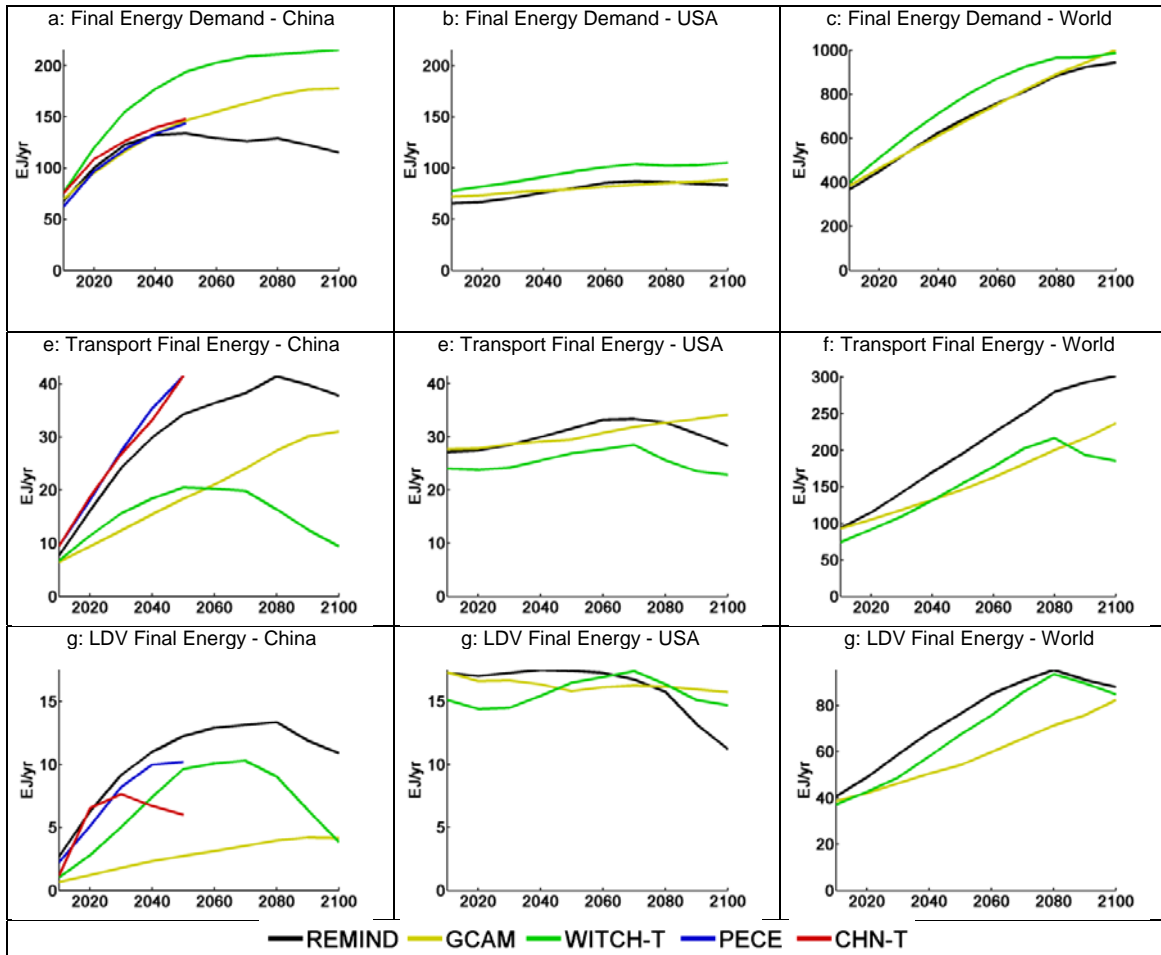


Figure 3. Final Energy Demand Projections in the Reference Scenario. a-c: Whole economy. d-f: Transport. g-i: Light duty vehicle sector.

3.2 Emissions

The observed growth in final energy demand in the reference scenario leads to a substantial growth in total CO₂ emissions from fossil fuels and industries, as can be seen in Figure 4a-c. Although the results show major differences in the exact emission paths projected by the different models, many patterns are similar. In REF in all models, the strong short-term economic growth drives a substantial growth of emissions for China, reaching 14-24 Gt CO₂ in 2050 (2010: ~8 Gt CO₂). For the US, the emission projections rise much slower, leading to 2050 emissions of 7-9 Gt CO₂ (2010: ~6 Gt CO₂). For the second half of the century, emissions either stay close to their 2050 levels (GCAM, WITCH-T) or decrease substantially towards the end of the century (REMIND). This decarbonization in REMIND even in REF results from the combination of high emissions in the midst of the century due to strongly fossil-fuelled growth (including substantial use of emission-intensive coal-to-liquid technologies) with a high long-term deployment of renewable electricity.

