THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Cost-effective fuel and technology choices in the transportation sector in a future carbon constrained world

Results from the Global Energy Transition (GET) model

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Göteborg, Sweden 2009

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Doktorsavhandlingar vid Chalmers Tekniska Högskola
Ny serie nr 2958
ISBN: 978-91-7385-277-7
ISSN: 0346-718X

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Printed by Chalmers Reproservice
Göteborg, Sweden 2009

Abstract

This thesis analyzes future fuel and technology choices focusing on transport in a carbon constrained world. The analysis tool used in all five appended papers is the cost-minimizing Global Energy Transition (GET) model. *Paper I* analyzes cost-effective fuel and technology choices for passenger vehicles under a variety of vehicle cost-assumptions and how these choices depend on technology paths in the electricity sector. We find that cost estimates as well as the availability of carbon capture and storage technology and concentrating solar power have a substantial impact, ranging from a dominance of hydrogen to a dominance of electricity. *Paper II* analyzes the cost-effectiveness of biofuels for transportation, assuming that industrialized regions start reducing their CO_2 emissions some decades ahead of developing regions. We find that biofuels may play a more important role for transportation in industrialized regions if these regions assume their responsibilities and reduce emissions before developing regions start reducing theirs, compared to the case in which all countries take action under a global cap and trade emissions reduction regime. *Paper III* analyzes how policy instruments aimed at increasing the use of biofuels for transportation in industrialized regions affect CO_2 emissions in industrialized and developing regions. We find that such policy instruments may lead to avoided emissions in industrialized regions, especially during the first 50 years, and in a few specific cases in the developing regions, too. However, in the majority of cases, such a biofuels policy leads to increased emissions in the developing regions, i.e., to “carbon leakage.” *Paper IV* analyzes why two global energy systems models reach different results on the cost-effectiveness of biofuels, although the models have strong similarities. We find biomass most cost-effectively used for heat production at low CO_2 taxes in both models. Biomass allocation at higher CO_2 taxes may depend on whether CO_2-neutral hydrogen and/or electricity are assumed available for the transportation sector at sufficiently low cost. *Paper V* investigates prices and costs in the GET model, and how these change over time, to get a deeper understanding of why biofuels generally are not a cost-effective transportation fuel choice in the model. We compare the total cost per km for each fuel choice, based on the primary energy prices and carbon tax generated by the model. We find that the required carbon tax level for biofuels to become cost-effective, compared to fossil-based fuels, is a “moving target.” The required tax level increases with an increase in carbon taxes, since the latter increases the price of biomass energy in the model.

Keywords: global energy systems modeling, CO_2 emissions, carbon tax, carbon leakage, energy prices, transportation, passenger vehicles, CCS, CSP, biomass, liquid biofuels, hydrogen

List of papers

This thesis is based on the following appended papers:

I. **Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO_2 targets: connections between transportation and other energy sectors.** Grahn M, Williander MI, Anderson JE and Wallington TJ. *Environmental Science and Technology* (2009) 43(9): 3365–3371.

II. **The role of biofuels for transportation in CO_2 emission reduction scenarios with global versus regional carbon caps**. Grahn M, Azar C and Lindgren K. *Biomass and Bioenergy* (2009) 33: 360–371.

III. **Will biofuels directives in industrialized regions lead to lower CO_2 emissions in non-industrialized regions – a reverse form of carbon leakage?** Grahn M, Azar C, Lindgren K and Hansson J. Work in progress.

IV. **Biomass for heat or as transportation fuel? A comparison between two model-based studies**. Grahn M, Azar C, Lindgren K, Berndes G and Gielen D. *Biomass and Bioenergy* (2007) 31: 747–758.

V. **Biomass for heat or transport? An investigation of prices and costs in the GET model.** Grahn M, Lindgren K and Azar C. Work in progress.

Other publications by the author

Grahn M, Williander M (2009). The role of ICEVs, HEVs, PHEVs, BEVs and FCVs in achieving stringent CO_2 targets: results from global energy systems modeling. *Conference Proceedings*, EVS24, Stavanger, Norway 13–16 May.

Grahn M (2007). Ecolabelling fuels for transport with the Swan label. *Background report*. 30 April.

Grahn M, Azar C and Lindgren K (2007). Cost effective fuel choices in the transportation sector under different international climate regimes – results from a regionalized version of the global energy transition model, GET-R. *Conference Proceedings*, Berlin, Germany, 7–11 May.

Azar C, Berndes G, Hansson J, Grahn M (2006). A critique of the "Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprint" by Dias de Oliveira *et al.*, BioScience, July 2005/Vol. 55 No.7 On Brazilian ethanol and the ecological footprint. *BioScience*, Vol. 55, No. 1.

Grahn M, Azar C, Lindgren K, Berndes G and Gielen D (2006). Cost-effective use of biomass – A comparison between two model-based studies. *Conference Proceedings* RIO6, World Climate and Energy Event, Rio de Janeiro, Brazil. 17–18 November.

