THESIS FOR THE DEGREE OF LICENTIATE IN ENVIRONMENTAL SCIENCE

Cost-effective fuel choices in the transportation sector under stringent CO_2-emission reduction targets

Global energy systems modelling

MARIA GRAHN

Physical Resource Theory
Department of Energy and Environment
Chalmers University of Technology
Göteborg, Sweden 2006

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Printed by Chalmers Reproservice
Göteborg, Sweden 2006

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Abstract

This thesis analyzes the world's future energy supply in general, and cost-effective fuel choices in the transportation sector in particular, under stringent CO_2 constraints. The analysis is carried out with the help of a global energy systems model (GET), developed and modified specifically for each project. GET is a linear programming model and it has three end-use sectors: electricity, heat and transportation fuel. It is set up to generate the energy supply mix that would meet exogenously given energy demand levels at the lowest global cost. This thesis consists of the following three papers (i) an analysis of why two similar global energy systems models, GET and BEAP, give different results as to whether biofuels will become cost-effective in the transportation sector, (ii) an analysis of cost effective fuel choices in a regionalized version of the GET model and (iii) an analysis of the cost dynamics in the GET model in a further developed version of the model. Conclusions drawn within the scope of this thesis are that biomass is most cost-effectively used for heat production at low CO_2 taxes, up to about 75 USD/tC, as shown in both the GET and the BEAP model. The sector in which biomass is most cost-effectively used at higher CO_2 taxes depends on assumed possible energy carriers and technologies. If hydrogen and/or electricity derived from carbon free energy sources will not be available in the transportation sector at sufficiently low costs, biofuels become an important option if low or zero carbon emissions are to be achieved. Thus, the long run future for the cost-effective transportation fuel choice is still in the open. Regionalizing the GET 1.0 model will not affect the overall pattern of transportation fuel choices, i.e. that gasoline/diesel remain for some decades in the transportation sector until the carbon constraint becomes increasingly stringent and that solar based hydrogen dominates by the end of this century. In paper III, we find that the required carbon tax level where biofuels become cost-efficient, compared to fossil based fuels, is evasive. The tax level moves upwards with increasing carbon taxes, since this leads to an increasing biomass primary energy price in the model.

Keywords: Global energy systems, energy scenarios, transportation sector, carbon dioxide emissions, biomass, liquid biofuels, hydrogen, carbon tax, primary energy price

List of publications

This thesis is based on the following appended publications:

I. **Biomass for heat or as transportation fuel? – a comparison between two model based studies**
Grahn M, C Azar, K Lindgren, G Berndes and D Gielen, 2005.
Submitted for publication in Biomass and Bioenergy.

II. **Regionalized global energy scenarios meeting stringent climate targets – cost effective fuel choices in the transportation sector**
Grahn M, C. Azar and K. Lindgren. Conference proceedings.
Risö International Energy Conference, 19-21 May, 2003.
To be submitted.

III. **Biomass for heat or transport – an exploration into the underlying cost dynamics in the GET model**
Grahn M, K. Lindgren and C. Azar, 2006.
Working paper. To be submitted.

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1. Introduction

Science is not and will never be static final knowledge. To explain nature we are using models and these models are further developed as soon as we get more information. A famous example of such continuously developed model is the model describing the movements within our solar system. The early Ptolemy's geocentric model, which assumed the earth at rest in the centre of universe with the rest of the planets revolving around it, was in 1543 replaced by Copernicus' heliocentric model in which the planets revolve around a fixed sun. The model was then further developed by Tycho Brahe, Johannes Kepler, Galileo Galilei and others into the model which we use today, based on physical laws described by Isaac Newton and Albert Einstein, where the sun is at the centre of our solar system, which is moving in the Milky Way galaxy which is moving in the universe. Science always reflects current knowledge and as far as we know today we are phasing the start of a climatic change.

By studying ice cores and actual measurements we can observe a dramatic increase in the concentration of carbon dioxide in the atmosphere since the year 1750, see Figure 1.

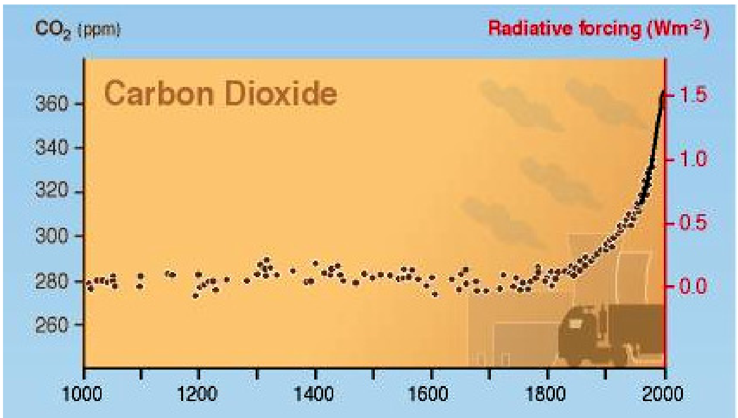

Figure 1. Atmospheric carbon dioxide concentration during the last millennium. The pre-industrial level was around 280 ppm and currently the concentration is 370 ppm. Source: IPCC (2001a).

There is complete consensus among scientists that carbon dioxide is a gas that absorbs and emits long-wave radiation. Thus, the higher the concentration of atmospheric carbon dioxide molecules, the more heat can be absorbed. The physics of the greenhouse effect[1], and the role of atmospheric carbon dioxide, have reached high levels of scientific understanding and it is now understood that the greenhouse effect depends on two factors: the difference between surface and atmospheric temperatures, and the atmospheric emissivity[2]. The greenhouse effect increases as either of these terms increases (Harvey, 2000). How sensitive the global climate is to the increase of greenhouse gases and how sensitive plants and animals are to a temperature rise are however questions to be further studied.

The Intergovernmental Panel on Climate Change (IPCC) has summarized current knowledge on the global annual average surface temperature, which may evolve under various CO_2 emission paths for various stabilization scenarios, see Figure 2.

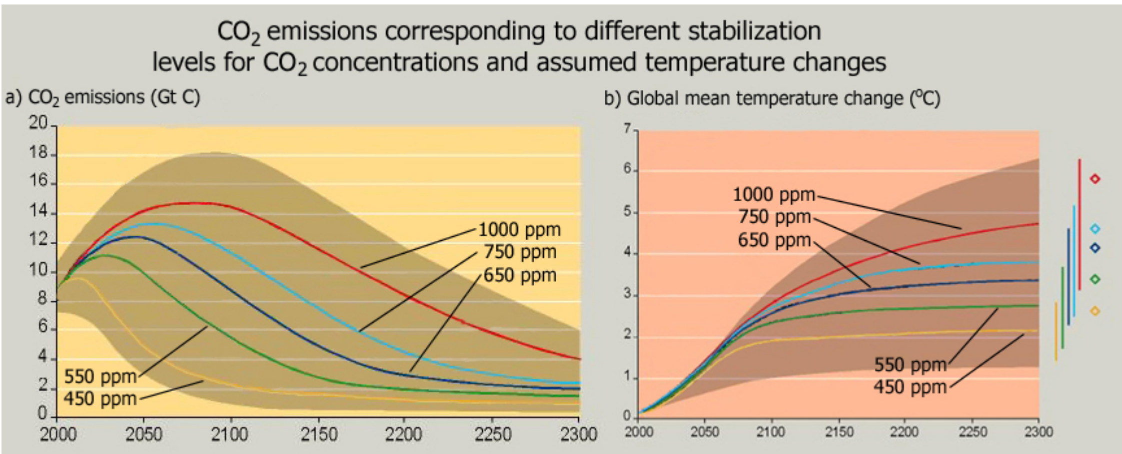

Figure 2. a) Different CO_2 emission reduction paths corresponding to various stabilization concentrations of atmospheric CO_2 and **b)** assumed increase in global annual average surface temperatures, from the base period 1961-1990 average, with corresponding uncertainty bars. Source: IPCC (2001a)

[1] The term greenhouse effect refers to the reduction in outgoing heat radiation to space due to the presence of atmosphere (Harvey, 2000). The natural greenhouse effect is necessary for the life on earth as we know it, since the surface temperature is about 30 °C higher than if the planet had been without a natural greenhouse effect (NE, 2005).

[2] All objects above absolute zero (-273 °C) emit electromagnetic radiation. Objects that emit the maximum amount of radiation are called blackbodies and the ratio of actual emission to blackbody emission is called the emissivity. The atmospheric emissivity depends on the concentration of gases such as CO_2 (Harvey, 2000).

The most ambitious carbon dioxide stabilization target, presented in Figure 2, is a 450 ppm scenario corresponding to approximately 1.5-3 ^{o}C [3] increase in global mean temperature above the base period 1961-1990 average and the least ambitious stabilization target is a 1000 ppm scenario corresponding to approximately 3-6.5 ^{o}C [4] increase in global mean temperature above the 1961-1990 average. To put these 1.5-6.5 ^{o}C in a broader perspective it can be noted that the global average surface temperature has increased over the 20th century by 0.6 ^{o}C and we can observe for example that snow cover and ice extent have decreased, that the global average sea level has risen and that precipitation patterns have changed (IPCC, 2001b). It can also be noted that there have been glacial periods on earth at approximately 5 ^{o}C lower mean temperature. Currently, large uncertainties remain on what will happen at a global mean temperature increase of 1.5-6.5 ^{o}C.

Defining what CO_2 concentration level that avoids "dangerous anthropogenic interference" with the climate system, remains a challenge. However, O'Neill and Oppenheimer (2002) argue that stabilizing the CO_2 concentrations near 450 ppm would likely preserve the option of avoiding shutdown of the density driven, large-scale thermohaline circulation of the oceans, e.g. the Gulf Stream, and may also forestall the disintegration of the West Antarctic Ice Sheet. However, such a target appears to be inadequate for preventing severe damage to some coral reef systems. Further Azar and Rodhe (1997) suggest that a temperature increase by 2 ^{o}C above pre-industrial levels may be seen as a critical level and that the global community should initiate policies that make stabilization in the range 350-400 ppm possible, to avoid reaching this critical level. The European Council has agreed on a climate target that the global annual mean surface temperature increase should not exceed 2 ºC above pre-industrial levels (European Council, 2005).

[3] Also 1.5-4 ^{o}C above pre-industrial levels are found in literature (Azar&Rodhe, 1997).
[4] Also 3-9 ^{o}C above pre-industrial levels are found in literature (Azar&Rodhe, 1997).

To stabilize the CO_2 concentrations near 450 ppm, Figure 1 indicate that the yearly global CO_2 emissions need to come down to about 2 GtC (2 billion ton carbon) within this century.

For the sake of illustrating the scale of the challenge, we do the following exercise: Assuming a future population of 10 billion people, the global average per capita emissions must decrease to 0.2 tC/yr, see the dotted line in Figure 3. This is less than what the lowest CO_2-emitting regions e.g. India and Africa emits per capita today. Reducing the global CO_2 emission down to 2 GtC/yr is a *huge* challenge.

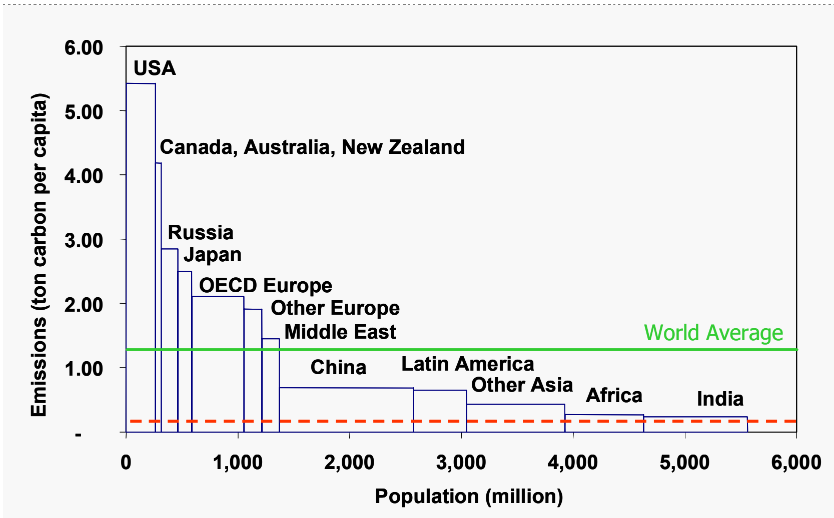

Figure 3. CO_2 emissions in ton carbon per capita, year 1998, for different regions (data from Marland *et al*., 2002). To meet the global goal of 2 GtC CO_2 emission per year, every country needs to reduce their CO_2 emissions per capita down to 0.2 tC/yr, by the year 2100. This per capita goal is marked with a dotted line, in the figure.

The major source, of anthropogenic CO_2 emissions, is the combustion of fossil fuels and a large transition of the global energy system is necessary to be able to reach ambitious CO_2 stabilization levels. Two of the three studies appended to this thesis analyses how the energy system can be transformed to meet a CO_2 concentration target of 400 ppm, which is even lower than the most ambitious concentration targets presented in Figure 2, but more in line with a 2 ^{o}C above pre-industrial target (Azar and Rodhe, 1997).

There are three main ways to reduce CO_2 emissions from the energy system.

- Use less energy.
- Use other primary energy sources instead of fossil fuels, e.g. nuclear, renewables and intra fossil fuel substitution (substitute coal with a less carbon intensive fuel e.g. natural gas).
- Use fossil fuels or biomass with carbon and capture storage technologies.

These three strategies are illustrated in Figure 4.

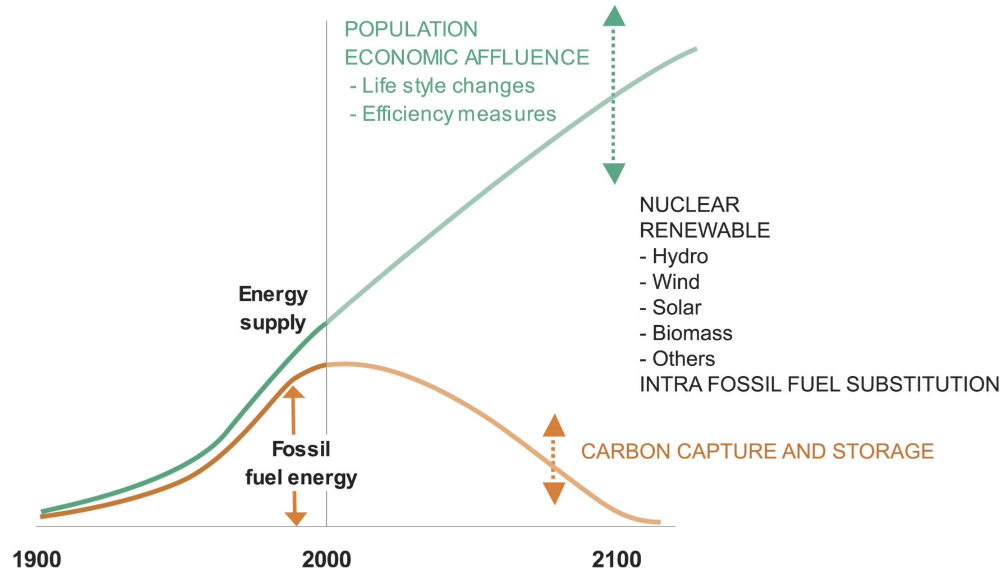

Figure 4. Strategies to reduce CO_2 emissions from the energy system. The upper line illustrates the increase in global energy demand during the past century and a projection for this century. The lower line represents the fossil fuel share of the global energy supply. Global CO_2 emissions from fossil fuels need to follow the lower line, during this century, to meet an ambitious climatic goal. Three main strategies are presented (i) using less energy, which can be achieved by life style changes, efficiency measures and a stabilized global population, (ii) use CO_2-neutral energy e.g. nuclear, renewables and by substitute carbon intensive fossil fuels e.g. coal with less carbon intensive fuels e.g. natural gas and (iii) use fossil fuels with carbon capture and storage technologies. (inspiration to the illustration from Björn Sandén, Environmental Systems Analysis, Chalmers)

The strategies to reduce carbon dioxide emissions from the energy system, presented in Figure 4, are of course associated with different advantages, disadvantages and constraints, which we have not weighed or analyzed within this thesis. To continue with possible strategies, we will in the next section present how renewables may replace mineral oil in the transportation sector.

1.1 Alternative transportation fuels

The energy system contains three main sectors, electricity, heat (including process heat) and transportation fuels. The focus within this thesis is to study cost-effective fuel choices in the transportations sector, under stringent restrictions on CO_2 emissions. In this section, current commercial alternative transportation fuels as well as promising future options will be presented.

Today there are several commercially available ways of producing both liquid and gaseous transportation fuels as alternatives to mineral oil based gasoline and diesel. These fuels can be used both in traditional internal combustion engines and in new more efficient engines, see Figure 5.

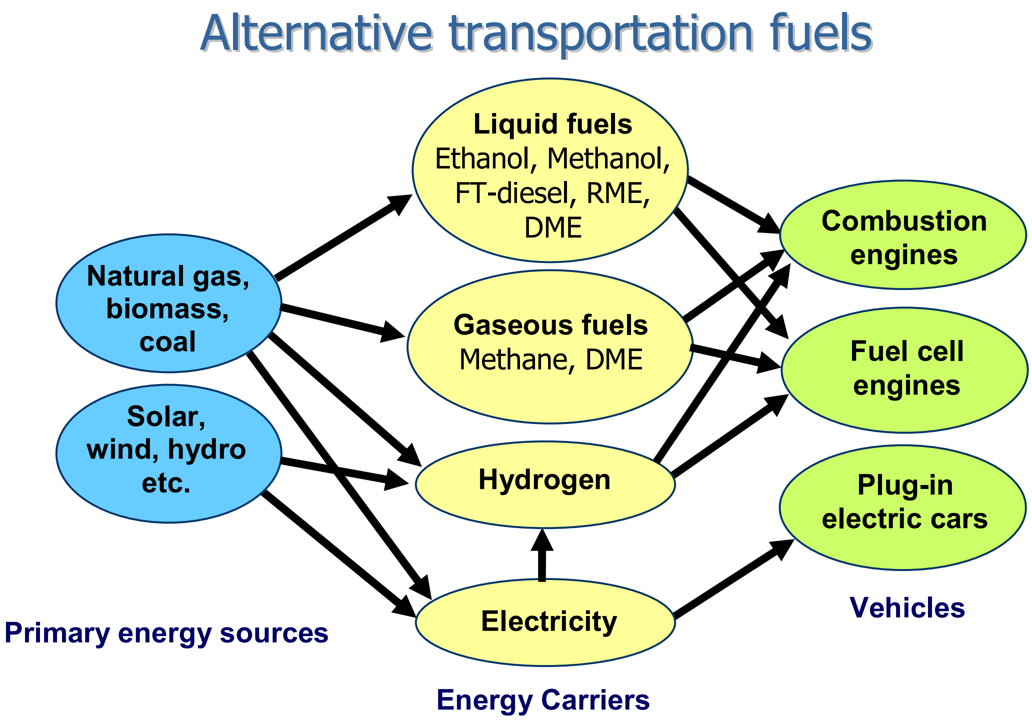

Figure 5. Current commercial alternative transportation fuels are ethanol, methane (biogas and natural gas), Fischer-Tropsch diesel and biodiesel here represented by rapesmethylester (RME). Promising future fuel options are hydrogen, methanol and dimethyleter (DME), where the latter two fuels are more suitable for fuel cell vehicles than other hydrocarbons. Alternative transportation fuels can be produced from solid and gaseous primary energy sources as well as from primary energy sources generating electricity.

If fossil fuels, i.e. coal, oil and natural gas, are used as primary energy sources, the carbon atoms can be captured and hindered to reach the atmosphere. The amount of captured carbon depends on what energy carrier is produced, e.g. methanol (CH_3OH) contains carbon while hydrogen (H_2) does not. Carbon capture and storage technology is possible today but associated with extra costs and not yet large-scale implemented. If hydrogen is to be produced via electrolysis it can only be CO_2-neutral if the electricity needed is CO_2-neutral, i.e. produced from renewables, nuclear or from fossil fuels with carbon capture and storage technology.

Biomass is a useful primary energy source and can be transformed into transportation fuels in several ways, e.g. anaerobic digested into biogas, fermented into ethanol, pressed and esterified into biodiesel (e.g. RME) or via gasification synthesized into Fischer-Tropsch diesel, dimethyleter (DME), methanol, methane or hydrogen, see Figure 6.

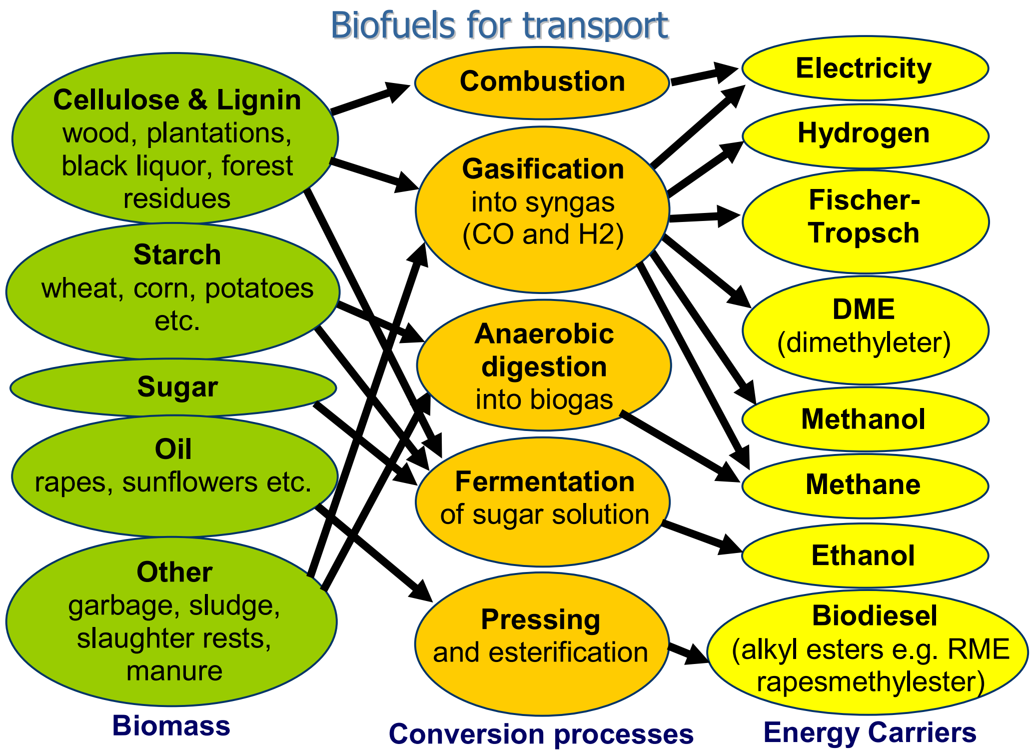

Figure 6. Biomass can be divided into groups depending on chemical composition of the biomass. Different elements are better suited for different conversion processes which convert the biomass into energy carriers useful for the transportation sector. Today all processes are in commercial production except gasification and ethanol production from cellulose, which are still on demonstration plant level. (inspiration to the illustration from Christian Azar, Physical Resource Theory, Chalmers)

Biofuels[5] that can be derived from lignocellulose is estimated to have a larger supply potential than biofuels derived from traditional annual crops. Lignocellulosic biomass is also suitable to produce a broader range of fuels than when applying traditional biofuels feedstock. Ethanol based on grain or sugar beets as well as biodiesel based on oil-crops have disadvantages when it comes to land use efficiency and overall potential to reduce CO_2 emissions. Ethanol, biodiesel and Fischer-Tropsch diesel are attractive liquid fuels today since they can be blended with gasoline and diesel.

Lowest production cost has ethanol produced from sugarcane, grown in tropical regions. Brazilian ethanol can be produced at a cost around 6-9 €/GJ_{HHV} (0.26-0.38 €/l gasoline eq.) (Goldemberg *et al*., 2004, Hamelinck, 2004, p.34) and shipped to Europe at an additional cost of 0.5-1 €/GJ_{HHV} (Hamelinck, 2004, p. 34). Ethanol from wheat and RME from rapeseed is expensive and has a wide uncertainty range, 21-39 €/GJ_{HHV} (0.89-1.66 €/l gasoline eq.) and 11-29 €/GJ_{HHV} (0.47-1.23 €/l gasoline eq.) respectively (Hamelinck, 2004, p. 20, 34).

In the future, around the year 2020, the total production costs, including distribution to the fuel station, range from 10-15 €/GJ_{HHV} (0.43-0.64 €/l gasoline eq.) for most biofuels, assuming a biomass feedstock cost of 3 €/GJ_{HHV}, except ethanol based on grain or sugar beets and biodiesel based on oil-crops, which are expected to remain more costly (Hamelinck, 2004, p. 35). Lignocellulosic methanol and sugarcane ethanol are assumed to have the lowest production costs among future biofuel options.

For comparison, gasoline over the last decennium cost 2.5-7.2 €/GJ_{HHV} at Rotterdam port and diesel 2.4-6.6 €/GJ_{HHV} (BP, 2005, cited in Hamelinck, 2004, p. 35) and by adding distribution costs to fuel stations (about 1.4 €/GJ_{HHV}) gasoline prices were in the range of 4-9 €/GJ_{HHV}[6] (Hamelinck, 2004, p.35).

[5] In this thesis, "biofuels" always means liquid or gaseous hydrocarbons made from biomass, to be used in the transportation sector.
[6] The sale price at the fuel station further usually includes excise duty and value added tax (VAT).

In the research done within this thesis we have used lignocellulosic methanol as a proxy for all liquid biofuels in our models, since it has a large supply potential, high conversion efficiency and relatively low production cost.

1.2 Cost-efficient fuel choices meeting ambitious climatic targets – Results from previous GET model studies

In an earlier study, Azar *et al*. (2003) analyzed the question of cost-efficient fuel choices in the transportation sector under global, stringent CO_2 constraints. The question was studied using a global energy systems model (GET 1.0) developed specifically for that study. GET 1.0 is a linear programming model that is globally aggregated and has three end-use sectors. It is set up to meet a specific atmospheric concentration target at the lowest energy system cost. They chose a stabilization target of atmospheric CO_2 concentrations of 400 ppm, but have also analyzed other stabilization targets (see Section 2 in this thesis for a more detailed description of the GET model).

Under the assumption that there are no carbon constraints, fossil fuels continue to dominate the energy system, since these primary energy sources in most cases are cheaper or more plentiful than others. The transportation sector is run on gasoline and diesel until conventional oil becomes scarce and replaced by coal based methanol.

When the model is run under stringent CO_2 emission constraints, a general result is that a substantial expansion of biomass, as well as other renewables, occurs. Oil and natural gas are two primary energy sources which can be converted into secondary energy flows at high conversion rates, so a second general result is that the whole reserve of oil and natural gas are used even though very ambitious climatic targets are reached. (CO_2 emissions from the use of coal are then, of course, small.) A third general result is that if carbon capture and storage (CCS) technology is assumed to be commercialized on a large scale, the use of coal increases but if CCS technology is banned the use of solar energy, converted into storable hydrogen, enters the energy system as soon as the biomass expansion is saturated. CCS technology is not allowed, in the 400 ppm scenario, presented in Figure 7 and 8.

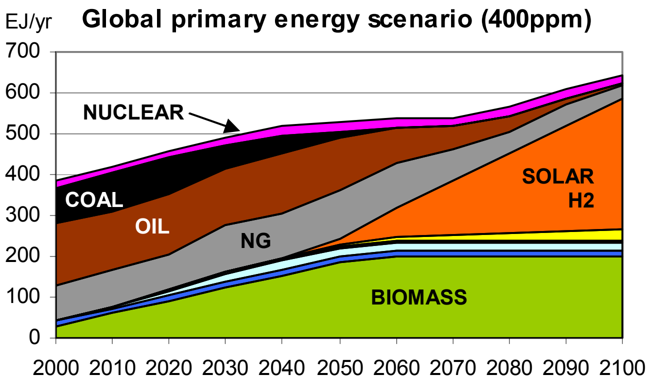

Figure 7. Global primary energy scenario, at a stabilized CO_2 concentration target of 400 ppm, from a run with the GET 1.0 model, where CCS technology is excluded as an option. Biomass and solar energy sources play an important role. If the use of CCS technology is assumed to make it on a large scale, a larger amount of coal will be used, which gives the result that the introduction of solar based hydrogen will be delayed for some decades.

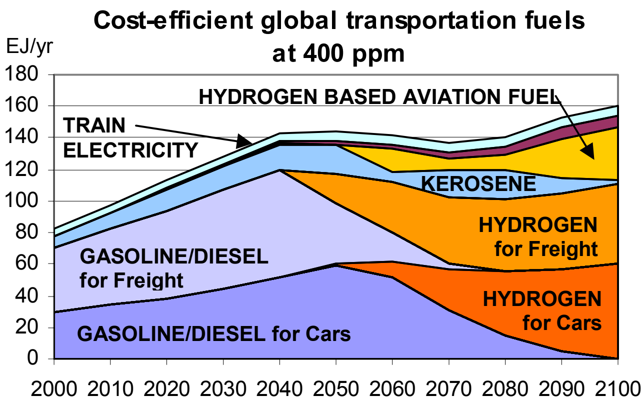

Figure 8. Cost-efficient fuel choices in the transportation sector at a stabilized CO_2 concentration target of 400 ppm, from a run with the GET 1.0 model, where the CCS technology is excluded as an option. The demand for the four transportation subgroups: Cars, Freight, Aviation and Rail are separated in this figure. Oil based transportation fuels, i.e. gasoline, diesel and kerosene, dominate until solar based hydrogen enters the transportation sector in 2040-2050. If the use of CCS technology is assumed to make it on a large scale, a larger amount of coal will be used, which lead to a short period of coal based methanol and the introduction of solar based hydrogen will be delayed. Biofuels do not enter the transportation sector in either of these two scenarios.