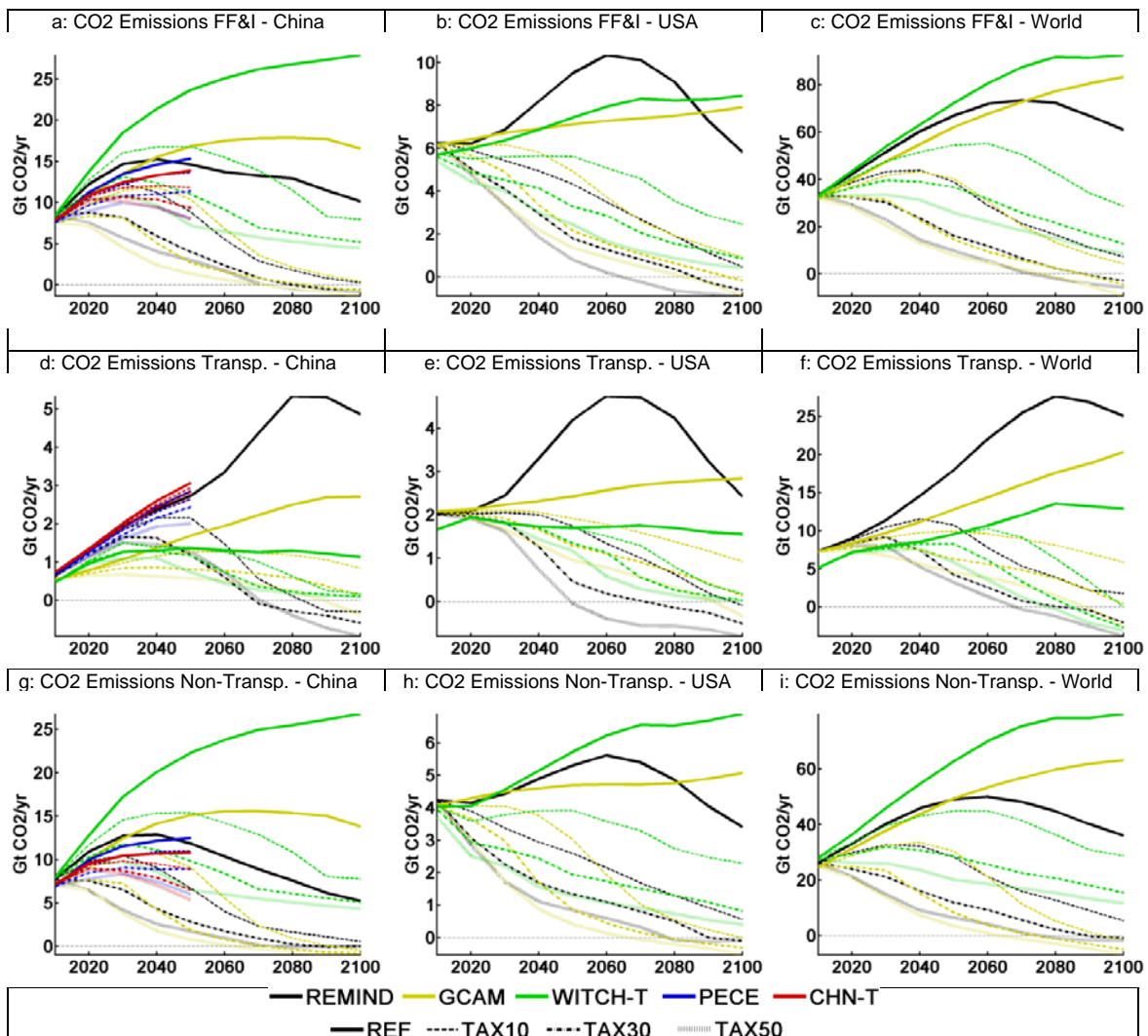


Figure 4: Well-to-wheel CO₂ emissions across policy scenarios. a-c: Fossil fuel and Industry. d-f: Transport Sector. g-i: Non-Transport Sectors

Under climate policy, all models show similar behavior in that the emission reductions achieved between TAX30 and TAX50 are much smaller than those achieved between REF and TAX10 or TAX10 and TAX30. Thus, the models become stiffer once a certain level of mitigation is reached, but the level at which the stiffness increases differs between the models. In most subsequent figures, only one climate policy scenario is shown to increase readability of plots.

REMIND and GCAM appear similar inasmuch as they project substantial decarbonization with emissions close to or even below zero at the end of the century even in the weakest climate policy scenario. WITCH-T projects a stronger increase in emissions in REF and also seems somewhat less flexible in the policy scenarios, leading to substantial residual emissions (close to 2005 emissions on world average) at the end of the century in the TAX10 scenario.

For China, CHN-T projects the lowest FF&I emissions until 2050, but also the least emission reductions vs. REF in all policy scenarios. In strong policy scenarios, REMIND and WITCH-T project negative emissions in the transport sector, while GCAM achieves negative emissions in the non-transport sector. These negative emissions arise from the combination of CCS technology with (near carbon neutral) biomass, used for the production of power, liquid biofuels, biogas or hydrogen.

4. Analysis and Discussion of Mitigation Pathways

4.1 Transport decarbonization

The results reveal that the models have very different visions of the routes towards transport decarbonization, as well as of the emission reductions achievable. To systematically analyze the mitigation pathways, we follow the chain of causality described in Section 2.2. We thus start with mobility demand, discuss the vehicle choices that translate the mobility demand into final energy demand, and then analyze the primary energies that are used to produce these final energies.

The models have regionally differentiated GDP and population growth assumptions, which lead to different transport mobility demand trends for the regions. When analyzing mitigation, however, the differences between models are much more pronounced than the differences between regions – thus, each model shows similar decarbonization patterns in most regions. For sake of brevity, we will thus limit the discussion of transport decarbonization patterns to China.

