Contribution to the 2010 ISEE conference: Advancing Sustainability in a Time of Crisis

Vehicle technologies and shifts in modal split as mitigation options towards a 2°C climate target

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Abstract

In this paper, we analyze different decarbonisation options for the transport sector with a modified version of the hybrid energy-economy-climate model ReMIND. ReMIND is an intertemporal optimization model that allows the analysis of long-term transitions of the global energy system under the constraint of an upper limit on global mean temperature change.

The newly-implemented transport sector is modeled through explicit vehicle technologies, which are then aggregated by constant elasticity of substitution functions into transport modes. The transport sector is fully linked to the other energy sectors and interacts with them through resource prices, carbon prices and competition for investments.

Our preliminary results strongly indicate that within our purely techno-economic modeling framework, the transport sector undergoes only little decarbonization while the other energy sectors strongly decarbonize to achieve the required 50% chance of keeping global warming below 2°C. The small transport decarbonization that can be observed is mostly achieved by a fuel switch to second-generation biofuels and compressed natural gas, and some modal shift towards train use. Under our default cost assumptions, new vehicle technologies like hybrid cars only achieve some market penetration around 2070, while battery-electric vehicles (BEVs) and fuel cell vehicles (FCVs) never enter the market.

The main reason that allows the model to stay below 2°C warming even though the transport sector is still heavily dependent on oil is the availability of second-generation biomass, which can be combined with carbon capture and storage to produce negative emissions. When testing the importance of biomass for the transport sector by reducing the total biomass potential from 200EJ to 100EJ, both hydrogen FCVs and BEVs are deployed by the end of the century.

1. Motivation

While a number of advanced carbon-free technologies exist for the power sector, and pathways for its decarbonization have been studied in some detail, it is very unclear how the transport sector has to change over the course of this century to deliver the substantial abatement necessary for limiting global warming to 2°C. Potential technological options for the transport sector include electro-mobility, fuel cell vehicles and biomass combined with carbon capture and storage (CCS). The first two options need to see strong cost decreases to become economically competitive and would require massive investments into new infrastructure. Biomass with CCS carries

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both the technological uncertainty about the safe storage of carbon dioxide as well as the host of social risks associated with intensive biomass use.

Complementary to these technological options are policy options such as infrastructure planning to change mobility behavior, influencing both modal shift and total volume of passenger and freight transport.

While there has been substantial transport modeling research in the past, early modeling studies were mostly concerned with the transport sector itself, not taking into account the interactions with other energy sectors. [18]

More recently, with the rising awareness of climate change, interest has turned to the emissions caused by passenger and freight transport. Most of these studies focus on the transport sector itself and use exogenous primary energy price paths, not taking into account the interactions with other energy sectors. [7], [15] Schäfer et al. take a step further and analyze transport emissions in a full energy system framework, but they limit themselves to the near future until 2030 as well as minor technological improvements, and they do not investigate long-term development with possibly major technology changes. [19]

For this reason, we developed a model whose specific strength and focus is the integrated assessment of the interactions between different energy sectors. It allows us to analyze long-term transformation pathways in a transport sector that is fully linked to the other energy sectors and interacts with them through resource prices, carbon prices and competition for investments.

2. Model Description: REMIND

We use the hybrid model ReMIND-G that couples a macroeconomic growth model with a highly disaggregated energy system model [1] and a simplified climate model (ACC2, [20]) to determine the changes in the transport sector under the constraint of an upper limit on global mean temperature change (see *Figure 1*). [2],[14] For this modeling exercise, we modified ReMIND-G to include a more detailed version of the transport sector, as will be detailed below.

The ReMIND model is completely hard-linked and solves the three integrated models simultaneously considering all interactions with perfect foresight. The present study uses a version which considers the world as a single region. This is equivalent to a multi-regional model with completely integrated markets and zero transportation costs that would lead to full price equalization of all traded goods. Subject to a number of constraints, ReMIND calculates a general equilibrium solution over the time horizon 2005 to 2100 in time steps of five years.

The macroeconomic growth model belongs to the class of Ramsey-type growth models and is formulated as a centralized maximization problem of an intertemporal welfare function. The Ramsey model is generally used for the analysis of intertemporal consumption, saving, and investment decisions. It is also suited for the analysis of optimal investments into energy systems under constraints and time-varying parameters such as emission restrictions due to climate protection, changing technological costs due to learning effects and changing resource costs due to scarcities. For all experiments, a pure rate of time preference of 3% was used. Together with the endogenously calculated GDP growth rate that varies between 2.5% and 3%, this yields an interest rate of about 6%.

