The role of biofuels for transportation in CO$_2$ emission reduction scenarios with global versus regional carbon caps

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Abstract

This study analyzes how international climate regimes affect cost-efficiency of fuel choices in the transportation sector. The analysis is carried out with a regionalized version of the Global Energy Transition model, GET-R 6.0. Two different carbon dioxide (CO$_2$) reduction scenarios are applied, both meeting an atmospheric CO$_2$ concentration target of 450 ppm by the year 2100. The first scenario, “global cap” (GC), uses a global cap on CO$_2$ emissions, and global emissions trading is allowed. In the second scenario, “regional caps” (RC), industrialized regions start to reduce their CO$_2$ emissions by 2010 while developing regions may wait several decades and emission reductions are not tradable across regions. In this second scenario, CO$_2$ emissions are assumed to meet an equal per capita distribution of 1.0 tC/capita, in all six regions, by 2040; emissions then follow a common reduction path, toward approximately 0.2 tC/capita by 2100. Three main results emerge from our analysis: (i) the use of biofuels in the industrialized regions is significantly higher in RC than in GC; (ii) the use of biofuels in RC actually increases the weaker (i.e., higher) the CO$_2$ concentration target (up to 550 ppm); and (iii) biofuels never play a dominant role in the transportation sector. We find that biofuels may play a more important role in industrialized countries if these take on their responsibilities and reduce their emissions before developing countries start reducing their emissions, compared to the case in which all countries act under a global cap and trade emission reduction regime.

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1. Introduction

The European Council has adopted a so-called two degree target for the global annual mean surface temperature. The target indicates that the global temperature should not rise more than 2 °C above pre-industrial levels [1]. To meet this climate target, global carbon dioxide (CO$_2$) emissions need to reach very low levels during this century. This requires major changes in energy and transportation systems. Which transportation fuels and technologies are likely to become cost-effective under such climate constraints?

An earlier study of cost-effective fuel choices in the global transportation sector, under stringent carbon constraints [2] using the Global Energy Transition model, GET 1.0, found that it is more cost-effective to substitute biomass for fossil fuels in heat production, than in the transportation sector. Which biofuels and transportation technologies are likely to become cost-effective under such climate constraints?
produced from fossil fuels with carbon capture and storage (CCS) enters. Biofuels for transportation were not found to offer a cost-effective strategy for reducing CO2 emissions.

In the earlier study (as well as in present study), “biofuels” only refer to advanced and well-developed second generation biofuels. Therefore, the reason biofuels were not found cost-effective, using GET 1.0, was not based on the observation that biofuels derived from traditional agricultural crops like corn, wheat, or rapeseed are expensive and often associated with large indirect greenhouse gas emissions.

Results from GET 1.0 show that oil continues to dominate the transportation sector for several decades while emissions are reduced largely by avoiding fossil fuels for stationary applications (e.g., coal for electricity generation). In essence: it is possible for oil to dominate the transportation sector, since emissions can be compensated by fuel switching in stationary sectors, largely in developing regions. During the final part of the century, hydrogen enters the transportation sector so that it, too, eventually becomes largely CO2 free. A key factor for biomass allocation to transport or to heat and power may in fact be the introduction or failure of hydrogen in fuel cell vehicles [3].

In the initial GET study it was assumed that all countries take action to reduce CO2 emissions by 2010. So far, not all nations have taken action, and it is not clear all countries will act by 2020, even. The United Nations Framework Convention on Climate Change, signed by most countries in 1992, contains goals and principles for the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” [4] (Article 2) and states that, “The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof” [4] (Article 3.1). The Kyoto Protocol, in accordance with the idea that developed nations should take the lead, only stipulates reduction targets for developed nations, and this basic principle remains in the Bali Action plan [5].

At the time of our initial study, some commentators were concerned with our global approach to the problem. They argued rich countries will have to act before developing countries, and this implies that efforts have to be directed to fuel switching also in the transportation sector. Thus, a key question is what will happen in the transportation sectors in the industrialized regions if emissions have to be significantly reduced over the coming years.

The aim of the current study is to analyze cost-effective fuel choices in the transportation sector, in a regionalized model version of the GET model, GET-R 6.0, given that industrialized countries take on their responsibilities and reduce emissions before developing countries start reducing their emissions. We then compare the results assuming these regional emission caps (scenario RC) with results assuming a global cap (scenario GC). These two scenarios (a global cap and full emissions trading and regionalized caps without inter-regional trading) are of course extremes and for that reason interesting to analyze. In current Kyoto agreement, industrialized regions are allowed to obtain a part of their reductions in developing regions, via carbon trading and regionalized mechanisms like CDM. Assuming such “hybrid scenario” would, however, only give a result in between the findings from scenario RC and scenario GC.