The main drivers of changes to the modeled transport system are fuel prices (incorporating the carbon price effect), which are displayed in Figure 5. For comparability reasons, we show the price for liquid fuels in terms of secondary energy, which includes carbon taxes but excludes all other taxes, as well as the distribution costs to the final customer. Although dependence on liquid fuels is reduced in the Tax30 scenario, the share of liquids from crude oil in transport fuels stays above 25% in all of the models, so the marginal price of oil-based liquids remains a useful proxy for transport costs.

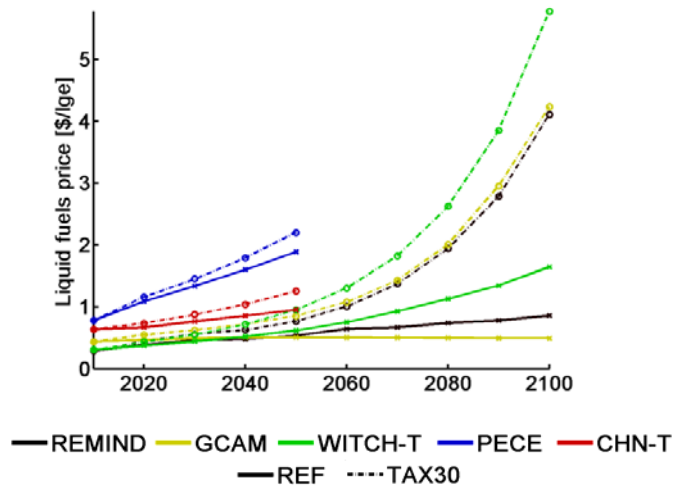


Figure 5: Liquid fuels price at secondary energy level (including carbon taxes, excluding transport and distribution costs and other taxes) for Reference and Tax30 scenarios.

Figure 5 shows the wide spread of fuel prices in the different models, as well as the strong long-term effect of carbon taxes on fuel prices. All the general equilibrium models show low fuel prices in the first half of the century, which can be traced back to the fact that they use extraction cost curves for oil based on detailed technological resource studies. As the fundamentals have not substantially changed over the last decade and the models do not include psychological factors like risk of unrest in the Middle East, these models have difficulties reproducing the tripling of oil prices after 2003. The partial-equilibrium models start at higher prices, and PECE also sees a doubling of prices from 2010 to 2050.

In the Tax30 scenario, the carbon content of crude oil increases the fuel price, which then drives mitigation action in the models. Until 2050 the carbon markup is smaller than the resource price, but the exponential increase of the carbon tax leads to very high carbon markups that are 2.5-7 times larger than the resource price at the end of the century.

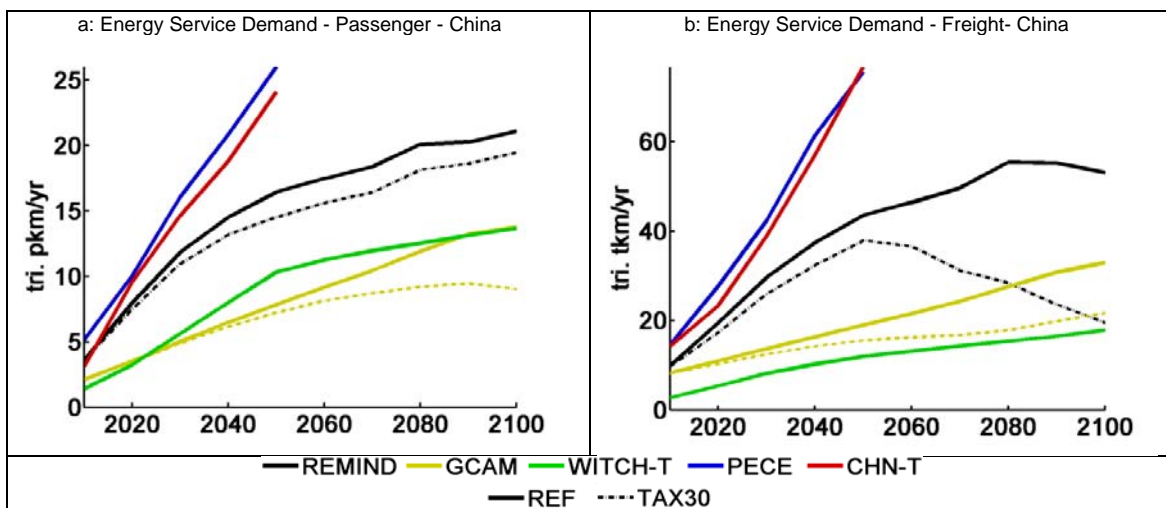


Figure 6: Reaction of Energy Service Demand to climate policy – REF and TAX30

The impact of the carbon policies on energy service demands can be seen in Figure 6. Although carbon prices reach 130 \$/tCO₂ in 2050 (equivalent to 0.3 \$/liter of gasoline) and 1500 \$/tCO₂ (3.5 \$/l) in 2100 in TAX30, only GCAM and REMIND show any reaction of either freight or passenger demand to the carbon policy, while CHN-TIMES, PECE and WITCH-T implement mobility demands that are not influenced by changes in transport prices between the scenarios and thus stay the same under all climate policies. The fixed energy service demand makes these models less flexible in reacting to climate policy.