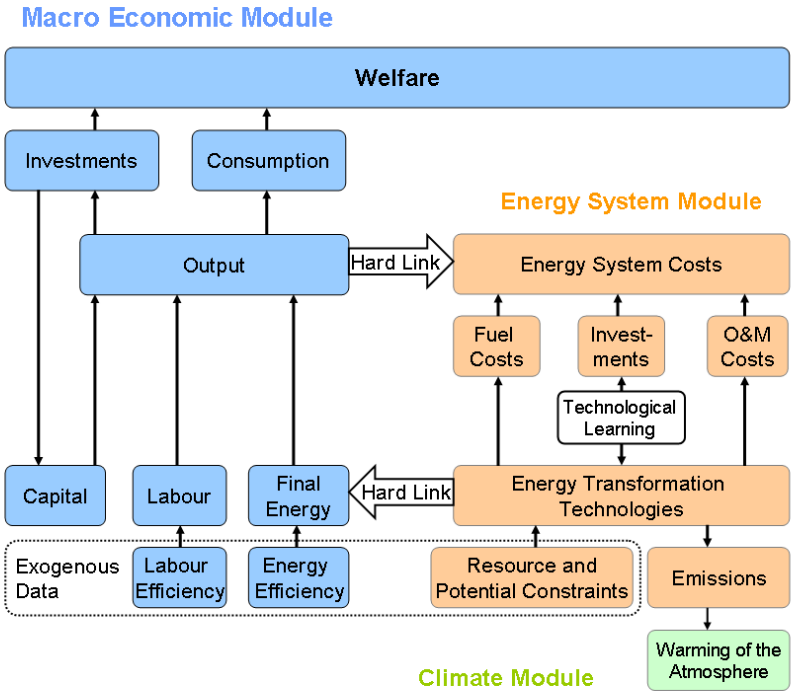

Figure 1: Overview of the ReMIND model structure

The macroeconomic model consists of a nested production structure, implemented with constant elasticity of substitution (CES) functions. The top level CES function produces GDP from the inputs energy, labor and capital. Labor input is directly determined by population and an exogenously rising labor productivity (we do not account for unemployment), and capital input is dependent on previous investments into a generalized capital stock. Energy input, however, is calculated from nested CES functions which have more disaggregated energy inputs. The inputs of the lowest CES level are final energy types like power, heating oil or distributed natural gas, which in turn are supplied by the energy system model. The full CES structure except for the newly-added transport structure is shown in *Figure 2*.

The energy system model (ESM) of ReMIND represents the energy sector at a high level of techno-economic disaggregation. Each technology is an energy conversion process that requires both capital and primary energy carriers to produce secondary or final energy. In contrast to the CES nests, different technologies producing the same output act as linear substitutes.

The model distinguishes between exhaustible and renewable primary energy carriers. The extraction costs of the exhaustible resources (uranium, coal, gas, oil) are given by Rogner Curves [16], [17] to incorporate increasing extraction costs. The renewable energy sources wind (on- and offshore), hydro, solar, geothermal and biomass are restricted by annual technical production potentials[2], which are divided into grades with different full load hours to represent the diverse site conditions.

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[2] The technical potential is the maximum amount of energy that can be produced when geographical and social constraints are taken into account, but economic constraints are not considered. It is thus smaller than the theoretical potential but larger than the economic potential.

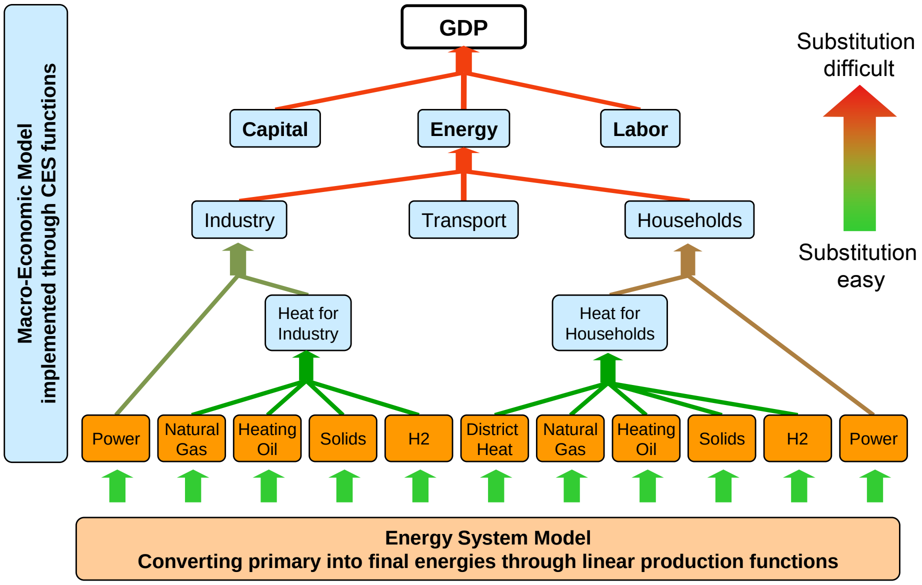


Figure 2: CES production function structure of the macroeconomic model

Technological Learning: To model technology development of comparatively young technologies like photovoltaics or hybrid cars through learning-by-doing, we use the "learning curve concept" [10]: costs decrease as a power law as cumulated installed capacity increases. To reflect that learning slows down as a technology matures, we modified this commonly used relationship by splitting investment costs into learning costs and floor costs. The former can be reduced through the normal learning curve, while the latter specify the minimum costs that are reached asymptotically at very high cumulated capacities. Thus, total learning slows down as the floor costs are approached.