Grahn M, Azar C, Lindgren K, Berndes G and Gielen D (2005). Biomass for heat or as transportation fuel? A comparison between two model-based studies. *Conference Proceedings*. Paris, 17–21 October.

Jonasson K, Hansson J, Grahn M, Berndes G and Sandén B (2005). *Remissyttrande* på slutbetänkandet från utredningen om förnybara fordonsbränslen, Introduktion av förnybara fordonsbränslen – SOU 2004:133 (in Swedish).

Grahn M (2005). Biodrivmedel ur ett globalt och svenskt perspektiv. Text till Sveriges riksdagsmän inför seminariet ”Bortom Kyotoprotokollet – vetenskap för långsiktig hantering av klimatfrågan” under Riksdagens Framtidsdagar, 15–17 March (in Swedish).

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”Miljöhänsyn handlar inte om att sluta leva, utan om att börja tänka.”[1]
Craig Venter,[2] biologist, USA

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[1] This quote is taken from a wall-poster at National Geographic’s headquarters. The renowned photographer Mattias Klum noticed the poster (email correspondence 2008-10-22). My free and loose translation back to English: *“Environmental awareness is not about deprivation, it's about inspiration”*.

[2] Dr. Craig Venter is the author of more than 200 research articles and the founder and President of the J. Craig Venter Institute (JCVI), a not-for-profit, research and support organization with more than 400 scientists dedicated to human, plant and environmental research, seeking alternative energy solutions through genomics.

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Acronyms and Definitions

Regions

AFR	Africa
AFSAPA	Regions with current very low GDP and CO_2 emissions (AFR+SAS+PAS)
CPA	Centrally Planned Asia (including China)
D-REG	Developing regions (AFSAPA+LAMEC)
EEU	Eastern Europe
EUR	Europe (WEU+EEU)
FSU	Former Soviet Union
I-REG	Industrialized regions (NAM+EUR+FSU+PAO)
LAM	Latin America
LAMEC	Regions with current modest GDP and CO_2 emissions (LAM+MEA+CPA)
MEA	Middle East
NAM	North America
PAO	OECD countries in the Pacific Ocean (including Japan and Australia)
PAS	Other Pacific Asia
SAS	South Asia (including India)
WEU	Western Europe

Energy carriers

Air_fuel	Aviation fuel alternatives: 1) Synthesized from coal, gas, oil or biomass, 2) liquefied natural gas or 3) liquefied hydrogen.
Biofuels	Biomass-based fuels in the transportation sector
BTL	synthetic fuels derived from biomass
CTL	synthetic fuels derived from coal
DME	Di-methyl ether
FT	Fischer-Tropsch products, e.g., synthetic diesel, gasoline, kerosene
GTL	synthetic fuels derived from natural gas
H_2	Hydrogen
HTU oil	Hydro Thermal Upgrading of biomass to gasoline and diesel qualities.
MeOH	Methanol
NG	Natural (fossil) Gas
Petro	Petroleum fuels, e.g., gasoline, diesel, kerosene

Synfuels	Fuels synthesized from syngas (via gasification), e.g., MeOH, DME, FT

Vehicle technologies

BEV	Battery electric vehicle
FCV	Fuel cell vehicle
HEV	Hybrid electric vehicles (an internal combustion engine and an electric engine)
ICEV	Internal combustion engine vehicles
PHEV	Plug-in hybrid electric vehicle (a HEV with a larger battery that can be loaded from the electric grid)

Energy demand sectors

Aviation	Passenger and freight transportation by air (in the regionalized model the energy demand for high speed train has been included in Aviation).
CARS	Motor vehicles for personal use, e.g., cars, motorbikes, light vans.
ELEC	Electricity
FRG	Freight: Ocean and road transports, e.g., trucks, buses, ships.
HEAT	Stationary energy sector including all energy use except for electricity or transportation fuels

Miscellaneous

BAU	Business as usual. A scenario assuming no actions taken for CO_2 reductions
CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
CSP	Concentrating solar power
EJ	10^{18} Joules
GET	Global Energy Transition. Acronym for our energy systems model
GHG	Greenhouse gases, (e.g., CO_2, CH_4, N_2O, and chlorofluorocarbons CFCs)
GJ	10^9 Joules
GUSD	10^9 US Dollars
N_2O	Nitrous oxide
PPM	parts per million
TW	10^{12} Watts
WRE	emission reduction curves developed by Wigley, Richels and Edmonds

1. Introduction

Science does not, and will never, deliver static final knowledge. To explain nature, we use models. Often, these models are further developed when we get more information. The model describing the movements within our solar system is a famous example of such a continuously developing model. Ptolemy's geocentric model, which assumed the Earth at rest in the center of the universe, with the rest of the planets revolving around it, was replaced in 1543 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 we use today, based on physical laws described by Isaac Newton and Albert Einstein, where the sun is at the center of our solar system, which moves in the Milky Way galaxy, which moves in the universe. Climate models have been developed over time (Weart, 2008),[3] including numerous complex interactions within the climate system, and from these models we now have a scientific understanding that the Earth is facing the beginning of a climate change.