We have chosen to run the model against an atmospheric concentration target of 450 ppm by the year 2100. This is likely to lead to an eventual equilibrium temperature increase in the range 2–4.5 °C [6] under the assumption that non-CO2 greenhouse gases will contribute an additional 100 ppm CO2-equivalents [7]. We nevertheless chose this target since lower emissions during the next century may make it possible for the atmospheric concentration to drop to around 400 ppm CO2. With efforts to reduce other greenhouse gases, the long-term equilibrium temperature change may in this case stay below 2 °C. The exact temperature response of course depends on climate sensitivity.

If the climate sensitivity is high, around 4 °C or more for a doubling of the CO2 equivalent, more ambitious reduction efforts are required. Our initial plan was therefore to develop a scenario that met a 400 ppm concentration target already in the year 2100. An assumption that all regions will meet at an equal per capita emission level a certain year (as in scenario RC) would lead to unrealistic emission reduction efforts for the industrialized regions (especially NAM) over the next decades if the convergence point is set to 2030 or earlier. Choosing 2040 as this convergence point requires on the other hand great reduction efforts for the developing regions in the period 2040–2080. Meeting 400 ppm would require more than 80% reduction over that period leading to the conclusion that a delayed action scenario for developing countries was not feasible meeting 400 ppm. Thus, in order to study fuel choices under a climate policy regime in which rich countries act first, we were compelled to study a less ambitious CO2 concentration target. Even reconciling 450 ppm with delayed action in developing countries is a challenging task.

Model description and scenario assumptions are presented in Section 2. In Section 3, we present the modeling results. A comprehensive sensitivity analysis is carried out in Section 4 followed by a discussion and concluding remarks in Section 5.

2. Method

In order to analyze a possible future transition of the global energy system, Azar and Lindgren have developed the GET (Global Energy Transition) model. The initial version, GET 1.0, was designed to study global fuel choices in the transportation sector [2,8] and later versions have been developed to analyze a variety of questions, e.g. GET 5.0 was used to analyze the costs and potential role of carbon capture and storage from fossil fuels and biomass in stabilizing atmospheric CO2 concentration [9].

In this study, we have regionalized a later version (GET 6.0) with six different regions: North America (NAM), Europe (EUROPE), the Former Soviet Union (FSU), OECD countries in the Pacific Ocean (PAO), Latin America, the Middle East and Centrally Planned Asia (LAMEC), and Africa, South Asia and Pacific Asia (AFSAPA), where the latter two are considered developing regions, roughly grouped by current GDP and CO2 emission levels.
2.1. Model structure

The regionalized energy systems model (GET-R 6.0) is a linear optimization model designed to select primary energy sources, conversion technologies, energy carriers, and transportation technologies meeting the energy demands of each region, at the lowest aggregate global cost subject to a carbon constraint (an emission cap or emission trajectories). The carbon constraint can be imposed on either emissions or atmospheric carbon concentration using the carbon cycle model presented in Maier-Reimer and Hasselmann [10]. The model does not include greenhouse gases other than CO₂.

The model focuses on the transportation sector, while the use of electricity and heat (including low and high temperature heat for the residential, service, agricultural, and industrial sectors) are treated in a more aggregated manner. Energy supply potentials, demand for electricity, heat and transportation fuels are given exogenously. The model is composed of three different parts: (i) the primary energy supply module, (ii) the energy conversion system with plants that convert primary energy sources into secondary energy carriers (e.g., electricity, hydrogen, synthetic fuels, and gasoline/diesel), and (iii) the final energy demand, which in the transportation sector is affected by choice of technologies. The following fuel options are available for the transportation sector: gasoline/diesel, natural gas, advanced second generation liquid biofuels (BTL), liquid fuel from coal (CTL), liquid fuel from natural gas (GTL), and hydrogen (H2). Technology options in the transportation sector are: internal combustion engine vehicles (ICEVs) and fuel cell vehicles (FCVs). Electric (battery-fed) vehicles are not included in the analysis. To some extent electric vehicles and fuel cell vehicles have comparable characteristics, e.g. strong barriers in technology development, superior efficiency potential, and allowance for other renewable options to enter the transport sector. In parallel studies, new versions of the GET model have been developed that include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) [11,12]. A sensitivity analysis is carried out in Section 4.2 to explore the impact on biofuel use when including these vehicle options. The basic energy flows in GET-R 6.0, i.e. primary energy supply options, trade, and final fuel choices, are presented in Fig. 1.

The description of the energy system in the model is a simplification of reality in at least four respects: (i) consideration of limited number of technologies, (ii) assumption of price inelastic demand, (iii) selections made only on the basis of cost and (iv) “perfect foresight” with no uncertainty of future costs, climate targets, or energy demand. The model is not designed to forecast the future development of the energy system. The model does however provide a tool to understand the system behavior and the interactions between energy technology options, under different circumstances, in a future carbon-constrained world.