The final energies used to supply the transport energy service demands can be seen in Figure 7. In the policy scenarios, all models reduce the total amount of final energy used for transport, either by deploying more efficient liquid-based vehicles, or by switching to other fuels which are more efficient (BEV, FCV).

Most striking is the strong reliance of all models on liquid fuels until 2050 – all models but WITCH-T keep the share of liquid fuels in transport final energy above 87% in every scenario. WITCH-T strongly increases the share of gaseous fuels in transport to up to 25% in REF, while in CHN-T, PECE and GCAM, the share is 1-6% in all scenarios. The use of gas is driven by fuel costs and not emission reductions: both PECE and CHN-T don't increase the gas use for transport in policy scenarios, and WITCH-T actually decreases the share as climate policy becomes more stringent. Electromobility is slow to enter the scene: Even in the strongest policy scenario, WITCH-T is the only model that supplies 25% of transport final energy in the form of electricity, while all other models stay below 10%. Hydrogen is even scarcer; no model goes beyond 3% of transport FE in 2050.

In 2100, however, the models react substantially to climate policy – WITCH-T increases electrification from REF to TAX50 from 51% to 76% (no hydrogen vehicles are included in WITCH-T), while REMIND and GCAM increase the combined share of electricity and hydrogen from less than 10% to about 50%. The strong electrification in WITCH-T is possible because the model a) includes electrification of freight, b) projects a higher oil price than the other global models, and c) does not include aviation and international navigation in the transport final energy demand.

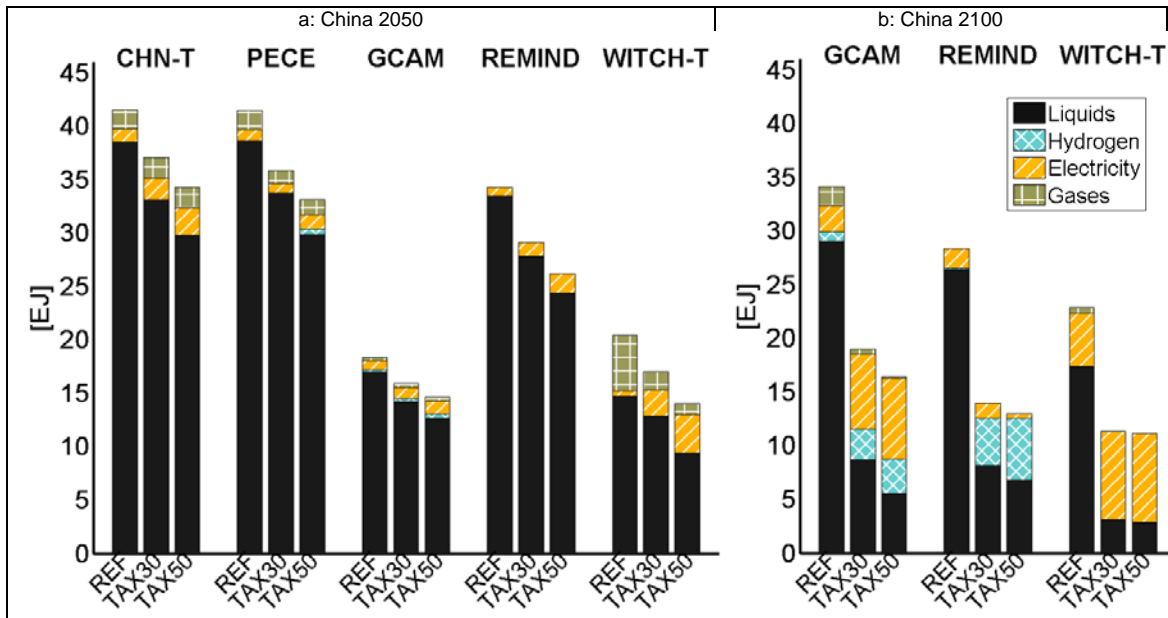


Figure 7: Reaction of Transport Final Energy Demand to climate policy

Given that transport final energy demand decreases only in the range of 25-55% in the TAX30 scenario compared to REF, the strong long-term transport emission reductions of 60-110% seen in the global models (refer to Figure 3Figure 4d-f and Figure 10a) must come from the decarbonization of the final energies used in the transport sector. This is demonstrated in Figure 8, which plots the shares of transport final energy demand broken down by the primary energy from which they were produced. This allows tracing back the different relative reduction levels achieved in the national and the global models to the changes in primary energy employed for transport.

In 2050, the main decarbonization action is the replacement of some crude oil by biomass as feedstock for liquid fuels (combined with CCS in GCAM and REMIND). When comparing the two national models, CHN-T is more flexible in introducing advanced vehicle types, doubling the share of electricity in transport final energy from REF to TAX30, while PECE keeps the electricity share the same and invests more into more efficient vehicles, reducing final energy demand from transport by 14% compared to a reduction of 11% in CHN-T. On the other hand, PECE is more flexible on the primary energy side: it substitutes crude oil with biomass in strong policy scenarios. In a TAX30 scenario, this leads to 2050 emission reductions of 14% relative to REF transport emissions, compared to 8% in CHN-T.