1.1 Background

Information from polar ice cores[4] makes it possible to place modern temperature and greenhouse gas (GHG) changes in the context of long-term natural cycles. By studying ice cores from, e.g., eastern Antarctica and Greenland, we know that the atmospheric CO_2 concentration and surface temperature[5] have been varying fairly regularly, due to changes in the Earth's orbit.[6] Over the last 800 000 years, atmospheric CO_2 concentrations have ranged between roughly 180 and 300 ppm (Lüthi *et al.*, 2008). Over the last period of 420 000 years (as shown in Fig. 1) five natural peaks at around

---

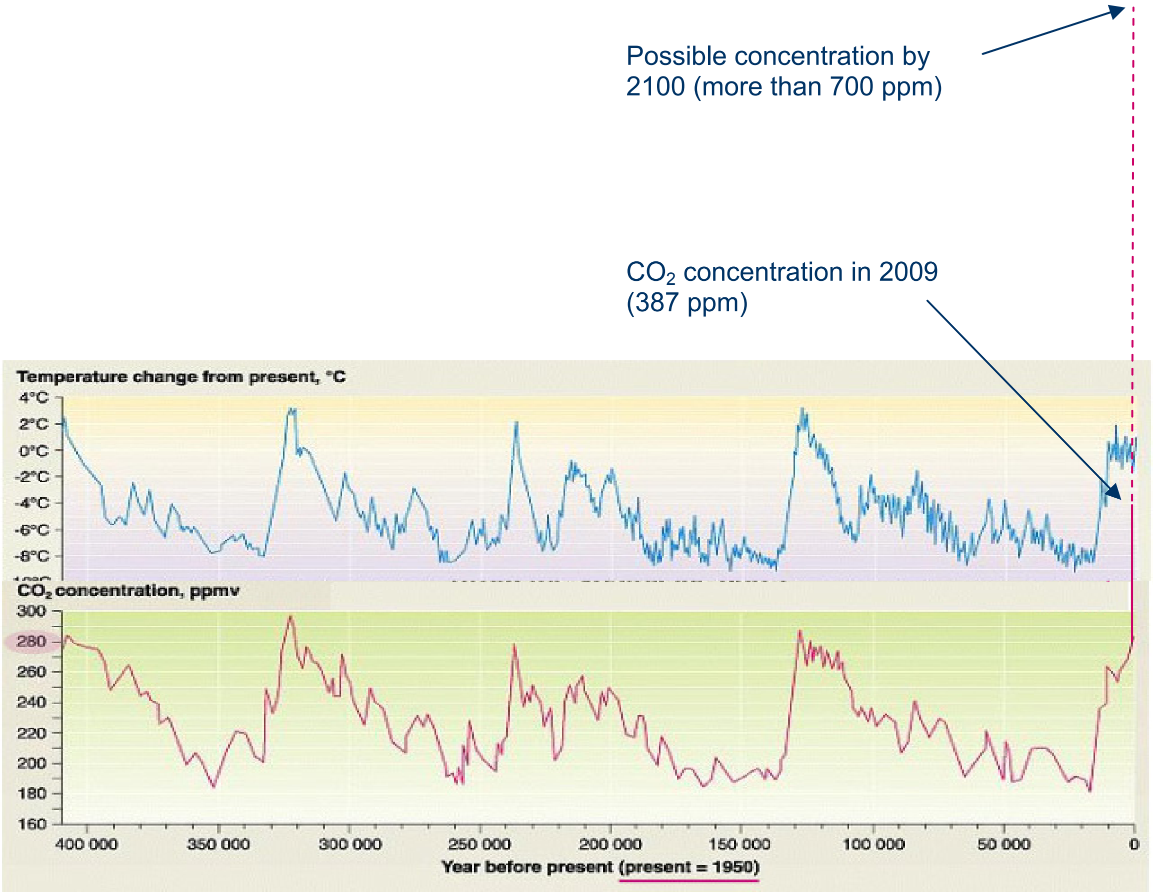
[3] Weart (2008) includes a description of how climate models have been developed over time. Simple climate models used in energy systems models include, e.g., the ICLIPS model (Bruckner *et al.*, 2003) and the MAGICC model (Wigley, 2008). See also summaries of climate model results in IPCC (2007a) and Solomon *et al.* (2007).

[4] For ice core studies, see, e.g., Petit *et al.* (1999) presenting the Vostok Ice core covering data for 420 000 years, Siegenthaler *et al.* (2005) presenting the EPICA's ice core covering data for 650 000 years and Jouzel *et al.* (2007) as well as Lüthi *et al.* (2008) presenting the ice core with the, so far, longest period, 800 000 years.

[5] Ice core scientists use the ratio of deuterium (hydrogen with both a proton and a neutron) to hydrogen in ice as a proxy for temperature (Brook, 2005).

[6] Much of the variability occurs with periodicities corresponding to that of the precession (changes in the direction of the axis), obliquity (angle of the rotational axis) and eccentricity (how much the Earth's orbit deviates from a circle) (Petit *et al.*, 1999).