2.1 Transport Sector

The transport sector that was developed for this modeling exercise is a hybrid combination of bottom-up and top-down approaches in itself, as can be seen in Figure 3. The different transport modes are formulated in a nested CES structure, while the vehicles used to travel in a certain transport mode are represented in a technology model with linear production functions that transform energy inputs into passenger or ton kilometers.

The nested CES structure was developed from the basic question "what transport service is similar to what other transport service and is easily replaced".

To best represent reality, the CES structure was developed by categorizing transport services into different layers according to how closely linked the services are and how easy one mode can replace another mode. The resulting CES structure is still preliminary, possible future improvements will be presented in the outlook.

While CES functions have several convenient properties, they have strong limitations when modeling paradigmatic shifts like the change expected in our global energy system if we decide to limit global warming to 2°C. The parameters of a CES function (efficiency and substitution elasticity) are not based on directly observable technology costs, but rather need to be guesstimated or calculated on the basis of past data – an

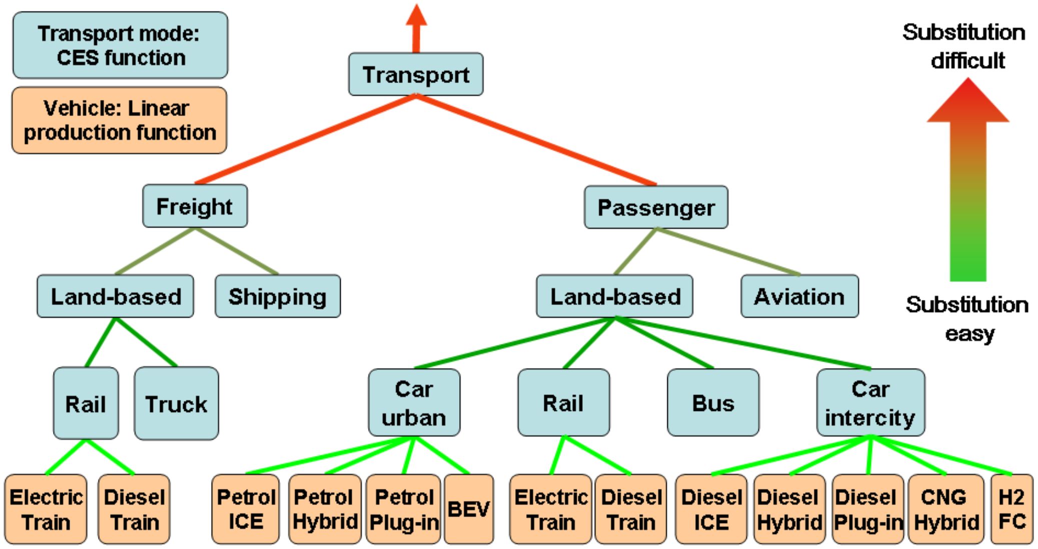


Figure 3: The transport model is made up of linear production functions for the vehicle technologies and CES functions for the transport modes. Transport modes which are shown without technology, e.g., truck, have only one technology that services them. Abbrev.: battery electric vehicle – BEV, internal combustion engine – ICE, compressed natural gas – CNG, hydrogen fuel cell – H2 FC

impossible task when trying to predict how new technologies like renewables, hybrid cars or fuel cell vehicles will enter the market.

Thus, for vehicle technologies, a bottom-up approach based on observable technological and cost data was chosen. Technology parameters like investment costs, conversion efficiencies, average km travelled per year, average occupancy rate, variable costs and life times were gathered from engineering studies or similar publications.

The presented model formulation with a split-up between transport modes and vehicles represents the viewpoint that a petrol car and a plug-in petrol hybrid are perfect substitutes, while two different transport modes like private motorized transport and public bus transport are less-than-perfect substitutes.

2.2 Additional features and constraints:

Cluster learning: As described above, ReMIND allows an individual technology to achieve cost reductions through increase of cumulative capacities, called “learning-by-doing”. While this concept is very useful for very different technologies like wind or photovoltaics, it becomes less usable for new vehicle technologies which use shared parts or technologies, the most notable being batteries. In the original implementation, both hybrid vehicles and battery-electric vehicles (BEVs) had an initial investment costs which included the costs of batteries in 2010, and were only able to reduce this cost individually, thus no knowledge transfer from hybrid cars to BEVs took place. In reality, when hybrids are built, the battery industry develops, and both hybrid vehicles and BEVs will benefit.

Thus, cluster learning was implemented: several technologies use a shared technology, and the learning curve is not only applied to the individual costs, but also to the shared technology. This is realized by splitting the original investment costs for a vehicle into battery costs and the rest of the car. The cumulative capacity of car batteries is increased – and thus the investment cost is decreased – whenever any vehicle technology using batteries (hybrid gasoline and diesel, plug-in hybrid gasoline, diesel and natural gas, BEV, fuel cell) is built.

Technology Ordering: The model sees individual vehicle technologies that supply the same transport mode as equivalent choices, and determines which technology it will build solely on levelized cost per passenger kilometer (pkm). In reality, technology deployment has a temporal order, because a new vehicle technology depends on advances made with a similar technology: It would be quite surprising to see BEVs for all user groups before a substantial market penetration by hybrid and plug-in-hybrid vehicles is reached.