In 2100, the use of electricity/hydrogen in combination with the high carbon prices in TAX30 leads to major changes: 20% (WITCH-T), 30% (GCAM) or 60% (REMIND) of the final energy used in transport are produced from renewables. REMIND relies mostly on biomass in combination with CCS (BECCS), producing both liquid fuels and hydrogen with net negative emissions, as well as non-biomass renewables to produce electricity. GCAM relies both on BECCS for liquid fuels as well as nuclear for hydrogen and electricity. The strong electrification in WITCH-T make nuclear, other low-

emissions sources for electricity and non-biomass renewables the main primary energy inputs to transport.

The deployment of second generation biomass increases in all models when going from REF to Tax30, as all models treat ligno-cellulosic biomass as a zero- or low-carbon fuel. Some authors have argued, however, that due to direct and indirect land-use change effects, emission reductions from biomass might be much smaller than expected [52]–[55]. It would be advisable to improve the existing models by fully including land-use into the assessment framework.

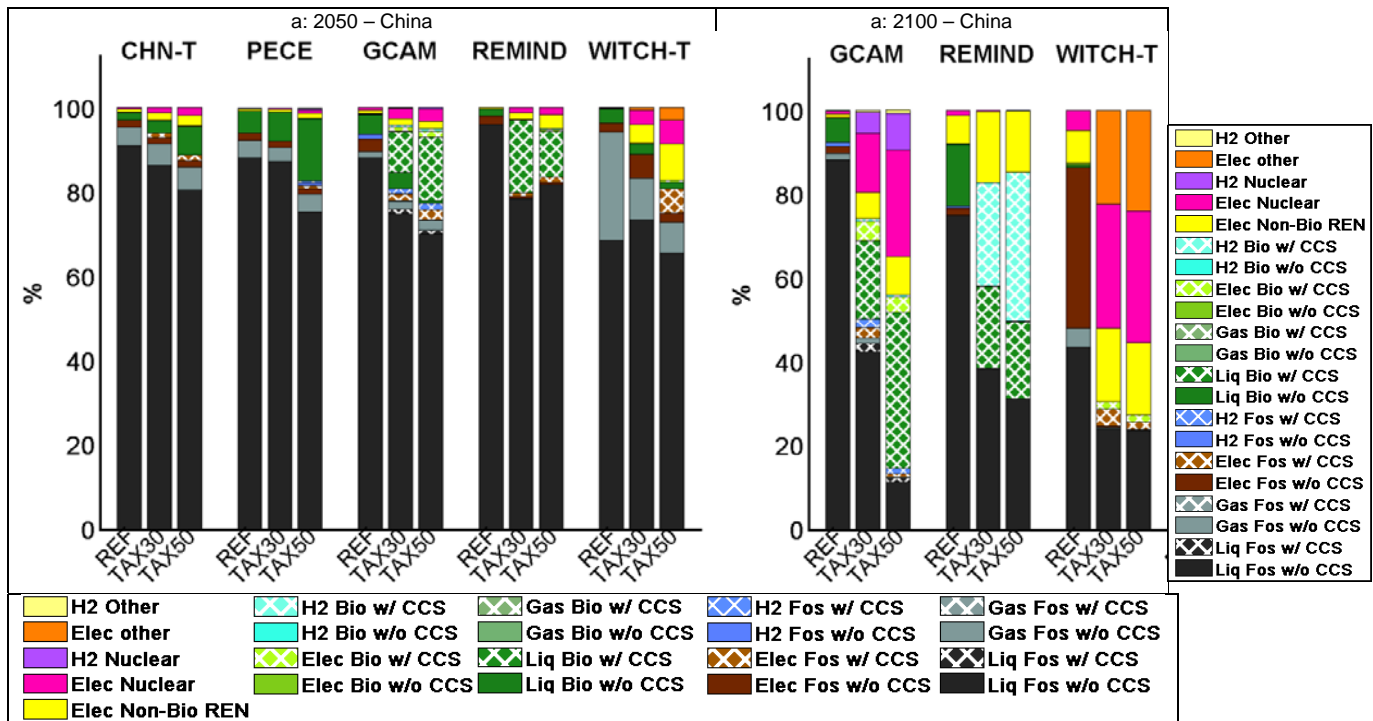


Figure 8: Share of Transport Final Energy broken down by Primary Energy type

These substantially different mitigation pathways depend on the competition between different technologies based on model assumptions about technology availability (e.g., no hydrogen use for transport in WITCH-T), conversion efficiencies, technology costs and constraints both on technology use and primary energy availability. The transport sector is deeply linked to the other energy sectors, thus the technology options and costs in all sectors matter. As one example, assumptions about carbon-free hydrogen availability or energy costs in the heat sector can strongly influence the use of biofuels in the transport sector [29].

4.2 Comparing decarbonization between Transport and Non-Transport Sectors

To find systematic differences between the transport and the non-transport sectors, the percentage reduction of FE per capita is plotted over the percentage reduction of CO₂ intensity of FE for both sectors (always comparing the values from TAX30 with REF) in Figure 9. Such a split allows for a clear distinction of the different decarbonization visions of the different models. If a model is strongly in the upper left half of the figure, it mostly reduces final energy use while not decarbonizing the energy it uses, if it is in the lower right half, it mostly decarbonizes but does not reduce final energy use.