280 ppm have occurred. The four intermediate periods (with the lowest around 180 ppm) are glacial periods, referred to as "ice ages" in everyday language. The most recent of these natural peaks started about 10,000 years ago. During the last 1000 years (until the industrial revolution), the atmospheric CO_2 concentration has been around 280 ppm. The fundamental conclusion from these ice core studies is that today's CO_2 concentration, 387 ppm (NOAA, 2009), has not been seen during the last 800 000 years. Reason for concern is twofold: the CO_2 concentration level is about 100 ppm higher than in these historical records, and the GHG emissions have soared over the last century. Present rapid increase in CO_2 concentration has not been seen during the last 800 000 years either. If the future use of fossil fuels is not constrained, it is possible that the CO_2 concentration level will reach 700–900 ppm[7] during this century, see Figure 1.



Possible concentration by 2100 (more than 700 ppm)

CO_2 concentration in 2009 (387 ppm)

Figure 1. Atmospheric carbon dioxide concentration and temperature change during the last 420 000 years from the Vostok ice core (Petit *et al.*, 1999; IPCC, 2001) and a projection of future concentration if current trends in fossil fuel use are sustained.

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[7] An atmospheric CO_2 concentration of 895 ppm is determined, for 2100, assuming the high growth demand scenario "A1" in Nakicenovic *et al.* (1998), combined with the carbon cycle from Maier-Reimer & Hasselman (1987). The range of 700-900 ppm is given in order to take different energy demand and technology paths scenarios into account.

Scientific understanding of the physics of the greenhouse effect[8] and the role of atmospheric carbon dioxide is good (Harvey, 2000). Scientific understanding regarding the anthropogenic contribution to global warming can be divided into two parts: (a) the theory that anthropogenic greenhouse gas emissions tend to contribute to global warming in a way that may have consequences in the long run, and (b) the hypothesis that these GHG emissions constitute the major contribution toward the already documented increase in global mean temperature (Häggström, 2008). Scientific agreement regarding theory (a) goes far back and is solid.[9] Measurements since 1958 from Mauna Loa on Hawaii clearly show a steady increasing CO_2 concentration (NOAA, 2009), and the greenhouse effect from an increased CO_2 concentration was first estimated over hundred years ago (Arrhenius, 1896). Regarding hypothesis (b), an indication of current scientific agreement is that Oreskes (2004) found that none of 928 abstracts published in refereed scientific journals listed in the ISI database with the keywords "global climate change"[10] (between 1993 and 2003) disagreed with the position that most of the observed warming in the past 50 years is likely due to human increases in GHG concentrations.

The tight link between historic greenhouse gases and surface temperature (as shown in Figure 1), is not yet fully understood. Historical carbon dioxide variability is likely an oceanic phenomenon, affected by changes in ocean circulation, biological productivity and carbon dioxide solubility, but the exact mix of mechanisms is not clear (Brook, 2008). How sensitive the climate is to the current increase of greenhouse gases and how sensitive plants and animals are to a temperature rise need further study.

The Intergovernmental Panel on Climate Change (IPCC) assesses current scientific knowledge on climate and produces books (assessment reports) every five years or so.

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[8] The term greenhouse effect refers to the reduction in outgoing heat radiation to space due to the presence of the atmosphere (Harvey, 2000). The natural greenhouse effect is necessary for 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). Azar (2008, p. 186) reminds us that this temperature difference is a simplification, since a planet mainly covered in ice would reflect more of the solar radiation and decrease the global mean temperature even more.

[9] By now, reservations regarding the claims that (i) anthropogenic CO_2 emissions tend to increase the atmospheric CO_2 concentration and (ii) an increased CO_2 concentration tends to increase the global mean temperature can no longer be found in the peer-reviewed literature (Häggström, 2008).

[10] The first year for which the database consistently published abstracts was 1993. Some abstracts were deleted from the analysis because, although the relevant authors had included "global climate change" as a key word, climate change was not the topic (Oreskes, 2004).

In the latest assessment report, the IPCC states that the equilibrium climate sensitivity (the global annual average surface warming following a doubling of the atmospheric carbon dioxide concentration) is likely to be in the range of 2°C to 4.5°C, with a best estimate of about 3°C. They also state that it is too early to exclude values even substantially higher than 4.5°C but that the climate sensitivity is very unlikely to be less than 1.5°C. The uncertainty is due to different feedback mechanisms in the climate system, and cloud feedbacks are currently the largest source of uncertainty (IPCC, 2007a).

The IPCC report presents examples confirming that we already see the effects of increasing the average global surface temperature. At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice coverage, changes in precipitation, ocean salinity, wind patterns, and aspects of extreme weather including droughts, heat waves, and the intensity of tropical cyclones. The observed global surface temperature increase is mainly caused by changes[11] in the concentration of atmospheric greenhouse gases (CO_2, CH_4 and N_2O) and aerosols, in solar radiation and in land surface properties affecting the energy balance of the climate system (IPCC, 2007a).