2.2. Energy demand scenarios

Regional population, GDPₚₚₚ per capita (GDP measured in purchasing power parities), heat and electricity demand are assumed to follow scenarios developed by the International Institute for Applied Systems Analysis (IIASA). In the global cap scenario, GC, we use an ecologically driven demand scenario, “C1”, which assumes that technological development leads to energy efficiency improvements, so that per capita heat and electricity demands in industrialized countries are reduced [13]. Minor modifications to the C1 scenario were carried out so as to match with actual values for the year 2000 for electricity and primary energy supplies with data taken from IEA [14], see Table 1.

For the second emission scenario, RC, we use the C1 demand scenario for the industrialized regions, but it is unlikely that the large energy efficiency improvements assumed in C1 will occur in developing regions before these have commitments on CO₂ emission reductions. We have, therefore, constructed an energy demand scenario, Dₐ₁ₙ₉, which is a weighted combination of the IIASA high-growth demand scenario, titled “A1”, and the demand scenario “C1”, for the developing regions. The weighting is carried out by applying the demand scenario mix as described in Eq. (1)

\[
D_{A1C1} = \frac{(t-2010)}{90} D_{A1} + \frac{(2100-t)}{90} D_{C1} \quad \text{for } 2010 \leq t \leq 2100
\]

Neither of the two chosen energy demand scenarios is sufficiently detailed for the GET analysis of the transportation sector. We have, therefore, developed our own transportation scenario by assuming that increase in person kilometers traveled is proportional to GDPₚₚₚ growth. Transportation scenarios are developed separately for passenger and freight transportation and disaggregated into trains, cars, buses, trucks, ships, and aviation. It is assumed that there is an exogenous improvement in energy efficiency in the transportation sector by 0.7% per year. For full details, see Azar et al. [2,8]. The total transportation demand per capita is presented in Table 1.

2.3. Assumptions and constraints

Primary energy supply potentials are given exogenously for each region. Biomass, uranium, oil, natural gas and coal can be traded between regions at additional costs. For global supply potential on oil and natural gas we have chosen approximately twice their present proved recoverable reserves, i.e., 12,000 and 10,000 EJ, respectively [15,16,17] and assumed a regional distribution following Johansson et al. [19]. For coal we have chosen a global supply potential of approximately 260,000 EJ following the total resource estimates in Rogner [15]. Reported resources at the end of 2005, add up to 125,000 EJ [18] but figures from China, Australia and many other countries are missing. In the model, CO₂ emission constraints limit the use of fossil fuels (generally less than 10% of the coal supply potential is used within this century when meeting 450 ppm). Also sensitivity analyses have shown that changes in the fossil fuel supply potentials do not have significantly impacts on our results of biofuel share in the transportation sector.

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3 The model does not distinguish between gasoline and diesel fuel, these are lumped together as Petro.

4 In this study “biofuels”, also denoted BTL, refer to liquid transportation fuels derived from biomass.
A detailed assessment of the biomass supply potential can be found in Hoogwijk [20]. For four different scenarios and two biomass production cost levels (lower than 2 USD/GJ and lower than 4 USD/GJ), she estimates the global supply potential to lie in the range of 130–439 EJ/year (with a mean value of 253 EJ/year) by the year 2050. This is similar to Johansson et al. [19] where estimates on regional biomass supply potentials add up to a global maximum of 205 EJ/year, which we have chosen in the present study. Sensitivity analysis of halving and doubling this biomass supply potential level is presented in Section 4.2. As biomass supply potential we assume woody biomass and residuals in equal amounts and the required land area for the assumed energy plantations corresponds roughly to a third of current agricultural cropland or around a 10th of total agriculture land, i.e. arable land plus pasture. The large but nevertheless limited biomass supply imply that biomass cannot completely replace fossil fuel use in all sectors. With higher competition for bioenergy a scarcity rent is generated in the model. The model thus chooses to use biomass in the sector where it is most cost competitive.

The supply potentials for wind and solar energy are huge and have therefore not been assigned an upper limit, but they are limited by expansion rate and intermittency constraints. In most cases investment costs, conversion efficiencies, lifetimes, and load factors are held constant at their “mature levels”. Regionalized load factors for solar energy technologies give some advantages to the regions NAM, AFSAPA and LAMEC. Parameter values are identical to those described in Azar et al. [9] and Grahn et al. [3], except for one difference. We have changed the energy efficiency for hydrogen used in fuel cells in cars, compared to internal combustion engines, from a factor of 2.2 more efficient to a factor of 1.5, following Åhman [21]. Hence, the use of hydrogen in fuel cell vehicles in GET-R 6.0 is less favorable than in earlier versions of GET.

The model includes constraints on the expansion rates of technologies (in general set to require 50 years to change the entire energy system), as well as annual or total extraction limits on the different available primary energy sources. We assume that technologies developed in one region are available for other regions. Global dissemination of technology is not seen as a limiting factor.