The main conclusion drawn in these earlier studies is that, on a global perspective to meet ambitious climatic goals, biofuels are not cost-effective under the assumption that hydrogen and fuel cells become available at reasonable costs. Instead, biomass is more cost-efficient to use for heat and to some extent power production.

1.3 My research

Our results received considerable attention by governmental bodies, industry and environmental organizations. Some argued that biofuels, e.g.Brazilian ethanol, already is competitive on the fuel market and that biofuels is a realistic and politically possible alternative, at least in a short-term scenario, so why is that not seen in the GET transportation fuel scenarios? In 2003, the European Commission proposed an increased use of biofuels in the transportation sector in a directive which states that biofuels should constitute 2% of the total amount of transportation fuels sold in 2005 (estimated as energy content) at the national level, and 5.75% in the year 2010 (European Council, 2003). Clearly, many arguments and factors that drive the biofuel agenda were not considered in our earlier studies. Therefore we decided to continue the above mentioned research. We wanted to further analyze if biofuels could turn out to be a cost-efficient fuel choice in modified versions of the GET model. My research consists of the following three studies:

1) An analysis of why two similar global energy systems models give different results on the cost-effectiveness of biofuels. Gielen *et al.* (2002, 2003), by using their BEAP model, conclude that it is cost-effective to use biofuels for transportation, whereas our study, using the GET model, find that it is not. What key assumptions and/or model structure differ between these two models?
2) Regionalization of the GET model in order to analyze whether biofuels could be a cost-efficient fuel choice in some regions.
3) An analysis on the cost dynamics in the GET model in a further developed version, GET 5.1, which hopefully will improve insights on why biofuels are not seen as a cost-effective fuel choice.

Results from the first study are given in appended Paper I and summarized in Section 3.1. It has been submitted to Biomass and Bioenergy and presented at the 14th European Biomass Conference and Exhibition - Biomass for Energy, Industry and Climate Protection, 17-21 October 2005, in Paris.

Results from the second study are given in appended Paper II and summarized in Section 3.2. It has been presented at the Risö international energy conference in Denmark, 19-21 May 2003 and at EnerEnv'2003, the first conference on energy and environment, 11-14 October 2003, in Changsha, China. A revised version of this conference paper will be submitted.

Results from the third study are given in appended Paper III and summarized in Section 3.3. It has been presented at Energitinget, 9-10 March 2004, in Eskilstuna, Sweden and at the 2nd World Conference and Technology Exhibition on Biomass, 10-14 May 2004, in Rome.

Some explanations for the model results, on fuel choices in the transportation sector, are presented in Section 4. A discussion is carried out in Section 5 and the conclusions drawn in this thesis are presented in Section 6. In Section 7, some policy implications are offered.

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 (Azar *et al.* 2000, 2003). The model has been further developed in various versions over the years but in this section we will present the initial version, GET 1.0. Developments made for the three studies, included in this thesis, will be presented under Section 3.1, 3.2 and 3.3 respectively.

2.1 Model structure

The global energy economic model, GET 1.0, is a linear programming model that is globally aggregated and has three end-use sectors. It 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 way.

The model is composed of three different parts: (i) the primary energy supply with the supply options coal, oil, natural gas, nuclear power, hydro, wind, biomass and solar energy, (ii) the energy conversion system with plants that may convert the primary energy sources into secondary energy carriers (e.g., electricity, hydrogen, methanol, and gasoline/diesel) and (iii) the final energy demand which includes technologies used in the transportation sector, see Figure 9.

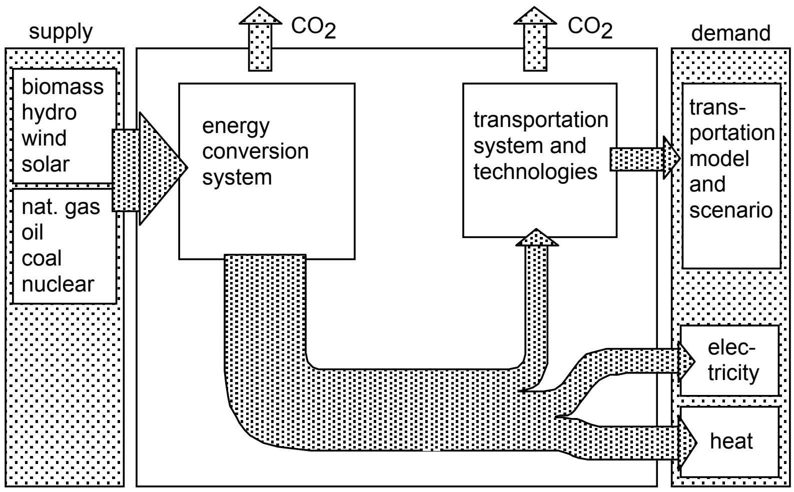

Figure 9. The global energy system model GET 1.0 is composed of three parts: supply, demand, and the energy conversion system. The supply is characterized by annual or total extraction limits on the different available energy sources. The demand is exogenously given for transportation, electricity, and heat (including high temperature process heat). The technology system is characterized by a large number of technologies available both for conversion between different energy carriers as well as for vehicle engines. A cost minimization algorithm with restriction on emissions of fossil carbon is then applied to generate energy scenarios.

An optimization algorithm is applied to the model in order to generate the solution that meets the energy demands and a specific atmospheric concentration target, at the lowest total costs.

2.2 Energy demand scenarios

In the year 2000 the world used about 400 EJ of primary energy, where about 250 EJ were used by the about 1.3 billion people living in the developed world (roughly 200 GJ/capita). Assuming that people in developed countries will continue to use the same amount of energy per capita as today and that people in developing countries increase their energy use to 200 GJ/capita, the total energy demand would be 2000 EJ/yr, assuming 10 billion people at the end of this century. As a first important tool, to reach an ambitious climatic goal, we have chosen an ecological driven energy demand scenario[7], where it is assumed that the energy demand of 2000 EJ/yr could be halved due to energy efficiency measures. This lower energy demand is exogenously given in the model.

The chosen energy demand scenario is not sufficiently detailed for the GET analysis of the transportation sector, so we have developed our own transportation scenario by assuming that the increase in the amount of person kilometers traveled is proportional to GDP growth (in PPP terms). The transportation sector includes separate demand for four subgroups: Cars, Freight, Aviation and Rail. Full details of the model and the demand scenarios are available in Azar *et al.* (2000, 2003).

2.3 Constraints and assumptions

Constraints have been added to the model to avoid solutions that are obviously unrealistic, primarily constraints on how fast changes can be made in the energy system. This includes constraints on the maximum expansion rates of new technologies (in general set so that it takes 50 years to change the entire energy system) as well as annual or total extraction limits on the different available energy sources.

[7] We have chosen an energy demand scenario called ”C1” developed by IIASA (Nakicenovic *et al*,1998). Details at: www.iiasa.ac.at/collections/IIASA_Research/Research/ECS/docs/book_st/node2.html

The contribution of intermittent electricity sources is limited to a maximum of 30% of the electricity use. To simulate the actual situation in developing countries, a minimum of 27 EJ/yr of the heat demand need to be produced from biomass the first decades. We have further put the upper level on biomass supply to 200 EJ per year[8], corresponding to an area of roughly 500 Mha[9], and constrained the contribution of nuclear power to the level we have today.

We have put the global discount rate at 5% per year. Energy supply potentials, maximum expansions rates and energy demand are exogenously given. In most cases investment costs, conversion efficiencies, lifetimes and load factors are assumed constant at their "mature levels". The model can allow carbon sequestration to be applied to most fossil fuel conversion technologies.

3. Research studies

In this section summaries of the three research studies, appended to this thesis, are presented.

3.1 Paper I: Biomass for heat or as transportation fuel? – a comparison between two model based studies

3.1.1 Background and research question

Among several candidates capable of supplying large amounts of CO_2-neutral energy, biomass ranks as one of the few options already competitive on some markets. However, biomass will not be sufficient for all possible energy applications, if CO_2 emissions should be very low, and it is therefore important to discuss where to use the scarce biomass resources for climate change mitigation.

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[8] For more on global biomass supply potentials, see Berndes *et al* (2003).
[9] We assume 500 Mha with a yearly yield of 200 GJ/ha and that 100 EJ/yr comes from the actual yield and that 100 EJ/yr comes from biomass residues.

In two different energy economy models of the global energy system, the cost-effective use of biomass under stringent carbon constraints has been analyzed. Azar *et al.* (2003) find that it is more cost-effective to substitute biomass for fossil fuels in power and heat production, whereas Gielen *et al.* (2002, 2003) conclude that most of the biomass is cost-effectively used as biofuels for transport, despite the fact that the assumptions in both models are rather similar.

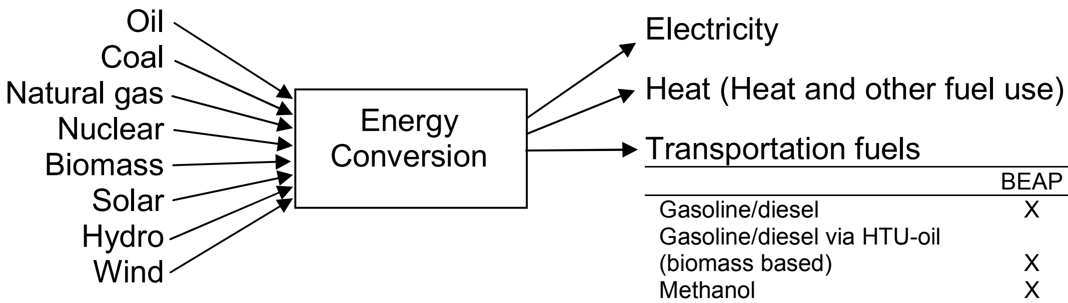
The aim of this study is to compare the two models with the purpose to find an explanation for the differing results.

3.1.2 Method

Both modeling groups base their results on models developed especially for these studies. Gielen *et al.* have developed the BEAP (Biomass Environmental Assessment Program) model and Azar *et al.* the GET 1.0 (Global Energy Transition) model. Both models are global energy systems optimization models. The BEAP model is a mixed integer programming (MIP) model and simulates an ideal market based on an algorithm that maximizes the sum of the consumers' and producers' surplus. The GET model is a linear programming model that is set up to meet exogenously given energy demand levels at the lowest energy system cost.

Both models exhibit so-called 'perfect foresight' which means that all features of the model (future costs of technologies, future emission constraints, availability of fuels etc) about the future are known at all times. The GET model is run under ambitious constraints on carbon dioxide emissions corresponding to an atmospheric carbon dioxide concentration target of 400 ppm by the year 2100, and the BEAP model is run with a CO_2 tax that roughly leads to the same CO_2 concentration target.

The primary energy supply options, the three energy demand sectors and fuel choices in the transportation sector are roughly outlined in Figure 10.



	BEAP	GET
Gasoline/diesel	X	X
Gasoline/diesel via HTU-oil (biomass based)	X	-
Methanol	X	X
Ethanol	X	-
Fischer-Tropsch diesel	X	-
Hydrogen (fossil fuel based)	X	X
Hydrogen (CO2-neutral)	-	X
Natural gas	-	X

Figure 10. The basic flow chart of supply and fuel choices in both energy systems models.

In the GET model, electricity and heat demand levels are exogenous and taken from the ecologically driven scenario C1 in IIASA/WEC (Nakicenovic *et al*., 1998). The transportation scenario is developed separately, assuming that increase in the amount of person-kilometers traveled is proportional to the GDP growth (in PPP terms).

The BEAP model covers the global energy, food and materials system. The demand for food and materials are based on statistics from the Food and Agricultural Organization (FAOSTAT 2001a, 2001b) and United Nations (UN, 1999). The energy demand is based on the BP review of world energy use (BP, 2001). Future demand in the base case is an extrapolation of historical trends and forecast as a function of regional GDP growth and income elasticities.

In the BEAP study, price elasticities in the range of −0.1 to −1 have been used for all demand categories. In the GET model energy efficiency is assumed to improve the heat, electricity and transportation demand scenario.

Constraints have been added to both models so as to avoid solutions that are obviously unrealistic. A difference between the two models restrictions is that in the BEAP model investments in some of the heat processes are constrained, i.e., no investments can take place in gas and biomass fuelled industrial heat boilers before the year 2020. Also urban heat produced from biomass is limited to very low levels (or even zero) for all industrialized regions.

3.1.3 Main results

The two models present different development paths for the transportation sector. Biofuels enter in the BEAP model but solar based hydrogen replaces gasoline and diesel in the GET model. However, if the cost of hydrogen vehicles drops, then hydrogen from natural gas enters the transportation sector in BEAP, and biomass will to a larger extent be used for heat production.

We shed light on technology options in the BEAP model by running it with a fixed CO_2 tax over the period 2005-2100. We made 13 runs with the tax set in the range 0-300 USD per ton C in steps of 25 USD/tC. The result for the year 2020 is presented in Figure 11.

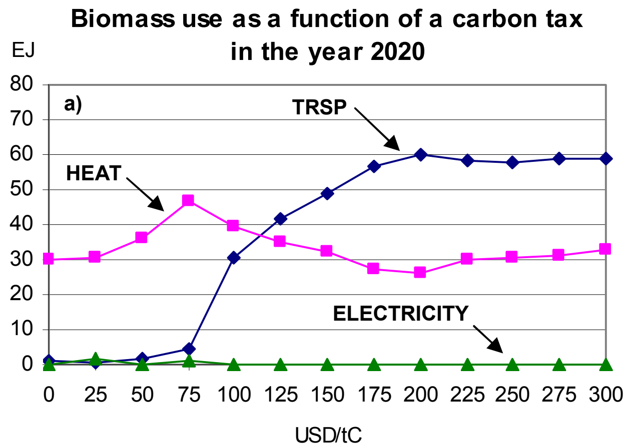


Figure 11. The biomass use (primary energy) in the BEAP model for various CO_2 taxes. The taxes have been fixed during each run and the figure includes 13 runs.

In Figure 11, it is shown that no biofuels are produced but 30 EJ of biomass is used for heat production by the year 2020 when no CO_2 tax is applied. When increasing the CO_2 tax, the use of biomass for heat production increases more rapidly than in the two other sectors, but only for taxes below 75 USD/tC. For higher taxes, biofuels increase rapidly at the expense of biomass for heat. Since the yearly biomass supply potential is limited[10], the biomass for heat production slightly decreases when the use of biofuels increase.

In the BEAP reference scenario the CO_2 tax has reached 300 USD/tC by the year 2020 and at that tax, as shown in Figure 11, most of the biomass is used for the production of biofuels. Since Gielen *et al.* ran their model with very high taxes right from the beginning this concealed the fact that biomass is more cost-effectively used for heat production also in the BEAP model for low taxes. Thus, BEAP and GET agree on that biomass is most cost-effectively used for heat when the carbon tax is low (in the year 2020 below 75 USD/tC).

For higher taxes, there is a difference between GET and BEAP. Biomass is most cost-effectively used for biofuels production in the BEAP model but in the GET model biomass remain most cost-effectively used for heat production.

The key reason for that is that GET allows for hydrogen from carbon free sources in the transportation sector, whereas BEAP has no other carbon free option than biomass. Due to the ambitious CO_2 target, also the transportation sector has to be almost CO_2-free towards the end of this century and biofuels are the only available option in the BEAP model for reaching zero emission levels. Both GET and BEAP has carbon free options in the two other sectors.

Our purpose has been to find an explanation for the differing results on the cost-effective use of biomass, and we came to the following conclusions:

1) Biomass is most cost-effectively used for heat productions at low CO_2 taxes, up to about 75 USD/tC in both models. This was not evident in previous runs of the BEAP model since these runs focused on higher carbon taxes.
2) The sector in which biomass is most cost-effectively used at higher CO_2 taxes depends on assumed possible energy carriers and technologies. In GET, hydrogen

[10] In the BEAP model an additional more expensive biomass supply is available and will be used when carbon taxes are high.

derived from carbon free energy sources are available in the transportation sector at a cost that makes this option more cost-effective than biofuels when very low carbon emissions are to be obtained. In BEAP, this option is not available and for that reason biofuels become the only option if low or zero carbon emissions are to be achieved.

Thus the assumptions about the availability of CO_2-neutral hydrogen and/or electricity as a fuel option in the transportation sector determine whether biomass will be used for transportation or not in the long run. If hydrogen is assumed to make it as an energy carrier in the transportation sector, then cost assumptions on fuel cells, storage options, infrastructure and supply will determine in which sector the biomass will be used. Clearly, these cost numbers are very uncertain, so the long run future is still in the open.

3.2 Paper II: Regionalization of the GET model

3.2.1 Background and research question

In this study we analyze the cost-effective use of biomass in a regionalized version of GET 1.0, to see whether regional differences in energy supply and demand may result in differences in fuel choices in the transportation sector. These new regionalized scenarios will show how each region can meet its energy demand, and thereby give a better understanding of the prospects for changes in the global energy system than a global aggregate model. More specifically, we ask the following questions:

1) when is it cost-effective to carry out the transition away from gasoline/diesel?
2) to which fuel is it cost-effective to shift?
3) will the cost-effective choice of fuel in the transportation sector be different if a globally aggregated model is used rather than a regionalized version?
4) how will the method of regionalization affect transportation fuel choices and trade in energy carriers?

3.2.2 Method

The regionalized energy systems model, GET-R 1.0, is, as the global model, a linear optimization model designed to choose primary energy sources, conversion technologies, energy carriers and transportation technologies that meet the energy demands of each region, at the lowest aggregate costs subject to a carbon constraint (a tax or an emission cap).

In GET-R 1.0 each region has a unique supply potential and energy demand and the eleven regions are as follows: North America (NAM), Latin America (LAM), Western Europe (WEU), Eastern Europe (EEU), Former Soviet Union (FSU), OECD countries in the Pacific Ocean dominated by Australia and Japan (PAO), Middle East (MEA), Africa (AFR), Centrally Planned Asia dominated by China (CPA), South Asia dominated by India (SAS) and Other Pacific Asia (PAS), see Figure 12.

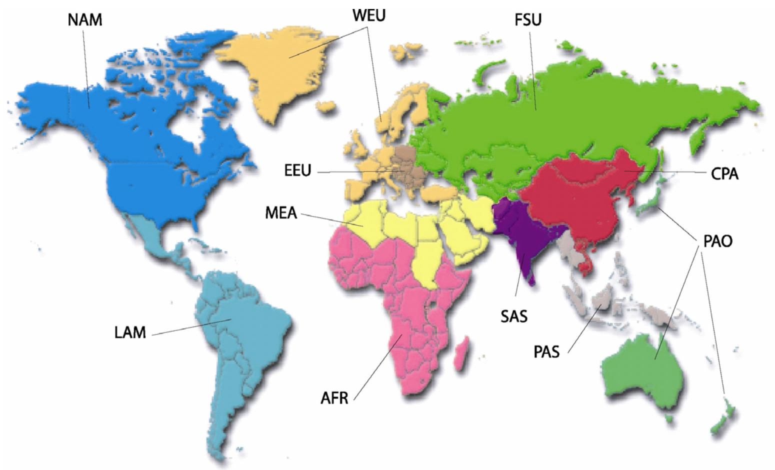


Figure 12. The eleven regions used in GET-R 1.0 are North America (NAM), Latin America (LAM), Western Europe (WEU), Eastern Europe (EEU), Former Soviet Union (FSU), OECD countries in the Pacific Ocean (PAO), Middle East (MEA), Africa (AFR), Centrally Planned Asia (CPA), South Asia (SAS) and Other Pacific Asia (PAS).

Regional population, heat and electricity demand are assumed to follow the ecologically driven scenario, C1, developed by International Institute for Applied Systems Analysis (IIASA) in Austria (Nakicenovic *et al.*, 1998). Transportation scenarios are developed separately for each region using the same method as for GET 1.0, described in Section 2.

The same values have been used in all regions for investment costs, energy conversions and fuel infrastructure. Regionalized load factors for solar energy technologies give some advantages to the four regions Middle East and North Africa, Africa, Latin America and North America.

It takes time to make profound changes in the energy system of the world. This inertia is captured using maximum expansion constraints on how fast new technologies might enter and we have assumed that 50 years is required for the development of a completely new energy system. The maximum expansion rate can be set as a global or as a regional constraint. If a global maximum expansion rate is chosen, the model will choose to expand technologies in regions where it is most cost-efficient, i.e. solar energy will expand at a faster rate in sunnier regions than what happens if regional expansion rate constraints are chosen. In this study we use the global maximum expansion rate as our base case, but we will also present some interesting differences to the base case using the other method of a regionalized maximum expansion constraint.

3.2.3 Main results

In order to stabilize atmospheric CO_2 concentrations at 400 ppm, approximately 500 GtC (billion ton carbon) may be emitted over the period 1990-2100, (IPCC, 1994). The following describes a global scenario (where the eleven regional results have been added together) in which this CO_2-reduction happens in a cost-effective manner.

The use of all renewables displays an increasing pattern throughout the century, where biomass and solar energy plays the most important role. Over the next fifty years, a rapid increase of biomass supply appears until the limitation of 200 EJ/year is met, thereafter solar energy for hydrogen production increases during the second half of the century. The use of oil and gas remains roughly constant until they become exhausted, by 2070-2090. The use of coal remains possible since carbon capture and storage technologies are used on a larger scale, from the middle of the century and onwards.

Oil and natural gas are phased out and biomass and coal dominate as primary energy sources for heat production. For electricity production oil is phased out early and by the end of the century coal with carbon capture and storage technologies become cost-effective. By the end of the century the use of natural gas is declining due to lack of availability. When solar based hydrogen is introduced by the middle of the century it will rapidly increase its share. All renewable energy sources, display an increasing pattern throughout the century. Wind and hydro power are used to their exogenously set maximum level.

The fuel use in the transportation sector is aggregated in four sub sectors, cars, freight aviation and rail. The rail sector is run on electricity and in the aviation sector there is a transition from fuels based on oil towards liquefied hydrogen. In cars and freight sectors a transition from petroleum-based fuels in internal combustion engines to hydrogen used in fuel cell engines, in the middle of this century. Some methanol in internal combustion engines will be used in the transition period in both sectors. The model also presents a short period of natural gas as a cost-effective transition fuel, in the sector cars.

The major impact of different ways of setting the maximum expansion rates is where solar hydrogen is being produced. Using a global maximum expansion rate, the region Middle East and North Africa (MEA) will extract almost 200 EJ/yr of solar produced hydrogen, in the year 2100, out of which 160 EJ/yr will be exported to other regions. Using a regionally set maximum expansion rate MEA will only produce solar hydrogen for its own need. The differences in primary extraction for MEA due to choice of expansion constraints, are illustrated in Figure 13.

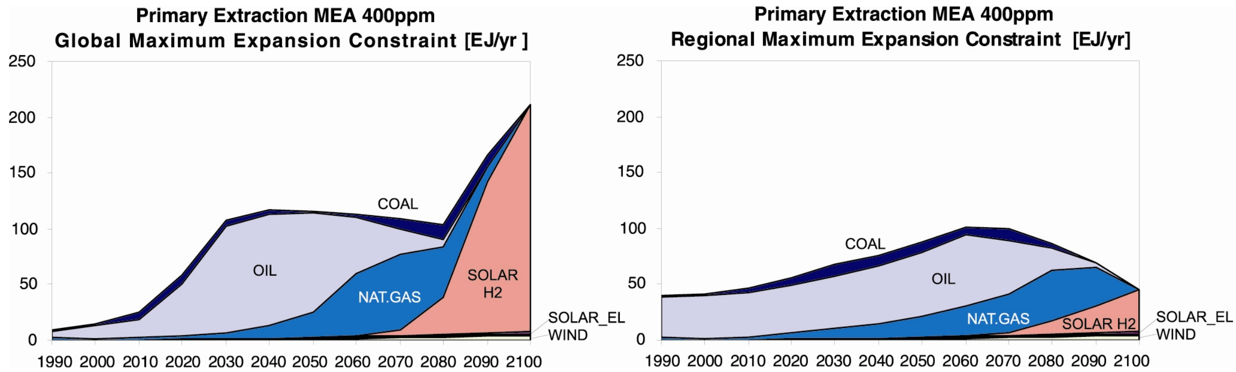


Figure 13. Primary energy extracted in region Middle East and North Africa, MEA. Solar produced hydrogen will be exported in the case of a global maximum expansion rate.

The Asian regions Centrally Planned Asia dominated by China (CPA), South Asia dominated by India (SAS) and Other Pacific Asia (PAS) are examples of regions which import hydrogen in the case of a global maximum expansion constraint and produce their own solar hydrogen in the other case, as illustrated in Figure 14.

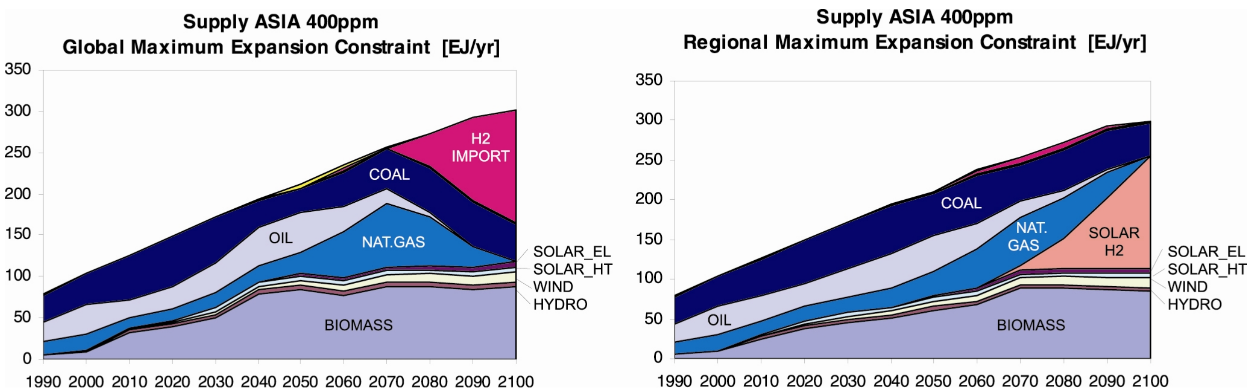


Figure 14. Primary energy sources to supply the energy demand in the Asian regions. No solar produced hydrogen will be developed in the case of a global maximum expansion rate. Instead hydrogen will be imported mainly from MEA. In the case of a regional maximum expansion rate the Asian regions will produce their own solar hydrogen.

One general result from this study is that it is possible to combine ambitious climatic goals with an increased demand for energy services, but below, we will answer the four questions asked in this study. The model results are explained in Section 4.

Question 1: When is it cost-effective to carry out the transition away from gasoline and diesel?
In both GET 1.0 and GET-R 1.0 the general pattern is that oil remains the dominant fuel, in the transportation sector, until 2030-2050, when a large scale transition to solar based hydrogen is initiated. Oil based transportation fuels are fully replaced by 2080-2090.

Question 2: To which transportation fuel is it cost-effective to shift?
Solar based hydrogen becomes the dominant fuel in the transportation sector at the end of this century.

Question 3: Will the cost-effective choice of fuel in the transportation sector be different if a globally aggregated model is used rather than a regionalized version?
No, when adding the eleven regional results together to produce a global scenario, the results of GET 1.0 and GET-R 1.0 are very similar.

Question 4: How will the method of regionalization affect transportation fuel choices and trade in energy carriers?
Both methods of regionalization produce the same overall pattern of transportation fuel choices, but the intercontinental trade in energy carriers will be different. The major impact of different ways of setting the maximum expansion rates is where solar hydrogen is being produced, as illustrated in Figure 13 and 14.

3.2.4 Future work

In a revised version of this study we have planned to regionalize the most recent GET model version, GET 6.0, to investigate if the regionalized results remain.

In the current study, it is assumed that there is a carbon constraint applied to all regions of the world. In the revised study, we intend to analyze fuel choices in the transportation sector under the more realistic assumption that developing countries adopt abatement policies perhaps a decade or two after the industrialized countries.

Further it could be of interest to look more into biomass supply and conversion options. In this study biomass is a collective name for forest biomass, energy crops and biomass residues. The end-use sector heat is a collective name for industrial process heat and residential heating (including district heating). If the model were developed by more supply and end-use options, it could maybe give another picture of the most cost-efficient use for biomass.

3.3 Paper III: Biomass for heat or transport – an exploration into the underlying cost dynamics in the GET model

3.3.1 Background and research question

In this study we want to achieve more detailed results on the cost dynamics in the GET model in order to get a deeper understanding on why biofuels are not found to be a cost-effective fuel choice.

3.3.2 Method

The analysis is carried out using a further developed version of the model, GET 5.1 and a simplified model implemented in Excel. There are four main new features in the GET 5.1 model, compared to GET 1.0: (i) waste heat generated in the production of biofuels may be sold to the heat market, (ii) carbon and capture storage technology can be applied on both biomass and fossil fuel use, (iii) a split of the primary energy "oil" into two primary oil sources, conventional and heavy oils and (iv) a further development of the refinery process in the model. The main difference with these two latter new features is that it has become more expensive to produce oil based transportation fuels. In earlier versions of the GET model 100% of the primary energy "oil" could be converted into transportation fuels, at a certain cost. Now, only 60% of the conventional oil can be converted into transportation fuels, at that cost.

Parameter values are identical to those described in Azar *et al.* (2005) with two minor changes. First the life times on truck engines have been shortened to 10 years instead of 15 years as in earlier GET models, following Kågeson (2004). Secondly we have changed the energy efficiency on fuel cells in cars, compared to internal combustion engines, from a factor of 2.2 more efficient down to a factor of 1.5, also following Kågeson (2004). Hence, a transition into hydrogen in fuel cell vehicles is in the GET 5.1 model less favorable than in earlier versions of the GET model.