In the transport sector, the two partial-equilibrium models CHN-TIMES and PECE only use the option of decreasing final energy use, making their transport emissions quite stiff and unreactive to climate policies – much stiffer than the non-transport sectors where CHN-TIMES strongly decreases carbon intensity. REMIND and GCAM go the opposite way – after an initial reduction of FE demand, they mostly decrease the carbon intensity of their final energies, using decarbonized electricity as well as BioCCS for both liquid fuels and hydrogen production. WITCH-T shows a different dynamic, first strongly reducing the FE intensity by earlier electrification of the transport sector, and then decarbonizing the electricity sector in the second half of the century.

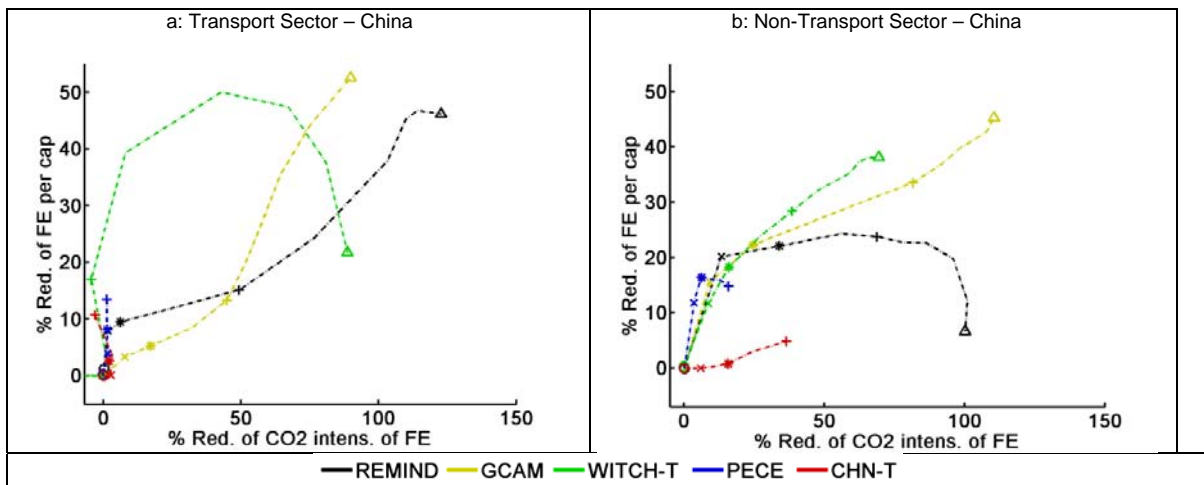


Figure 9: Percentage reduction from REF to TAX30 of FE per Capita over CO₂ intensity per FE. The dots mark the years 2010, 2020, 2030, 2050, 2100.

All models show a similar characteristic: the decarbonization of the transport sector strongly lags behind that of the other sectors. In Figure 9, this can be seen in the position of the time markers – in the transport sector, most of the action happens after 2050, while in the non-transport sector, substantial reductions the time markers are more evenly spaced. It becomes even more apparent when comparing relative levels of mitigation in the transport and non-transport sectors in Figure 10. A given level of relative mitigation is usually achieved 10-30 years later, with the largest time lag of initially 30 years showing in WITCH-T. CHN-MARKAL and PECE also show a substantial lag, as

transport never decarbonizes by more than 7 and 15% respectively. GCAM first shows a very small time lag of ~10 years which widens over time to >30 years, while REMIND shows a 10-20 year gap. This time lag is only reversed in REMIND around 2060 at mitigation levels above 80%, when the strong use of BioCCS liquids leads to higher negative emissions in the transport sector than in the non-transport sectors, and in WITCH-T around 2070, when the relative mitigation in the transport sector surpasses that of the other sectors as transport relies strongly on low-carbon electricity, while the non-transport sectors have substantial residual emissions from coal and oil.