We have further constrained the contribution of intermittent electricity sources (wind and solar PV) to a maximum of

![Fig. 1 – The basic flow chart of supply and fuel choices in GET-R 6.0. Acronyms used: hydrogen (H2), electricity (ELEC), low and high temperature heat for the residential, service, agricultural, and industrial sectors (HEAT), natural gas as transportation fuel (GAS FOR TRSP), synthetic fuels (biomass to liquid, coal to liquid and gas to liquid), e.g. methanol, DME or Fischer–Tropsch diesel (BTL/CTL/GTL), diesel and gasoline (PETRO) and synthetic fuels for aviation (AIR FUEL).](image-url)
30% of the regional electricity demand and fixed the contribution of nuclear power to the level each region has today. Sensitivity analyses of these assumptions are carried out in Section 4.2. To simulate the actual situation in developing countries, a minimum of 30 EJ/year of the heat demand needs to be produced from biomass during the first decades.

This model version allows for carbon capture and storage (CCS) technologies for the production of heat, electricity, and hydrogen, based on fossil fuels and biomass. The total use of CCS is limited by the global carbon storage capacity, and we have set a conservative upper limit of 400 GtC [22]. Sensitivity analysis on a larger storage capacity is carried out in Section 4.2.

### 2.4. Carbon reduction scenarios

Our ambition in this paper is to analyze how cost-effective fuels’ choices for transportation depend on international climate policy regimes. Thus, we run the model under two different types of emission scenarios (both leading to atmospheric CO2 stabilization at 450 ppm).

In the first emission scenario, GC, all regions are assumed to start reducing their CO2 emissions by 2010, and global emission trading is allowed.

In the second emission scenario, RC, emission reductions are not tradable across regions and, industrialized regions take the lead in mitigating global warming. These regions start to reduce their CO2 emissions by 2010 while developing regions may wait until 2030 (in order to prepare for their binding targets by 2040). CO2 emissions are assumed to meet an equal per capita distribution of 1.0 tC/capita, in all six regions, in 2040 and then jointly follow an emission reduction path, toward approximately 0.2 tC/capita/year by 2100. Several authors have argued in favor of an allocation of emission rights (tradeable or not) on an equal per capita basis, see e.g. [23,24,25].

Developing countries as a group do not have to reduce emissions between 2010 and 2030. However, many individual developing countries are already far above that target or about to exceed that level. China, for instance, is already at 1 tC/capita/year. South Africa is at 2.5 tC/capita/year, Saudi Arabia at 3.7 tC/capita/year [26]. In our model, these countries are included in regions with lower emissions and the higher levels are averaged out. In the real world, targets are likely to be imposed on individual countries, but we have not considered that fact here. Instead, the focus is on cost-effective fuel choices in the industrialized regions.

### 3. Results

In this section, we present the CO2 emission trajectories as well as cost-effective fuel choices in the transportation sector from the two carbon reduction scenarios, described in Section 2.4. Both scenarios are run toward concentration stabilization at 450 ppm.

#### 3.1. CO2 emission trajectories

The CO2 emission trajectories generated in GC and RC, expressed in ton carbon per capita per year are presented in Fig. 2, and expressed as billions of ton carbon per year in Fig. 3. Both emission scenarios lead to an atmospheric CO2 concentration of 450 ppm by the year 2100. Negative CO2 emissions are obtained in a few regions through the use of Biomass Energy with Carbon Capture and Storage (BECCS) [9].

The main difference between Fig. 2a and b is that RC requires much faster reductions for the industrialized regions. In GC, per capita emissions in North America (NAM) in 2040 are as high as 4.5 tC/capita, whereas they are assumed to be only 1.0 tC/capita in RC. Similarly, per capita emissions in Europe and PAO (Japan, Australia and New Zealand) are much higher in GC compared to assumptions made in RC. These differences are of course also reflected in the total emissions from these regions, see Fig. 3.

Note (see Fig. 2b) that AFSAPA does not reach the allowed limit of 1.0 tC/capita in 2040. Their emissions peak at 0.7 tC/capita in 2050, which follows from the scenario assumption that AFSAPA has a very low per capita energy demand during the next 50 years, i.e., even if AFSAPA would use 100% fossil fuels they would still not reach 1.0 tC/capita.

Fig. 3 shows that developing region’s total emissions are increasing much faster, and reaching in total higher levels, compared to the industrialized regions (despite the fact that they are still below the rich world emissions per capita). Total emissions in the developing regions are allowed to increase more in RC (Fig. 3b) than in GC (Fig. 3a). Since both GC and RC will meet the same CO2 concentration target in the year 2100, the more the emissions are allowed to increase before the point of convergence for per capita emissions, the higher is the reduction challenge during the second half of the century. This important feature of the regional emission reduction problem is hidden in Fig. 2.