One important observation for the understanding of the underlying cost dynamics in the GET model is that the primary energy price, *P,* [USD/GJ] in the GET 5.1 model, consists of three parts, as

$$P = P_C + P_{SR} + P_T ,$$

where P_C is the primary energy cost including the extraction costs and distribution, P_{SR} is a scarcity rent[11], generated in the model, and P_T is a carbon tax on fossil fuel emissions. The primary energy cost, P_C, on conventional oil is taken from the GET 5.0 model (Azar *et al.*, 2005) and the primary energy cost on heavy oils is estimated following EIA (2002) and in the model set to 3.5 USD/GJ [12] and 5 USD/GJ respectively. Primary energy cost on biomass is set to 2 USD/GJ, natural gas is set to 2.5 USD/GJ and coal is set to 1 USD/GJ following Azar *et al.* (2005).

In the simplified model, implemented in Excel, we use parameter values and equations equivalent to the GET 5.1 model and we calculate the cost per km for all fuel and vehicle choices, see Table 1.

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[11] Scarcity rent (or scarcity value) is the economic term for the additional cost, added to the primary energy cost, due to the fact that the relative price on an item increases as a result of its relatively low supply, e.g. an exhaustible resource or raw materials in high demand.

[12] In reality, the extraction cost is only a few dollars per barrel (corresponds to 0.1-0.4 USD/GJ) in the Middle East and higher in other major oil producing regions. The price observed in the market is much higher still and reflects scarcities and the fact that oil supply is controlled by a cartell (OPEC). It would be too complicated in a model like this to simulate the price setting behaviour of a cartell. For that reason, we have chosen to set the primary energy cost, P_C, (extraction cost and distribution) for conventional oil at 3.5 USD/GJ. This oil price, which prevailed towards the end of the 90s, includes the impact of the cartell's activities. When oil reserves decline the scarcity rent will increase. We get roughly the same price development for oil ($P=P_C+P_{SR}$) in our model even if we put the extraction cost to zero.

Table 1. Derived total cost for each fuel choice used in either internal combustion engines or in fuel cell engines. Costs are derived using primary energy costs P_C, i.e., without scarcity rents and carbon taxes.

Year 2000	[USD/GJ] Fuel production cost [a)]	Total cost[b)] [USD/km] Internal com-bustion engines	Fuel cell engines
Oil Conventional_gasoline	10.29	**0.139**	**0.154**
Oil Conventional_costly refinery_gasoline	12.24	**0.146**	**0.159**
Oil Heavy_gasoline	11.96	**0.145**	**0.158**
Oil Heavy _costly refinery gasoline	13.91	**0.151**	**0.164**
Natural gas	8.90	**0.140**	-
Biomass_methanol	11.69	**0.149**	**0.158**
Natural gas_methanol	9.97	**0.143**	**0.153**
Coal_methanol	10.02	**0.143**	**0.153**
Biomass_hydrogen	15.92	**0.171**	**0.161**
Natural gas_hydrogen	12.76	**0.160**	**0.154**
Coal_hydrogen	13.53	**0.163**	**0.155**
Oil Conventional_hydrogen	14.89	**0.168**	**0.158**
Oil Heavy_hydrogen	17.37	**0.176**	**0.164**
Solar_hydrogen	31.04	**0.223**	**0.196**

a) includes the investment cost of the energy conversion plant, the operation and maintenance cost, the primary energy cost per energy output and the distribution cost to fuel stations.
b) includes the fuel production cost, the vehicle investment cost, an engine efficiency factor, vehicle annual energy demand and engine life times

3.3.3 Main results

In the base case run of the GET 5.1 model, aiming for 450 ppm, no carbon capture and storage technology is included. Results on cost-efficient fuel choices in the transportation sector are presented in Figure 15.

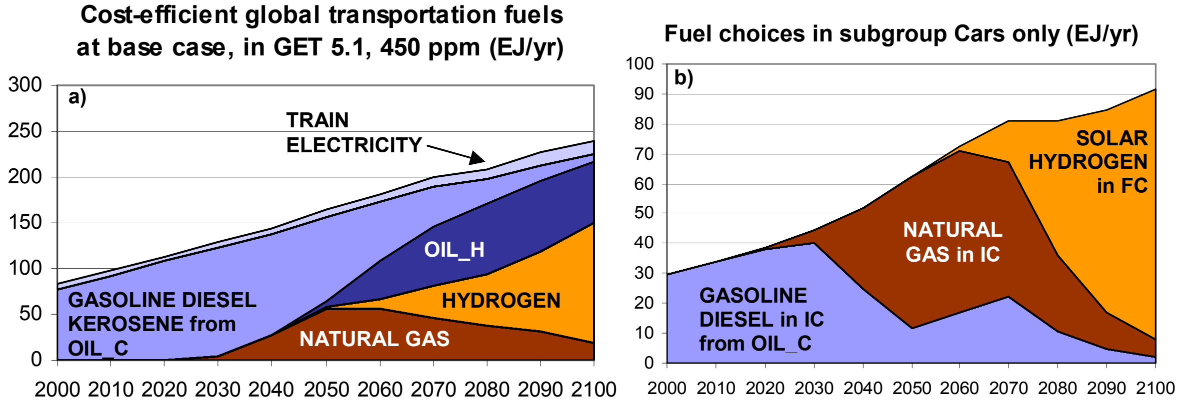

Figure 15. Cost-efficient transportation fuels, in the base case scenario, using the GET 5.1 model and a) shows the fuel choices for the whole transportation sector where the three subgroups: Cars, Freight and Aviation are aggregated and b) shows the fuel choices for subgroup Cars only. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= gasoline, diesel and kerosene produced from unconventional heavy oils, IC= internal combustion engines and FC= fuel cell engines.

The same overall results as in previous GET model studies appear, i.e. that gasoline/diesel remain for some decades in the transportation sector until the carbon constraint becomes increasingly stringent and that solar based hydrogen dominates by the end of this century. Biofuels do not appear as a cost-effective fuel choice. One significant exception from previous GET model results is, however, that natural gas has taken a larger share of the transportation fuels, which is a result of that only 60% of the conventional oil can be converted to gasoline and diesel at conventional refinery cost, in the GET 5.1 model, compared to 100% in earlier GET versions.

To analyze the underlying cost dynamics in the GET model we use the calculated total costs [USD/km] in the simplified model, presented in Table 1, but instead of using the primary energy costs, P_C, we run the full GET model, aiming for 450 ppm, to obtain shadow prices (scarcity rents) from the primary energy supply equation. In the base case run of the GET 5.1 model scarcity rents are generated on natural gas, conventional oil and biomass[13].

These new costs, based on primary energy prices, P, (minus P_T) are then plotted as a function of the carbon tax [USD/tC] to illustrate how the relation between the costs per km changes with higher carbon taxes. The scarcity rents generated in the run for a specific time step are kept constant[14] in each plot. Plots for time steps 2030, 2050, 2070 and 2090 are presented in Figure 16. The vertical dotted line in each graph marks the generated carbon tax for the specific time step.

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[13] Scarcity rents are generated on biomass due to the fact that the demand for biomass exceeds the supply potential at high carbon taxes. When the model is run without restrictions on CO_2 emissions, no scarcity rent is added to the biomass primary energy cost.

[14] If the GET model were run with higher carbon taxes, scarcity rents on biomass would increase as a consequence of an even stronger competition for biomass. Thus, it is not possible to foresee any other GET results from the plots outside the intersection with the dotted vertical carbon tax curve.

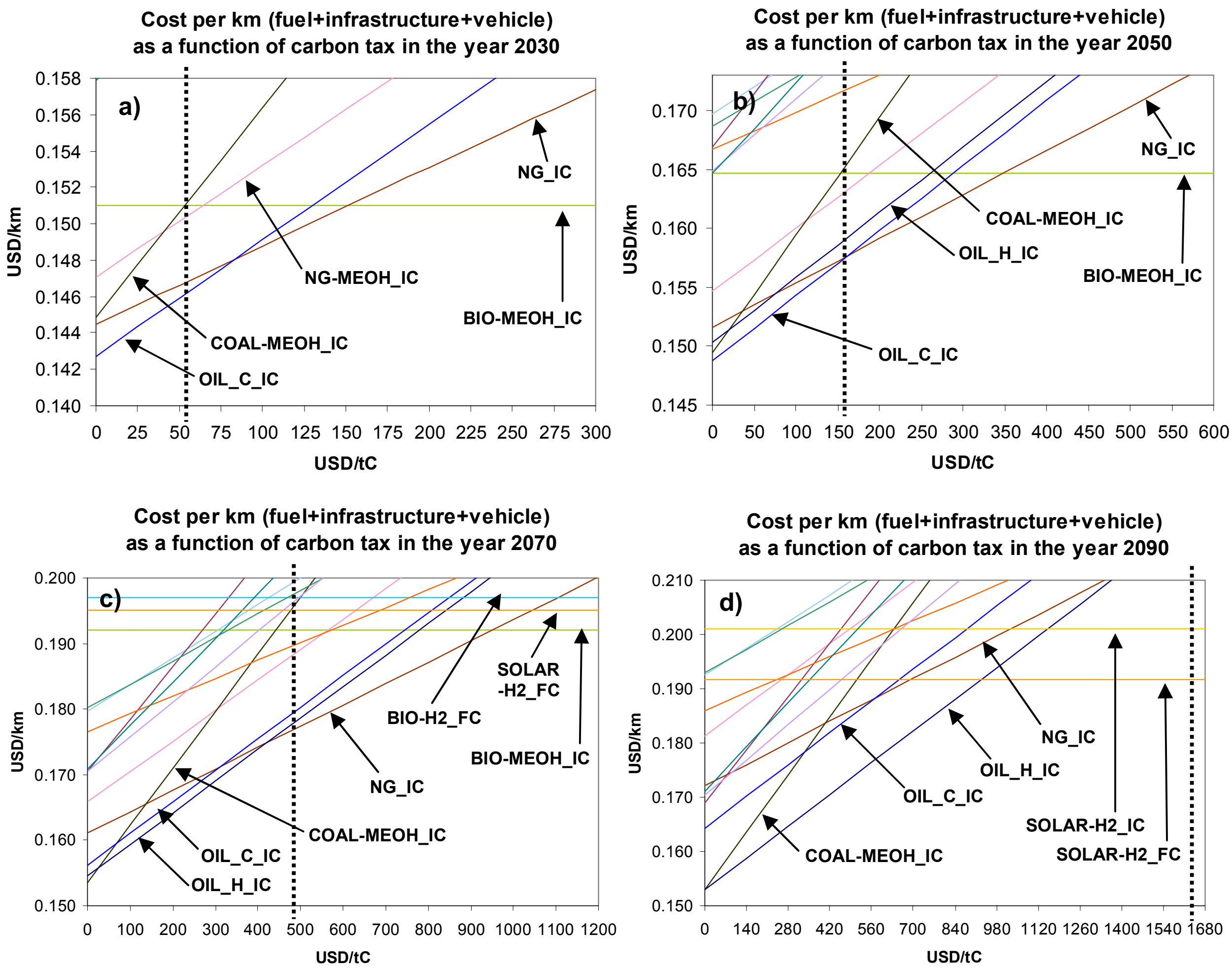

Figure 16. Costs per km (subgroup Cars only) using primary energy costs generated in the base case set up, of the GET 5.1 model. Note that the scarcity rents generated in each time step are kept constant in each plot. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= heavy oils, NG= natural gas, MEOH= methanol, H2= hydrogen, IC= internal combustion engines and FC= fuel cell engines.

In Figure 16 it is shown that in the year 2030 (a) and the year 2050 (b) cars run on fossil fuel options, i.e. gasoline and diesel from conventional oil and natural gas, have the lowest cost per km up to the carbon tax level of (a) 150 USD/tC and (b) 350 USD/tC when cars run on biomass based methanol have the lowest cost per km.

In Figure 16c it is shown that in the year 2070 cars run on fossil fuel options, i.e. coal based methanol, gasoline and diesel derived from heavy oils and natural gas, have the lowest cost per km up to the carbon tax level of 950 USD/tC when cars run on biomass based methanol have the lowest cost per km. Note that two other carbon neutral alternatives are close to biomass based methanol in the year 2070, i.e. solar based hydrogen in fuel cell vehicles and biomass based hydrogen in fuel cell vehicles.

In Figure 16d it is shown that in the year 2090 cars run on fossil fuel options, i.e. coal based methanol and gasoline and diesel derived from heavy oils, have the lowest cost per km up to the carbon tax level of 930 USD/tC when cars run on solar based hydrogen in fuel cell vehicles have the lowest cost per km. Note that the cost per km on biomass based methanol now is higher than solar based hydrogen, which is due to a high scarcity rent on biomass (the generated primary energy price, *P,* on biomass is 37 USD/GJ in the year 2090).

The intervals where a certain fuel has the lowest cost per km are identified for each time step, by analyzing the plots presented in Figure 16, and then the identified intervals are presented in bars as shown in Figure 17, where also the carbon tax generated in the GET 5.1 base case is plotted as a line curve above the bars.

The fuel range that crosses the carbon tax line curve will first and foremost be chosen in the scenario in a linear optimization model. However, since the model has expansion rate constraints a technology might enter some time steps earlier to be able to expand into large volumes. This is the case with solar based hydrogen, which enters the scenario in 2060-2070, see Figure 15b, but crosses the carbon tax line curve, in Figure 17, first in the year 2080. The model also has constraints on the rate of which a fuel can be phased out which, together with the fact that capital decays exponentially, explains why conventional oil remains in the transportation sector for some decades in the scenario even though natural gas crosses the carbon tax line curve earlier, in Figure 17. The reason for the increasing use of gasoline and diesel derived from conventional oil in the years 2060 and 2070, in the scenario for subgroup Cars, is that investments are made in new refinery capacity to supply the Freight and the Aviation sector. Using some of the capacity to produce gasoline/diesel for cars will lower the total energy system cost, but that can not be seen in Figure 17.

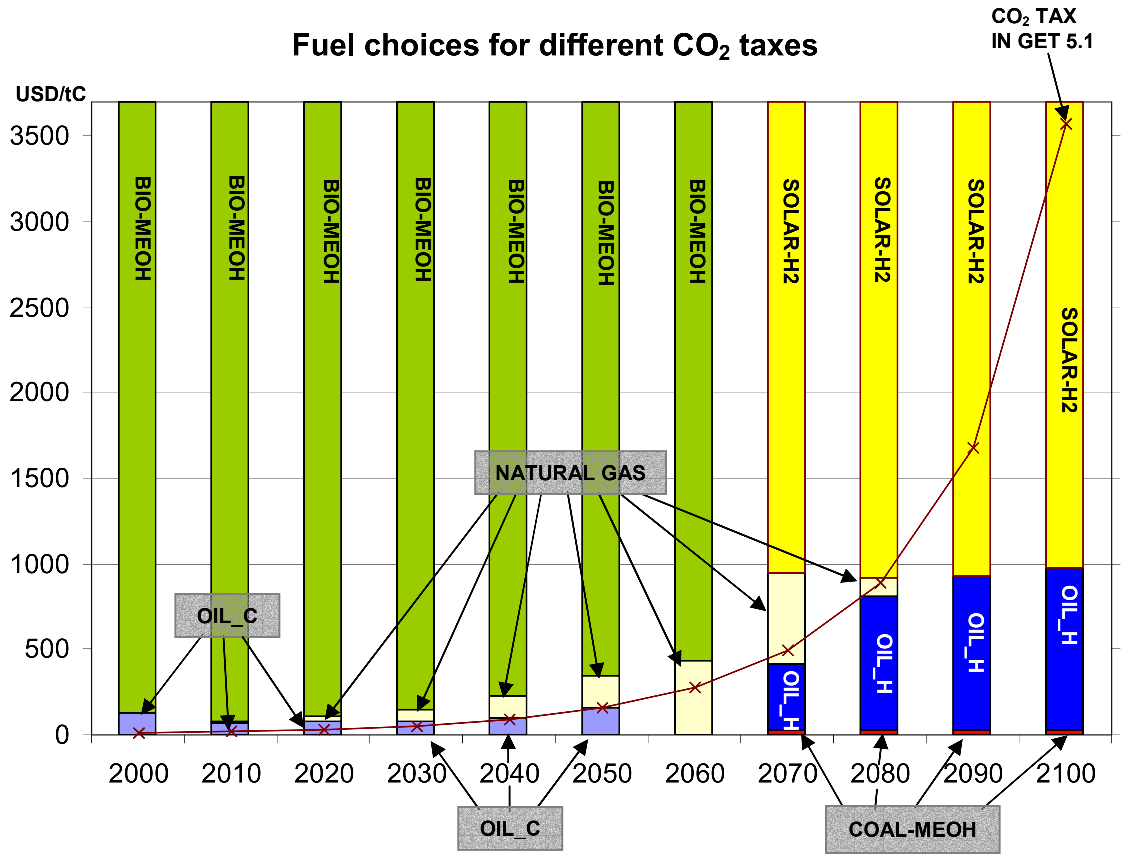

Figure 17. Fuel choices in the transportation sector (subgroup Cars only) for different carbon tax intervals in the base case scenario, aiming for 450 ppm. For each time step the lowest fuel cost per km for a certain range of carbon taxes are identified and plotted in bars. The carbon tax generated in the run is plotted as a line curve in front of the bars, with the tax values marked with x. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= unconventional heavy oils, MEOH= methanol and SOLAR-H2= solar based hydrogen.

By studying Figure 17 it would be tempting to interpret the carbon tax intervals as that biofuels would become a cost-effective fuel choice if the carbon tax would be higher than 150 USD/tC in the year 2030, but this can not be taken for granted. A run where the carbon tax is locked to 160 USD/tC for the years 2010-2030, does not introduce any biofuels. Instead, the primary energy price, *P*, on biomass increases to 4.4 USD/GJ compared to 2.3 USD/GJ in the base case, which increases the cost on biomass based methanol to 0.161 USD/km compared to 0.151 USD/km in the base case.

Increasing the carbon tax to 400 USD/tC will still not introduce any biofuels. In this run the competition, between biomass based heat and biofuels, is even stronger and the primary energy price, *P*, on biomass has increased to 10.7 USD/GJ leading to a cost of biomass based methanol at 0.190 USD/km. In this run the carbon tax level when biofuels become cost-efficient, has moved up to 990 USD/tC for year 2030.

This evasive carbon tax level when biofuels become cost-efficient, compared to fossil based fuels, is an effect of the system effect in the model. The tax level moves upwards with increasing carbon taxes, since this leads to an increasing biomass primary energy price in the model.

The system effect can also be understood by comparing the costs for the two competing CO_2-neutral energy options (solar and biomass) in the three energy demand sectors. In the transportation sector, by going from biomass based methanol in internal combustion engines (0.149 USD/km) to solar based hydrogen in fuel cells (0.196 USD/km), we get an increase of the cost per km by a factor of 1.3. In the electricity sector by going from biomass based electricity (11.4 USD/GJ) to electricity derived from solar based hydrogen (25.8 USD/GJ) we get an increase of the cost per Joule by a factor of 2.3. In the heat sector by going from biomass based heat (3.82 USD/GJ) to heat derived from solar based hydrogen (23.6 USD/GJ) we get an increase of the cost per Joule by as much as a factor of 6.2. Hence, biofuels are not introduced in the transportation sector since biomass is most cost-effectively used in the heat sector.

Since the system effect in the GET 5.1 model prioritizes the limited biomass to the heat sector it indicates that a situation in which biofuels enter the transportation sector should involve other types of changes to the model, for example, other cost assumptions, features, and/or constraints. To analyze under what circumstances biofuels could become a cost-effective strategy to reduce CO_2 emissions, we have carried out a sensitivity analysis in the GET 5.1 model. We find that biofuels enter the transportation scenario, if we assume a lower conventional oil supply potential, a larger biomass supply potential, that waste heat generated in the production of transportation fuels may be sold to the heat market and that 25% of all biomass used for heat production need to be refined. When these four assumptions are put together, a large amount of biofuels, accounting for 44% of total transportation fuel production by the year 2050, is used, see Figure 18

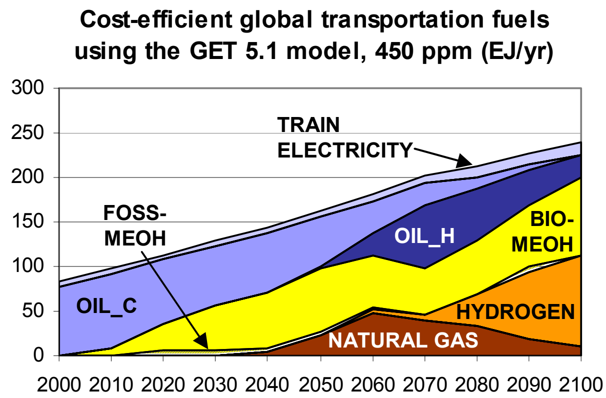

Figure 18. Cost-efficient fuel choices in the transportation sector in a sensitivity run. In this run biofuels account for 44% of total transportation fuels in the year 2050. Acronyms used in the figure are OIL_C= conventional oil, OIL_H= unconventional heavy oils, FOSS-MEOH= methanol derived from fossil fuels and BIO-MEOH= biomass based methanol, i.e. biofuels.

4. Explaining the model results

The general result, on cost-effective fuel choices in the transportation sector, seen in this thesis is that oil based transportation fuels, i.e. gasoline, diesel for Freight and Cars and kerosene for Aviation, dominate until solar based hydrogen enters the transportation sector in 2040-2050. In some run natural gas plays an important role but biofuels do not enter in either of the GET model base case set ups. This result is explained in detail in paper III of this thesis but it can also be understood by the rough explanations made in the following subsections.

4.1 How can oil remain dominant in the transportation sector for several decades despite the introduction of stringent climate targets?

A perhaps somewhat surprising result from the GET-models is that oil remains dominant in the transport sector several decades ahead, despite stringent climate targets. Here we offer two separate explanations for that result.

4.1.1 A physical explanation

A physical explanation for that is that all known oil and natural gas reserves combined, contain about 200 billion ton carbon (GtC). Since we allow about 400 GtC (in the form of CO_2) to be emitted during this century, it is possible to release more carbon than what exists in the total reserves of oil and natural gas, and still stabilize the atmospheric CO_2 concentration at an ambitious level (CO_2 emissions from the use of coal will then of course need to be less than 200 GtC, which implies clear deviation from business as usual scenarios).

When CO_2-neutral primary energy sources, e.g. biomass and wind power, replaces fossil fuels for the production of heat and electricity, large amounts of CO_2 emissions are abated in these two sectors. This leaves space for CO_2 emissions that is large enough for oil to remain as a primary energy source several decades ahead, despite stringent climate targets. The advantages of using oil in the transportation sector are larger than using oil for heat or electricity production which explains the result that oil remains as the dominant fuel in the transportation sector several decades ahead. Gasoline and diesel emits large amount of CO_2 but it is in general easier, from a technical and economical perspective to abate CO_2 emissions from other sources.

4.1.2 Energy conversion efficiency

The energy conversion efficiency becomes very important when using limited primary energy sources. Generally it can be stated that it is always easier (and therefore often cheaper) to convert a liquid raw material into a liquid fuel compared to convert a solid material into a liquid fuel. Gasoline and diesel can be produced at about 90% conversion efficiency from oil, but liquid transportation fuels from solid raw material can only be produced at conversion efficiencies between 25-60%. It is therefore very difficult for all fuel alternatives to compete with gasoline and diesel when it comes to production costs, as long as the primary energy cost for oil is moderate. Comparing the two limited energy sources oil and biomass, both can be used with high energy conversion efficiency for heat production but oil has higher energy conversion efficiency, compared to biomass, when producing transportation fuels. This explains why oil based fuels have an advantage over other transportation fuels.

4.2 Why are not biofuels seen as a cost-effective strategy to reduce CO_2 emissions?

Biomass is a relatively cheap energy source and can already today be used for electricity generation, heat production and for the production of transportation fuels. The global biomass supply potential is large (we assume that 200 EJ/yr biomass, corresponding to about 500 Mha[15] land, can be used for energy purposes in future), but it is however not large enough to supply the whole energy sector, which implies that competition for carbon neutral energy such as biomass is likely to arise. Biomass can be converted to heat at an efficiency of about 80-90% while conversion efficiencies for bio-electricity and biofuels lies between 25-60%. The conversion efficiency may increase if co-generation of heat and/or power is implemented with biofuel production, but the market for surplus heat is uncertain. Biomass can almost always replace more[16] fossil fuels if it is used for heat production, compared to when biomass is used for the production of biofuels. This is an important issue since biomass is a globally limited resource.

Using biomass to produce biofuels would imply that the heat demand would have to be satisfied from other CO_2-neutral sources (hydrogen from solar or fossil fuels with carbon capture and storage technology), which would increase the overall cost of meeting the energy demand. Biofuels are hence not seen as a cost-effective strategy to reduce CO_2 emissions since biomass is more cost-effectively used for heat production.

[15] We assume that 100 EJ/yr comes from the actual yield of 200 GJ/ha from 500 Mha and that 100 EJ/yr comes from biomass residues.

[16] The conversion efficiencies for heat production from fossil fuels and biomass are roughly the same, which implies that 1 GJ biomass roughly replaces 1 GJ fossil fuels when used for heat production. The conversion efficiencies for the production of transportation fuels differ, where gasoline and diesel can be produced roughly twice as efficient from oil compared to biofuels from biomass, which implies that 1 GJ biomass roughly replaces 0.5 GJ oil when used for the production of transportation fuels.

5. Discussion

In this section we discuss factors not considered in the GET model and how reasonable some assumptions are in the model.

5.1 Factors not considered in the GET model

The energy system description in the GET model is a simplification of reality in many ways, e.g., the number of available technologies is limited, demand is price-inelastic, decisions in the model are only based on cost considerations, and there is no uncertainty about future costs, climate targets or energy demand levels etc. The global energy system, in GET, is then optimized with perfect foresight and with a single goal function. Thus, the model is not attended as a tool for making forecasts of the energy system development.

An energy-economy model like this is, however, useful for constructing and comparing scenarios. The model makes it possible to quantitatively explore the role and cost-efficiency of various technologies given different carbon emission constraints, resource availabilities, and parameter values for technologies. The model can be seen as an experimental box where we can investigate relations between subunits which otherwise are not obvious.

Some factors difficult to take into consideration in a global model are for example:

- Valuation of energy security
- Public acceptance of new technologies
- Convenience aspects
- Alternatives may not be identical[17] for customers
- Real decision making more complicated than cost-minimization[18]

[17] It is for example difficult to model willingness of buying electric cars, which is an energy-efficient technology but not really comparable to current standard cars.
[18] In a linear optimization model, the total cost is minimized, and therefore a specific fuel will always be selected even if it differs in cost by only one percent. In reality human choices are not that black and white. If the range of prices is narrow, people may choose the higher cost alternative.

- Future agriculture and industry policies
- The impact of lobby groups
- Political instabilities e.g. war

Neither of these factors are considered in the GET model. Adding a price premium for these factors could help but it will also add uncertainties.

Cost-effectiveness in dealing with climate change is not the only criterion for fuel choices in the transportation sector and biofuels may be chosen for other reasons. As mentioned before, if technical, economical and social barriers of using hydrogen in the transportation sector prove to be too difficult to overcome, biofuels or CO_2-neutral electricity are two very important alternatives when we run out of conventional oil. Also three more commonly heard reasons for choosing biofuels are presented in the following sections.

5.1.1 Surplus of cropland

Many industrialized countries have a surplus of cropland and the production of traditional agricultural crops as feedstock for ethanol production can be attractive to farmers, since this does not involve any major change in present agricultural practices. Surplus cropland can also be used for the production of cellulosic crops for heat and electricity production purposes and, as technologies become available, production of so-called second generation biofuels such as FT-diesel, methanol and lignocellulose-based ethanol. This requires, however, that farmers take decision in switching to new crops of which they have limited experience and in many cases less flexibility, e.g., a willow plantation is typically lasting for 20-25 years. This leads to reduced willingness to establish long-term willow plantations, especially among grain producers with a high equipment capacity for grain cultivation (Börjesson and Berndes, 2006).

5.1.2 Energy security

Energy security is also a possible objective that could be considered more important than cost-efficient CO_2 abatement. Most countries wish to become less dependent on imported oil. If energy security is regarded an important objective, biofuels have a larger potential than hydrogen to be introduced in the transportation sector in a short-term scenario. However, one should also recall that measures aimed at reducing fuel demand are also possible and may be equally or even more cost-efficient in improving energy security.

5.1.3 Barriers for biomass in the heat sector

If biomass for some reasons has difficulties to supply a large share of the heat demand, biomass instead will likely be used for biofuels or for electricity generation. One current barrier for a large-scale introduction of biomass for industrial heat production has to do with the inconvenience of using solid fuels. A rapid switch from solid fuels to natural gas has occurred during the last decades in many world regions where gas is available (Gielen, 2004). Gaseous and liquid fuels are more convenient to use compared to solid fuels and the industrial sector is currently willing to pay more for gaseous and liquid fuels compared to solid biomass (on a per GJ basis). However, with an increasing carbon tax the price difference may in the future be large enough to make this argument invalid.

5.2 Is it reasonable to assume that CO_2-neutral hydrogen will overcome its barriers and be available in the transportation sector?

In this thesis, we have found that biomass is most cost-efficiently used in the heat sector, assuming that CO_2-neutral hydrogen will be available at sufficiently low costs. It is currently very difficult to judge how reasonable this assumption about the future is.

Fuel cells have been around since the 19^{th} century and have been used successfully for decades for power generation in spacecraft, but not yet in mass produced road vehicles.

Car companies have produced about 70 prototype fuel cell cars[19] and trucks as well as dozens of buses (Service, 2004). Energy and car companies have also built hydrogen fuelling stations worldwide, with many more on the drawing boards (Cho, 2004), but fuel cell reliability, life time and production cost still need to be improved (Service, 2004, Ny Teknik, 2004).

In addition to fuel cells a second large barrier is the onboard storage. At room temperature and atmospheric pressure, hydrogen takes up roughly 3000 times as much space as gasoline containing the same amount of energy. That means storing enough of it in a fuel tank requires compressing it, or liquefying it, or using some other form of advanced storage system. Many options are promising, but some still have severe drawbacks, such as requiring high temperature or pressures, releasing the hydrogen too slowly, or requiring complex and time-consuming materials recycling (Service, 2004).