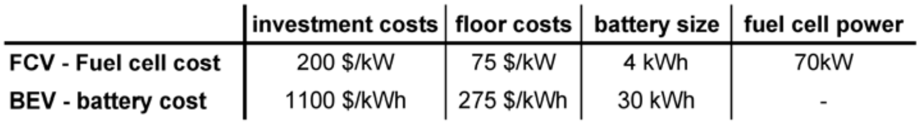
Thus, an ordering constraint was introduced into ReMIND, forcing the model to build a certain amount of a vehicle technology before its successor technology can be built on a large scale.

2.3 Vehicle Data

Technological and cost data for all vehicles were collected from engineering and other scientific studies. The data on automobiles were mostly based on the doctoral thesis of Gül. [8] Automobile conversion efficiencies were taken from the EU JRC's Tank-to-Wheels Report. [5] Data for other transport technologies were adopted from the doctoral thesis of Krey. [12]

Current and future investment cost data for car batteries and fuel cell vehicles (FCV) were gathered from several recent industry studies. [3],[4],[6],[11],[13] In contrast to conventional vehicle technologies, a wide range of price estimations was observed.

The chosen parameters can be seen as slightly conservative assumptions[3]:



	investment costs	floor costs	battery size	fuel cell power
FCV - Fuel cell cost	200 $/kW	75 $/kW	4 kWh	70kW
BEV - battery cost	1100 $/kWh	275 $/kWh	30 kWh	-

3. Experiments and Results:

BAU and POL:

This section shows the major results from the simulations carried out with the model ReMIND-G-Transport, considering two basic classes of scenarios: BAU (business-as-usual) and POL (policy). In the BAU run we simulate a development as if no climate policy was imposed. Thus there is no constraint on global CO_2 emissions, and the only forces that might lead to a change in the energy system are rising primary energy extraction costs and technological development. Within the POL scenario, the CO_2 emissions are limited in such a way as to have a 50 percent chance of achieving the EU climate policy target of limiting global warming to 2°C compared to the pre-industrial level.

The resulting energy mixes can be seen in Figure 4 and Figure 5.

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[3] All cost data is given in US$ 2009.

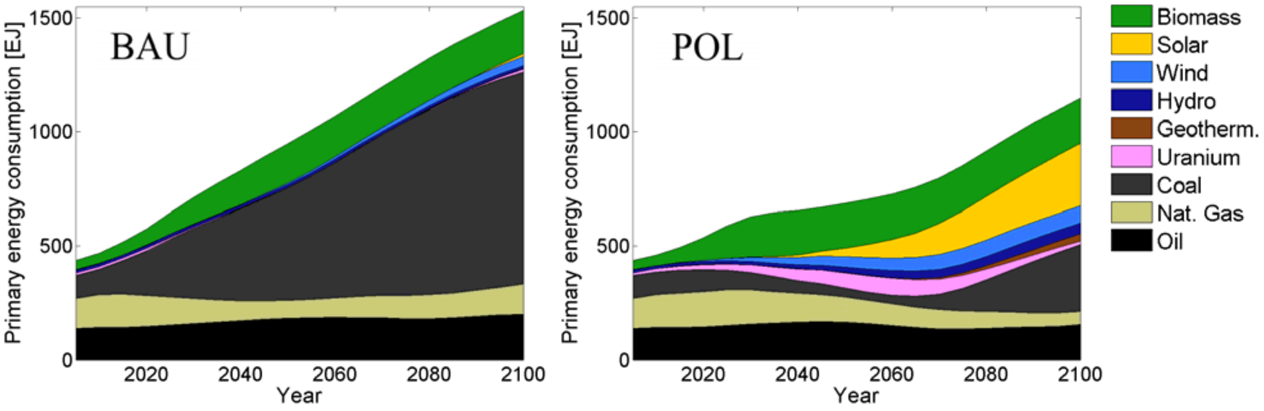

Figure 4: Primary energy production (direct equivalent method)

In the business-as-usual scenario, energy uses increases steadily during the century. This growth in energy use is determined largely by two factors: the assumed population growth scenario (exogenous assumption) and the economic growth calculated endogenously by ReMIND-G. In the BAU scenario, the primary energy mix is dominated by coal. The total use of gas and oil stay relatively constant, while biomass use increases. Wind, hydro, solar and nuclear energy together supply less than 5% of primary energy.

In the policy or climate protection scenario, the picture changes drastically: most of the coal is replaced; first by nuclear, then by wind, solar and hydrogen power. Oil use stays relatively constant, while gas use declines. Biomass use is similar to the BAU case, but the maximum of 200EJ per year is reached earlier. Primary energy use rises much slower than in the BAU scenario, although this is mostly a result of the direct equivalent accounting method in which all renewable energy sources and nuclear energy are counted at their electricity value. Interestingly, coal reappears in the second half of the century.

The electricity mixes in *Figure 5* help explain why coal increases so strongly in the BAU scenario, and why it is heavily used after 2070 in the POL scenario: in BAU, it completely dominates the power production; while in POL, it is used in combination with carbon capture and storage (CCS) once uranium has become expensive due to rising extraction costs. In POL, solar becomes the dominant energy source for electricity production around 2070, and its share surpasses 50% by the end of the century.