#### 3.2. Cost-effective fuels for transportation

The cost-effective fuel choices in the transportation sector are plotted for each decade. We have chosen to present the results for North America and Europe, see Figs. 4 and 5, as an example of how fuel choices for transportation evolve over the century and how they generally differ between GC and RC, in industrialized regions. We have also chosen to exclude results on fuel choices for aviation and rail from the figures since biofuels never enter these transport categories. The rail sector was supplied with electricity and the aviation sector with oil-based kerosene, a small fraction of CTL/GTL in an intermediate period and hydrogen as dominating fuel option by the end of the century in both GC and RC. A sensitivity analysis is carried out in Section 4.2 on the impact of biofuel use when excluding hydrogen from aviation.

Synthetic fuels based on coal or natural gas do not enter the transportation sector in North America when industrialized regions take on their responsibilities and start reducing CO2 emission before developing regions, see Fig. 4b. Instead, the use of biofuels and hydrogen increases. Note that results on CTL and GTL are lumped together to reduce the number of fuel options displayed in the figures, but the options are...
modeled separately, with different emission factors, costs, supply potentials and so on. A similar result holds for the European transportation sector, see Fig. 5b.

One somewhat striking difference is that gasoline and diesel play a more dominant role in the European transportation sector. The reason for this is complex and depends on a number of factors. First, we have not run the model with pre-existing fuel taxes and we have assumed, which is the case, that American cars drive longer distances. This means that it becomes more cost-effective to switch fuels in North America first. In reality, other factors will of course also be important, but our model is based on cost-minimization. The second reason is that in RC, North America has to reduce its emissions much faster than Europe. This increases the regional carbon price and makes it even more cost-effective to switch fuels in North America.

A general pattern, for all four industrialized regions and both scenarios, is that there is a transition from petroleum-based fuels used in internal combustion engines to hydrogen used in fuel cell engines. Natural gas and synthetic fuels (BTL/CTL/GTL) are cost-effective fuel choices during a transition period. More specifically, gasoline and diesel dominate for several decades ahead. Natural gas and synthetic fuels enter the scenarios around 2010–2030, showing a larger total use in industrialized regions in RC compared to GC. Hydrogen is generally introduced beyond 2050 and will eventually dominate in most regions around or after year 2100.

To compare the total biofuel use in the two emission scenarios, we add up the regional results fuel by fuel, see Figs. 6 and 7. Fig. 6 shows that gasoline and diesel dominate all regions in GC and add up to a global share of 52%. Natural gas is the largest alternative fuel reaching a global share of 26%, while hydrogen, CTL/GTL and biofuels take the remaining global market shares.

The hydrogen share over the 100 year period in developing regions is 11–14%, and this is larger than in the industrialized
regions, 3–10%. This is a result of the rapid expansion of fuel demand in developing regions where the demand for road and sea-based transportation in 2100 is approximately 140 EJ (when hydrogen dominates) compared to less than 20 EJ/year at the beginning of the century (when petroleum-based products dominate). Note that, in the end of the century, hydrogen is the most expanding fuel option in all regions (with the hydrogen shares of road and sea-based transport, in 2100, being 33–82% in RC and 48–73% in GC). Biofuels play a limited role in developing regions 4–6%.

In the industrialized regions, North America and the Former Soviet Union have a larger share of natural gas than the global average, while natural gas is hardly used in PAO. Fossil-based synthetic fuels (CTL/GTL) play an important role in PAO 24%, NAM 14%, and EUR, 13%. Biofuels have a smaller share PAO 4% and NAM 8%, whereas FSU and EUR have zero. The mean value in the four industrialized regions for use of biofuels is 4.4%.

Fig. 7 shows that gasoline and diesel dominate the global picture in RC, too, and add up to the same share as in GC 52%. For the alternative fuels, results are also very similar in the two scenarios, except there is almost no CTL/GTL in RC.

In developing regions, the share of hydrogen is 17–19%, compared to 11–14% in GC, while there is almost no use of either kind of synthetic fuels.

In the industrialized regions, the use of hydrogen increases to 5–15%, compared to 3–10% in GC. There is almost no use of CTL/GTL, while the use of biofuels increases to 6–18%, compared to 0–8%. The mean value for the four industrialized regions’ use of biofuels is 12%, almost three times higher than in GC.

Biofuel trade between regions is not shown in GC, whereas a significant trade occurs in RC where developing regions export biofuels to industrialized regions.

Natural gas is shown to be a cost-effective strategy to reduce carbon dioxide emissions in most regions. A sensitivity analysis on this result is carried out in Section 4.3.

4. Sensitivity analysis

In this section we will analyze the robustness of our main result that the use of biofuels in the industrialized regions is significantly higher in scenario RC than in scenario GC.