Carbon dioxide is the most important anthropogenic greenhouse gas. The increased atmospheric concentration of carbon dioxide results first and foremost from fossil fuel use, with land-use change providing another significant, but smaller, contribution. The IPCC finds that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations and very likely not due to known natural causes alone. The IPCC also finds it is likely that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place (IPCC, 2007a).

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[11] These changes are from both human and natural factors, e.g., aerosols from volcanoes and storms, tropospheric emissions of ozone-forming chemicals (nitrogen oxides, carbon monoxide, and hydrocarbons), changes in surface albedo, due to land cover changes and deposition of black carbon aerosols on snow, and emissions of greenhouse gases.

1.1.1 Reducing CO_2 emissions from the energy system

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty created in Rio de Janeiro, 1992. The principal update is the Kyoto Protocol, which has become better known than the UNFCCC itself. The UNFCCC's stated objective is "to achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 2008).

Defining what CO_2 concentration level would avoid "dangerous anthropogenic interference" with the climate system remains a challenge. However, the 2007 Bali Climate Declaration, prepared at the Climate Change Research Centre in Sydney and signed by more than 200 scientists worldwide, states that the primary goal must be to limit global warming to no more than 2ºC above the pre-industrial temperature (Allan *et al.*, 2007). This limit has already been formally adopted by the European Union (European Council, 2005) and a number of other countries (Meinshausen, 2009). Allan *et al.* (2007) argue that this requires that greenhouse gas concentrations, in the long run, be stabilized at a level well below 450 ppm measured in CO_2-equivalents[12], which equals 350–400 ppm measured in CO_2 concentration alone (Fisher *et al.*, 2007 [Fig 3.16]; Johansson, 2009; IPCC, 2007b [Table 5.1]). Also Azar and Rodhe (1997) suggest that a temperature increase of 2ºC 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 CO_2 possible, to avoid reaching this critical level.

O'Neill and Oppenheimer (2002), further, argue that stabilizing 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.

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[12] Bowman *et al.* (2009) strongly recommend referencing atmospheric concentrations of all long-lived greenhouse gases, as CO_2-equivalents, not only CO_2. However, the uncertainties, especially in N_2O emissions, are currently large. In this thesis, all values of atmospheric concentrations are expressed in CO_2 concentration alone, if not stated otherwise.

A large transition of the global energy system is necessary to be able to reach ambitious CO_2 stabilization levels. 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, renewable, and intra fossil fuel substitution (substitute coal with a less carbon-intensive fuel, e.g., natural gas).
- Use fossil fuels or biomass with carbon capture and storage (CCS) technologies.

These three strategies are illustrated in Figure 2.

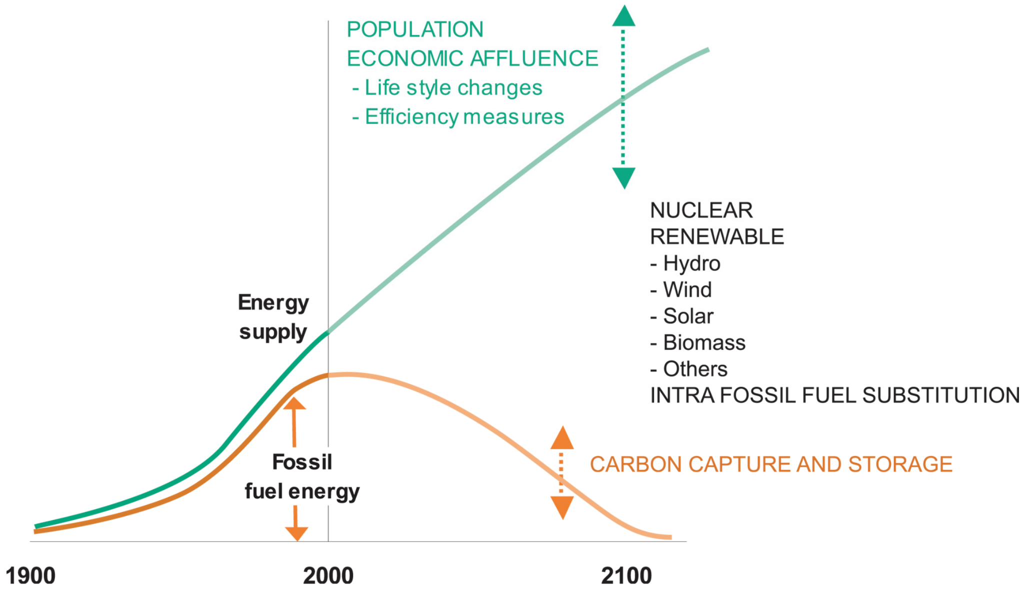

Figure 2. Strategies to reduce CO_2 emissions from the energy system. The upper line illustrates the increase in global energy demand during the past century and a projection for this century. The lower line represents the fossil fuel share of the global energy supply. Global CO_2 emissions from fossil fuels need to radically decrease during this century to meet an ambitious CO_2 reduction 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, renewable, and substituting 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 (figure inspired by Björn Sandén, Environmental Systems Analysis, Chalmers).