Each of the problems faced by the hydrogen economy, e.g. a simple and cheap way to produce CO_2-neutral hydrogen in large scale, hydrogen storage, fuel cells, safety, and infrastructure, would be challenging on its own. For a hydrogen economy to succeed, all of these barriers must be solved. One loose end could block a broad-based changeover (Service, 2004). Currently hydrogen as a large scale energy carrier faces huge barriers and it is not obvious that it will be available in a future transportation sector, at reasonable costs. It is, however, a general opinion among car manufacturer that hydrogen, in either fuel cells or in internal combustion engines, is an attractive long-term solution. Clearly, the long run future is still in the open.

6. Conclusions

Conclusions, drawn in earlier GET model studies, that have been re-confirmed in this thesis are that (i) it is possible to decrease carbon dioxide emissions at the same time as the demand for energy services increases, (ii) in the near term improved energy efficiency

[19] Photos and description of more than 200 hydrogen cars and more than 200 hydrogen filling stations are presented at www.h2cars.de (H2cars, 2005).

and increased use of biomass are two promising options, (iii) to reach ambitious CO_2 stabilization levels, a radical change of the energy system is needed, (iv) the required changes are not likely need to occur by themselves, i.e. a wise use of global and regional policy instruments will be necessary and (v) low[20] carbon taxes (below 75 USD/tC) do not generate sufficiently strong incentives to introduce biofuels.

New conclusions, drawn within the scope of this thesis, leads to a further refined picture of earlier conclusions, i.e. that the results differ between the short and the long term as well as between low and high carbon taxes.

- Biomass is most cost-effectively used for heat productions at low CO_2 taxes, up to about 75 USD/tC, as shown in both the GET and the BEAP models.
- The sector in which biomass is most cost-effectively used at higher CO_2 taxes depends on assumed possible energy carriers and technologies. If hydrogen and/or electricity derived from carbon free energy sources will not be available in the transportation sector, biofuels become an important option if low or zero carbon emissions are to be achieved.
- If hydrogen is assumed to make it as an energy carrier in the transportation sector, then cost assumptions on hydrogen production, fuel cells, storage options and infrastructure will determine in which sector biomass will be used. Clearly, these costs are currently very uncertain, so the long run future for the cost-effective transportation fuel choice is still in the open.
- Regionalizing the GET 1.0 model will not affect the overall pattern of transportation fuel choices, i.e. that gasoline/diesel remain for some decades in the transportation sector until the carbon constraint becomes increasingly stringent and that solar based hydrogen dominates by the end of this century. Biofuels do not appear as a cost-effective fuel choice.
- In paper III, we have developed a method, implemented in Excel, which explains the GET model result and gives deeper insights about the system effect. By studying the cost dynamics in the GET model, i.e. comparing the generated total

[20] Biofuels will not be introduced at high carbon taxes either, in the GET model, but in this thesis we found that the results for higher carbon taxes depend on assumptions on future energy carriers and technologies. At very low or zero carbon taxes biofuels may be cost-efficient if the primary energy cost on oil are high.

costs per km for each fuel choice and identify the carbon tax intervals for each time step where biofuels have the lowest cost per km, we find that the required carbon tax level where biofuels become cost-efficient compared to fossil based fuels, is evasive. The tax level moves upwards with increasing carbon taxes, since this leads to an increasing biomass primary energy cost in the model.

- In a sensitivity analysis, carried out in Paper III, we find that the model is sensitive for some type of changes. If we assume a lower conventional oil supply potential, a larger biomass supply potential, that waste heat generated in the production of transportation fuels may be sold to the heat market and that 25% of all biomass used for heat production need to be refined, and combine these four assumptions a large amount of biofuels will enter the transportation fuel scenario. We have, however, not looked into how reasonable these new assumptions are and neither analyzed possible barriers for introducing them.

7. Some implications for policy

7.1 Policy instruments for the transportation sector

Optimization models are useful and important tools for insights, but model results should be treated with care. The model results highlight cost-effective pathways to low CO_2 emission futures. This does not mean, however, that we suggest that governments should adapt policies that make sure that these particular futures materialize, e.g. maintain the dominance of oil based transportation fuels for several decades. Instead our view is that policies should be implemented with the long-term goal of bringing down the CO_2 emissions from the transportation sector to a low stabilization target and CO_2 emissions from the transportation sector can be reduced by (i) turning the vehicle fleet more energy-efficient, (ii) changing transportation patterns, and (iii) changing from fossil based fuels into CO_2-neutral alternatives.

The fact that carbon taxes do not generate sufficiently strong incentives[21] to introduce biofuels in the model does not mean that biomass should not be used in the transportation sector, since cost-effectiveness in dealing with climate change is not the only criterion for policy makers. Rather, the implication is that if governments would want to see biofuels take off, then they would probably also need to introduce complementary policies (e.g., mandatory blending). Whether this should be done or not is a prescriptive question which lies outside the scope of this thesis.

7.2 Bring down costs for all promising CO_2-neutral options

One misinterpretation of our result has been that no new technologies in the transportation sector would need to be developed until the middle of the century. But even though oil may remain as a dominant fuel for several decades it is important to continue research, development and demonstration of alternative fuels and vehicles. A fuel and technology transition in the transportation sector may take longer time than a fuel transition in the two other sectors, since three separate parts of the transportation system, i.e. fuel production, infrastructure and vehicles, need to be transformed almost simultaneously. Since it still is an open question, whether CO_2-neutral hydrogen will be available in the transportation sector at sufficiently low costs, policies at present should primarily aim at trying to bring down costs for all promising CO_2-neutral options, e.g. biofuels, electricity and hydrogen.

7.3 Policy instruments for the energy system

To realize ambitious climatic goals, a wise use of global and regional policy instruments will be necessary to achieve a large transition of the whole energy system. These policy instruments should cover three main areas (i) increase the cost for emitting fossil carbon e.g. a CO_2 tax, (ii) steer towards energy efficiency, e.g. introduce fuel consumption standards and (iii) support research, development and diffusion of new advanced energy technologies (Sandén & Azar, 2005).

[21] Assuming that other CO_2-neutral fuel alternatives are available. If no other alternatives are available high carbon taxes will generate sufficiently strong incentives to introduce biofuels.

Acknowledgement

Ten years ago I was responsible for the Volvo Truck Corporation's Art Service account at Lennart Larsson advertising agency. I had signed a professional secrecy, to be able to check the photographic quality of all new confidential cars, trucks and buses. I was fascinated by all these new concept vehicles running on new engines and alternative fuels. At that time I would never have guessed that I ten years later would be doing research on energy systems and that I would be invited to the Swedish Parliament to talk about alternative transportation fuels. Thank you Carina Möller-Liderfors, Lisa Andersson and Anna Järvholm for your ongoing friendship including our fifteen year tradition of Christmas candy production. I'm very grateful for your support when I decided to totally change careers, at that time with the goal of becoming a math and science teacher. Sending in my resignation, ten years ago, was the first, and maybe the most difficult, step to carry out towards writing this thesis.

I would like to offer a special thanks to Roy Tärneberg, my teacher in Physics during the preparatory year in Science. You have a remarkable enthusiasm and you inspired me to look for a university program that included more Physics than the teacher education offered.

I also would like to express my gratitude to Lena Gustafsson, professor of Biotechnology and presently Vice President at Chalmers. You held an inspiring public lecture at Vetenskapsfestivalen 1997, on how mutants of Saccharomyces cerevisiae (baker's yeast) could improve ethanol production from cellulose, and you mentioned that ethanol based on cellulosic biomass could be an important substitute for gasoline in future. Thanks to that lecture I knew what I would like to work with after finishing a university program. Being involved in energy research preferably with a connection to transportation fuels became my highest goal.

I studied an interdisciplinary university program called "Problem Solving in Science", at Göteborg University, and during my first year I came in contact with the department of Physical Resource Theory. Thank you Björn Sandén for being a fantastic supervisor for me and my student group and Christian Azar for not just being an inspiring teacher but also for asking me to work for you during my student time, which was very interesting and highly instructive. Also thanks to all other brilliant teachers I met during the university program, especially Maria Sundin, Ann-Marie Pendrill and Maj Hansson, your knowledge and enthusiasm have made a deep impression on me. Further thanks to all my classmates and friends; Björn Adolfsson, Igor Anakijoski, Daniel Andersson, Peo Björck, Samuel Brohede, Filip Edström, Mikael Ekenstam, Erik Filipsson, Julia Franzén, Fredrik Hedenus, Stina Hemdal, Jakob Heydorn Lagerlöf, Stefan Högberg, Charlott Johansson, Hanna Jönsson, Marcus Krantz, Milcco Larsson, Lena Lundqvist, Elin Löwendahl, Björn Persson, Martin Persson, Lotta Svensson, Camilla Thulin, Luis Young, Frida Wahl and Johan Österman for the terrific mix of serious studying and fun parties. Björn, Erik and Peo, I will always remember our study trip to the Ruhr-area in Germany where we took a close look at hydrogen pipelines. Great fun.

To enter deeper into optimizing theory I took a Postgraduate Diploma in Statistics and Operation Research by studying one year at Royal Melbourne Institute of Technology in Australia. A special thanks to Denise and David who became, and still are, dearest friends to me and my family. Denise, I love you! Are you coming over for some champagne tonight? Thanks also to Astrid Linder who is another very good Australian (and Swedish) friend always very interested in my PhD-studies. Astrid, I admire your energy, your hard work and your fabulous results. Torbjörn and Susanne Bladby, our friendship was also initialized during the year in Australia and means a lot to me. Susanne, are you ready for a game of Rummy?

Soon after returning to Sweden, I started my position as a PhD-student at the department of Physical Resource Theory. I would like to thank everyone I have come to know, both currently and previously working at the department, for making it such a stimulating environment as it is. Thank you Karl-Erik Eriksson, Eija Hyttinen, Jenny Hanell, Bernhard Mehlig, Johan Stäring, Peter Nordin, Krister Wolff, Peter Jönsson, Jessica Johansson, Fredrik Fredriksson, Tomas Kåberger, Björn Sandén, Ingrid Råde, Johan Swahn, Pia Sundh and Elin Löwendahl for your contribution to the FRT-atmosphere. I wish you all luck in the future at your new positions. Also thanks to Professor Dean Abrahamson and Professor Bob Ayres for your regular visits to the department and for sharing your great knowledge with us. Thank you Sten Karlsson, for your never-ending interest in all subjects and every seminar. Your sharp comments and questions always enrichen our discussions, which lead to improved research. Also thanks to John Holmberg, for being an excellent head of the department, which demands a large amount of time and patience. Your development of the department, as well as us individuals, is gratefully acknowledged. A special thanks to Tobias Persson and Julia Hansson for being the best conceivable room mates. You are always in a good mood and loaded with good arguments on every discussion subject. I really enjoy working close to you. Thank you Sandra Malentacchi, Fredrik Hedenus, Frances Sprei, Martin Persson, Daniel Johansson, Jonas Nässén, Wathanyu Amatayakul, Stefan Wirsenius, Ulrika Lundqvist, Martin Jacobi, Anders Eriksson, Claes Andersson, Olof Görnerup, Kolbjørn Tunstrøm and Johan Nyström for your support, friendship and laughter. You all contribute to an inspiring environment and I hope to spend some more years with you at the department.

I would like to offer special thanks to my supervisors and co-authors. Dolf Gielen, your quick responses to my many questions as well as your clear-sighted and thorough comments are gratefully acknowledged. Per Kågeson, your knowledge about vehicles and transportation systems has had a deep impact on me. Göran Berndes, your guidance is a splendid mix of rapid funny replies and thoughtful words of wisdom. Kristian Lindgren, I am particularly grateful for your excellent, calm and encouraging guidance. Thank you for letting me share your office for six months. Last but not least thank you Christian Azar, my main supervisor, for all inspiration and support. You have a fantastic gift to explain things in a simple and pedagogical way. Your intellect, humour, ambition and knowledge have made a deep impression on me. You inspire me.

Financial support from Swedish Agency for Innovation Systems, Vinnova, and Swedish Energy Agency is gratefully acknowledged. Without your funding this thesis would not have been materialized.

I would also like to thank my family whose support means a lot to me; Ulla Lidbeck, Sven Holländer, Thomas Lidbeck, Anette Aretjäll, Camilla and Thomas Bako, Lena and Daniel Roos. Thanks also to the whole “Grahn-clan” especially my parents in-law Rosa and Gerhard Grahn.

Emma and Viktor, by your appearance you have richened my life. I love you and wish you the very best of futures.

Finally and most importantly, thank you Roberto for being the most generous, considerate, handy, well-informed and sharp man I have ever met. I love you!

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Paper I

Biomass for heat or as transportation fuel? – a comparison between two model based studies

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Abstract

In two different energy economy models of the global energy system, the cost-effective use of biomass under a stringent carbon constraint has been analyzed. Gielen *et al* conclude that it is cost-effective to use biofuels for transportation, whereas Azar *et al* find that it is more cost-effective to use most of the biomass to generate heat and process heat, despite the fact that assumptions about the cost of biofuels production is rather similar in the models. In this study, we compare the two models with the purpose to find an explanation for these different results. It is found that both models suggest that biomass is most cost-effectively used for heat production for low carbon taxes (below 50-100 USD/tC, depending on the year in question). But for higher carbon taxes the cost effective choice reverses in the BEAP model, but not in the GET model. The reason for that is that GET includes hydrogen from carbon free energy sources as a technology option, whereas that option is not allowed in the BEAP model. In all other sectors, both models include carbon free options above biomass. Thus with higher carbon taxes, biomass will eventually become the cost-effective choice in the transportation sector in BEAP, regardless of its technology cost parameters.

Keywords: Energy scenarios, Energy system model, Biomass, Alternative transportation fuels, Liquid biofuels, Hydrogen, Carbon dioxide emissions, Carbon tax

1. Introduction

Due to the expected increase in global energy demand, the supply of CO_2-neutral energy may have to grow to levels similar to or even larger than the present global total fossil fuel use, if we are to avoid venturing into a future with a doubled, tripled or even quadrupled pre-industrial atmospheric CO_2 level. Among several candidates capable of supplying large amounts of CO_2-neutral energy, biomass ranks as one of the few options already competitive on some markets. It is a low cost renewable fuel, and it is near penetration into new applications as policies, markets and related technologies develop.

There are large uncertainties about the potential for biomass, but it is nevertheless clear that the potential supply is low compared to the future required levels of climate neutral energy, almost regardless of whether one is optimistic or pessimistic about the global bioenergy potential (see, e.g., Azar 2005, Berndes *et al*, 2003). Biomass will thus not be available for all possible energy applications and it is therefore important to discuss where to use the scarce biomass resources for climate change mitigation.

In their study of cost-effective fuel choices in the transportation sector, Azar *et al* (2003) find that it is more cost-effective to substitute biomass for fossil fuels in power and heat production (Azar *et al*, 2003). Oil based fuels remain in the transportation sector for the next four to five decades and thereafter solar hydrogen or hydrogen produced from fossil fuels with carbon capture and storage enters. However, in another study, Gielen *et al* (2002, 2003) conclude that, most of the biomass is cost-effectively used as biofuels[1] for transport. These two studies base their results on global energy system models developed especially for these studies. Gielen *et al* have developed the BEAP (Biomass Environmental Assessment Program) model and Azar *et al* the GET 1.0 (Global Energy Transition) model. The two models are in many ways similar to each other and both models are run under ambitious constraints on carbon dioxide emissions.

The aim of this paper is to compare the two models with the purpose to find an explanation for the differing results.

The paper is structured as follows: In Section 2, we summarize the results by Azar *et al* and Gielen *et al*. In Section 3 we briefly describe the two models and present main input data

[1] In this paper "biofuels" always means liquid biofuels in the transportation sector.

assumptions and in Section 4 we identify four key reasons for the differing results. The impact of using assumptions similar to the GET model is tested in the BEAP model. In Section 5 we analyze how the GET model changes when using assumptions similar to the BEAP model and in Section 6 we present an explanation for the differing results. Finally in Section 7 we discuss the results and offer some conclusions for modelers and policy makers.

2. A summary of the two different model results

In this section, we summarize results from the two models[2]. When presenting the results from the GET model, we have used an updated version of the GET 1.0 model, thus the graphs shown are very similar, but not identical to the results presented in Azar *et al* (2003). Details of GET 5.0 can be found in Azar *et al* (2005). The graphs for the BEAP model have been generated by running version BEAP2100 with GLOB-policy (the runs were carried out by Maria Grahn). In Figures 1a,b the global primary energy supplies are shown. Figures 2a,b show the transportation sectors and Figures 3a,b show the biomass use in the two models. Both models are run under stringent CO_2 constraints. In the BEAP model a global carbon tax of approximately 300 USD per ton C is applied from the year 2020 and onwards. The cumulative emissions during this century amount to approximately 450 Gt C. This emission level corresponds roughly to an atmospheric carbon dioxide concentration target of 400 ppm by the year 2100. In the runs with the GET 5.0 model performed for the purpose of this paper, CO_2 emissions were constrained by assuming a stabilization target by the year 2100 at 400 ppm. Such a target might be required if we are to be relatively certain that we meet the EU target that the global temperature increase should remain below 2^{o}C (see Azar & Rodhe, 1997).

[2] Results from the BEAP model and from the GET model have been published in Gielen et al (2002, 2003) and in Azar et al (2003).

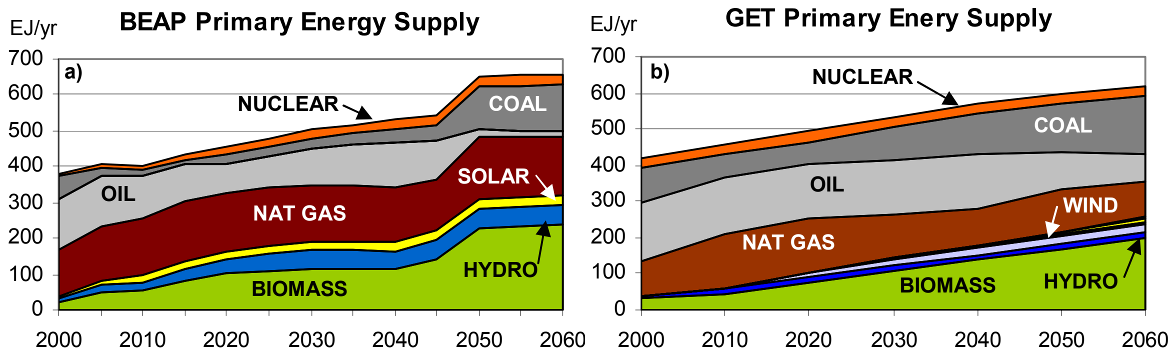


Fig. 1. Results on global primary energy supply as presented in a) the BEAP paper and in b) the GET paper. In both models there is an increasing use of biomass to meet the stringent CO_2 constraints. These are referred to as the reference scenarios of the models.

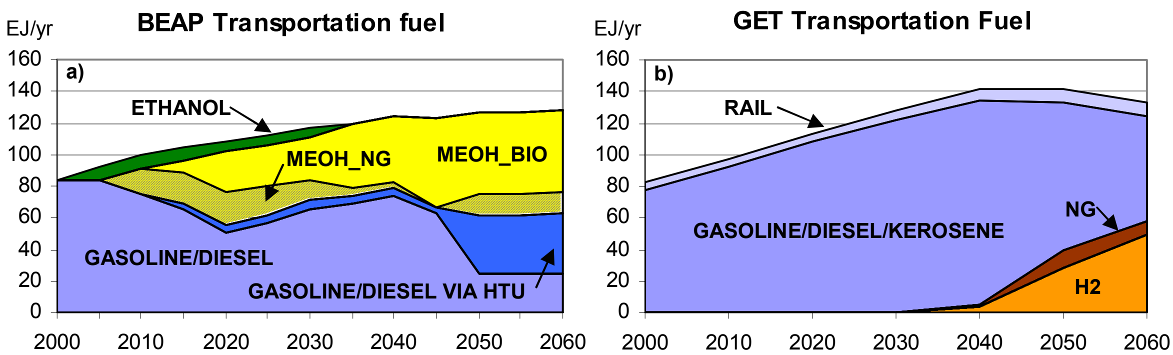


Fig. 2. Transportation fuels as presented in a) the BEAP paper and in b) the GET paper. In the BEAP model there is an increasing use of biofuels , i.e. ethanol, methanol from biomass and diesel/gasoline from biomass via HTU-oil (Hydro Thermal Upgrading). In the GET model there in not any biofuels in the base case run. These are referred to as the reference scenarios of the models.

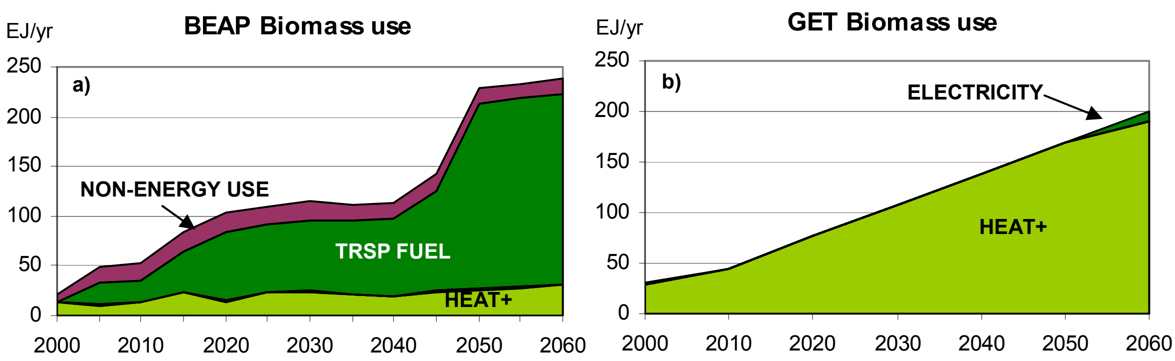


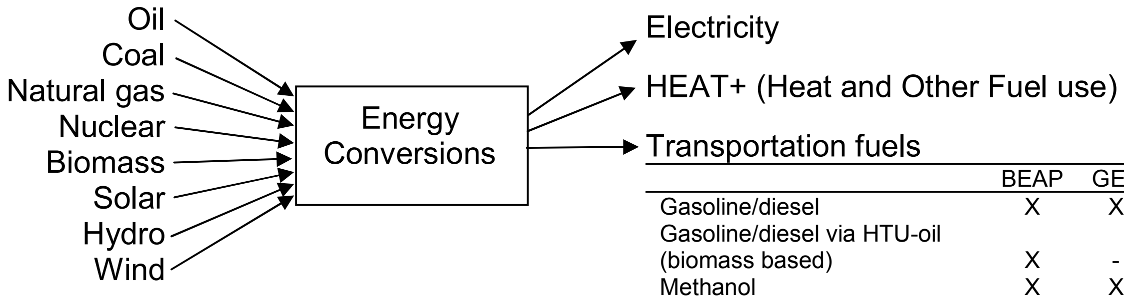
Fig. 3. Biomass use as presented in a) the BEAP paper and in b) the GET paper. In the BEAP model the largest share of biomass is used for the production of fuels for transport but in the GET model the largest share of the biomass is used for HEAT+ production (stationary energy use that neither aims at generating electricity nor transportation fuels but mainly heat production). These are referred to as the reference scenarios of the models.

In both models there is a steady increase in total biomass use, but fuel choices in the transportation sector and what the biomass is used for differ between the two models (see Figures 2-3). The result in the GET model, that hydrogen in the long run takes over as the fuel for the transportation sector, remains unchanged under a variety of parameter choices. However, during a transient phase other fuels, e.g. methanol or natural gas, play a significant role in some runs.

3. Model descriptions

Both models are global energy systems optimization models. The BEAP model is a mixed integer programming (MIP) model and simulates an ideal market based on an algorithm that maximizes the sum of the consumers' and producers' surplus. The GET model is a linear programming model that is set up to meet exogenously given energy demand levels at the lowest energy system cost. Both models exhibit so-called 'perfect foresight' which means that all features of the model (future costs of technologies, future emission constraints, availability of fuels etc) about the future isare known at all times.

The GET model includes constraints on the expansion rates for different primary energy sources and energy technologies. In the GET model, there is only one aggregate heat and process heat sector that includes all stationary use of energy that neither aims at generating electricity nor at producing transportation fuels. We refer to this as HEAT+. The BEAP model has a more careful treatment of the heat sector in that it distinguishes between industrial heat, urban heat and rural heat. In order to facilitate comparisons between the models, we aggregate energy demand into three main sectors: Electricity, Transportation fuels and HEAT+. The primary energy supply options, the three energy demand sectors and fuel choices in the transportation sector are roughly outlined in Figure 4.



	BEAP	GET
Gasoline/diesel	X	X
Gasoline/diesel via HTU-oil (biomass based)	X	-
Methanol	X	X
Ethanol	X	-
Fischer-Tropsch diesel	X	-
Hydrogen (fossil fuel based)	X	X
Hydrogen (CO2-neutral)	-	X
Natural gas	-	X

Fig. 4. The basic flow chart of supply and fuel choices in both energy system models.

The BEAP model database, including the model output files, is available on the Internet (EMP, 2001). Details of the BEAP and GET models are available in Gielen *et al*, (2002, 2003) and Azar *et al* (2000, 2003, 2005), respectively.

3.1. Assumptions on supply potentials

Resources on coal, oil, natural gas and biomass are considered limited and the supply potentials assumed in both models are presented in Table 1, as well as the assumed primary energy cost.

Table 1. Supply potentials of limited resources and assumed primary energy cost

	Supply potential [EJ]		Primary energy cost [USD/GJ]	
	BEAP	GET	BEAP[c)]	GET
Coal	22000	300000	1.8	2
Coal (additional)	230000	-	4.4	-
Oil conventional	12000	12000	1.6	3
Oil other	14000	-	3.6 – 5.2	-
Natural gas conventional	12000	10000	2.2	2.5
Natural gas other	11000	-	3.0 – 3.8	-
Fuel wood [EJ/yr]	70[a)]	-	-	-
Energy plantations & straw [EJ/yr]	Not well defined[b)]	-	-	-
Total biomass supply potential [EJ/yr]	Not well defined [b)]	200	2.4	3

a) This refers to potential wood extraction in existing forests.
b) The potential depends on land and biomass prices calculated by the model.
c) In the BEAP model the primary energy cost depends on distance of transport. Mean values are presented.

3.2. Assumptions on conversion efficiencies, investment costs and production costs

The conversion efficiencies and investment costs of energy conversion plants are key factors that determine the total production cost. Assumptions on O&M costs and plant life times can be found in Gielen *et al*, (2002, 2003) and Azar *et al* (2005). Total production costs include primary energy costs but exclude taxes, see Table 2.

Table 2. Investment costs, conversion efficiencies and production costs in the two models.

		Conversion efficiency		Capital cost		Total production cost[a)]	
		BEAP	GET	BEAP	GET	BEAP	GET
		η	η	[USD/kW][b)]	[USD/kW]	USD/GJ	USD/GJ
Coal	Industrial heat	0.71	0.90	67[c)]	300	4.2[c)]	3.2
Oil	Industrial heat	0.83	0.90	34[c)]	100	2.8[c)]	3.7
Natural gas	Industrial heat	0.91	0.90	17[c)]	100	2.7[c)]	3.1
Wood	Industrial heat	0.71	0.90	84[c)]	300	4.4[c)]	4.3
Coal	Urban heat	0.56	0.90	34	300	4.0	3.2
Oil	Urban heat	0.80	0.90	0	100	3.2	3.7
Natural gas	Urban heat	0.80	0.90	34	100	2.9	3.1
Wood	Urban heat	0.67	0.90	34	300	4.9	5.4
Coal	Electricity (conventional)	0.36	-	1009	-	8.4	-
Coal	Electricity (advanced)	0.45	0.45	1093	1100	7.7	7.6
Coal	Electricity (with CO_2 removal)	0.36	0.38	1682	1500	9.9	10.1
Oil	Electricity	0.43	0.50	841	600	7.2	7.9
Natural gas	Electricity	0.56	0.55	673	500	6.4	5.8
Natural gas	Electricity (with CO_2 removal)	0.48	0.47	1009	900	6.7	8.2
Wood	Electricity	0.45	0.40	1346	1200	10.1	9.9
Coal	Methanol	-	0.60	-	1000	-	5.7[E)]
Natural gas	Methanol	0.67	0.70	673	600	4.8	5.3[E)]
Sugar/starch	Ethanol	0.56	-	841	-	6.0	-
Wood	Ethanol	0.33	-	1177	-	9.3	-
Wood	Methanol	0.56	0.60	1009	1000	7.2	7.8[e)]
Wood	Fischer-Tropsch diesel	0.50	-	1346	-	9.3	-
Wood	Gasoline/diesel via HTU-oil	0.56	-	841[d)]	-	7.2	-
Oil	Gasoline/diesel	n.a.	0.90	n.a.	1000	n.a.	6.2
Coal	Hydrogen	-	0.65	-	700	-	5.7[e)]
Oil	Hydrogen	-	0.75	-	400	-	5.5[e)]
Natural gas	Hydrogen	0.78	0.80	336	300	4.2	4.3[e)]
Wood	Hydrogen	-	0.60	-	800	-	8.0[e)]
Solar	Hydrogen	-	1.00	-	2000	-	18.1[e)]

a) Total production costs depend on conversion efficiencies, investment costs, O&M costs, plant life times and primary energy costs, which vary between technologies. No taxes are included.
b) Investment costs are in the BEAP model given in Yen per GJ. To be comparable, values have been converted in the following way: The cost in USD/kW is equal to the cost in Y/GJ multiplied by 0.008USD/Y and 31.54 GJ/kW and 1/LF where LF (load factor) assumed to 0.75 for all plants.
c) Investment cost after the error has been corrected.
d) The capital costs only consider the two plants for the production of a biocrude (505 USD/kW) and for upgrading the biocrude into a naphta-like product (336 USD/kW). Thereafter it is assumed that diesel and gasoline can be produced using existing steam cracking technology (Naber *et al*, 1999).
e) To be able to compare the methanol and hydrogen costs per vehicle, one also has to consider costs for infrastructure, extra costs per vehicle, storage, fuel cells and efficiency change.