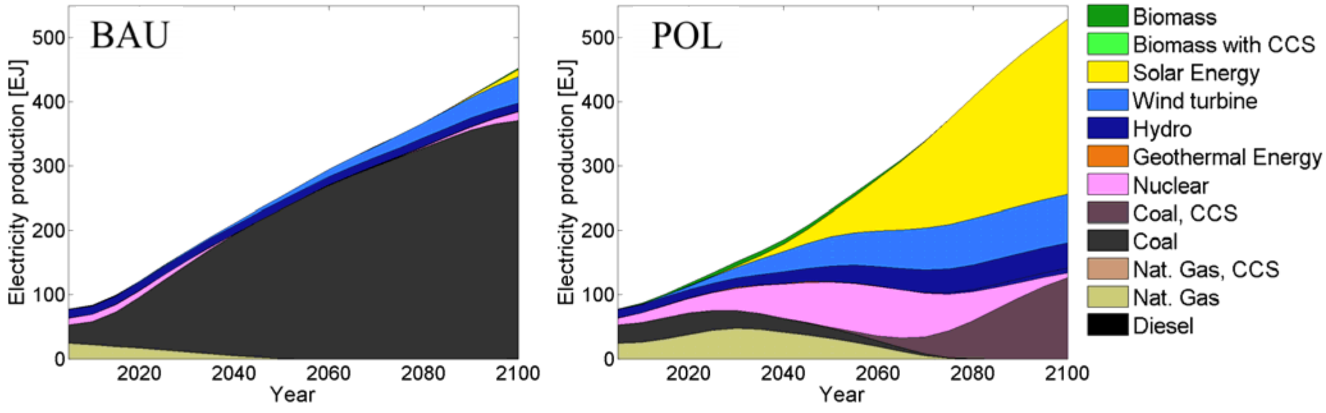

Figure 5: Electricity production

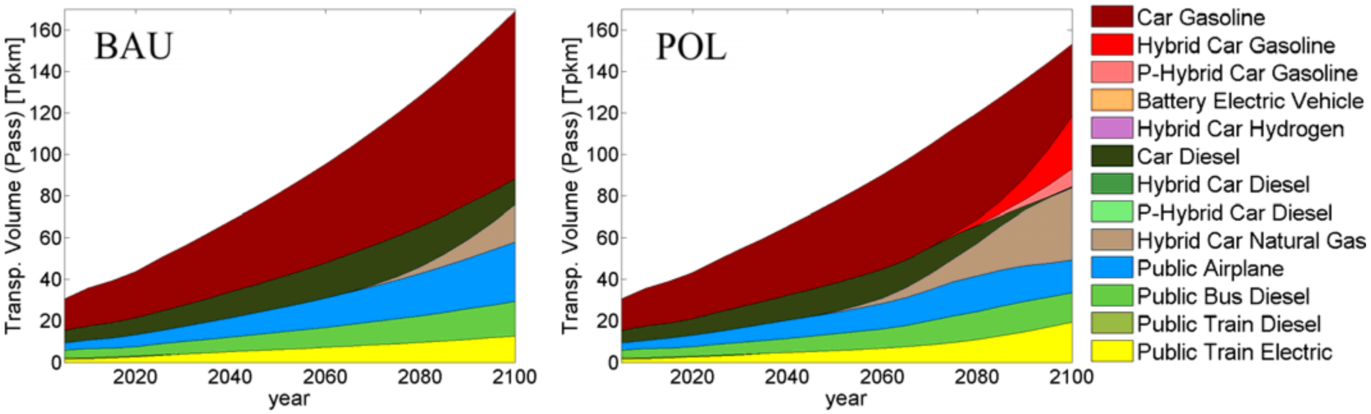

Figure 6: Passenger transport volumes

When turning to passenger transport mixes in Figure 6, the situation looks quite different. Only minor changes can be observed between BAU and POL scenario. In BAU, total transport volume increases by a factor of five over the next century, with all transport modes keeping their shares. The short-distance-private-car mode is completely supplied by conventional gasoline cars, with no hybrid vehicles being used. In the long-distance-private-car mode, we observe a shift from diesel to natural gas hybrids starting in 2070 – however, still no other hybrids are used.

In POL, transport volume increases almost the same, but we can observe some modal shift from plane and bus to trains and long-distance-private-car. After 2090, the long-distance-private-car mode is completely serviced by natural gas hybrids. Under the emission constraint in the POL scenario, we also see some gasoline hybrids and gasoline plug-in hybrids becoming cost-competitive after 2070, but still most gasoline cars stay conventional internal combustion engines (ICEs) until 2100.

Freight transport shows a similar behavior: in BAU, total transport volume quadruples, but the modes keep their constant shares. The only change we observe is the replacement of diesel trains by electric trains for reasons of efficiency.

In the POL case, we observe a reduction of transport volume as well as some modal shift from trucks and ships to trains. This shift can be explained by the nearly complete decarbonization of the power sector, reducing the emissions from electric trains to almost zero.