Fig. 5 – How cost-effective fuel choices evolve over time for road and sea-based transportation in Europe from (a) GC and (b) RC, expressed as EJ per year. Acronyms used H2 = hydrogen, CTL/GTL = synthetic fuels derived from coal or natural gas, BTL = synthetic fuels derived from biomass, GAS = natural gas, FC = fuel cells and IC = internal combustion engines.
4.1. The role of biofuels for other CO₂ concentration targets

In this subsection, we analyze the biofuel share of road and sea transportation fuels for eight alternative atmospheric CO₂ targets. To be able to compare the runs toward different CO₂ concentration targets, we strive for making as few other changes as possible. Therefore, we have chosen to keep the same energy demand assumptions as described in the earlier 450 ppm analysis, for all eight concentration targets, even though energy demand would in reality be higher the weaker (i.e., higher) the concentration target is.

We have chosen to analyze biofuel use also for 400 ppm as part of the exercise even though this lower concentration target is very difficult to realize in scenario RC, as described in the Section 1.

The average share of biofuels in the road and sea transportation sectors in the industrialized regions is significantly higher in RC compared to GC, for all CO₂ targets, see Fig. 8.

In RC, the highest value is 21%, obtained with the 550 ppm target; in GC, the highest value is 4.4%, for 450 ppm. Mid-range targets yield the highest values for biofuel share.

In scenario RC, the average share is greater than 15% for targets 500–650 ppm, while 5–15% for 400 and 450 ppm, as well as 700 and 750 ppm. The same pattern holds for developing regions (data not shown), where the values are 8–12% for the mid-range targets and 3–8% for the targets on either end.

In scenario GC, the use of biofuels is significantly lower, below 5% for all CO₂ stabilization targets. The same pattern holds for developing regions (data not shown), where the values are below 3% for all CO₂ stabilization targets.

4.2. Changes in some parameter values

In this subsection, we analyze the robustness of our main result, i.e., that the use of biofuels in the industrialized regions is significantly higher in RC than in GC also for changes in parameter values. In this sensitivity analysis we have chosen to make rough and large variations in key parameters expected to have an impact on the biofuel use. In general we test halving, doubling or tripling parameter values (or a complete failure of a specific technology) with the aim of first and foremost identifying if results on biofuel use from scenario RC remain higher compared to scenario GC for all tests. Of course other parameters (and changes in model structure) could affect the biofuel use, but our intention is not to cover all alternative futures but to identify in what directions results go. We carried out 20 sensitivity tests for the base case 450 ppm, see Table 2.

In Fig. 9, we present the result from the 20 sensitivity tests in descending order of the RC result. For the sake of comparison the base values from Fig. 8 are included.

Fig. 6 – Cost-effective fuel choices as share of total fuel use for road and sea-based transportation in GC, toward 450 ppm, for the time period 2000–2099.

Fig. 7 – Cost-effective fuel choices as share of total fuel use for road and sea-based transportation in RC, toward 450 ppm, for the time period 2000–2099.

Fig. 8 – Mean values of cost-effective biofuel use for the four industrialized regions as share of total fuel use for road and sea-based transportation, over this century.
Table 2 – Parameter values for sensitivity analysis.