This table offers a first order explanation for the result in the GET model. In the near term, at a zero CO_2 tax, the cost of biomass based energy carriers is higher than all alternatives in all sectors, but the difference between alternatives is smaller in the heat than in the transportation sector. For that reason, biomass can replace fossil fuels in the heat sector at a lower cost compared to replace fossil fuels in other sectors.

As the carbon constraint becomes increasingly stringent, or at higher CO_2 tax, fuel changes become necessary also in the transportation sector. Then hydrogen based on solar energy enters the energy system. If biomass is used for transportation fuels, then hydrogen from solar energy becomes necessary to satisfy the demand for HEAT+. This is, using our technology cost parameters, more costly than using biomass for the HEAT+ sector and using the hydrogen in the transportation sector. For that reason, hydrogen from solar becomes the cost-effective choice in the long run in the GET model transportation sector.

3.3. Energy demand

In the GET model, electricity and HEAT+ demand levels are exogenous and taken from the ecologically driven scenario C1 in IIASA/WEC (see Nakicenovic *et al*, 1998). The transportation scenario is developed separately, assuming that increase in the amount of person-kilometers traveled is proportional to the GDP growth (in PPP terms). Details of the demand scenarios are available in Azar *et al* (2000).

The BEAP model covers the global energy, food and materials system. The demand for food and materials are based on statistics from the Food and Agricultural Organization (FAO 2001a, 2001b) and United Nations (UN, 1999). The energy demand is based on the BP review of world energy use (British Petroleum, 2001). Future demand in the base case is an extrapolation of historical trends and forecast as a function of regional GDP growth and income elasticities. Details on demand projections in the BEAP model are available in Gielen *et al*., (2003) and on the Internet (EMP, 2001).

In the BEAP study, price elasticities in the range of −0.1 to −1 have been used for all demand categories. In the GET model energy efficiencies are assumed in the C1 demand scenario and it is also assumed that there is an exogenous improvement in energy efficiency in the transportation sector by 0.7% per year.

3.4. Constraints

Constraints have been added to both models so as to avoid solutions that are obviously unrealistic. In the GET model, there are constraints on the maximum expansion rates of new technologies (in general set so that it takes 50 years to change the entire energy system). There is also a constraint, which limits the contribution of intermittent electricity sources to a maximum of 30% of the electricity use. To simulate the actual situation in developing countries at least 20% of the heat demand needs to be produced from biomass the first decades.

In the BEAP model the growth of exports is constrained for all products except cereals. Investments in some of the heat processes are constrained, e.g., no investments can take place in gas and biomass fuelled industrial heat boilers before the year 2020. Also urban heat produced from biomass is limited to very low levels (or even zero) for all industrialized regions.

3.5. Summary model constructions

Key assumptions made in the BEAP and GET model construction are summarized in Table 3.

Table 3. Summary constructions of the two models

	BEAP	GET
Coverage	Global	Global
Regions	12	1 a)
Time period	1965-2100, 5-year periods	1990-2100, 10-year periods
Sectors	Energy, food, steel, petrochemicals, paper, building materials	Energy
Energy sectors	Industrial heat, urban heat, electricity, transportation fuels	HEAT+, electricity, transportation fuels
Energy demand		
- heat and electricity	Price elastic, baseline demand based on extrapolation of past trends.	Energy demand exogenous, taken from low demand scenario, C1, from IIASA(WEC (1995).
- transportation sector	Price elastic, baseline demand based on extrapolation of past trends.	Transportation km roughly proportional to GDP but vehicle efficiencies improve by 0.7% per yr. Modal shifts exogenous.
Primary energy supply potential	Similar (see Table 1)	Similar (see Table 1)
Expansion rate	Not constrained, but processes have upper bounds	Constrained
Energy carriers in the transportation sector	**Oil based:** Gasoline/diesel **Biomass based:** methanol, ethanol, FT-diesel and gasoline/diesel via HTU **Natural gas based:** methanol and hydrogen.	**Oil based:** Gasoline/diesel and hydrogen **Biomass based:** methanol and hydrogen **Natural gas based**: methane, methanol and hydrogen. **Coal based:** methanol and hydrogen **Electrolyzed:** hydrogen
Parameter values		
- conversion efficiencies	Similar in all cases except heat production where current technologies are assumed.	Similar in all cases except heat production where advanced technologies are assumed.
- cost assumptions on primary energies	Similar (see Table 1)	Similar (see Table 1)
- total production cost on secondary energies	Similar (see Table 2)	Similar (see Table 2)
- investment cost on fuel cell vehicles	High	Optimistic
Method to constrain CO_2 emissions	Penalty on CO_2 emissions	Ceiling on CO_2 concentration by the year 2100 or penalty on CO_2 emissions
- options to reduce CO_2 emissions	Afforestation, fuel/feedstock switch, price elastic demand reduction, recycling, carbon capture and storage technologies. Upper bound on nuclear.	Fuel/feedstock switch, demand reduction by technology switches in the transportation sector, carbon capture and storage technologies. Nuclear fixed to current level.

a) One region in this version, but in another version GET-R 1.0 there is 11 regions (Grahn, 2002).

4. Results – key reasons for the differences in model results

In this section, we present four key reasons that explain the differences between the two models: (i) a correction of a data input error (ii) the method to constrain carbon dioxide emissions, (iii) assumptions on the amount of biomass that can be used for heat production and (iv) the long-run fuel options for the transportation sector.

4.1. Capital costs for industrial heat plants

When analyzing the BEAP model, some data errors were found. Too high capital costs for all industrial heat plants had been used, e.g. a factor of 100 too high for plant investments and a factor of 10 too high for operation and maintenance costs. This run, after correcting these data, is referred to as the BEAP corrected reference scenario and results are presented in Figure 8 and 9. The production of biofuels decreases by 26 and 39 percent by the year 2020 and 2050 respectively and the use of biomass for HEAT+ production increases by a factor of 2.4 in the year 2020 and by a factor of 2.2 in the year 2050.

4.2. Methods to constrain carbon dioxide emissions

The method to constrain carbon dioxide emissions differs between the models. In the BEAP model a global carbon tax of approximately 300 USD per ton C is applied from the year 2020 and onwards, see tax profile "BEAP" in Figure 5. The GET model is run under an atmospheric carbon constraint equal to 400 ppm. In Figure 5, we have also included a tax profile that is close to the tax profile (shadow price on carbon) that is implicit in the GET run towards 400 ppm. We refer to this tax profile as "GET".

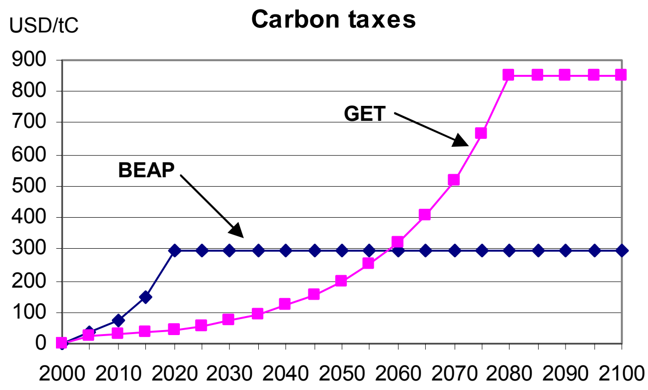


Fig. 5. Two carbon tax profiles where tax profile "BEAP" is used in the BEAP model and tax profile "GET" is close to the carbon price implicit in the GET model run towards 400 ppm CO_2 concentration in the atmosphere.

Interestingly, the BEAP tax profile is also consistent with a 400 ppm target, by the year 2100, thus the long term concentration is essentially the same in the two model runs. But these approaches obviously yield different emission pathways, see Figure 6. In the BEAP model, the emissions drop rapidly and then remain relatively stable at a rather low level. Some would argue that this is not a cost-effective emissions trajectory (basically because the marginal cost of emission reductions remain flat from 2020 and onwards, see Figure 5) whereas cost-efficiency would require that it increases at a rate close to the discount rate. The GET model shows more successive reductions over time, see Figure 6. One benefit with the BEAP tax profile is that it leads to lower emissions during the transient period, and thus lower atmospheric concentrations in the near term. The maximum difference between the two scenarios is 25 ppm atmospheric CO_2 concentration obtained by using the carbon cycle model by Maier-Reimer & Hasselmann, (1987).

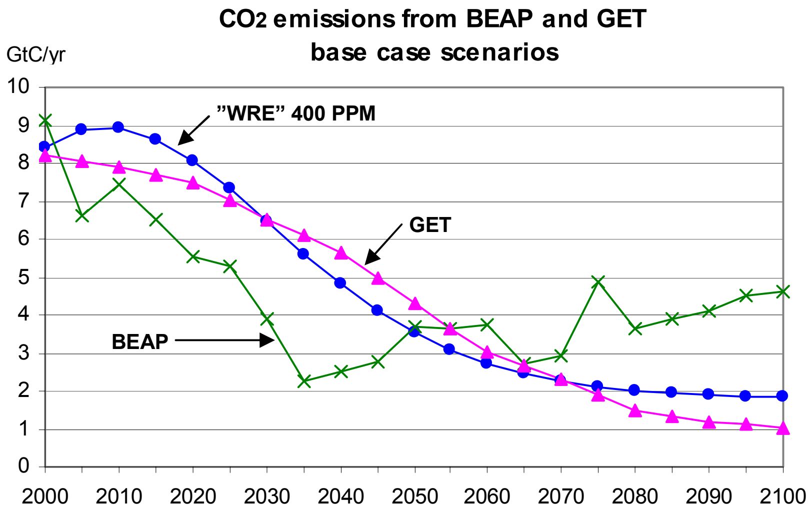


Fig. 6. Three different emission trajectories to reach 400 ppm CO_2 concentration in the atmosphere. Carbon dioxide emissions per year in the BEAP corrected reference scenario, presented in Figure 8 and 9 and from the GET model reference scenario, presented in Figures 1-3. For the sake of comparison, we have included an emission trajectory called "WRE" 400 ppm. It is calculated as the average of the 350 ppm and 450 ppm emission trajectories in Wigley *et al* (1996).

In Figures 8 and 9, we present results from a run where we have used the "GET" tax profile in the BEAP model. There are substantial changes when it comes to the cost-effective use of biomass and the choice of fuels in the transportation sector. The use of biomass for HEAT+ production increases by 30% by the year 2050, compared to the BEAP corrected reference scenario. Biomass used to produce biofuels disappears almost completely in year 2020 and is halved by the year 2050. Thus, the transportation sector changes significantly. No alternative fuel enters the transportation sector until year 2025.

The reason for this difference is that with the "GET" tax profile, the tax is too low during the initial decades of this century to induce any changes in the transportation sector. However, it should also be noted that once the tax becomes sufficiently large, an increasing share of the biomass is used for transportation fuels. In Section 6 we will explain why this happens in BEAP but not in GET.

4.3. Assumptions on the amount of biomass that can be used for heat production

The BEAP model constrains the use of biomass for urban heat in developed regions. Results when releasing this constraint are presented in Figures 8 and 9.

The use of biomass for HEAT+ production increases by 50-60% for the years 2020 and 2050, whereas the production of biofuels drops by around 40%, compared to the BEAP corrected reference scenario. The reason for the increase in bio-derived heat production is that the model finds it more cost-effective to use biomass for heat production than for the production of transportation fuels. The more bio-heat allowed, the more biomass will be used for heat production.

4.4. Long run fuel options for the transportation sector

Both models are run towards an ambitious CO_2 target, which means that also the transportation sector has to be almost CO_2 free towards the end of the century. The remaining key reason, for why the two models present different solutions for the transportation sector, is that GET allows for CO_2-neutral hydrogen in the transportation sector, whereas BEAP does not. The implication is that biofuels are the only available option in the BEAP model to reach zero emission levels, and for that reason biomass has to enter. In the GET model, the decision to go for hydrogen, rather than biomass, is based on cost-minimization, but clearly the outcome of this optimization depends on highly uncertain assumptions about future costs and technological performance.

Since it would take too much time and effort to redevelop the BEAP model to encompass CO_2-neutral hydrogen, we do not generate any specific graphs for this case. However, it may be noted that hydrogen derived from natural gas can be used in the transportation sector also in BEAP. If the costs of hydrogen vehicles drop, then hydrogen from natural gas enters the transportation sector, in BEAP, and biomass is used to a larger extent for HEAT+ production.

4.5. The impact of all changes combined

In Figure 7, we present results from a run where changes (i), (ii), (iii) but not (iv) are made (it would be too complicated to include CO_2-neutral hydrogen and natural gas, methane, as fuel options in the BEAP model).

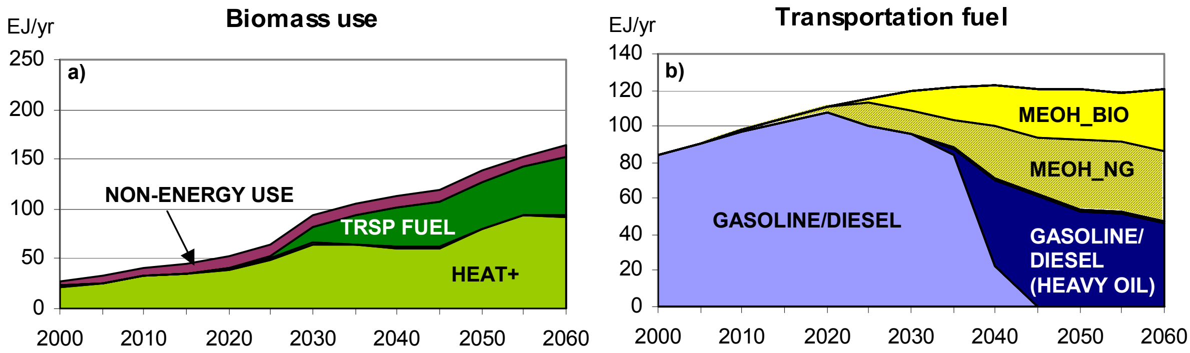


Fig. 7. The BEAP model with changes (i), (ii) and (iii) combined.

The use of biomass for HEAT+ production increases by 20% and 40% in year 2020 and year 2050, respectively, compared to the BEAP corrected reference scenario, presented in Figures 8 and 9. The use of biomass for transportation vanishes completely by the year 2020 and is more than halved by the year 2050, which is very close to the result we got in Section 4.2, where the only change was applying tax profile "GET". Since the use of biomass for transportation diminishes, the use of gasoline/diesel for transportation increases by 50-100% over the period 2020-2050.

The overall result, that most of the biomass is used for HEAT+ production and that alternative transportation fuels enter the market by year 2025, is similar to the result found in the GET model. The five runs discussed in this section are summarized in Figures 8 and 9.

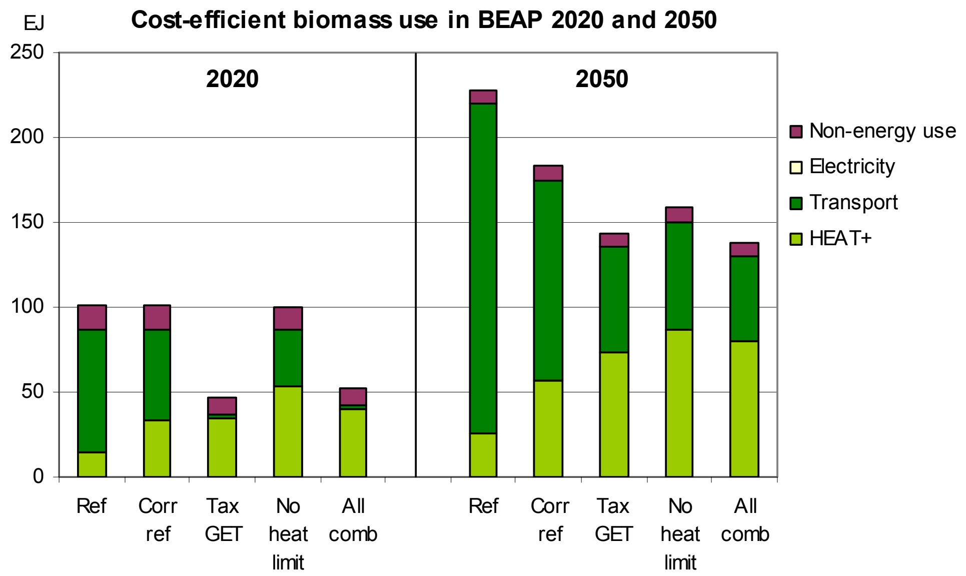


Fig. 8. A summary of the five BEAP model runs. Cost-efficient biomass use from the reference scenario presented in Figure 3, the corrected reference scenario described in Section 4.1, the run with tax profile "GET" described in Section 4.2, the run with no bio-heat constraint described in Section 4.3 and the changes combined presented in Figure 7.

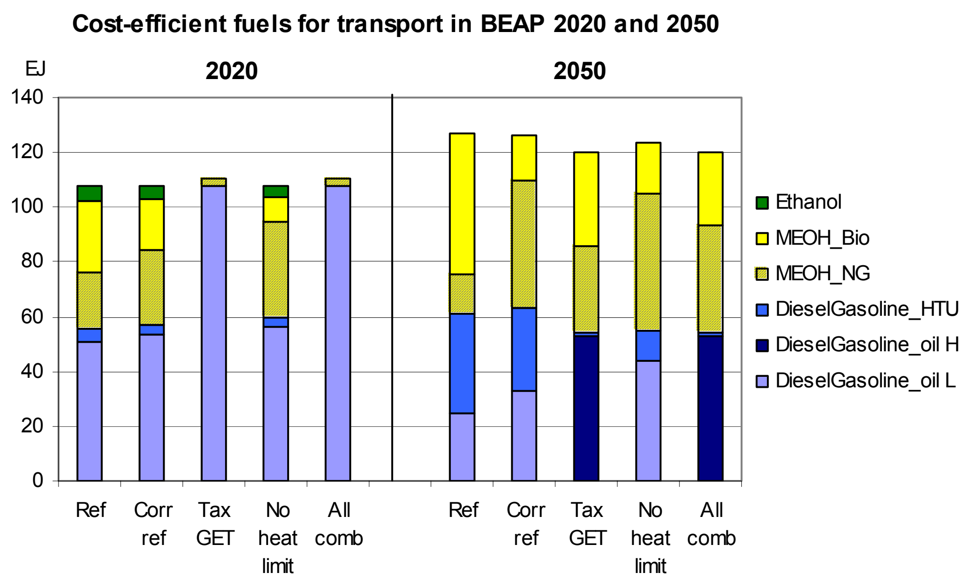


Fig. 9. A summary of the five BEAP model runs. The choice of transportation fuels from the reference scenario presented in Figure 2, the corrected reference scenario described in Section 4.1, the run with tax profile "GET" described in Section 4.2, the run with no bio-heat constraint described in Section 4.3 and the changes combined presented in Figure 7. Acronyms used are methanol derived from biomass (MEOH_Bio), methanol derived from natural gas (MEOH_NG), Diesel/Gasoline derived from biomass via a High Thermal Upgrade technique (DieselGasoline_HTU), Diesel/Gasoline derived from unconventional (heavy) oil (DieselGasoline_Oil_H) and Diesel/Gasoline derived from conventional (light) oil (DieselGasoline_Oil_L).

4.6. Model assumptions that meant less than expected

As presented in Table 2, assumptions on conversion efficiencies for heat production differ between the two models. In the BEAP model the chosen conversion efficiencies on boilers, for residential heating, reflects the current real-world standard, whereas the GET model assume advanced technology with higher conversion efficiencies to reflect a future global standard. It can easily be thought that these differences in conversion efficiencies are crucial for the result, but altering the conversion efficiencies, in the BEAP model, to 0.9 for urban heat derived from natural gas, LPG and oil and to 0.8 for urban heat derived from coal and biomass, only results in minor changes. The use of biomass for heat production in BEAP increases by 20% in year 2020 and 10% in year 2050, compared to the BEAP corrected reference scenario, presented in Figures 8 and 9. The choice of transportation fuels is not affected at all.

Changes in assumed costs on primary energy and supply potentials are other factors that do not have any significant impact on the results.

5. Analyzing the GET model

So far, we have only analyzed the impact of changes made to the BEAP model. A similar approach could of course also be taken when analyzing the GET model. In Figure 10 we present results from the GET model in which natural gas (methane) and CO_2-neutral hydrogen are not allowed as transportation fuels. Hydrogen derived from natural gas is an option in the BEAP model and therefore allowed in this run. We also add a constraint on the amount of biomass that can be used for heat production (maximum 100 EJ/year biomass for the production of HEAT+), to simulate the upper bound in BEAP on biomass derived heat, as well as applying tax profile "BEAP" to the GET model. The results of this run are presented in Figure 10.

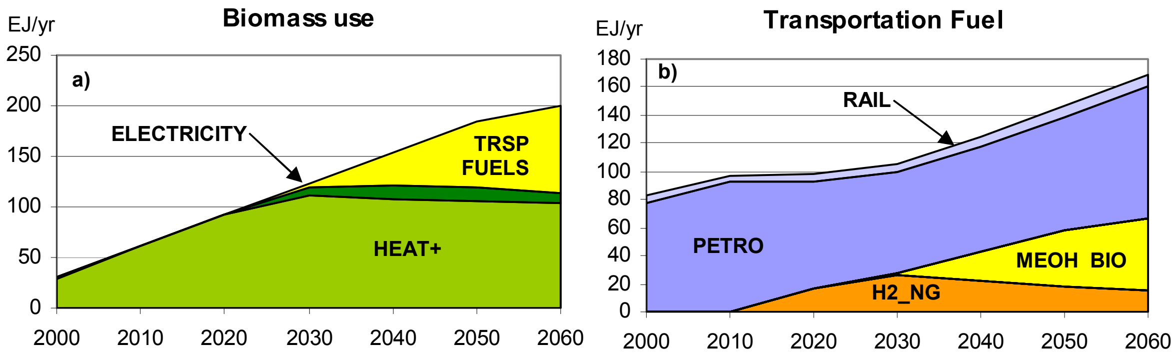


Fig. 10. The GET model when excluding the transportation fuels natural gas (methane) and CO_2-neutral hydrogen. Acronyms used in Fig 10b stand for methanol derived from biomass (MEOH_BIO), petroleum products i.e. gasoline, diesel and kerosene (PETRO) and hydrogen derived from natural gas (H2_NG).

Since the BEAP tax is rather high already by the year 2020, changes in the transportation sector will occur earlier in this run compared to the GET reference scenario presented in Figure 2. In this run, hydrogen derived from natural gas enters the transportation sector in a transient period before biofuels replace gasoline and diesel. It can also be noted that if the investment costs on fuel cell vehicles are increased in the GET model to the level used in the BEAP model, no hydrogen will enter the transportation sector but a larger share of biofuels. Since biofuels now are the only option if low or zero carbon emissions are to be achieved, this outcome is similar to the result in the BEAP reference scenario. The constraint that at most 100 EJ/year of biomass can be used for HEAT+ production is a strong driver for this result. If, however, a more long-term perspective had been taken with CO_2 emission targets approaching zero, then the fact that there is no CO_2-free alternative to biofuels in the transportation sector would be sufficient to drive the introduction of biofuels in the modified GET model.

6. Explaining the results

In Section 4 we showed that changes in one parameter value, one constraint and the tax profile may change the "BEAP" conclusion that biomass is optimally used in the transportation sector. But we do get biofuels in the BEAP model even when these changes have been applied (see Figure 9). How can this result be understood? There seems to be some inherent feature in the BEAP model that favors biofuels, and there seems to be some aspects in the GET model that works in the opposite direction. We will here show that this is only partially true.

We attempt to shed light on technology options in the BEAP model by running it (with the corrected cost parameter for industrial heat) with a fixed CO_2 tax over the period 2005-2100. We made 13 runs with the tax set in the range 0-300 USD per ton C in steps of 25 USD/tC. The results for the years 2020 and 2040 are presented in Figure 11.

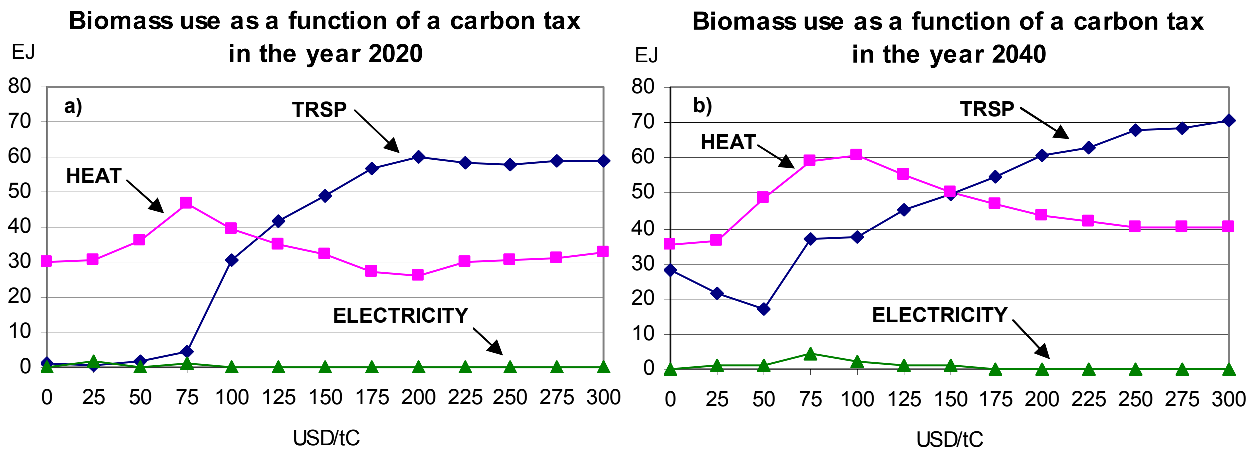


Fig. 11. The biomass use (primary energy) in the BEAP model for various CO_2 taxes. The taxes have been fixed during each run and each figure includes 13 runs. Results from a) year 2020 and b) year 2040 are shown.

In Figure 11a, it is shown that no biofuels are produced but 30 EJ of biomass is used for heat production by the year 2020 when no CO_2 tax is applied. When increasing the CO_2 tax, the use of biomass for heat production increases more rapidly than in the two other sectors, but only for taxes below 75 USD/tC. For higher taxes, biofuels increase rapidly at the expense of biomass for heat. Since the yearly biomass supply potential is limited[3], the biomass for heat production decreases when the use of biofuels increase.

In the BEAP reference scenario the CO_2 tax has reached 300 USD/tC by the year 2020 and at that tax, as shown in Figure 11a, most of the biomass is used for the production of biofuels. Thus, we can conclude that in the year 2020 biomass is most cost-effectively used for heat when the carbon tax is low (below 75 USD/tC) and most cost-effectively used for biofuels production when the tax is higher than that level.

In year 2040 a similar pattern is seen, with one important exception: in this year biomass is

[3] The total biomass supply in any given year depends on the tax. The higher the tax the larger total supply, but the supply never becomes so large that it can cover the total demand in all sectors. For that reason, the question about in which sector it is most cost-effective to use remains important to address.

used for biofuels even when there is no carbon tax (almost 30 EJ, see Figure 11b). The reason for that is that conventional oil becomes scarce and needs to be replaced. It turns out that in BEAP, biofuels are less costly than unconventional oils and therefore chosen in the transportation sector (coal based synthetic fuels are not available in the model). Biofuels are thus not just an option to reduce CO_2 emissions but a cost-effective choice of fuel in a business as usual scenario without CO_2 abatement policies.

It is important to observe that in the year 2040 the use of biomass for heat production increases whereas the use of biomass for transportation fuels decreases for increasing carbon taxes in the range 0-50 USD/tC. This trend is reversed for higher taxes. The reason for the decrease in use of biofuels, between 0 and 50 USD/tC year 2040, is that biomass lower the total energy system cost when used in the heat sector and the supply potential is limited (see footnote 3 upwards.

Thus, it is found that biomass is more cost-effectively used for heat production than for the production of biofuels at low carbon taxes. Gielen *et al* ran their model with very high taxes right from the beginning and this concealed the fact that biomass is more cost-effectively used for heat production *also* in the BEAP model for low taxes. For that reason, BEAP and GET are similar.

For higher taxes, biomass is most cost-effectively used for biofuels production. Here there is a difference between GET and BEAP. GET allows for hydrogen from carbon free sources in the transportation sector, whereas BEAP has no other carbon free option than biomass. GET and BEAP has carbon free options in essentially all other sectors. Thus, when the tax becomes sufficiently high biofuels become the cost effective option in the BEAP model.

7. Discussion and conclusions

In this paper, we have analyzed two different global energy system models (the BEAP model developed by Gielen *et al* and the GET model developed by Azar *et al*). These models have reached different results regarding in which sector it is cost-effective to use biomass, under a carbon constraint. Our purpose has been to find an explanation for the differences between the two modeling based studies and we came to the following conclusions:

1) Biomass is most cost-effectively used for heat productions at low CO_2 taxes, up to about 75 USD/tC in *both* models. This was not evident in previous runs of the BEAP model since these runs focused on higher carbon taxes.

2) The sector in which biomass is most cost-effectively used at *higher* CO_2 taxes depends on assumed possible energy carriers and technologies. In GET, hydrogen derived from carbon free energy sources are available in the transportation sector at a cost that makes this option more cost-effective than biofuels when very low carbon emissions are to be obtained. In BEAP, this option is not available and for that reason biofuels become the only option if low or zero carbon emissions are to be achieved.

3) In addition, there are other assumptions that are of importance: In BEAP there is an exogenously set limit on the use of biomass in the heat sector in developed countries, whereas that biomass can be used in this sector without any hazzles or extra costs in GET. Further, in GET all oil can be used for transportation without extra costs, whereas this is not the case in BEAP. Clearly, these assumptions are important but conclusion 1) and 2) are identified as the key explanations for the differing results on biomass use.