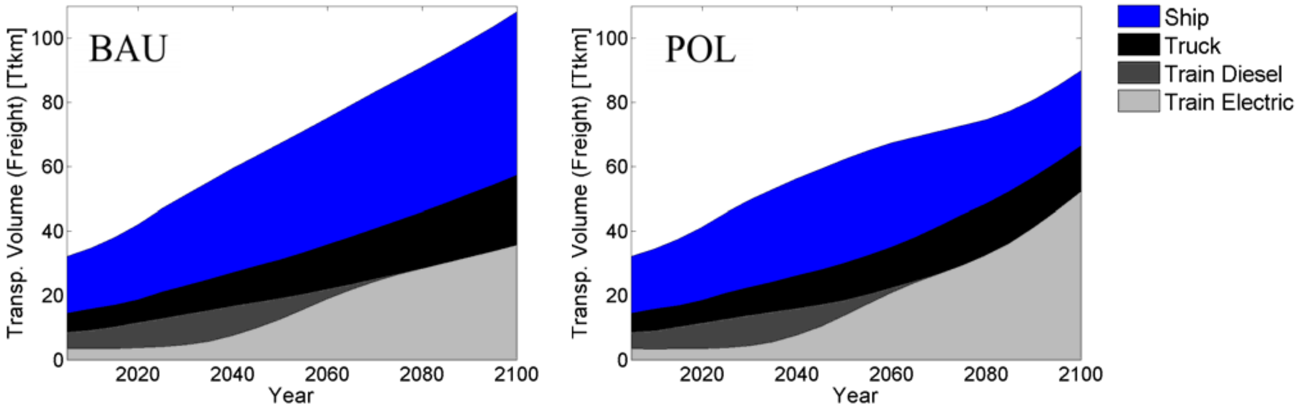

Figure 7: Freight transport volumes

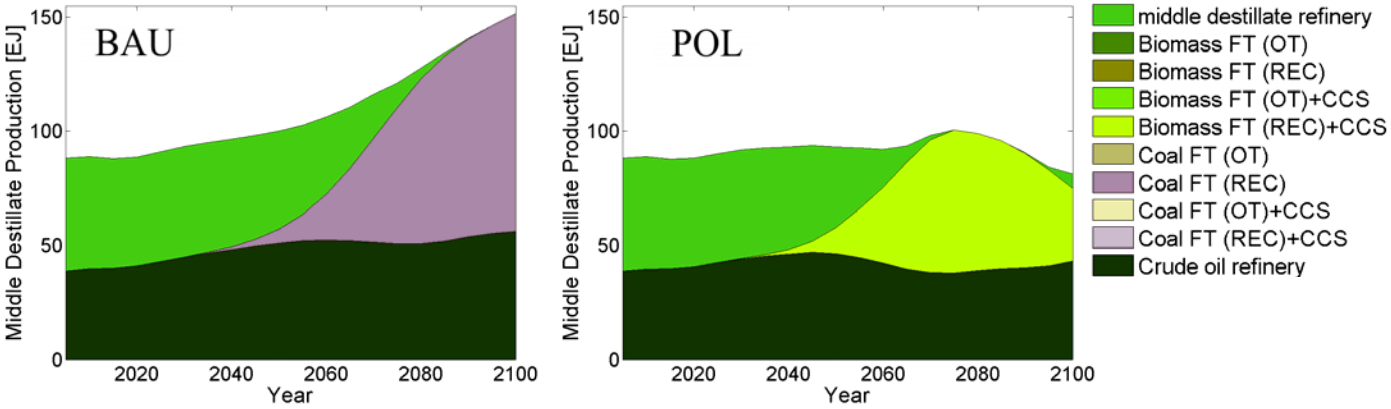

Figure 8: Production of middle distillate, from which diesel, kerosene and heavy fuel oil are produced

Figure 8 shows the inputs used for middle distillate, the substance from which diesel, kerosene and heavy fuel oil are produced. In BAU, rising oil prices lead to the use of Fischer-Tropsch processes to make middle distillate from coal. Under emission constraints, this process is not feasible anymore and gets replaced by a Fischer-Tropsch process based on biomass in combination with CCS, thus leading to net negative emissions.

Sensitivity to battery and fuel cell costs

As both batteries and fuel cells are still in the early development phase, a wide range of best guesses for current and future costs exists. At they same time, these technologies are the major cost driver for the respective vehicles, with batteries accounting for more than half the cost of a new BEV. As observed above, neither of the technologies is used in our POL scenario. To test how close these technologies are to cost-efficiency in a climate protection scenario, we decreased both battery and fuel cell costs until either BEVs or FCVs were used.

For BEVs, initial battery costs had to be reduced from 1200 to 900$/kWh, with floor costs reduced from 275 to 200$/kWh, to finally make BEVs cost-competitive after 2085, as can be seen in Figure 9.