Population is one of the factors affecting CO_2 emissions from the energy systems. According to Hardin (1991) it is scientifically possible to support 50 billion people at the "bread" level, if we give up all luxuries such as wine and beef. Stabilizing the global population close to the current level instead of increasing population continuously would have a significant effect on future emissions. Richard E. Smalley suggests that a stabilization of global population may occur on its own: “whenever a nation begins to develop, the fertility rate generally drops. During our lifetime, we will see worldwide population growth continue to slow down, then level out at somewhere around 10 billion people. Our challenge then is to make it possible for 10 billion people to live a reasonable lifestyle on this planet" (Smalley, 2005).

CO_2 emissions reductions from life style changes and energy efficiency measures are often identified as the most important strategies. In industrialized regions, future energy demand per person for transportation, heating, and electricity may even be cut in half. A challenge to this theoretical potential is that energy efficiency improvements may rebound through increasing consumption. There are at least two categories of rebound effects: (i) *the price effect*, energy efficiency lowers the costs and increases the demand, and (ii) *the income effect*, energy efficient technologies save money that can be used for increased consumption (Nässén, 2007).

Uncertainties regarding population, life style, and efficiency factors may mean that we need to rely even more on the two other options for cutting emissions, i.e., changing primary energy sources and carbon capture and storage[13].

The three main strategies to reduce carbon dioxide emissions from the energy system, presented in Figure 2, have different advantages and disadvantages, which I have not weighed or analyzed within this thesis. Possible emissions reduction strategies for the transportation sector are presented in the next section.

1.1.2 Reducing CO_2 emissions from the transportation sector

There are four main strategies for reducing CO_2 emissions from the transportation sector:

1. replace current vehicles with more energy efficient vehicles;
2. select modes of transportation that emit less CO_2 emissions per person, e.g., rail instead of aviation, bicycle or public transport instead of cars, and so on;
3. build cities that reduce transportation needs;
4. introduce low CO_2 emitting transportation fuels.

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[13] Two sectors where it may be difficult to count on these two options are, however, emissions from cattle farms and high level emissions from aviation (Azar, 2008).

Current commercial alternative transportation fuels, as well as promising future options, which can be used in both traditional internal combustion engines and in new more efficient engines, are presented in Figure 3.

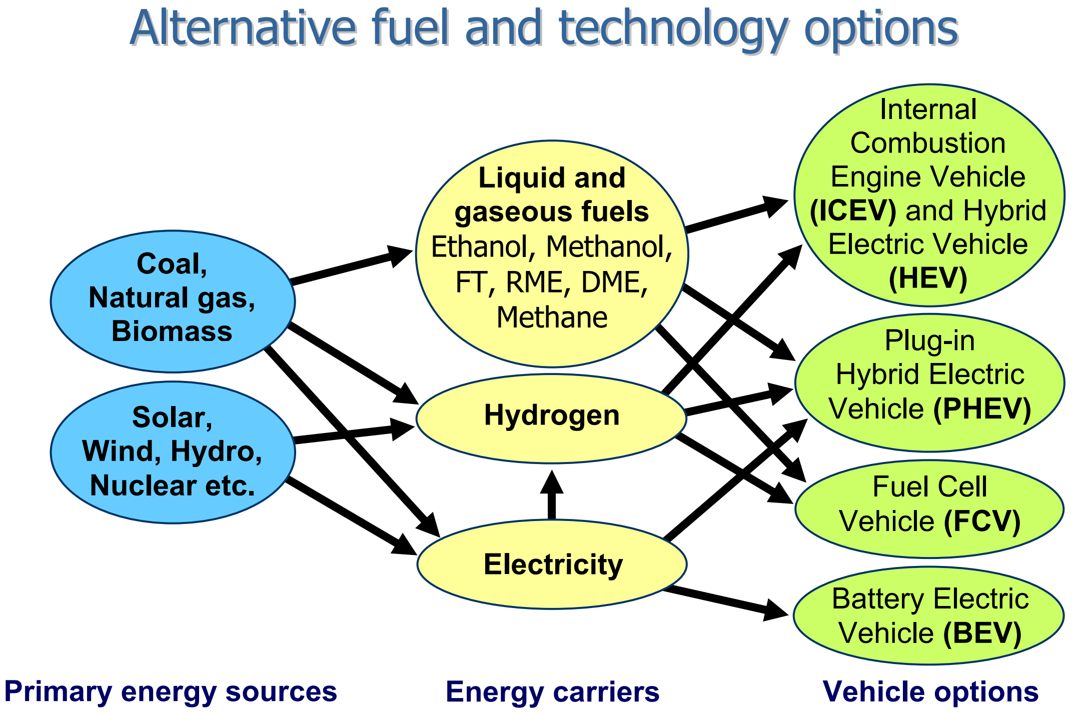

Figure 3. Alternative transportation fuels can be produced from solid, liquid and gaseous primary energy sources as well as from primary energy sources generating electricity. Current commercial alternative transportation fuels are ethanol, methane (biogas and natural gas), biodiesel here represented by rapeseedmethylester (RME) and fossil-based Fischer-Tropsch (FT) gasoline and diesel. Promising future low CO_2 emitting energy carriers are electricity, hydrogen, and biomass-based synthetic fuels, i.e., methanol, FT products, dimethyl ether (DME), and methane.