7.1. Discussion and conclusions for modelers

Attempts to model optimal fuel choices in the transportation sector or optimal biomass use are fraught with difficulties. Since these choices are determined at a global market (both oil and biofuels can be traded very long distances) the model needs to be global. But regionally specific factors and local factors are also of critical importance, which means that regional characteristics and technology richness is required. Here important trade-offs need to be considered. A very detailed model is difficult to run: extensive sensitivity analysis becomes almost impossible (solving time for the BEAP model is in the order of hours) and an understanding of the results becomes more difficult. That speaks in favor of models that are simple to solve. Solving time for the GET model is in the order of minutes, and Azar *et al* (2003) present dozens of alternative scenarios (extracted from several hundred runs prepared when doing the research for the paper), several of which with a substantial share of biofuels.

The problem with simple models, however, is that these models suffer from a lack of technology richness that implies that important features that could determine the result are left out.

Another important aspect is that there are several factors that are important for the result that can be expected to depend primarily on non-economic factors, such as comfortability. Clearly, oil or natural gas is more comfortable for residential heating than solid biomass, industries might prefer natural gas to biomass for reasons related to requirements on temperature variability/stability, or if the fuel is used as a feed stock (steel, ammonia etc). Further it is difficult to model willingness of buying electric cars, which is an energy-efficient technology but not really comparable to current standard cars. (Neither BEAP or GET consider electric cars as an option.) These factors are difficult to include in an optimization model: adding a price premium for different fuels and technologies could help but it will also add uncertainties.

Further, technological change is exogenous in both models, i.e., the cost and performance etc are independent of how much they are used. This is of course a drawback. Models with endogenous learning would improve the situation but they too have their drawbacks.

Finally, the result in this case does not primarily depend on choices for parameter values but on the carbon tax scenario and whether CO_2-neutral hydrogen/electricity is available or not in the transportation sector. Communicating this result is perhaps key for clarifying what are the critical factors that determine the outcomes from the two investigated models.

Thus the assumptions about the availability of CO_2-neutral hydrogen and/or electricity as a fuel option in the transportation sector will determine whether biomass will be used for transportation or not in the long run. If hydrogen is assumed to make it as an energy carrier in the transportation sector, then cost assumptions on fuel cells, storage options, infrastructure and supply will determine in which sector the biomass will be used. Clearly, these cost numbers are very uncertain, so the long run future is still in the open.

7.2. Discussion and conclusions for policy makers

A separate question is related to which policy conclusions that should be drawn from models like this. Before drawing such conclusions, all the problems and difficulties with the models should be made clear to the policy makers. It should also be made clear that these models not are prescriptive. For instance, the fact that low carbon taxes do not generate sufficiently strong incentives to introduce biofuels does not mean that biomass should not be used in the transportation sector, since cost-effectiveness in dealing with climate change can not be the only criterion for policy makers. Rather, the implication is that if governments would want to see biofuels take off, then they would also need to introduce complementary policies (e.g., mandatory blending). Similarly, the models are not predictive in the sense that they purport to say what will happen. If it turns out that a lot of biomass are used in the transportation sector, that does not necessarily mean that the GET results were wrong, but it could equally well have been a result of a government decision to force the introduction of biofuels.

Further, even if both models would find that biomass is cost-effectively used in the transportation sector, this does not necessarily mean that governments should introduce policies that make biofuels mandatory. The reason for this is that if biofuels enter in the model with a carbon constraint as the only policy, and the model is a reasonably correct representation of reality, then biofuels should also enter the transportation sector in the absence of a biofuels obligation. If, on the other hand, biofuels are not used in the real world, despite being cost efficient in the model, there would be reasons to analyze possible barriers in the market that prevent the use of a cost-effective option (e.g., information barriers, monopolistic situation, hen and the egg problem with the expansion of infrastructure etc). If such barriers are shown to exist and play a decisive role in preventing the introduction of biofuels, then this would be a reason for governments to introduce policies to make sure that the markets function more properly, e.g., a law mandating biofuels. The models should be used to generate insights about the cost-effectiveness of different technology options under different policy scenarios.

The first insight generated in this paper is that both models suggest that biomass is most cost-effectively used for heat generation for low carbon taxes. This is also in line with the Swedish experience where biomass is expanding rapidly in the heat sector, but not in the transportation sector, despite extensive additional subsidies (worth several hundred dollars per ton carbon).

The second insight generated in this paper is that assumptions about the possibility to use CO_2-neutral hydrogen/electricity at reasonable costs and performance are the determining factor of the long run fuel choice, in the transportation sector. If these options do not become available, then biomass will have to enter in order to bring down overall energy and transport related emissions to low levels. Since this is still an open question, policies at present should primarily aim at trying to bring down costs for both the biofuels option and the hydrogen option, rather than trying to force a large-scale introduction of biofuels since that may lock us into a suboptimal technology choice for a long time to come (see Sandén & Azar, 2005).

Acknowledgement

We would like to acknowledge Per Kågeson for stimulating discussions and for spending time on valuable reviewing of manuscript. Financial support from Swedish Agency for Innovation Systems, Vinnova, and Swedish Energy Agency is gratefully acknowledged.

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Paper II

Paper II. Grahn *et al.,* "Regionalized global energy scenarios meeting stringent climate targets – cost effective fuel choices in the transportation sector", Conference proceedings, Risö International Energy Conference, 19-21 May, 2003

Regionalized global energy scenarios meeting stringent climate targets – cost effective fuel choices in the transportation sector

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Abstract

The aim of this study is to analyze the world's future energy supply, in general, and cost-effective fuel choices in the transportation sector, in particular, under stringent CO_2 abatement targets. The analysis is carried out with the help of a global energy systems model GET-R 1.0, developed specifically for this project. It is a linear programming model and it has three end-use sectors: electricity, heat and transportation fuel. It is set up to generate the energy supply mix that would meet exogenously given energy demands at the lowest global energy system cost. We have chosen an upper limit on CO_2 emissions corresponding to an atmospheric CO_2 concentration target of 400 ppm, by the year 2100. We find that it is cost-effective to carry out the transition from gasoline/diesel in the middle of the century and that hydrogen becomes the most cost-efficient fuel in the long run. Within the electricity production sector all renewable energy sources show a pattern of increasing contributions during the century and solar produced hydrogen will dominate by year 2100. Biomass is the dominant fuel in the heat sector. Scenarios are also presented which show the effects of different way of regionalizing the model. Here significant changes may occur, in particular when it comes to the where solar hydrogen is being produced. Further, we compare our results with those generated using a globally aggregated version of the model. We find that the regionalization only marginally affects the general pattern.

1 Introduction

As the global population reaches 9-10 billion, and living standards increase, energy requirements will increase dramatically. Currently, 80% of energy used is based on fossil fuels and unless alternatives are introduced, huge increases in atmospheric CO_2 are to be expected. Substantial reductions of the global CO_2 emissions are required in order to minimize risks of severe climatic changes, but this would involve considerable changes in the present energy system.

To stabilize the atmospheric CO_2 at 400 ppm, which might be an acceptable level (see Azar and Rodhe, 1997), global CO_2 emissions need to drop to around 2 Gton C/yr, by the year 2100 (IPCC, 1994). This corresponds to 0.2 ton C per capita per year, assuming a population of 10 billion people, which can be compared to the current 5.5 tonC/cap/year in the US and 0.3 ton C/cap/year in India. This study explores the possibility of combining increasing energy demand with strong reductions in CO_2 emissions over the 21st century.

The transportation sector has a negative impact on local air quality and is a major emitter of CO_2. In 1990, the transportation sector was responsible for some 25% of the world's energy use, and 22% of the global CO_2 emissions (IPCC, 1994). Fuel cell vehicles are seen by many as a promising option or even solution to these problems. Emissions of local pollutants are reduced to near-zero levels, and CO_2 emissions are lower or zero if renewable primary energy sources are used. However, it is still being discussed which fuel should be used in the long run, when there are stronger restrictions on CO_2 emissions. The two main candidates are liquid biofuels and hydrogen (from renewables or fossil fuels with carbon sequestration).

The purpose with this study is to analyze cost-effective fuel choices in the transportation sector under stringent CO_2 constraints and to investigate whether regional differences in energy supply potentials may result in differences in fuel choices. We do this by regionalizing a global energy systems model, designed to develop global energy scenarios. More specifically, we ask the following questions:

1) when is it cost-effective to carry out the transition away from gasoline/diesel?
2) to which fuel is it cost-effective to shift?
3) will the cost-effective choice of fuel in the transportation sector be different if a globally aggregated model is used rather than a regionalized version?
4) how will the method of regionalization affect transportation fuel choices and trade in energy carriers?

Model and scenario assumptions are presented in section 2 followed by global and some regional results presented in section 3. The results are discussed and conclusion are drawn in section 4 followed by some ideas for future work in section 5.

2 Model and scenario assumptions

2.1 Model description

A global energy systems model (GET 1.0) has been developed by Azar et al, 2000. The model was used to study fuel choices in the transportation sector (see Azar et al 2003). In this study, we have regionalized this earlier model into eleven different regions: North America, Latin America, Western Europe, Eastern Europe, Former Soviet Union, OECD countries in the Pacific Ocean, Middle East and North Africa, Africa, Centrally Planned Asia, South Asia and Other Pacific Asia. These new scenarios will show how each region can meet its energy demand, and thereby give a better understanding of the prospects for changes in the global energy system than a global aggregate model.

The regionalized energy system model (GET-R 1.0) is a linear optimization model designed to choose primary energy sources, conversion technologies, energy carriers and transportation technologies that meet the energy demands of each region, at the lowest aggregate costs subject to a carbon constraint (a tax or an emission cap). In this study, the only environmental concern is CO_2 emissions. Energy supply potentials and the demand for electricity, heat and transportation fuel, are exogenously given. The transportation sector is disaggregated into cars, trains, buses, trucks, ships and air planes whereas the electricity and heat sectors is analyzed in aggregate. Primary energy supply options, the three energy demand sectors and fuel choices in the transportation sector, are presented in Figure 1.

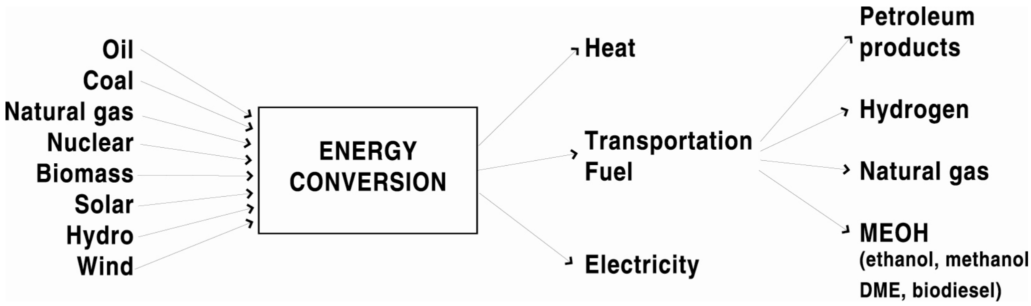

Figure 1: The basic flow chart of supply and fuel choices in the energy system model.

2.2 Scenario assumptions

2.2.1 Energy demand

Regional population, heat and electricity demand are assumed to follow an "ecologically driven" scenario developed by International Institute for Applied Systems Analysis (IIASA) in Austria. In this scenario, titled "C1", it is assumed that technological development leads to energy efficiency improvements, so that per capita heat and electricity demands in industrialized countries are reduced. In some regions, strong economic development will increase the per capita demand even if efficiency improvements are taken into account (Nakicenovic et al, 1998).

In all regions, per capita income increases. The developments of GDP_{PPP} per capita (GDP measured in purchasing power parities) are also taken from IIASA/WEC scenario C1. GDP_{PPP} per capita in industrial regions will increase from about 20,000 USD/yr today to about 50,000 USD/yr by the end of the 21st century. Developing regions will reach the level at which Western Europe is today. Increased income is followed by an increased demand for heat, electricity and transportation fuel.

Transportation scenarios are developed separately for passenger transportation and freight transportation. The energy requirement is derived from scenarios of transportation activities measured as person kilometer, pkm, and ton kilometer, tkm, combined with scenarios for the energy intensities measured as MJ/pkm and MJ/tkm (Azar et al, 2000).

Public use of aviation will increase rapidly and by the end of the century an American will travel 40,000 km/year by air compared to 4,300 km/year currently. Domestic motor vehicle use is also assumed to strongly increase, especially in the developing countries. The average citizen of India drives about 150 km per year, which will increase to 10,000 km per year by the end of this century. Assuming a population of 10 billion, a total of 5 billion cars will exist by the year 2100. The global density of cars will be 0.5 cars/capita, which is the current car density in Germany.

From 1990 to 2100 total passenger transportation is assumed to increase ten fold. Passenger rail increases by a factor three, bus by a factor of five, car by a factor of eight and passenger aviation by a factor of 40 in the scenarios. Freight transport will increase by about a factor of four. Intercontinental ocean transport dominates, although road transport will have the highest relative growth rate. Road transport will grow by a factor of six, air and ocean transport by a factor of four and continental water and rail approximately doubles. More details are given in Azar et al, 2000.

2.2.2 Energy availability

Regional oil and gas supply potentials and the annual hydro and biomass supply are assumed to follow Johansson et al, (1993). The regional coal maximum supply potentials are assumed to follow Rogner, (1997). The potential for solar energy is huge and therefore has not been assigned an upper limit. This model allows carbon capture and storage technologies when applied to fossil fuels for heat, electricity and hydrogen production. Biomass is limited upwards to around 200 EJ/yr (Johansson et al, 1993). This constraint has important implications since the total energy demand is much larger. Thus, the model chooses to use biomass in the sector where it is most competitive.

Efficiency of energy conversions, cost of industrial plants, vehicle engines and fuel infrastructure are discussed in detail in the paper presenting the global model GET 1.0 (Azar et al, 2000). The same values have been used in all regions. Regionalized load factors for solar energy technologies give some advantages to the regions Africa, Middle East and North Africa, Latin America and North America.

2.3 Maximum expansion constraint

It takes time to make profound changes in the energy system of the world. This inertia is difficult to capture in energy system models. In the GET model, inertia is introduced in several ways. First, it takes time before the capital stock is replaced and second, we have introduced both percentage and exogenous constraints on how fast new technologies might enter and this latter constraint is the most sensitive in GET-R 1.0, since this maximum expansion rate can be set as a global or as a regional constraint, see Sections 2.3.1 and 2.3.2.

If a global maximum expansion rate is chosen, the model will choose to expand technologies in regions where it is most cost-efficient, and this means that solar will expand at a faster rate in sunnier regions than what happens if regional expansion rate constraints are chosen. In this study we use the global maximum expansion rate as our base case, but we will also present some interesting differences to the base case using the other method of a regionalized maximum expansion constraint.

2.3.1 Global maximum expansion rate constraint

The expansion of supply potential and the expansion of energy conversion plants are controlled by an expansion constraint expressed as

$$\sum_r C_{rt}(r,t+1) \leq \sum_r \left(C_{rt}(r,t) + \frac{M(r,t)}{L} \right) \tag{1}$$

where $C_{rt}(r,t)$ [TW] is the capital stock in a specific decade t, and a specific region r, L is a load factor and $M(r,t)$ is the exogenous maximum expansion rate, calculated out of the global energy demand for each decade as

$$M(r,t) = \frac{D^{el}(r,t) + D^{h}(r,t) + D^{tr}(r,t)}{\alpha T} \quad \text{TW/decade} \tag{2}$$

where $D^{el}(r,t)$ [EJ/yr] is the global demand for electricity, $D^{h}(r,t)$ [EJ/yr] is the global demand for heat, $D^{tr}(r,t)$ [EJ/yr] is the global demand for transport fuel and T is the number of decades assumed to be required for the development of a completely new energy system. Here we put T=5. The constant α=31 Ms/yr is included to account for the conversion between GJ and TW.

2.3.2 Regional maximum expansion rate constraint

A different way of regionalizing the global maximum expansion rate is by limiting the expansion for each technology in each region. Instead of summing over all regions the expansion constraint is here expressed as

$$C_{rt}(r,t+1) \leq C_{rt}(r,t) + \frac{M(r,t)}{L} \tag{3}$$

where $C_{rt}(r,t)$ [TW] is the accumulated capacity of capital in a specific decade t, and a specific region r, L is a load factor and $M(r,t)$ is the maximum expansion rate, calculated in equation (2).

3 Results

3.1 Global results

Due to space limitations, it is only possible to present a short summary of our results here. A more complete description can be found in (Grahn, 2002).

3.1.1 Primary energy supply

In order to stabilize atmospheric CO_2 concentrations at 400 ppm, approximately 500 Gton C may be emitted over the period 1990-2100, (IPCC, 1994). This means that emissions may on average be around half of current levels (if we include the contribution from deforestation). In turn, this means that the emissions may increase perhaps a decade, but that they would then have to decline over the next couple of decades. Figure 2 displays a scenario in which this happens in a cost-effective manner.

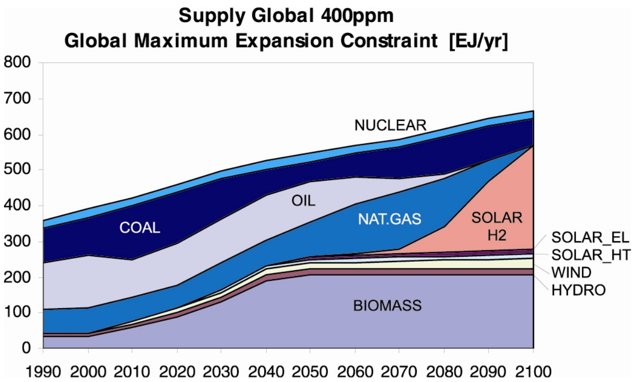

Figure 2: Primary energy sources required to supply the world's energy system, if atmospheric CO_2 concentrations are stabilized at 400 ppm. The eleven regional results have been added to produce this global figure.

Over the next fifty years, the model suggests that a rapidly increasing supply for biomass is a cost-effective way of meeting ambitious climate targets. The use of oil and gas remains roughly constant until they become exhausted. The use of coal remains possible since carbon capture and storage technologies are used on a larger scale, from the middle of the century and onwards. Of the three solar energy technologies in this model, solar energy for electricity production and solar energy for heat production remain at about the same level as wind and hydro, but solar energy for hydrogen production increases rapidly during the second half of the century.

3.1.2 Transportation

The scenario describing the cost-effective fuel choices in the transportation sector is presented in Figure 3.

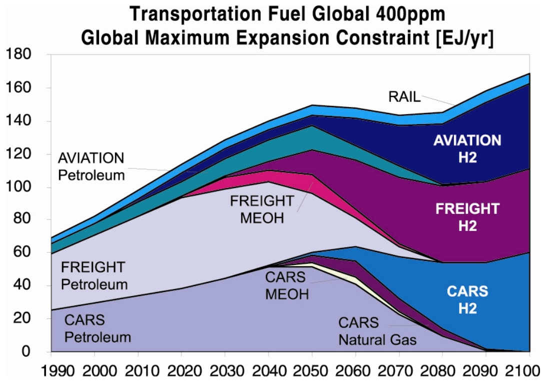

Figure 3: Projected transportation fuels requirements, if atmospheric CO_2 concentrations are stabilized at 400 ppm. Note that regional results are added to give a global figure.

In cars and freight sectors there is a transition from petroleum-based fuels in internal combustion engines to hydrogen used in fuel cell engines. Some methanol in internal combustion engines will be used in the transition period in both sectors. The model also present natural gas as a cost-effective transition fuel in the sector cars. In airplanes, there is a transition from fuels based on oil towards liquefied hydrogen.

3.1.3 Heat and electricity production

The end-use sector heat is defined as the heat required domestically as well as process heat in industries. The regional results, showing the scenarios for heat and electricity production, are added to give the global figures presented in Figure 4.

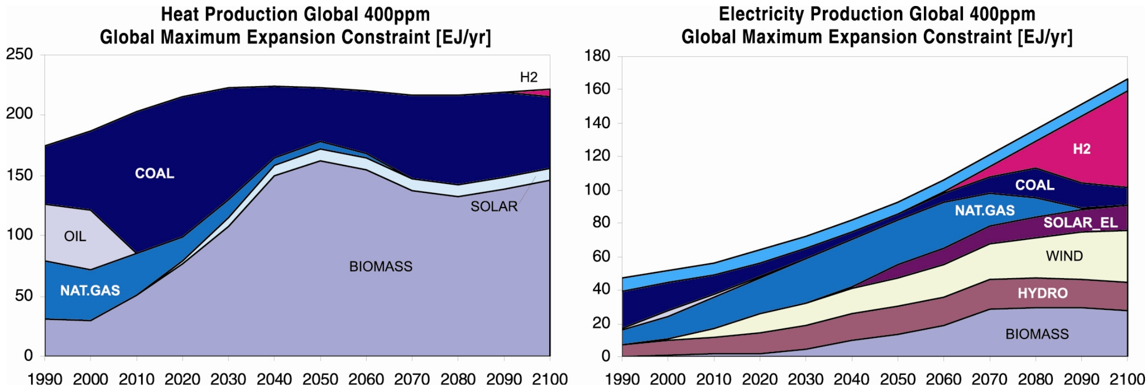

Figure 4: Primary energy sources used to supply households and industries global demand for heat as well as primary energy sources to supply the world's demand of electricity, given that atmospheric CO_2 concentrations are stabilized at 400 ppm. These graphs are produced using the global maximum expansion constraint and regional results are added together.

Biomass and coal dominate as primary energy source for heat production. For electricity production oil is phased out early and by the end of the century coal increases due to the fact that decarbonization techniques become cost-effective and used on a larger scale. When solar based hydrogen is introduced by the middle of the century it will rapidly increase its share and dominate as a primary energy source in year 2100. Biomass, as well as the other renewable energy sources, displays an increasing pattern throughout the century. Wind and hydro power are used to their exogenously set maximum level. The decline in gas use, by the end of the century, is caused by lack of availability.

3.2 The impact of different ways of setting the maximum expansion rates

When it comes to fuel choices in the transportation sector, the difference between the two ways of setting maximum expansion rates are minor. We will compare our two results with the figure generated using a globally aggregated version of the model, in section 3.3

The major impact of different ways of setting the maximum expansion rates is where solar hydrogen is being produced. Using a global maximum expansion rate, the region Middle East and North Africa (MEA) will extract almost 200 EJ/yr of solar produced hydrogen, in year 2100, out of which 160 EJ/yr will be exported to other regions. Using a regionally set maximum expansion rate MEA will only produce solar hydrogen for its own need. The differences in primary extraction for MEA due to choice of expansion constraint, are illustrated in Figure 5. The Asian regions Centrally Planned Asia dominated by China (CPA), South Asia dominated by India (SAS) and Other Pacific Asia (PAS) are examples of regions which import hydrogen in the case of a global maximum expansion constraint and produce their own solar hydrogen in the other case, as illustrated in Figure 6.

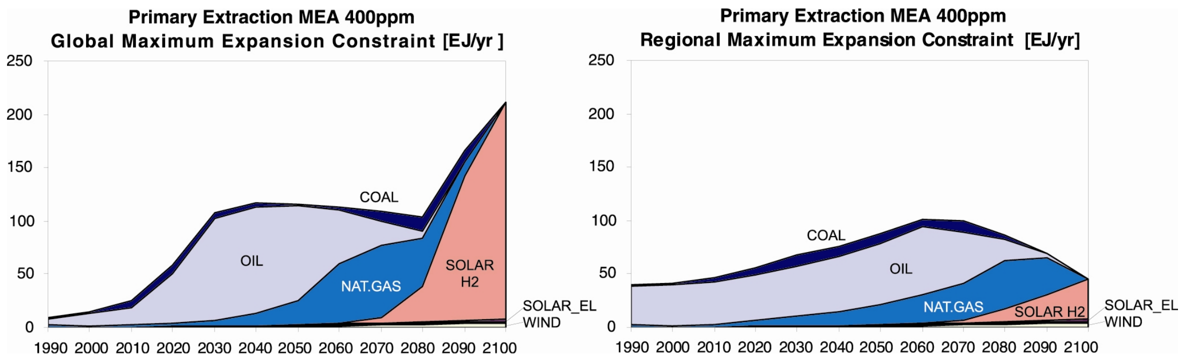

Figure 5: Primary energy extracted in region Middle East and North Africa, MEA. Solar produced hydrogen will be exported in the case of a global maximum expansion rate.

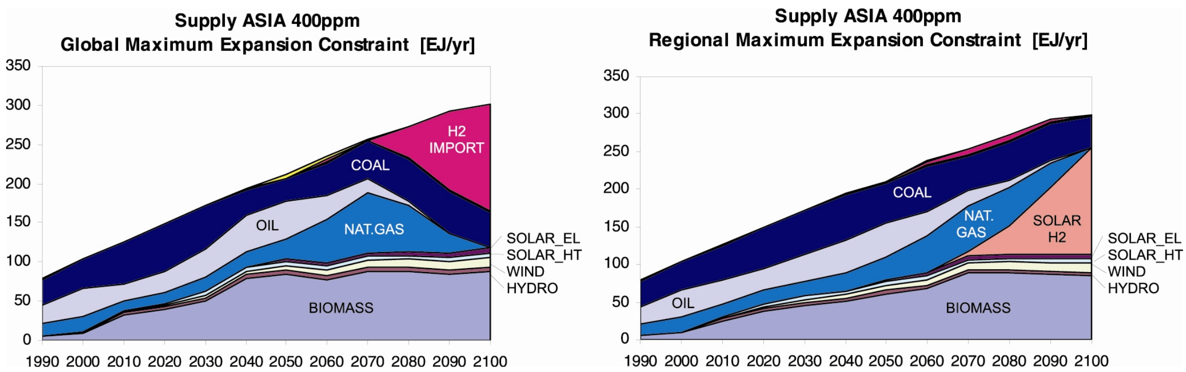

Figure 6: Primary energy sources to supply the energy demand in the Asian regions. No solar produced hydrogen will be developed in the case of a global maximum expansion rate. Instead hydrogen will be imported mainly from MEA. In the case of a regional maximum expansion rate the Asian regions will produce their own solar hydrogen.

3.3 The difference between a globally aggregated model and a global regionalized model

To explore if the cost-effective choice of fuel in the transportation sector will be different if a globally aggregated model is used rather than a regionalized version, we will produce two more figures as a comparison to Figure 3. A globally aggregated model, of this version of the energy system model, as well as the run with regional maximum expansion constraint, are presented in Figure 7. These two figures are very similar to Figure 3, shown in section 3.1

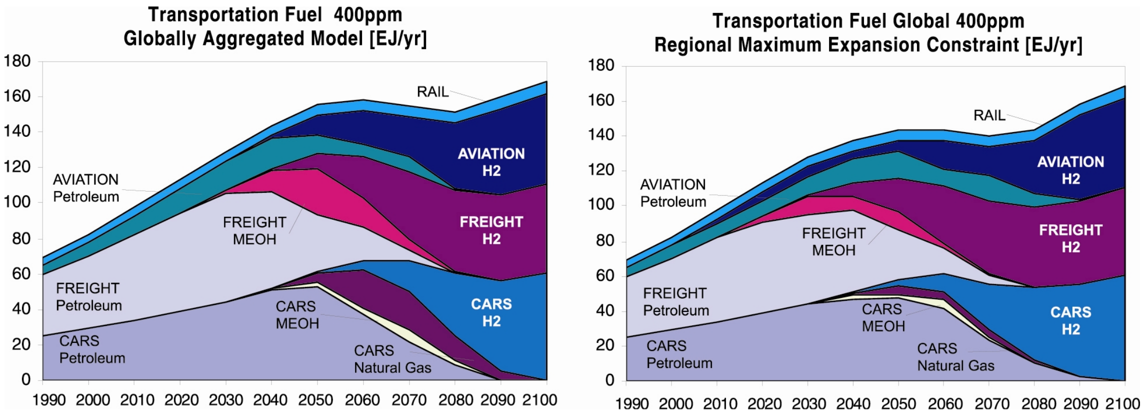

Figure 7: Fuel choices in the transportation sector will show the same over all pattern no matter global or regionalized model.

4 Discussion and conclusions

In this paper, we asked the following questions: When is it cost-effective to carry out the transition away from gasoline/diesel? To which fuel is it cost-effective to shift? Will the cost-effective choice of fuel in the transportation sector be different if a globally aggregated model is used rather than a regionalized version? How will the method of regionalization affect transportation fuel choices and trade in energy carriers? Below, we summarize our results and offer some explanations for them.

4.1 Oil remains dominant in the transportation sector for several decades despite stringent climate targets

A perhaps somewhat surprising result from our modeling exercise is that oil remains dominant in the transportation sector several decades ahead. A physical explanation for that is that known oil and natural gas reserves, contain about 200 Gton C (and we have assumed that the ultimately recoverable oil and natural gas resources are twice the current reserves). It is thus possible to release more CO_2 emissions than what exist in the total reserves of oil and natural gas, and still stabilize the atmospheric CO_2 concentration at 400 ppm. The most cost-effective use for oil is in the transportation sector (the advantages of using oil in the transportation sector is larger than using oil for heat or electricity production).

One tempting interpretation may be that no new technologies would need to be developed until the middle of the 21st century, but other elements ensure that this is not the case. The transition to hydrogen in the transportation sector will start around 2030 – 2050, and to make this possible, hydrogen should be used in vehicles before 2030. It is only by 2030 – 2050 that the carbon constraint becomes stringent enough to make hydrogen and fuel cell engines in cars and trucks competitive with gasoline and diesel.

4.2. Hydrogen and not biofuels become the dominant transportation fuel in our model

Hydrogen becomes the dominant fuel in the transportation sector, as it is more cost-efficient to use biomass for heat production. Using biomass to produce methanol would imply that the heat demand would have to be satisfied from other CO_2-neutral sources (hydrogen from solar or fossil fuels with decarbonization), which would increase the overall cost of the model. The reason why biomass can not be used for both heat and transportation is that the overall supply is limited upwards due to availability constraints.