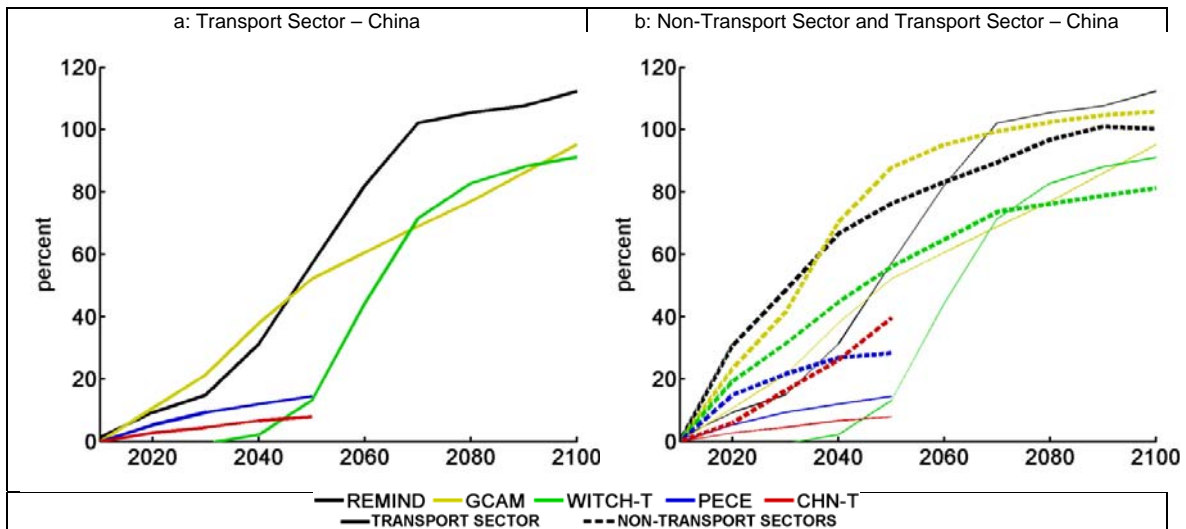


Figure 10: Mitigation in TAX30 relative to REF in the different sectors

When thinking of long-term sustainability, it is not only emission reductions that matter, but also the dependence on fossil resources. According to the models, this is another difference between the transport sector and the non-transport sectors: Over the second half of the century, all models see more than 43% of transport final energy coming from fossil resources. In the non-transport sectors, REMIND and GCAM manage to decrease the fossil share to much lower numbers between 15 and 26%. In WITCH-T, the story is somewhat different due to the incorporation of aviation in a fossil-fuel-heavy non-electricity sector (hence it is not present in the transportation sector results discussed within this paper) and the strong electrification of the freight sector. As a result, the fossil share of the transport sector can be reduced to levels below that in the non-transport sectors with electricity being sourced from low-carbon electricity in the latter part of the century.

5. Summary and Conclusion

In this study, we have compared long-term transport energy demand and emission projections from five large-scale energy-economy models, as well as the models' reaction to a set of climate policies. Special focus was on i) analyzing the mitigation levers along the chain of causality from mobility to primary energy, and ii) discussing the structural differences between mitigation in the transport sector and the non-transport sectors. The analysis is based on full well-to-wheel emissions accounting. It should be noted that the results do not represent lower limits to decarbonization, but rather the reaction to carbon prices that span a plausible range.

The major findings were:

- The different models project very different decarbonization pathways. The type and amount of mitigation strongly depends on the choice of technologies implemented and the structure of the model. One could thus interpret the participating models as studies of different possible futures in which certain options (battery electric vehicles, fuel cell vehicles, large-scale sustainable biomass use) become viable or not.
- In the first half of the century, transport decarbonization lags 10-30 years behind mitigation efforts in the non-transport sectors in all models when subject to the same monetary incentives to decarbonize. This trend is persistent in GCAM, whereas it is reversed in the second half of the century in REMIND and WITCH-T. All three models achieve substantial transport emission reductions of 90% and more in stringent climate policy scenarios.
- Even in the most stringent policy scenario, transport strongly relies on liquid fuels until 2050, with more than 85% of transport final energy coming from liquids even in the strongest climate policy in all models (except for WITCH-T, which incorporates aviation in a fossil-fuel-heavy non-electricity sector and hence does not account for aviation in the transportation sector results discussed within this paper).
- Early (pre-2050) emission reductions achieved in GCAM and REMIND beyond the efficiency improvements seen in all models can be mostly attributed to the use of biomass to produce liquid fuels, in strong climate policies in combination with CCS.
- The global models achieve deep long-term emission reductions through substantial use of very efficient battery electric or fuel cell vehicles. The very deep emission reductions of more than 90% of the reference emissions seen in stringent policy scenarios are realized through the reduction of the carbon intensity of the used final energies, either through clean electricity or BioCCS used for both liquid fuels and hydrogen.
- Both partial-equilibrium models focusing on China (PECE and CHN-TIMES) are less flexible in their reaction to climate policies, as they a) do not include reductions in mobility demand

as a reaction to increased transportation costs, b) see only limited electrification of transport even under stringent climate policies and c) only use a limited amount of less carbon intensive primary energies (biomass) to produce liquid fuels, and do not combine them with CCS. Instead, they almost exclusively reduce emissions via use of more efficient vehicles.

- Apart from differing assumptions about the economic growth trends in China and US which drive differing energy service demands, the differences between models has a much stronger influence on the decarbonization path than the differences between regions. Thus, the choice of technologies implemented and the structure of the model determine a large part of the observed mitigation results.
- To prevent model artifacts and improve plausibility of the scenarios, the analyzed transport models should better incorporate all decarbonization options along the chain of causality, e.g., price-responsive mobility demand, better representation of modal shift, finer granularity of investments into vehicle efficiency, as well as more complete representation of the technological options to use advanced fuels (including hydrogen) in both passenger and freight sectors. Also, detailed comparisons with bottom-up scenarios are needed to validate the chosen parameterization.

It can be concluded that amongst the models studied, the hypothesis that the transport sector is more difficult to decarbonize than the non-transport sectors with a carbon price of plausible size is confirmed when looking at the time period before 2060. In the long run, however, the three global models achieve deep emission reductions by 90% and more in the strong climate policy scenario. This almost complete decarbonization hinges on the use of advanced vehicle technologies in combination with carbon-free primary energy sources; especially biomass combined with CCS plays a crucial role. The extent to which earlier mitigation is possible strongly depends on the choice of technologies implemented and the structure of the model, with both partial-equilibrium models proving to be less flexible.

One could thus interpret the different projections by the participating models as studies of different possible futures in which certain options (battery electric vehicles, fuel cell vehicles, large-scale sustainable biomass use) become viable or not, or in which behavioral trends are either broken or reinforced – e.g., the growth of freight transport and the shift to private mobility almost independent of prices.