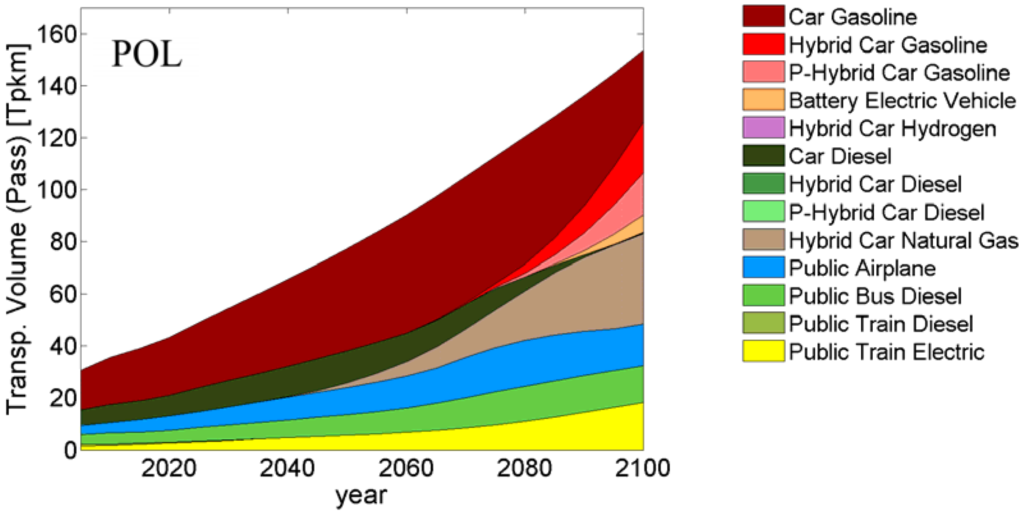

Figure 9: Passenger Transport with battery costs reduced to 900$/kWh (floor cost: 200$/kWh)

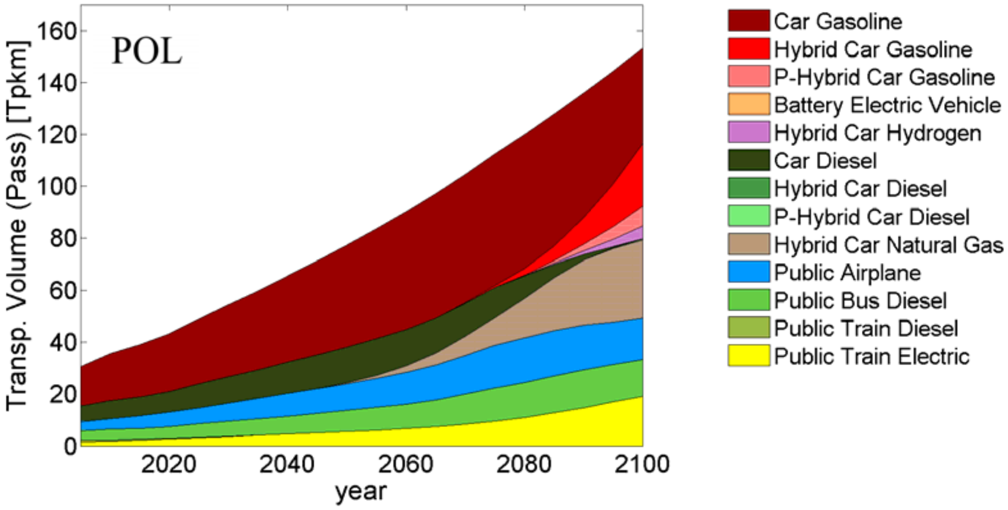

Figure 10: Passenger Transport with fuel cell costs reduced to 150$7kW (floor cost: 30$/kW)

For fuel cells, the necessary cost reductions to introduce FCVs were even larger: initial investment costs had to be decreased from 200 to 150$/kW, with floor costs decreased from 75 to 30$/kW.

Limited biomass availability

As observed before, except for a shift to natural gas vehicles, little technological change occurs in the passenger part of the transport model. The heavy reliance on normal combustion engines is possible even in a 2° policy scenario due to two reasons: First, half of the diesel used is supplied from second generation biomass through a Fischer-Tropsch process in combination with carbon capture and storage. Second, the production of hydrogen (used for industry and household heat) from biomass in combination with carbon capture and storage can be seen as negative emissions which make up for the burning of oil-based fuels in the transport sector.

Thus, the very slow penetration of hybrid vehicles, BEVs and fuel cell cars can probably be attributed to the ready availability of biomass. The intensification of biomass use as seen in POL scenarios may have severe negative real-world effects that are not modeled in ReMIND, such as food scarcity, additional emissions from land use change or reduced biodiversity.

These various impacts of biomass use are a controversial research topic, and different assessments of their importance exist. While some research groups claim that 250 to 500EJ of biomass can be used annually, [9] others propose that only 80 to 170EJ of biomass can be harvested once sustainability and equity criteria are incorporated. [21] To analyze the impact that reduced biomass availability would have on the transport sector and the introduction of novel vehicle technologies, we conducted a model run in which the total available biomass potential in 2050 was reduced from the default 200EJ/year to 100EJ/year.

The results as shown in Figure 11 show a clear change: even though the default battery and fuel cell costs were kept unchanged, we now observe an earlier phase-in of hybrid technologies, and both BEVs and FCVs are used after 2085. Thus, the deployment of novel vehicle technologies is strongly dependent on the scarcity or availability of biomass.