4.3 A global but regionalized model versus a globally aggregated model

As shown in Figure 3 and in Figure 7, cost-effective choice of fuel in the transportation sector will, more or less, not be different if a globally aggregated model is used rather than a regionalized version. In fact many fuel choices are very close to each other in costs, and the transition fuels is not an effect by regionalization, but an effect due to development of the model.

4.4 Affects of the two methods of regionalization

The two methods of regionalization will not affect the overall pattern of transportation fuel choices, but will affect the trade in energy carriers. The major impact of different ways of setting the maximum expansion rates is where solar hydrogen is being produced, as illustrated in Figure 5 and 6, in section 3.2.

4.5 Model results are not a prediction of the future

The purpose of this study is not to predict the future. This model illustrates which fuels are most cost-efficient, based on presented assumptions. It is of course possible to use this study as an indication of which fuels and technologies are most cost effective, but even if assumptions in this model are reasonable by current standards, a great deal can occur within the next few decades, which may change the input data and produce different results. Also, since the model is an LP model, the less costly solution will always be chosen completely no matter how small the difference in cost is to the closest competing option. In reality, many options may be chosen simultaneously if the difference in cost is minor, but this cannot happen in our model.

One general result from our study that is less dependent on the actual parameter choices is that it is possible to combine ambitious climatic goals with an increased demand for energy services.

5 Future work

The development of hybrid cars (electricity and internal combustion engine) has come to a point when its energy efficiency is close to what is expected for a fuel cell car. This is an important issue to follow up and include as an option in the model. In the current version of our model, we have not included hybrid cars.

Further it could be of interest to look more into biomass supply and conversion options. In this study biomass is a collective name for forest biomass, energy crops and biomass residues. The end-use sector heat is a collective name for industrial process heat and residential heating (including district heating and pellets production). If the model had more supply and end-use options, it could maybe give a more balanced picture of the most cost-efficient use for biomass. The use of biomass for electricity and transportation fuel becomes more interesting, the higher the cost of using biomass for heat production.

The model could also be further developed by study the effect of more combined energy options. The model includes co-generated electricity and heat production, but as a future work options as for example co-generated production of methanol and heat, could be of interest to study.

Finally, the results presented here are based on the assumption that there is a carbon constraint applied to all regions of the world. It could be interesting to analyze fuel choices in the transportation sector under the more realistic assumption that developing countries will adopt abatement policies perhaps a decade or two after the industrialized countries.

Acknowledgement

We would like to acknowledge Per Kågeson for his valuable comments. Financial support from Swedish Agency for Innovation Systems, Vinnova, and Swedish Energy Agency is gratefully acknowledged.

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Paper III

Biomass for heat or transport – an exploration into the underlying cost dynamics in the GET model

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Abstract

In earlier assessments using the global energy transition model, GET, biomass has been found to be most cost-efficiently used for heat and to some extent power production, to meet stringent restrictions on CO_2 emissions. The aim with this study is to achieve more detailed results on the cost dynamics in the GET model in order to get a more clear picture on why biofuels are not seen as a cost-effective fuel choice. The analysis is carried out in a simplified model implemented in Excel that reflects the cost data in a further developed version of the model, GET 5.1, which has a more detailed oil and refinery section. In the analysis, we study and compare the total cost per km for each fuel choice, based on the primary energy prices generated by the model, and we identify the carbon tax interval, for each time step, where biofuels have the lowest cost per km. The simplified model explains the GET model result and gives deeper insights about the system effect causing the result on cost-efficient fuel choices in the GET model. We find that the required carbon tax level where biofuels become cost-efficient compared to fossil based fuels, is evasive. The tax level moves upwards with increasing carbon tax since this leads to an increasing biomass primary energy price in the model.

Keywords: Energy scenarios, energy systems modeling, system effect, scarcity rent, carbon tax, primary energy price, liquid biofuels, hydrogen, carbon dioxide emissions

1. Introduction

In order to analyze a possible future transition of the global energy system, Azar and Lindgren have developed a global energy economy model, the GET (Global Energy Transition) model (see e.g. Azar *et al.* 2000, 2003). In earlier assessments with the GET model, biomass is found to be most cost-efficiently used for heat and to some extent power production, to meet stringent restrictions on CO_2 emissions. Biofuels[1] are not seen as a cost-effective strategy to reduce CO_2 emissions.

In 2003, the European Commission proposed an increased use of biofuels in the transportation sector in a directive which states that biofuels should constitute 2% of the total amount of transportation fuels sold in 2005 (estimated as energy content) at the national level, and 5.75% in the year 2010 (European Council, 2003).

In the light of this we want to further analyze why biofuels do not appear as a cost-effective strategy to reduce carbon dioxide emissions in the GET model. The aim with this study is to achieve more detailed results on the cost dynamics in the GET model in order to get a deeper understanding on why biofuels are not found to be a cost-effective fuel choice. The analysis is carried out using a further developed version of the model, GET 5.1 and a simplified model implemented in Excel.

The paper is structured as follows: In Section 2, we describe the initial GET 1.0 model, the new further developed model GET 5.1 and the simplified model implemented in Excel. In Section 3 we present results of the GET 5.1 model base case set up and in Section 4 we explain the result. In Section 5 we present a sensitivity analysis and in Section 6 we present our conclusions.

[1] In this study "biofuels" always mean transportation fuels derived from biomass.

2. Method

To further analyze why biofuels do not appear as a cost-effective strategy to reduce carbon dioxide emissions in the GET model (GET 5.1) we will make the analysis in two steps. First we develop the GET model with a more detailed oil and refinery section, to analyze if biofuels will appear as a cost-effective strategy to reduce CO_2 emissions. Secondly, to analyze the underlying cost dynamics in GET 5.1 we also develop a simplified model implemented in Excel.

2.1 The initial GET 1.0 model

The global energy systems model, GET 1.0, is a linear programming model that is globally aggregated and has three end-use sectors. It 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 way. The transportation sector includes separate demands for four subgroups: Cars, Freight, Aviation and Rail.

The model is composed of three different parts: (i) the primary energy supply with the supply options coal, oil, natural gas, nuclear power, hydro, wind, biomass and solar energy, (ii) the energy conversion system with plants that may convert the primary energy supplies into secondary energy carriers, e.g., electricity, hydrogen, methanol, and gasoline/diesel and (iii) the final energy demand which includes technologies used in the transportation sector, see Figure 1.

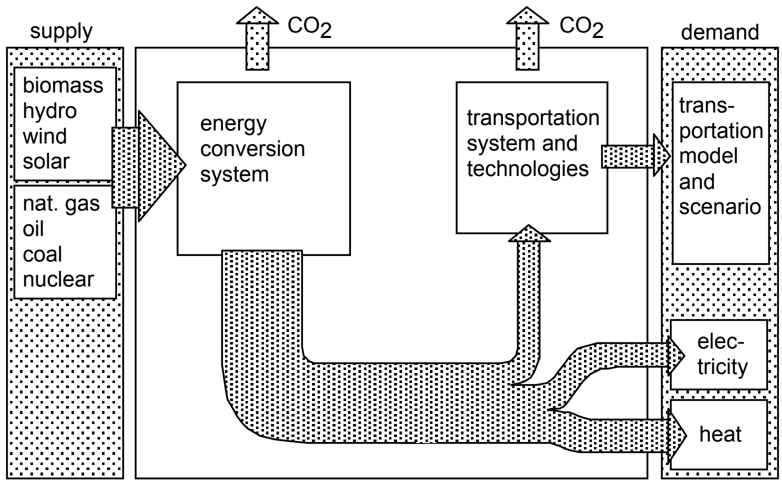

Fig. 1 The global energy systems model GET 1.0 is composed of three parts: supply, demand, and the energy conversion system. The supply is characterised by annual or total extraction limits on the different available energy sources. The demand is exogenously given for transportation, electricity, and heat (including high temperature process heat). The technology system is characterized by a large number of technologies available both for conversion between different energy carriers as well as for vehicle engines. A cost minimization algorithm with restriction on emissions of fossil carbon is then applied to generate energy scenarios.

Energy demand for electricity and heat/process heat are assumed to follow the C1 scenario developed by IIASA/WEC (Nakicenovic *et al.*, 1998). This is one of their "ecologically driven" scenarios in which they assume that technological development leads to efficiency improvements, so that per capita energy demand in developed countries is reduced. Heat/process heat is defined as all stationary use of fuels that neither aim at generating electricity nor transportation fuels. The C1 transportation scenario is not sufficiently detailed for the GET analysis, so a transportation scenario has been developed by assuming that the increase in the amount of person kilometers travelled is proportional to GDP growth (in PPP terms). Full details of the model and the demand scenarios are available in Azar *et al.* (2000, 2003).

Constraints have been added to the model to avoid solutions that exhibit vary fast changes in the energy system. This includes constraints on the maximum expansion rates for different technologies (in general chosen so that it takes 50 years to change the entire energy system) as well as annual or total extraction limits on the different available energy sources. The contribution of intermittent electricity sources is also limited to a maximum of 30% of the electricity demand. To reflect the actual situation in developing countries a minimum of 27 EJ/yr of the heat demand need to be produced from biomass the first decades. The contribution of nuclear power has been constrained to the level we have today.

We have put the global discount rate at 5% per year. Energy supply potentials, maximum expansions rates and energy demand are exogenously given. In most cases investment costs, conversion efficiencies, lifetimes and load factors are assumed constant at their "mature levels". The model can allow carbon sequestration to be applied to most fossil fuel conversion technologies.

An optimization algorithm is applied to the model in order to generate the solution that meets the energy demands and a specific atmospheric concentration target, with the lowest total cost.

The energy system description in the GET model is a simplification of reality in many ways, e.g., the number of available technologies is limited, demand is price-inelastic, decisions in the model are only based on cost considerations, and there is no uncertainty about future costs, climate targets or energy demand levels etc. The global energy system, in GET, is then optimized with perfect foresight and with a single goal function, and therefore the model is not suitable for making predictions of the energy system development.

An energy-economy model like this is, however, useful for constructing and comparing scenarios. The model makes it possible to quantitatively explore the role and cost-efficiency of various technologies given different carbon emission constraints, resource availabilities, and parameter values for technologies.

2.2 The GET 5.1 model

There are four main new features in the GET 5.1 model, compared to GET 1.0: (i) waste heat generated in the production of biofuels may be sold to the heat market, (ii) carbon and capture storage technology can be applied on both biomass and fossil fuel use, (iii) a split of the primary energy "oil" into two primary oil sources, conventional and heavy oils and (iv) a further development of the refinery process in the model. Parameter values are identical to those described in Azar *et al.* (2005) with two minor changes. First the life times on truck engines have been shortened to 10 years instead of 15 years as in earlier GET models, following Kågeson (2004). Secondly we have changed the energy efficiency on fuel cells in cars, compared to internal combustion engines, from a factor of 2.2 more efficient down to a factor of 1.5, also following Kågeson (2004). Hence, a transition into hydrogen in fuel cell vehicles is in the GET 5.1 model less favorable than in earlier versions of the GET model.

Instead of, as in earlier GET models, one refinery process this model has two, one conventional and one more costly, where the latter process represents the additional costs associated with converting heavier fractions into transportation fuels. The share of conventional and heavy oils that can go to the conventional refinery process is maximized following rough estimates done by Wernersson (2003) and Kågeson (2004). It is in GET 5.1 not possible to convert all oil into transportation fuels. The heaviest fractions, 10% of the oil, may be used in the heat or electricity sectors. The new part in the model structure is presented in Figure 2.

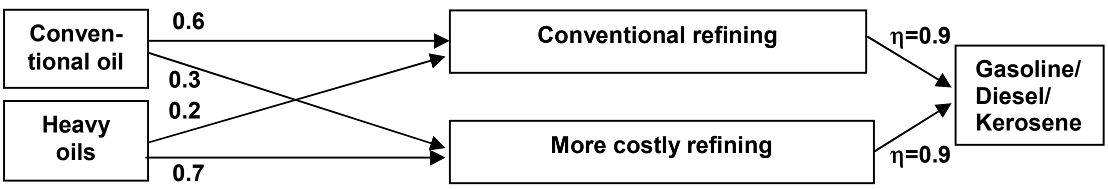

Fig 2. Illustration of the added new model structure in GET 5.1. The numbers to the left show the maximum share allowed of a certain primary energy to be converted into transportation fuels using each refinery process, e.g. a maximum of 60% of the conventional oil can be converted into transportation fuels by the conventional refinery process and a maximum of 30% of the conventional oil can be upgraded to transportation fuels using the more costly refinery process. Thus, at the most 90% of the oil can be converted into transportation fuels.

The main difference with this new model structure, is that it has become more expensive to produce oil based transportation fuels. In earlier versions of the GET model 100% of the primary energy "oil" could be converted into transportation fuels, at a certain cost. Now, only 60% of the conventional oil can be converted into transportation fuels, at that cost.

The primary energy supply potentials of the two different types of oil are estimated following Rogner (1997), EIA (2002) and WEA (2000) and in the base case set to 12,000 EJ for conventional oil and 12,000 EJ for heavy oils. The primary energy cost[2] for conventional oil is taken from the GET 5.0 model (Azar *et al.*, 2005) and the primary energy cost for heavy oils is estimated following EIA (2002) and in the model set to 3.5 USD/GJ[3] and 5 USD/GJ respectively.

2.3 The simplified model implemented in Excel

In this study we have developed a simplified model, implemented in Excel, to explore the underlying cost dynamics in the GET model. The parameter values and equations which we implement in Excel are equivalent to the data and equations in the GET 5.1 model and we calculate the costs per km for all fuel and vehicle choices.

2.3.1 Primary energy price

The primary energy price P [USD/GJ] in the GET 5.1 model, consists of three parts, as

$$P = P_C + P_{SR} + P_T \,, \qquad (1)$$

[2] Read more about the term "primary energy cost" in Section 2.3.1.
[3] In reality, the extraction cost is only a few dollars per barrel (corresponds to 0.1-0.4 USD/GJ) in the Middle East and higher in other major oil producing regions. The price observed in the market is much higher still and reflects scarcities and the fact that oil supply is controlled by a cartell (OPEC). It would be too complicated in a model like this to simulate the price setting behaviour of a cartell. For that reason, we have chosen to set the primary energy cost, P_C, (extraction cost and distribution) for conventional oil at 3.5 USD/GJ. This oil price, which prevailed towards the end of the 90s, includes the impact of the cartell's activities. When oil reserves decline the scarcity rent will increase. We get roughly the same price development for oil ($P=P_C+P_{SR}$) in our model even if we put the extraction cost to zero.

where P_C is the primary energy cost including the extraction costs and distribution, P_{SR} is a scarcity rent[4] generated in the model as a shadow price for each time step and P_T is the price for emitting fossil carbon, i.e. a carbon tax.

2.3.2 Production costs of transportation fuels

Total fuel production costs C_F [USD/GJ], in the GET 5.1 model, is equivalent to

$$C_F = C_I + C_{OM} + C_P + C_D, \tag{2}$$

where C_I is the investment cost of the energy conversion plant, C_{OM} is the operation and maintenance cost, C_P is the primary energy cost per energy output and C_D is the distribution cost to fuel stations. The investment cost C_I [USD/GJ] is

$$C_I = \frac{(1+r)^5 I}{10\alpha L}\left(1 - \frac{(1-1/T)^{10}}{(1+r)^{10}}\right), \tag{3}$$

where I [USD/kW] is the investment cost, r is the discount rate (0.05/yr in the base case), T [yr] is the life time of the conversion plant (25 yr for fuel plants) and L is the load factor. The constant α=31 Ms/yr is included to account for the conversion into GJ and since one time step is ten years in GET 5.1, we put in the number of seconds for a ten year period. The factor $(1+r)^5$ reflects that investments are made between two time steps. The operation and maintenance cost C_{OM} [USD/GJ] is assumed to be 4% of the investment cost and calculated as

$$C_{OM} = \frac{0.04I}{\alpha L} \approx 0.0018I, \tag{4}$$

where I [USD/kW] is the investment cost, L is the load factor, here assumed to 0.7 for all plants and the constant α=31 Ms/yr is included to account for the conversion into GJ. The actual operation and maintenance cost [USD] depends on the energy flow, secondary energy, in each conversion plant and will be lower if the plant is not fully used. The cost for the primary energy, per energy output, C_P [USD/GJ] is calculated as

$$C_P = \frac{P}{\eta}, \tag{5}$$

[4] Scarcity rent, P_{SR}, is the economic term for the additional cost, added to the primary energy cost, P_C, due to the fact that the relative price on an item increases as a result of its relatively low supply, e.g. an exhaustible resource or raw materials in high demand.

where P [USD/GJ] is the primary energy price described in equation (1) and η is the energy conversion efficiency. The distribution cost to fuel stations C_D [USD/GJ] is assumed to be 2 USD/GJ for gasoline and diesel, 3.5 USD/GJ for methanol and 8 USD/GJ for hydrogen, see Azar *et al*. (2000) for more details.

Total fuel production cost for all transportation fuel options calculated in the simplified model, implemented in Excel, with data equivalent to the GET 5.1 base case, are presented in Table 1.

Table 1. Assumed investment cost, conversion efficiency, conversion plant load factor, primary energy cost, distribution cost and total fuel production cost of all transportation fuel options calculated in the simplified model with results equivalent to GET 5.1. All costs are derived using primary energy costs P_C, i.e., without scarcity rents and carbon taxes.

Year 2000	Investment cost I [USD/kW]	Conv. effic. η	Load factor L	O&M cost C_{OM} [USD/GJ]	Primary energy cost P_C [USD/GJ]	Distribu-tion cost C_D [USD/GJ]	Tot. fuel prod. Cost[a)] C_F [USD/GJ]
Oil Conv_Gasoline	900	0.9	0.8	1.7	3.5	2	10.3
Oil C costly_Gasoline	1300	0.9	0.8	2.4	3.5	2	12.2
Oil Heavy_Gasoline	900	0.9	0.8	1.7	5.0	2	12.0
Oil H costly_Gasoline	1300	0.9	0.8	2.4	5.0	2	13.9
Natural gas	0	1.0	1.0	0.0	2.5	6.5	8.9
Biomass_Methanol	1000	0.6	0.8	1.8	2.0	3.5	11.7
Natural gas_Methanol	600	0.7	0.8	1.1	2.5	3.5	10.0
Coal_Methanol	1000	0.6	0.8	1.8	1.0	3.5	10.0
Biomass_Hydrogen	800	0.6	0.6	1.5	2.0	8	15.9
Natural gas_Hydrogen	300	0.8	0.6	0.6	2.5	8	12.8
Coal_Hydrogen	700	0.65	0.6	1.3	1.0	8	13.5
Oil Conv_Hydrogen	400	0.75	0.8	0.7	3.5	8	14.9
Oil Heavy_Hydrogen	400	0.7	0.8	0.7	5.0	8	17.4
Solar_Hydrogen	2000	1.0	0.25	3.7	-	8	31.0

a)To be able to compare the fuel costs per vehicle, one also has to consider extra costs per vehicle, storage, fuel cells and efficiency change, see Table 3.

In Table 1 it is shown that the total fuel production costs of biomass and fossil based methanol is similar to gasoline/diesel derived from conventional oil. It is also shown that the production costs of natural gas, biomass and fossil based methanol are lower than fuels based on heavy oils and lower than all hydrogen alternatives. It is, however, not clear, from Table 1, which transportation fuel will be chosen in a cost minimization model for two main reasons: (i) one has to consider costs for the vehicle use, e.g. extra costs for different engine types, efficiency change and driving distances, read more in

Section 2.3.3, and (ii) primary energy prices, *P*, are affected by scarcity in the model and change over time, read more in Section 2.3.1.

2.3.3 Total costs per kilometer

On top of the production cost of energy carriers there are costs related to the vehicle use which need to be taken into account when comparing fuel choices in the transportation sector. The total transportation cost $C_{tot}(t)$ [USD/km] for a certain vehicle and fuel is calculated as

$$C_{tot}(t) = C_F E(t) + C_V(t), \tag{6}$$

where C_F [USD/GJ] is the total fuel production cost derived in equation (2), $E(t)$ [GJ/km] is the energy demand for each engine type and $C_V(t)$ [USD/km] is the vehicle cost, for a certain time step *t*. The energy required for each engine type $E(t)$ [GJ/km] is calculated as

$$E(t) = \frac{\gamma(t)}{\delta}, \tag{7}$$

where $\gamma(t)$ [GJ/km] is the energy demand per km, which is assumed to decrease by time following the used demand scenario for the transportation sector and δ is an efficiency factor related to gasoline cars (a gasoline car is defined as 1 and a more efficient engine type has a value larger than 1). The vehicle cost $C_V(t)$ [USD/km] is calculated as

$$C_V(t) = \frac{(1+r)^5 I}{10\beta(t)} \left(1 - \frac{(1-1/T)^{10}}{(1+r)^{10}}\right), \tag{8}$$

where *I* [USD/vehicle] is the investment cost, *r* is the discount rate (0.05/yr in the base case), *T* [yr] is the life time of the vehicle and $\beta(t)$ [km/vehicle] is the annual driving distance. The factor 1/10 accounts for bringing the capital cost down to an annual cost and the factor $(1+r)^5$ reflects that investments are made between two time steps. Parameter values used in GET 5.1, derived values on vehicle cost $C_V(t)$, and derived values on energy demand for each engine type $E(t)$, are presented in Table 2.

Table 2. Assumed investment cost on different engine types, engines life time, engines efficiency factor compared to a gasoline car, derived energy required for each engine and derived vehicle costs, for the year 2000.

Year 2000	Investment cost I [USD/car]	Life time T [yr]	Engine efficiency factor δ	Energy demand $E(t)$ [GJ/km]	Vehicle cost $C_V(t)$ [USD/km]
Gasoline_IC[a)]	20000	15	1.0	0.0035	0.103
Methanol_IC	21000	15	1.0	0.0035	0.109
Natural gas_IC	21200	15	1.0	0.0035	0.110
Hydrogen_IC	22500	15	1.0	0.0035	0.116
Gasoline_FC[b)]	24500	15	1.3	0.0027	0.127
Methanol_FC	24500	15	1.3	0.0027	0.127
Hydrogen_FC	24000	15	1.5	0.0023	0.124

a) IC is an acronym for internal combustion engines.
b) FC is an acronym for fuel cell engines.

Further, in the calculations presented here we have used a weighted global average, for the year 2000, on a car's annual driving distance, $\beta(t)$ = 16,384 km/car and a weighted global average, for the year 2000, on energy demand per km, $\gamma(t)$ = 3.7 MJ/km. Total cost per km for various combinations of fuel use and engine types calculated in the simplified model, equivalent to the result in the GET 5.1 base case for the year 2000, are presented in Table 3.

Table 3. Derived total cost [USD/km] for each fuel choice used in either an internal combustion engine or in a fuel cell engine, equivalent to GET 5.1 results. All costs are derived using primary energy costs P_C, i.e., without scarcity rents and carbon taxes.

Year 2000		Internal combustion engines				Fuel cell engines			
	Total fuel cost C_F [USD/GJ]	Energy demand [GJ/km]	Fuel cost [USD/km]	Investment cost [USD/km]	**Total cost [USD/km]**	Energy demand [GJ/km]	Fuel cost [USD/km]	Investment cost [USD/km]	**Total cost [USD/km]**
Oil Conv_gasoline	10.29	0.0035	0.035	0.103	**0.139**	0.0027	0.027	0.127	**0.154**
Oil C_costly_gasoline	12.24	0.0035	0.042	0.103	**0.146**	0.0027	0.032	0.127	**0.159**
Oil Heavy_gasoline	11.96	0.0035	0.041	0.103	**0.145**	0.0027	0.032	0.127	**0.158**
Oil H_costly gasoline	13.91	0.0035	0.048	0.103	**0.151**	0.0027	0.037	0.127	**0.164**
Natural gas	8.90	0.0035	0.031	0.110	**0.140**	-	-	-	**-**
Biomass_methanol	11.69	0.0035	0.044	0.109	**0.149**	0.0027	0.031	0.127	**0.158**
Nat. gas_methanol	9.97	0.0035	0.034	0.109	**0.143**	0.0027	0.026	0.127	**0.153**
Coal_methanol	10.02	0.0035	0.035	0.109	**0.143**	0.0027	0.027	0.127	**0.153**
Biomass_hydrogen	15.92	0.0035	0.055	0.116	**0.171**	0.0023	0.037	0.124	**0.161**
Nat. gas_hydrogen	12.76	0.0035	0.044	0.116	**0.160**	0.0023	0.029	0.124	**0.154**
Coal_hydrogen	13.53	0.0035	0.047	0.116	**0.163**	0.0023	0.031	0.124	**0.155**
Oil Conv_hydrogen	14.89	0.0035	0.051	0.116	**0.168**	0.0023	0.034	0.124	**0.158**
Oil Heavy_hydrogen	17.37	0.0035	0.060	0.116	**0.176**	0.0023	0.040	0.124	**0.164**
Solar_hydrogen	31.04	0.0035	0.107	0.116	**0.223**	0.0023	0.071	0.124	**0.196**

In Table 3 it is shown that the use of gasoline, produced from conventional oil, leads to the lowest cost per km, closely followed by natural gas and thereafter natural gas and coal based methanol, all four options used in internal combustion engines, assuming primary energy costs, P_C. Biomass based methanol used in internal combustion engines has the lowest cost per km among the four biofuel options.

2.3.4 Production costs of electricity and heat

Total production costs C [USD/GJ] is calculated as

$$C = C_I + C_{OM} + C_P, \qquad (9)$$

where C_I is the investment cost of the energy conversion plant, C_{OM} is the operation and maintenance cost and C_P is the primary energy cost per energy output. C_I, C_{OM} and C_P are calculated following equation (3), (4) and (5) respectively.

Total production costs for various heat and electricity options, equivalent to the GET 5.1 base case in 2000, are calculated in the simplified model and presented in Table 4.

Table 4. Assumed investment costs, energy conversion efficiency, conversion plant load factors and primary energy costs are listed. The total production costs for various heat and electricity options are calculated in the simplified model, equivalent to GET 5.1. All costs are derived using primary energy costs P_C, i.e., without scarcity rents and carbon taxes.

Year 2000	Investment Cost I [USD/kW]	Conv. effic. η	Load factor L	O&M cost C_{OM} [USD/GJ]	Primary energy cost P_C [USD/GJ]	Tot. prod. cost C [USD/GJ]
Biomass_heat	300	0.9	0.7	0.6	2.0	3.8
Natural gas_heat	100	0.9	0.7	0.2	2.5	3.3
Oil Conventional_heat	100	0.9	0.7	0.2	3.5	4.4
Oil Heavy_heat	100	0.9	0.7	0.2	5.0	6.1
Coal_heat	300	0.9	0.7	0.6	1.0	2.7
Solar_heat	400	0.9	0.25	0.7	0	4.6
Solar_H2+H2_heat	2000/100	1.0/0.9	0.25/0.7	3.7/0.2	0	23.6
Biomass_electricity	1200	0.4	0.7	2.2	2.0	11.4
Natural gas_electricity	500	0.55	0.7	0.9	2.5	7.2
Oil Conv_electricity	600	0.5	0.7	1.1	3.5	10.2
Oil Heavy_electricity	600	0.45	0.7	1.1	5.0	14.3
Coal_electricity	1100	0.45	0.7	2.0	1.0	8.1
Solar_electricity	1200	1.0	0.25	2.2	0	13.9
Solar_H2+H2_electricity	2000/500	1.0/0.55	0.25/0.7	3.7/0.9	0	25.8

In Table 4 it is shown that heat derived from coal has the lowest production cost followed by heat derived from natural gas. The same two primary energy sources also have the lowest production costs for electricity generation but in the opposite order where natural gas has the lowest production cost followed by coal.

3. Results

In the base case run of the GET 5.1 model, aiming for 450 ppm, no carbon capture and storage technology is included. Results on primary energy supply and cost-efficient fuel choices in the transportation sector are presented in Figures 3 and 4.

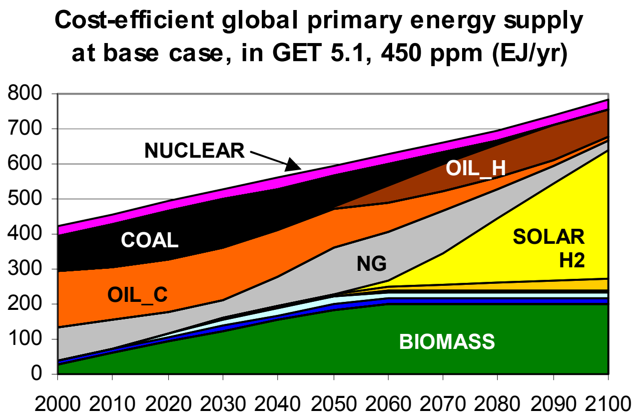

Fig 3. Cost-efficient primary energy choices to supply the global energy system, in the base case scenario aiming for 450 ppm using the GET 5.1 model. Carbon capture and storage technology is not included. Coal is phased out and biomass as well as solar energy play an important role. Acronyms used in the figure are: OIL_C=conventional oil, OIL_H=unconventional heavy oils, NG=natural gas and SOLAR_H2=solar energy stored in hydrogen.