<table>
<thead>
<tr>
<th>Sensitivity test</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Doubled bioresource</td>
<td>In base runs we assume biomass supply potential of approx 200 EJ/year. In this run we double this potential</td>
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<tr>
<td>2. Halved bioresource</td>
<td>In this run we half the biomass supply potential to max 100 EJ/year</td>
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<tr>
<td>3. Halved oil resource</td>
<td>In base runs we assume a global oil supply potential of approx 12,000 EJ. In this run we halve this potential</td>
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<tr>
<td>4. Lower BTL/CTL/GTL vehicle cost</td>
<td>In base runs the incremental investment costs for BTL/CTL/GTL vehicles are 1000 USD/car and 3000 USD/truck. In this run we assume that these vehicles could be produced with only minor changes from conventional ICEVs and lower the incremental costs to 1000 USD/car and 300 USD/truck</td>
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<tr>
<td>5. Tripled FC-cost</td>
<td>In the base case, a fuel cell car costs 4000 USD/car more than a conventional car. We triple this incremental cost for hydrogen fuel cells (for other FC technologies we assumed the following incremental costs: 13,500 USD/synthetic fuel, 13,500 USD/gasoline, 54,000 USD/H2, 57,000 USD/synthetic fuel)</td>
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<tr>
<td>6. Tripled H2-infra cost</td>
<td>The investment cost of large scale hydrogen infrastructure is tripled to 6000 USD/kW</td>
</tr>
<tr>
<td>7. No H2 in aviation</td>
<td>In this run we assume that hydrogen is not a fuel option for aviation</td>
</tr>
<tr>
<td>8. Higher bio-heat cost</td>
<td>In base runs we assume that biomass can be used for heat production in plants with an investment cost of 300 USD/kW leading to a heat production cost of 3.8 USD/GJ. In this run we assume that biomass needs to be pelletized at an additional cost of approx 3 USD/GJ [27]. By increasing the investment cost to 800 USD/kW, the biomass-based heat production cost is 6.5 USD/GJ</td>
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<tr>
<td>9. Only stationary FC</td>
<td>In this run we assume that fuel cells cannot be used in the transportation sector, only in stationary applications</td>
</tr>
<tr>
<td>10. No BECCS</td>
<td>BECCS is not yet a commercial option. In this run we assume that this option will not be commercialized. CCS from fossil fuels is, however, still an available option in this run</td>
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<tr>
<td>11. No CCS</td>
<td>In this run we assume that CCS will never be commercialized, not in conjunction with bioenergy nor with fossil fuels</td>
</tr>
<tr>
<td>12. Doubled CCS storage</td>
<td>In base runs we assume there is a geological storage capacity of 400 GtC. In this run we double that to 800 GtC</td>
</tr>
<tr>
<td>13. Tripled nuclear max level</td>
<td>In base runs we have fixed nuclear contribution to current level. In this run we set an upper limit which is three times higher</td>
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<tr>
<td>14. Less crude oil to trsp.fuel</td>
<td>In base runs there are no restrictions on how much of the crude oil that can be converted to gasoline, diesel and kerosene. In this run we assume that maximum 75% of each barrel can be used to produce fuels for transportation</td>
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<tr>
<td>15. Higher energy demand</td>
<td>In base runs we assume that future energy demand follows an ambitious energy efficiency path, i.e. IIASAs C1 scenario. In this run, we instead assume a higher “business as usual” energy demand, i.e. the IIASA A1 scenario</td>
</tr>
<tr>
<td>16. Doubled intermittent level</td>
<td>In base runs we have constrained the contribution of intermittent electricity sources (wind and solar PV) to a maximum of 30% of the regional electricity demand. Here we double this constraint</td>
</tr>
<tr>
<td>17. Halved intermittent level</td>
<td>Here we half the constraint on the contribution of intermittent electricity to a maximum of 15% of the regional electricity demand</td>
</tr>
<tr>
<td>18. Higher discount rate</td>
<td>In base runs we have set the discount rate to 5%. Here, we assume a discount rate of 7%</td>
</tr>
<tr>
<td>19. Lower discount rate</td>
<td>Here, we assume a discount rate of 3%</td>
</tr>
<tr>
<td>20. Incl. HEVs, PHEVs, BEVs</td>
<td>Electric vehicles are not included in the analysis. In a parallel study the GET-R model has been developed including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). Here we test a GC and RC approach in the GET-RC 6.1 model version [11]</td>
</tr>
</tbody>
</table>

From Fig. 9, it is clear that the use of biofuels in the industrialized regions is significantly higher in RC than in GC for all tests, which indicates that our main result is robust. From Fig. 9, also other interesting observations can be noted. Higher biomass supply potential (1), lower investment cost for BTL/CTL/GTL vehicles (4), and no BECCS (10) yield the highest share of biofuel use. Doubling the biomass supply potential increases the use of biofuels, and decreases the use of hydrogen, in all regions. A lower investment cost for BTL/CTL/GTL vehicles increases the use of both biomass and fossil fuel based synthetic fuels and decreases the use of natural gas, in all regions. Assuming BECCS will not be available decreases the use of CTL/GTL while the use of biofuels and hydrogen increases, again in all regions.

The six tests (5)–(9), and (11) yield a small increase in biofuel use. The first three correspond to disadvantages for hydrogen which lead to an increased use of both biomass and fossil fuel based synthetic fuels and natural gas, by varying amounts. If hydrogen cannot be used for aviation (7), less oil is used by road and sea since more is used for producing kerosene. This leads to an increased use of CTL/GTL and hydrogen in most regions and a small increase in natural gas and biofuels. If biomass-based heat costs more (8), biofuel use increases in all regions while CTL/GTL and natural gas decrease. If CCS is never commercialized (11), biofuel use increases, first and foremost in NAM, taking shares from natural gas. The use of hydrogen increases, while CTL/GTL decreases, in all regions.

Changes in biofuel use are very small, almost negligible, in the remaining sensitivity tests.

4.3. The use of natural gas in the transportation sector

In our earlier study natural gas was used as a feedstock for the production of hydrogen for the transportation sector, but natural gas in gaseous form did not enter as a major fuel for
transportation [2]. In the current study, natural gas is extensively used in most regions. However, this result is very sensitive with respect to changes in certain parameter values. In base runs the additional investment costs for a car and a truck with gas-engines are 1200 USD and 7000 USD over vehicles with conventional internal combustion engines. In this sensitivity run, we assume that more expensive gas storage material will be used, e.g. a tank made of composite materials instead of steel, leading to higher investment costs for natural gas vehicles. We have chosen to analyze the effect on gaseous natural gas use by increasing the additional cost to 3000 USD/car and 10,000 USD/truck.