If fossil fuels, i.e., coal, oil, and natural gas, are used as primary energy sources, the carbon atoms can be captured, pumped underground, and prevented from reaching 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 and is, e.g., used in the Sleipner Gas Field in the North Sea (Statoil-Hydro, 2009; Bellona, 2009) but has extra costs and is not yet used in large-scale power generation or alternative fuel production. If hydrogen is produced via electrolysis it can only be CO_2 neutral if the electricity used 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, which can be converted into transportation fuels in several ways, e.g., via anaerobic digestion into biogas, fermented into ethanol, gasified and synthesized into synfuels, (e.g., Fischer-Tropsch diesel, dimethyl ether (DME), methanol, methane, hydrogen), or vegetable oils can be transesterified into biodiesel (e.g., RME), see Figure 4.

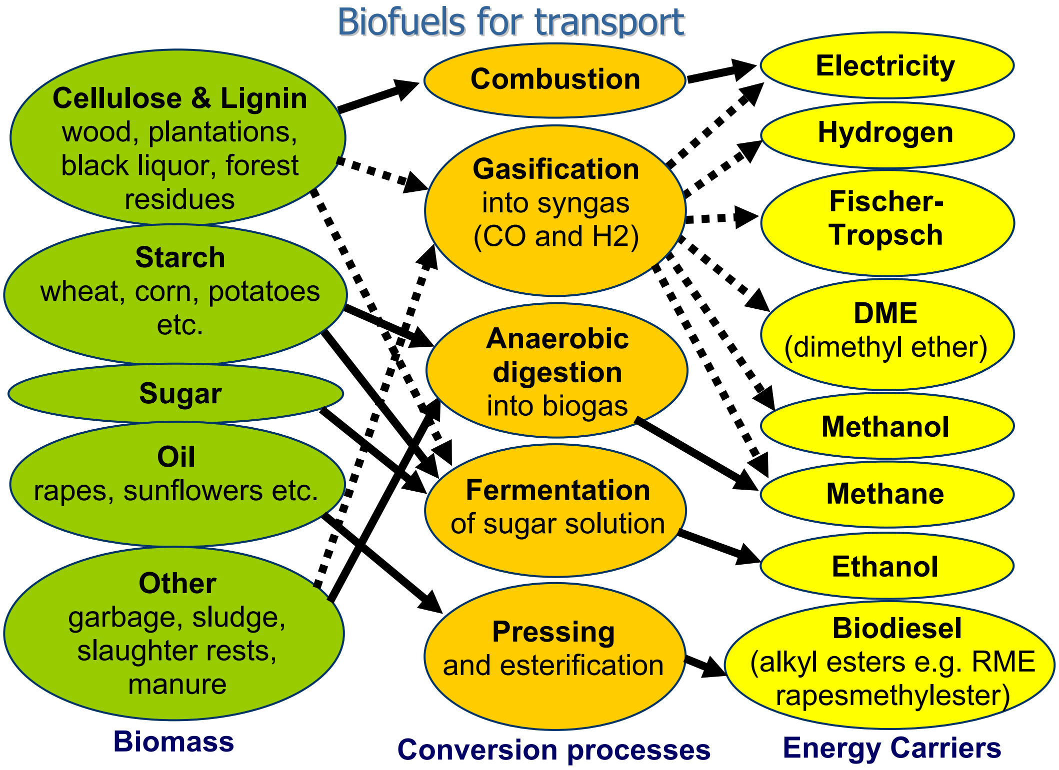

Figure 4. Biomass can be divided into groups depending on chemical composition of the biomass. Different elements are better suited for different processes that convert the biomass into energy carriers useful for the transportation sector. Commercially available options are marked with solid lines, while processes still on demonstration plant level are marked with dotted lines (figure inspired by Christian Azar, Physical Resource Theory, Chalmers).

In the research done within this thesis, we have simplified the different biomass-based fuel options to one category called *biofuels*,[14] or *BTL* (biomass to liquid), with cost estimates taken from the gasification process and methanol as final fuel.