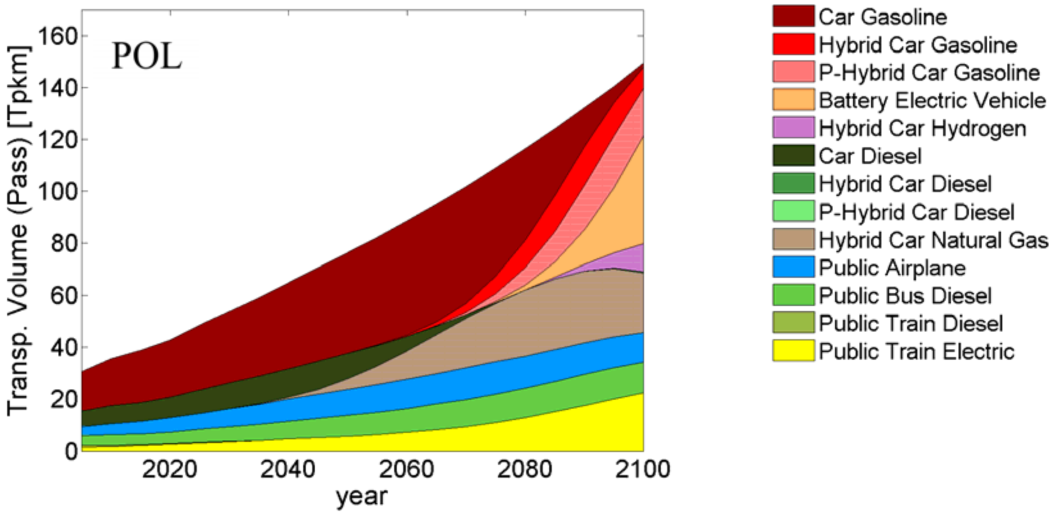

Figure 11: Passenger transport with biomass use limited to 100 EJ/year

4. Conclusion & Outlook:

In this paper, we presented first results from the addition of an explicit transport sector to the energy-economy model ReMIND. We analyzed through what options the transport sector decarbonizes when the system has to fulfill a constraint on global emissions, namely to achieve 50% chance of staying below 2°C global mean temperature increase. While the results are still preliminary, several main messages emerge from this modeling exercise:

- In a purely economic framework, hybrid technologies, BEVs and fuel cell cars enter the market only very slowly, even under the constraint of achieving a 50% chance of staying below 2°C global mean temperature increase.
- In almost all scenarios, natural gas vehicles strongly enter the market and replace diesel ICEs by the end of the century. This is quite remarkable, as – to the author’s best knowledge – few other studies consider CNG vehicles as a major contributor to passenger transport.
- The reliance on conventional combustion engines is only possible due to the extensive use of biomass in combination with CCS, both to directly fuel vehicles and to offset the emissions from petroleum-based fuels.
- In the freight sector, we see some modal shift from trucks and ships to rail, and total transport volume is decreased. In the passenger sector, only little modal shift occurs, and the transport volume stays almost the same in BAU and policy scenarios.

We believe this modeling exercise to be very insightful as it considers all energy uses and transformation processes, thus realistically modeling price influences from one sector on another sector. However, we see several shortcomings which will be addressed in future publications:

- First and foremost, the model is a purely economic optimization model. While this approximation makes sense in the power sector, it becomes weaker for the transport sector. Numerous studies exist that show how the choice for a certain transport mode and vehicle is influenced by a large number of factors like
  - Infrastructure: How close is the next train/bus station? How densely populated is the city I live in?
  - Circumstances: Do I live in a society in which a private vehicle is seen as an important status symbol? Am I used to biking a lot and chose my work and living locations accordingly?
  - Policy regulation: taxation on transport; speed limits; support programs for hybrid or battery-electric vehicles.
  - Personal preferences: do I buy a hybrid car because it is fashionable? Do I prefer to take the train as it allows me to relax while travelling?
- Furthermore, transport has many externalities besides greenhouse gas emissions, including local pollutants, accidents, noise, and land consumption. When analyzed from a cost-benefit point of view, some of these externalities have a much higher impact per km than the effect on global warming. Consequently, even over the last 50 years, transport has been regulated in many countries. Thus, the future development of the transport sector will also be influenced by regulation that targets these other externalities, which might favor certain technologies or a certain transport mode more strongly than the climate externality does.

Future technical improvement of the transport sector model will include:

- Increasing the choice of vehicle technologies to include, e.g., close-distance transport by bike and tuktuks, which play a large role in South Asia, or hybrid busses for public transport.
- Changing the CES structure of passenger-based transport so the main split is between urban and intercity transport.
- Linking the storage requirement in the power sector to the use of BEVs (“vehicle-to-grid”) and hydrogen vehicles.

To better analyze the influence that modal shifts may have on the decarbonization of the transport sector, it will be necessary to explore the parameter space of the CES structure. An interesting experiment would be to mimic regulation that favors one transport mode over another, e.g., the implementation of a bus rapid transit system, by changing CES substitution elasticities and efficiencies between the transport modes.

Owing to these caveats, the presented results should only be seen as a first sketch of an economic analysis of the decarbonization of the transport sector. Nevertheless, they reveal information about the important interactions between the different energy sectors, and may help to better understand the key determinants of future transport development.

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