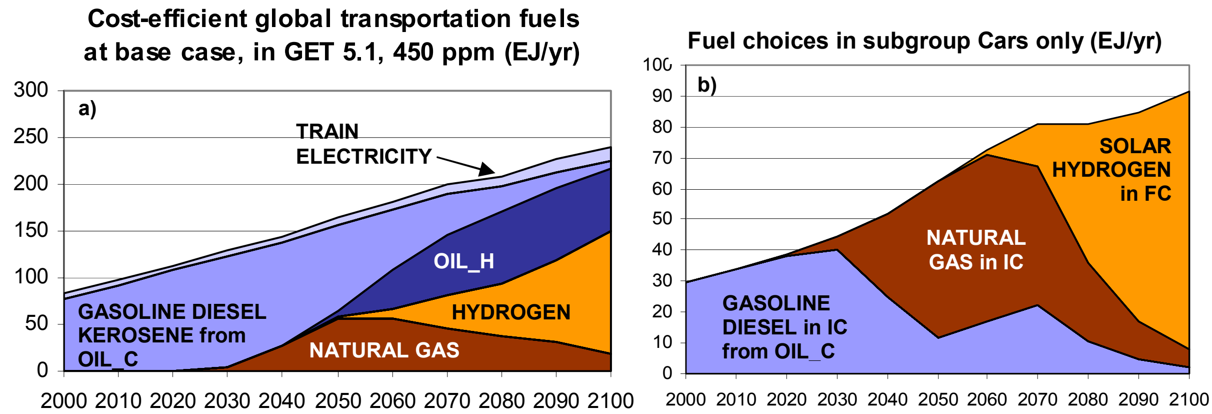

Fig 4. Cost-efficient transportation fuels, in the base case scenario, aiming for 450 ppm, using the GET 5.1 model. Oil based transportation fuels dominate until natural gas enters the transportation sector by the year 2030 and solar based hydrogen by the year 2060. Biofuels do not appear as a cost-effective fuel choice in this scenario. Figure 4a shows the fuel choices for the whole transportation sector where the three subgroups: Cars, Freight and Aviation are aggregated. Figure 4b shows the fuel choices for subgroup Cars only. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= gasoline, diesel and kerosene produced from unconventional heavy oils, IC= internal combustion engines and FC= fuel cell engines.

In this run of the GET 5.1 model, the same overall results as in previous GET model studies appear, i.e. that gasoline/diesel remain for some decades in the transportation sector until the carbon constraint becomes increasingly stringent and that solar based hydrogen dominates by the end of this century. One significant exception from previous GET model results is, however, that natural gas has taken a larger share of the transportation fuels, which is a result of that only 60% of the conventional oil can be converted to gasoline and diesel at conventional refinery cost, in the GET 5.1 model, compared to 100% in earlier GET versions, see Figure 2 and Table 3.

4. Explaining the result

In this section we attempt to shed light on fuel choices for the subgroup Cars in the transportation sector, by using results from the simplified model, implemented in Excel.

4.1 Total costs per kilometer as a function of carbon tax

We use equation (6) to calculate the total costs [USD/km] in the simplified model (see Table 3). These costs are then plotted as a function of the carbon tax [USD/tC] to illustrate how the relation between the costs change with higher carbon taxes, i.e that carbon taxes make it more expensive to use coal, oil and natural gas, see Figure 5. Note that these costs are derived using primary energy costs, P_C, i.e., without scarcity rents. If the full GET model were run with high carbon taxes, scarcity rents would arise, but these rents are not included in Figure 5.

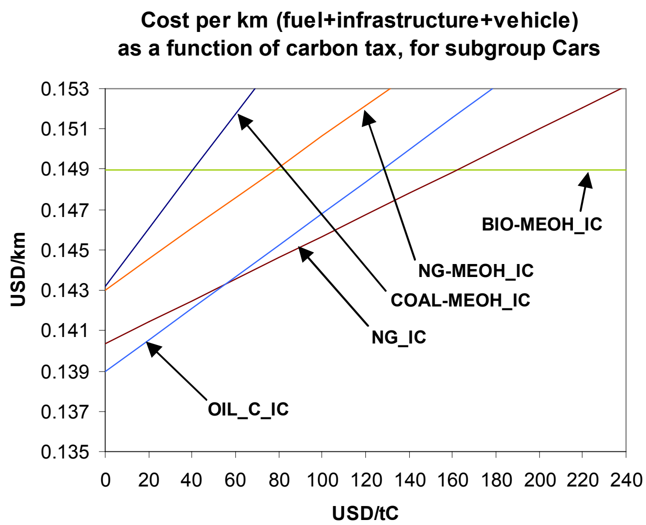

Fig 5. Costs per km as a function of carbon tax for subgroup Cars. Note that these costs are based on primary energy costs P_C, presented in Table 1, and not affected by scarcity. Conventional oil has the lowest cost per km in the carbon tax interval 0-58 USD/tC, natural gas in the interval 58-160 USD/tC and biomass based methanol in the interval 160-∞ USD/tC. Acronyms used in the figure are: OIL_C= conventional oil, NG= natural gas, MEOH= methanol and IC= internal combustion engines.

In Figure 5 it is shown that cars run on gasoline and diesel from conventional oil have the lowest cost per km at carbon taxes up to 58 USD/tC. At taxes between 58 and 160 USD/tC natural gas cars have the lowest cost per km and at taxes above 160 USD/tC cars run on biomass based methanol have the lowest cost per km. The figure illustrates how the costs per km change by increasing carbon tax, using primary energy costs P_C.

However, in the GET model scarcity rents, obtained from shadow prices on the primary energy supply equation, are generated for each time step. In the base case run of the GET 5.1 model scarcity rents are generated on natural gas, conventional oil and biomass[5].

In Figure 6, the costs per km generated in the base case run of the GET 5.1 model are presented for four time steps. The graphs show how the cost per km for different fuel choices would change with the carbon tax, given the primary energy price, P, (minus P_T) generated by the model for each time step, i.e. scarcity rents generated in the run for a specific time step are kept constant[6] in each plot. Plots for time steps 2030, 2050, 2070 and 2090 are presented in Figure 6. The vertical dotted line in each graph marks the generated carbon tax for the specific time step.

[5] Scarcity rents are generated on biomass due to the fact that the demand for biomass exceeds the supply potential at high carbon taxes. When the model is run without restrictions on CO_2 emissions, no scarcity rent is added to the biomass primary energy cost.

[6] Note that if the GET model were run with higher carbon taxes, scarcity rents on biomass would increase as a consequence of an even stronger competition for biomass. Thus, it is not possible to foresee any other GET results outside the point of intersection with the dotted vertical carbon tax curve.

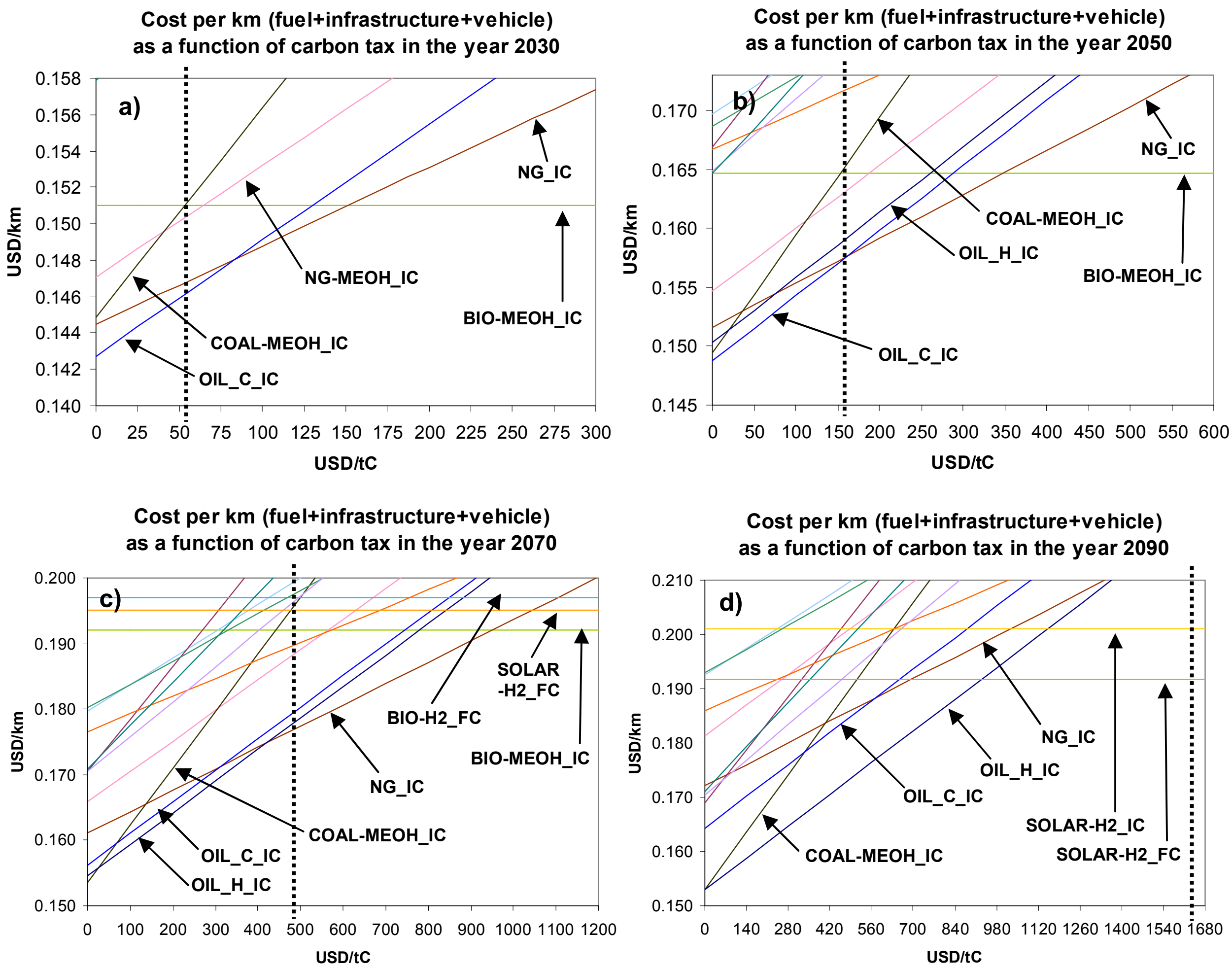

Fig 6. Costs per km (subgroup Cars only) generated in the base case set up, aiming for 450 ppm, of the GET 5.1 model. Graphs for the time steps 2030, 2050, 2070 and 2090 are presented and the vertical dotted line marks the generated carbon tax, which is in a) 52 USD/tC, b) 157 USD/tC, c) 490 USD/tC and d) 1673 USD/tC. Note that the scarcity rents generated in each time step are kept constant in each plot. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= heavy oils, NG= natural gas, MEOH= methanol, H2= hydrogen, IC= internal combustion engines and FC= fuel cell engines.

In Figure 6 it is shown that in the year 2030 (a) and the year 2050 (b) cars run on gasoline and diesel from conventional oil lead to the lowest cost per km at carbon taxes up to (a) 80 USD/tC and (b) 160 USD/tC. For carbon taxes in the interval of (a) 80-150 USD/tC and (b) 160-350 USD/tC natural gas cars have the lowest cost per km and at carbon taxes above (a) 150 USD/tC and (b) 350 USD/tC cars run on biomass based methanol have the lowest cost per km.

In Figure 6c it is shown that in the year 2070 cars run on coal based methanol have the lowest cost per km up to 25 USD/tC. For carbon taxes in the interval of 25-410 USD/tC cars run on gasoline and diesel derived from heavy oils have the lowest cost per km and for taxes between 410-950 USD/tC natural gas cars have the lowest cost per km and at carbon taxes above 950 USD/tC cars run on biomass based methanol have the lowest cost per km. Note that two other carbon neutral alternatives are close to biomass based methanol in the year 2070, i.e. solar based hydrogen in fuel cell vehicles and biomass based hydrogen in fuel cell vehicles.

In Figure 6d it is shown that in the year 2090 cars run on coal based methanol have the lowest cost per km up to 25 USD/tC. For taxes in the interval of 25-930 USD/tC cars run on gasoline and diesel derived from heavy oils have the lowest cost per km and for taxes above 930 USD/tC cars run on solar based hydrogen in fuel cell vehicles have the lowest cost per km. Note that the cost per km on biomass based methanol now is higher than solar based hydrogen, which is due to a high scarcity rent on biomass (the generated primary energy price, *P*, on biomass is 37 USD/GJ in the year 2090). The costs per km, in the year 2090, for the six carbon-neutral alternatives are presented in Table 5.

Table 5. Generated total costs [USD/km] for the six fossil carbon-neutral alternatives in the GET 5.1 model, for the year 2090. The costs are based on the generated primary energy price, *P*, i.e. include scarcity rent on biomass.

Year 2090	Internal combustion engines [USD/km]	Fuel cell engines [USD/km]
Biomass_methanol	0.263	0.256
Biomass_hydrogen	0.281	0.245
Solar_hydrogen	0.201	**0.192**

In Table 5 it is shown that biomass based alternatives have received a higher cost per km compared to solar based alternatives. Note that the cost per km is lower if the fuels are used in fuel cell engines compared to internal combustion engines. This is a result of that a smaller amount of the relatively expensive primary energy is needed to drive one kilometer using fuel cell engines since they are more energy efficient than internal combustion engines.

4.2 Fuel choices for different carbon taxes

The intervals where a certain fuel has the lowest cost per km are identified for each time step, by analyzing the plots presented in Figure 6. Note that the scarcity rents generated in the model run are kept constant[7] in each of the analyzed plots. The identified intervals for each time step are summarized in Figure 7, where also the carbon tax generated in the GET 5.1 base case is plotted.

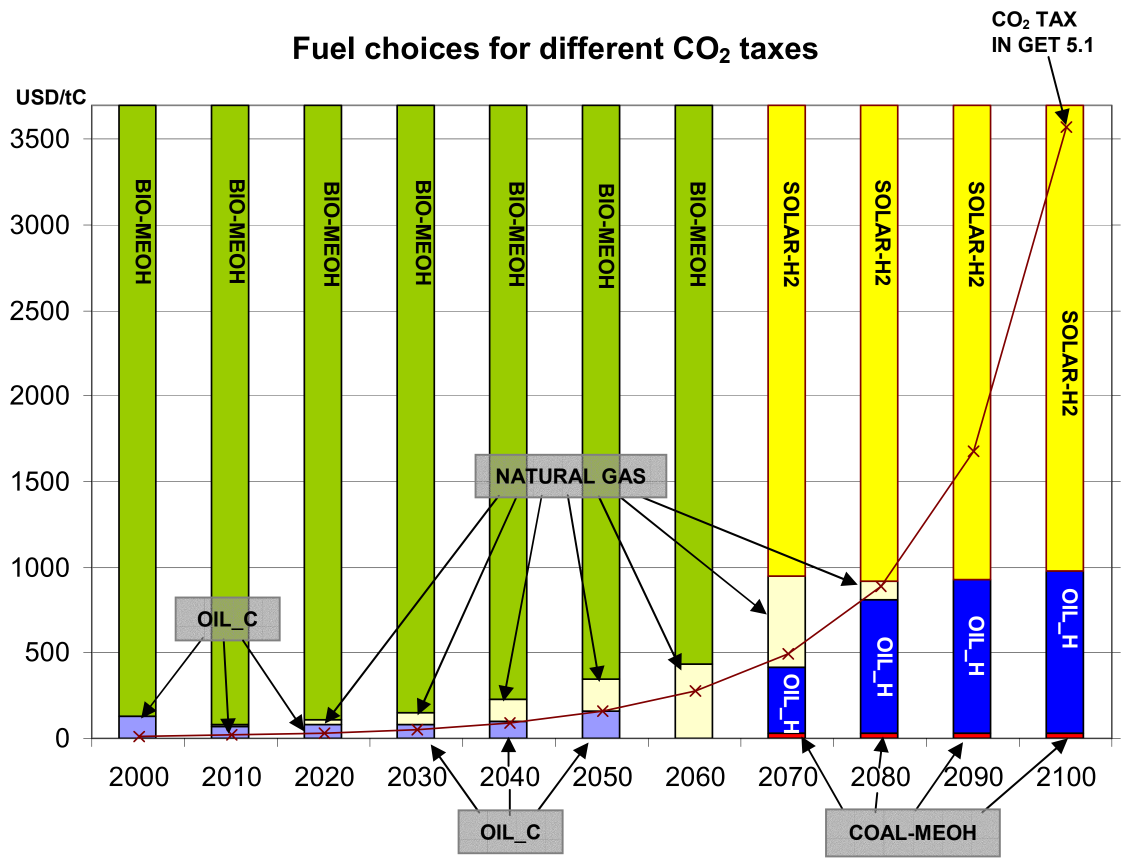

Fig 7. Fuel choices in the transportation sector (subgroup Cars only) for different carbon tax intervals in the base case scenario, aiming for 450 ppm. For each time step the lowest fuel cost per km for a certain range of carbon taxes are identified and plotted in bars. The carbon tax generated in the run is plotted as a line curve in front of the bars, with the tax values marked with x. The fuel range that crosses the carbon tax line curve will first and foremost be chosen in the scenario. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= unconventional heavy oils, MEOH= methanol and SOLAR-H2= solar based hydrogen.

[7] Read more in Section 4.1

In a linear optimization model the technology and fuel choice which offers the lowest cost per km will first and foremost be chosen (when primary energy prices include scarcity rents from competition with other end uses), but since the model has expansion rate constraints a technology might enter some time steps earlier to be able to expand into large volumes. This is the case with solar based hydrogen, which enters the scenario in 2060-2070, see Figure 4b, but crosses the carbon tax line curve, in Figure 7, first in the year 2080. The model also has constraints on the rate of which a fuel can be phased out which, together with the fact that capital decays exponentially, explains why conventional oil remains in the transportation sector for some decades, see Figure 4b, even though natural gas crosses the carbon tax line curve in the years between 2040 to 2080, in Figure 7. The reason for the increasing use of gasoline and diesel derived from conventional oil in the years 2060 and 2070, in the scenario for subgroup Cars, is that investments are made in new refinery capacity to supply the Freight and the Aviation sector. Using some of the capacity to produce gasoline/diesel for cars will lower the total energy system cost, but that can not be seen in Figure 7.

4.3 The system effect

The fuel choices in the transportation sector depend highly on fuel choices in the heat and the electricity sector, i.e. a system effect. By studying Figure 7 it would be tempting to interpret the carbon tax intervals as biofuels would become a cost-effective fuel choice if the carbon tax would be higher than 150 USD/tC in the year 2030, but this can not be taken for granted. A run where the carbon tax is locked to 160 USD/tC for the years 2010-2030, does not introduce any biofuels. Instead, the primary energy price, *P*, on biomass increases to 4.4 USD/GJ compared to 2.3 USD/GJ in the base case. The increased primary energy price on biomass is a result of an increased demand for CO_2-neutral energy in all three sectors, when the carbon tax is raised. The higher cost on biomass increase the cost on biomass based methanol to 0.161 USD/km compared to 0.151 USD/km in the base case, while the cost per km for the fossil fuel options, when the carbon tax is subtracted, are roughly the same, see Figures 6a and 8a.

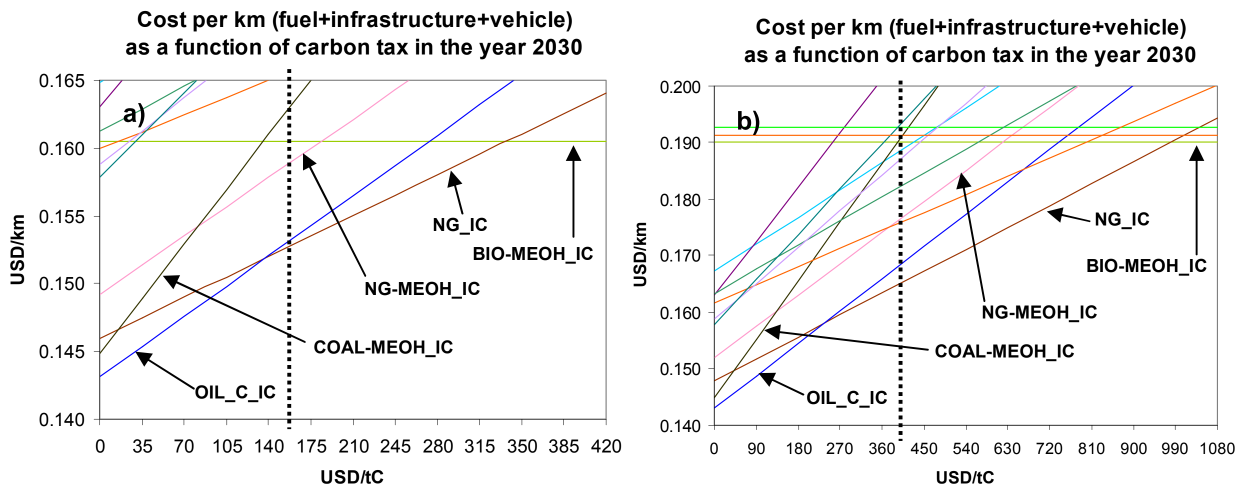

Fig 8. Costs per km (subgroup Cars only) generated in two runs with fixed carbon taxes on a) 160 USD/tC for the years 2010-2030 and b) 400 USD/tC for the years 2010-2050. Both scenarios reach 450 ppm by the year 2100. Cars run on gasoline and diesel, from conventional oil, have the lowest cost per km at carbon taxes up to a) 140 USD/tC and b) 260 USD/tC. For carbon taxes in the interval of a) 140-340 USD/tC and b) 260-990 USD/tC natural gas cars have the lowest cost per km and for carbon taxes above a) 340 USD/tC and b) 990 USD/tC cars run on biomass based methanol have the lowest cost per km. Thus, biomass based methanol has a higher cost per km in these two runs compared to the base case, presented in Figure 6a.

Even though the carbon tax is increased to a level where biofuels seemed to be cost-effective in Figure 7, the same fuel choices appear in Figure 6a as in 8a with the difference that biomass based methanol has a higher cost per km in Figure 8a. Instead of having the lowest cost of all fuel choices at taxes above 150 USD/tC, biomass based methanol now has the lowest cost per km at taxes above 340 USD/tC. Increasing the carbon tax to 400 USD/tC for the years 2010-2050 will still not introduce any biofuels, see Figure 8b. In this run the competition, between biomass based heat and biofuels, is strong and the primary energy price, *P*, on biomass has increased to 10.7 USD/GJ leading to a cost of biomass based methanol of 0.190 USD/km. In this run it seems that biomass based methanol will not be able to compete until the carbon tax is above 990 USD/tC.

This evasive carbon tax level when biofuels become cost-efficient, compared to fossil based fuels, is an effect of the system effect. The tax level moves upwards with increasing carbon taxes, since this leads to an increasing biomass primary energy price, *P*, in the model.

Biofuels are not introduced in the transportation sector since biomass is more cost-effectively used in other sectors. This can also be understood by studying Table 3 and Table 4 where the costs for the two competing CO_2-neutral energy options (solar and biomass) can be compared. In the transportation sector, by going from biomass based methanol in internal combustion engines (0.149 USD/km) to solar based hydrogen in fuel cells (0.196 USD/km), we get an increase of the cost per km by a factor of 1.3. In the electricity sector by going from biomass based electricity (11.4 USD/GJ) to electricity derived from solar based hydrogen (25.8 USD/GJ) we get an increase of the cost per Joule by a factor of 2.3. In the heat sector by going from biomass based heat (3.82 USD/GJ) to heat derived from solar based hydrogen (23.6 USD/GJ) we get an increase of the cost per Joule by as much as a factor of 6.2. Hence biofuels are not introduced in the transportation sector since biomass is most cost-effectively used in the heat sector.

5. Sensitivity analysis

As explained in Section 4, the system effect in the GET 5.1 model prioritizes the limited biomass to the heat sector. This indicates that a situation in which biofuels enter the transportation sector should involve other types of changes to the model, for example, other cost assumptions, features, and/or constraints. To analyze under what circumstances biofuels could become a cost-effective strategy to reduce CO_2 emissions, we have carried out a sensitivity analysis with respect to parameter values in the GET 5.1 model as follows. We investigate how the fuel choices in the transportation sector change if we

1) assume a lower conventional oil supply potential. We have chosen to decrease the conventional oil reserves into 9,000 EJ and increase the heavy oils reserves into 15,000 EJ (Compared to base case 12,000 EJ each).
2) assume that waste heat generated in the production of transportation fuels may be sold to the heat market. We introduce co-generation of methanol and heat as well as hydrogen and heat, to the model.
3) assume a larger biomass supply potential. We have chosen to increase the supply potential from 200 EJ to 300 EJ/yr.

4) assume that 25% of all biomass used for heat production needs to be refined, e.g. using wood pellets instead of using wood chips for the production of bio-heat. We have chosen to add 3 USD/GJ for the refining process which increases the production cost for heat produced from wood pellets into 6.82 USD/GJ (compared to heat produced from standard wood chips 3.82 USD/GJ) following Andersson *et al.* (2003).
5) assume that carbon capture and storage technology can be applied on both biomass and fossil fuels.

We have observed that change number 3 (increasing the biomass supply potential) has a positive effect[8] on biofuel use and that change number 1 (lowering conventional oil supply potential) has a small positive effect. Also change number 2 (including co-generation of transportation fuels and heat) has a positive effect, but assuming that waste heat generated in the transportation fuel production does not only have a positive effect on biomass based methanol but also on fossil based methanol.

Change number 4 (assuming that 25% of all biomass based heat needs to be refined) generally shows no effect on the production of biofuels. The higher production cost on biomass based heat leads to that a smaller amount of biomass is used in the heat sector. In early decades, when the CO_2 constraint is moderate, more fossil fuels are possible to use. Biomass based heat is replaced by coal based heat and the surplus biomass is used in the electricity sector and generally not in the transportation sector. Change 4, however, has a positive effect on biofuel production when it is combined with change 2 where biofuels replace most of the fossil based methanol, see Figure 9.

Change number 5 (including carbon and capture storage technology) has a negative effect on biofuel production. The use of coal increases as a result of including carbon and capture storage technology. Coal replaces, to some extent, natural gas in the electricity sector and the surplus natural gas replaces biofuels in the transportation sector. Also some coal based hydrogen enters the transportation sector and replaces bio-methanol.

[8] "Positive effect on biofuel use" means an increased share of biofuels in the transportation fuel scenario.

Changes 1, 2 and 3 are combined to generate Figure 9a and changes 1, 2, 3 and 4 are combined to generate Figure 9b.

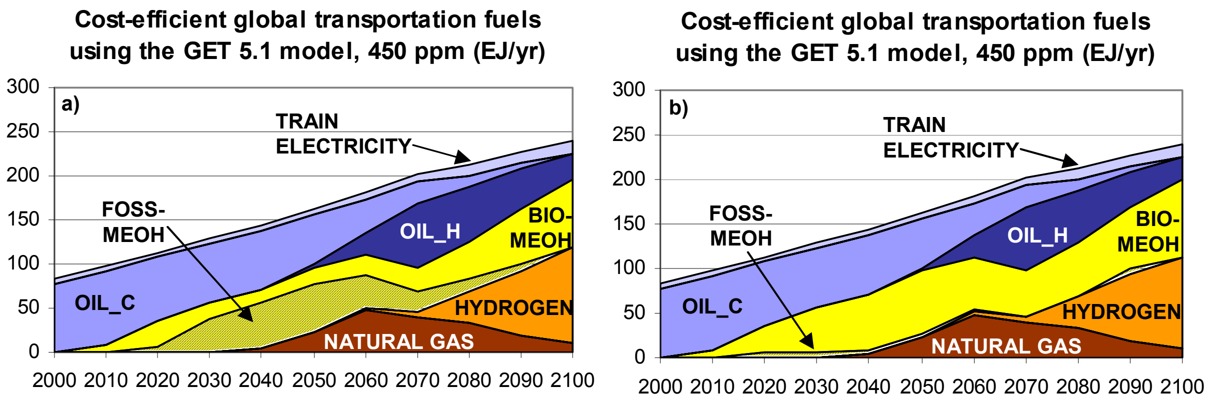

Fig 9. Cost-efficient fuel choices in the transportation sector in two runs with a) changes 1, 2 and 3 combined and b) changes 1, 2, 3 and 4 combined. In these runs biofuels account for a) 12% and b) 44% of total transportation fuels in the year 2050. Both runs reach 450 ppm by year 2100. Acronyms used in the figure are OIL_C= conventional oil, OIL_H= unconventional heavy oils, FOSS-MEOH= methanol derived from fossil fuels and BIO-MEOH= biomass based methanol.

It is shown that the use of biofuels is a cost-effective strategy to reduce CO_2 emissions, if we assume a lower conventional oil supply potential, a larger biomass supply potential, that waste heat generated in the production of transportation fuels may be sold to the heat market and that 25% of all biomass used for heat production need to be refined. In Figure 9b, a large amount of biofuels, accounting for 44% of total transportation fuel production by the year 2050, is used.

6. Conclusions

Cost-effective fuel choices generated in the GET model are first and foremost a result of a system effect. Biofuels do not appear as a cost-effective fuel choice since that would imply that hydrogen from solar energy would be necessary to satisfy the demand for heat (to be able to reach ambitious CO_2 concentration levels). This is, using our technology cost parameters, more costly than using biomass for the heat sector and using the hydrogen in the transportation sector. For that reason, hydrogen from solar becomes the cost-efficient fuel choice in the long run also in the GET 5.1 model transportation sector.

In this study, we have developed a method, implemented in Excel, which explains the GET model result and gives deeper insights about the system effect. By studying the cost dynamics in the GET model, i.e. comparing the generated total costs per km for each fuel choice and identify the carbon tax intervals for each time step where biofuels have the lowest cost per km, we find that the required carbon tax level where biofuels become cost-efficient compared to fossil based fuels, is evasive. The tax level moves upwards with increasing carbon taxes, since this leads to an increasing biomass primary energy price in the model.

In the sensitivity analysis we find that the model is sensitive for some type of changes. If we assume a lower conventional oil supply potential, a larger biomass supply potential, that waste heat generated in the production of transportation fuels may be sold to the heat market and that 25% of all biomass used for heat production need to be refined, and combine these four assumptions, a large amount of biofuels will enter the transportation fuel scenario. In a future work we will, however, continue the sensitivity analysis and also look deeper into how reasonable these new assumptions are and analyze possible barriers for introducing them.

Acknowledgement

Financial support from Swedish Agency for Innovation Systems, Vinnova, and Swedish Energy Agency is gratefully acknowledged.

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