Although the models clearly state that a carbon tax of a plausible size will not lead to strong near-term decarbonization in the transport sector, one should not conclude that near-term emission reductions are impossible. There is a substantial literature on other policies beside pricing carbon pricing that target consumer behavior and infrastructure and that can have a major influence on travel behavior and thus emissions (see Section 5.1). Most of the policies targeting mobility demand have long

inertias – consumer behavior is slow to change [56], and infrastructure change or city compacting can take decades. If these policies are to contribute to emission reductions in the mid-term, they have to be started right away. Thus, while carbon pricing is necessary for achieving economy-wide deep long-term emission reductions, it should be complemented with region-specific and integrated policies aimed at changing mobility demand and promoting the use of and innovation in alternative transport options.

5.1. Caveats and future work

This study analyzes modeling results and thus is subject to all the caveats adhering to long-term energy-economic models. The strongest qualification is that all participating models are economic models that have cannot fully capture non-monetary costs and behavioral drivers. This is especially a problem when modeling transportation, as passenger transport is much more influenced by non-monetary drivers than, e.g., the choice of primary fuels in electricity generation. One major determinant is the speed of a travel mode, which only GCAM addresses explicitly by including the value of travel time into the costs that determine the choice of transport mode [22]. Behavioral aspects like habituation, status consumption, life styles or public acceptance, in combination with environmental factors, such as infrastructure availability and city design, have a substantial influence on the choice of both transport mode and vehicle used. Including these drivers in future policies may allow much easier mitigation action than through price signals alone and result in faster introduction of alternative transport options.

Banister et al perform an in-depth theoretical analysis of transport decarbonization and come to the conclusion that substantial measures beyond carbon pricing and green infrastructure are necessary to achieve deep cuts in transport emissions. They diagnose that the current transport decarbonization research is limited by the strong influence from engineering and neoclassical economics, and emphasize the need to “rethink transport governance” and to include all possible interventions [5]. Some examples of these interventions follow. Policies disincentivizing single occupancy of LDVs can lead to a substantial reduction in emissions [57]. According to a review by Cairns et al, “soft mobility management” measures including teleworking, school travel plans and transport awareness campaigns can reduce overall traffic levels by about 11% within ten years [56]. Goodwin reviews a large group of policies all targeting passenger travel behavior and comes to the conclusion that “the evidence available is rich concerning reductions in car use up to about 20%-30%” [58]. Bristow et al require a combination of “soft” measures and price signals to reach stringent UK transport mitigation targets [59]. Tight et al find a limit of about 20% reduction in passenger transport emissions that can be achieved by behavioral changes alone [60], while Anable et al register a 58% reduction in 2050 UK transport CO₂ emissions achieved only by lifestyle changes when coupling a storyline for pro-environmental lifestyle change to a detailed transport model [61].

These studies point to relevant decarbonization options, but they also have their limitations: they have a local focus, the results are difficult to transfer or generalize, and they usually do not include empirical validation. For a fair evaluation of different policies, it would be necessary to have a quantitative understanding of the achieved impacts as well as the direct and indirect costs incurred through such policies like zoning, tolls, car license limitations, etc. More bottom-up research is needed to provide robust knowledge and consolidate the individual case studies into stylized facts for the transport sector.

Also not included in the current studies are local benefits due to reduced air pollution from advanced vehicles such as BEVs or FCVs. These local benefits can be substantial: Creutzig et al analyzed the current transportation system in Beijing and found that social costs of air pollution are four times higher than those from climate change [62]. The implementation of emission-dependent road pricing or city-wide bans of high-emission vehicles that are targeted at local air pollution can help the spread of advanced technologies: The ban of gasoline-based scooters in many Chinese metropolitan areas has fostered the fast market penetration of electric two-wheelers.

An issue that is present in most of the models participating in this study is the lack of depth in the modeling of vehicle granularity and consumer heterogeneity. The participating models only differentiate between different vehicle technologies, not between different vehicle sizes, and they only model one consumer with a single set of preferences. Increasing fuel prices would incentivize reductions in vehicle size and weight, thus reducing final energy demand. Also, as the majority of trips, as well as the average daily driving distances are below 100km, a subgroup of car owners might be willing to buy short-range electric cars, which then could act as enabling technology for BEVs [24]. In addition, strategic national industry policies might change the timing of technology deployment. According to some analyses, Chinese firms might better compete with German and US car manufacturers in the electric car industry than in internal combustion engine (ICE) technology. If such strategic thoughts induce a national government to support its electric car industry, BEVs might penetrate the market much earlier than projected in the models.

Due to these limitations, the results can probably be interpreted as a conservative estimation of possible changes to vehicles and modal split. On the other hand, the global models seem rather optimistic on the substitution possibilities on the primary energy side, specifically the use of biomass liquids in combination with CCS.

To improve transport modeling, further research would be needed in the following areas: improved representation of price-elasticity of demand in the models that project price-insensitive mobility demand, improved differentiation between urban and intercity travel, more detailed modeling of modal shifts, representation of infrastructure network effects (both for the build-up of hydrogen/electric refueling infrastructure and for public transport systems), representation of

additional transport policies targeting behavior and infrastructure, inclusion of local air pollution benefits, and engineering analysis of final energy substitution possibilities for freight, aviation and navigation – as seen above, the WITCH-T assumption that freight transport can be electrified at reasonable costs allows strong decarbonization of transport to occur without having to resort to BioCCS.

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