We find that, with higher investment costs for natural gas vehicles, the use of gaseous natural gas practically disappears in all regions, replaced by first and foremost liquefied natural gas, GTL.

Our base results showing a large amount of natural gas used in the transportation sector in gaseous form do not appear particularly robust.

5. Discussion and conclusions

In this study, we have analyzed cost-effective fuel choices in the transportation sector under different international climate regimes leading to an atmospheric CO₂ concentration of 450 ppm by the year 2100.

In one regime, scenario GC, a cap-and-trade system is imposed on global carbon emissions. In the other regime, scenario RC, regional emission targets are set and emission trading is not allowed between regions. These regional targets were constructed so that industrialized regions had to reduce their emissions toward a global per capita target by the year 2040. This requires rather sharp reductions during the next couple of decades for the industrialized regions.

Three main results emerge from our analysis.

First, the use of biofuels in the industrialized regions is significantly higher in RC than in GC. Hence, we find that biofuels could play a more important role in industrialized regions if these take on their responsibilities and reduce their emissions before developing regions start reducing their emissions, compared to a scenario in which all regions take action under a global cap and trade emission reduction regime.

Second, the use of biofuels in RC actually increases the weaker (i.e., higher) the CO₂ concentration target (at least up to 550 ppm).

Third, biofuels never play a dominant role in the transportation sector. The highest observed level in any region is 30% (FSU 550 ppm), and the highest observed average share over the next century in the industrialized regions is 21% (550 ppm). Instead, when oil is phased out and the emissions have to reach very low levels, natural gas and hydrogen enter and dominate as energy carriers for transportation in both emission scenarios.

What are the fundamental drivers for these results? The reason biofuels become more attractive in RC is that the industrialized countries have to commit to much more

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\[\text{Biofuel share of total fuel use for road and sea transportation, for the time period 2000-2099 (\%)}\]

**Fig. 9 – Mean values for the four industrialized regions for biofuel use as share of total road and sea fuel use over this century for various sensitivity analyses. All runs meet the 450 ppm target.**

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\[\text{6 The difference is due to two parameter changes and one structural change in the GET model. First, as described in Section 2.3, compared to the earlier model, the current model assumes a lower efficiency for hydrogen fuel cells. This makes other fuels, including natural gas, more competitive. Second, the initial model did not consider BECCS. BECCS allows for a greater use of fossil fuels. Third, the earlier study used the 400 ppm target. While 400 and 450 ppm targets use the same total amount of natural gas, the lower target requires more of this fossil fuel to be used later in the century, with CCS, which only applies to stationary facilities. To reach the 400 ppm target, the price on carbon has to be more than doubled, compared to the 450 target; this allows natural gas with CCS to be cost-effective in the electricity sector. All these changes are required to make natural gas as a transport fuel cost competitive.}\]
stringent reductions early on. This means that they cannot rely on only reducing emissions from stationary sources; they also have to address fuel choices for transportation. This also explains why there are more biofuels in the North American transportation sector than in the European, see Figs. 4 and 5. In GC, overall emissions are to a larger extent reduced by using cheaper options in the stationary sectors in developing countries. Thus, oil and natural gas may remain in the transportation sectors of the industrialized regions.

The second result is somewhat counterintuitive. In scenario GC the use of biofuels decreases with higher concentration targets but in scenario RC (up to about 600 ppm) the use of biomass for heat decreases in all regions while the use of biofuels increases. This is due to the fact that less ambitious targets allow for an increased use of fossil fuels, i.e. coal, and hence a reduced competition for biomass in the world as a whole (the use of oil and natural gas remains constant). The demand for biomass, however, remains high in scenario RC, since industrialized regions need to follow a stringent emission trajectory, before 2040, also when meeting 500–600 ppm. The additional amount of coal is most cost-effectively used for electricity generation but also for heat production and thus the potential supply of biomass is large enough to be used both in stationary applications and the transportation sector, in scenario RC.

If the concentration targets become even weaker, the need to reduce emissions becomes lower, and biomass is needed less and less. For 550 ppm and higher, the demand for biomass starts to drop in the energy system as a whole, since the global energy sector mainly will be supplied by fossil fuels.

For very ambitious CO2 targets, on the other hand, the competition for biomass is higher and the limited supply of biomass will first and foremost be used in the heat sector, thus the use of biofuels for transportation decreases.

Finally, biofuels never play a dominant role in any region’s transportation system, in the model, since biomass initially has a difficulty in competing with gasoline/diesel and is more cost-effectively used for heat and co-generation. Once oil starts diminishing, other fuels, such as hydrogen or natural gas enter the transportation sector, and biomass remains in the heat system. The introduction or failure of hydrogen use in fuel cell vehicles might, however, be a critical factor for this result [3].

Extensive sensitivity analysis was performed to corroborate the main results of the paper.

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References