1.2 Objective and scope of this thesis

The thesis consists of five appended papers and these introductory remarks contextualizing the research, presenting the methods and main results, as well as discussing and comparing the results with other similar studies. The objective of this

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[14] In this thesis, "biofuels" always means liquid or gaseous hydrocarbons made from biomass, to be used in the transportation sector.

thesis is to analyze future fuel and technology choices, focusing on transport, in a cost-minimizing, energy systems modeling framework. The research is a continuation of earlier research at Physical Resource Theory, where Christian Azar and Kristian Lindgren have developed a global energy systems model for the purpose of analyzing cost-effective fuel choices in the transportation sector (Azar *et al.*, 2000, 2003). This initial globally aggregated version of the Global Energy Transition model (GET 1.0) did not generally find biofuels a cost-effective strategy for reducing CO_2 emissions. This raised questions. In all five papers within this thesis, we have used further-developed versions of the GET model for the purpose of studying the cost-effective fuel and technology choices in the transportation sector in more detail. The research in this thesis can be grouped in the following topics:

- The effect of different technology paths in the electricity sector
- The effect of regionally different CO_2 policies
- Identifying and analyzing critical parameters affecting results on biofuels

The main questions posed in each paper and their relation to the topics above is as follows:

Paper I: At the time when the GET 1.0 model version was developed there were limited reports regarding battery improvements and electricity was not included as an energy carrier for passenger vehicles in the model. Battery improvements, over the last years, as well as the trends seen in the car industry towards hybrids and plug-in hybrids, motivate the inclusion of electricity as an energy carrier for passenger vehicles in a further developed GET model version. This study analyzes cost-effective fuel and technology options shown for the passenger vehicle sector under a variety of cost-assumptions and how these results depend on the developments assumed in the electricity sector. *Related to topic: "The effect of different technology paths in the electricity sector".*

Paper II: The Kyoto Protocol, in accordance with the idea that industrialized regions should take the lead, only stipulates reduction targets for developed nations, and this basic principle remains in the Bali Action plan. This study analyzes the cost-effectiveness of biofuels, assuming that industrialized regions start reducing their CO_2 emissions some decades ahead of developing regions. Will biofuels be a cost-effective strategy to reduce CO_2 emissions when there are regionally different CO_2 policies? *Related to topic: "The effect of regionally different CO_2 policies".*

Paper III: This study analyzes how policy instruments aimed at increasing the use of biofuels in industrialized regions, e.g., a biofuels directive, affect CO_2 emissions in industrialized and non-industrialized regions. Does such a biofuels directive lead to CO_2 reductions in the developing regions? Can it lead to globally increased emissions? *Related to topic: "The effect of regionally different CO_2 policies".*

Paper IV: This study analyzes why two similar global energy systems models reach different results on the cost-effectiveness of biofuels. In one study it is cost-effective to use biofuels for transportation, whereas the other study comes to the opposite conclusion. What key assumptions and/or model structure differs between these two models? *Related to topic: "Identifying and analyzing critical parameters affecting results on biofuels".*

Paper V: The aim of this study is to reach a deeper understanding of the prices and costs in the GET model to get a more clear picture on why biofuels generally are not a cost-effective fuel choice in the model. We study and compare the total cost per km for each fuel choice, based on the primary energy prices and carbon tax generated by the model. Why do not biofuels become cost-effective when carbon taxes increase? *Related to topic: "Identifying and analyzing critical parameters affecting results on biofuels".*

2. Method

All research done in this thesis involves global energy systems modeling.

2.1 Global energy systems modeling

Global energy systems models are generally well-suited for providing insights regarding energy/environmental policy and planning, e.g., CO_2 emissions reduction, market-based instruments, technology dynamics, and R&D (Seebregts *et al.*, 2002). When analyzing fuel and technology options in a carbon constrained world, a global energy systems model has the ability to account for competing demands for primary energy sources and fuels that may be used for transportation. Energy systems models are also useful for comparing the cost-effectiveness of greenhouse gas abatement activities in different sectors (Turton and Barreto, 2007). Energy systems models can further be used to address the cost of meeting stabilization targets, see, e.g., Barker *et al.* (2002) and Azar (1996) for an overview.

Energy systems models are, moreover, useful for constructing and comparing scenarios. The models make it possible to quantitatively explore the role and cost-effectiveness of various technologies given different carbon emissions constraints, resource availabilities, and parameter values for technologies. The models can be seen as experimental boxes where we can investigate relations between subunits that without the help of the model are not obvious. For a discussion regarding limitations of energy systems models, see Section 2.3.

Within this thesis, the GET model has been used as a tool for generating insights regarding:

- system effects between different energy sectors (electricity, heat and transportation)
- key technologies for reaching ambitious CO_2 reduction targets
- cost-effective fuel and technology choices in the transportation sector under different regionalized CO_2 targets, cost assumptions, etc.
- the effect on regional CO_2 emissions of introducing policies to reduce emissions in industrialized regions.

Many energy systems models and model versions have been developed over the last 30–40 years to study different aspects of fuel and technology choices in a carbon constrained world. For an overview of model types, see, e.g., Azar (1996), Barker *et al.* (2002) and Börjeson *et al.* (2005). Over the last years, an increasing number of model analyses have also included technological development through learning (e.g., Barreto, 2001; Hedenus *et al.*, 2006; Mattson & Wene, 1997), based on experience curves developed by, e.g., Neij (2003, 2008). Some model studies have focused on analyzing the effect of different fuel taxes (e.g., Endo, 2007; Börjesson & Ahlgren, 2008). Differences between cost-minimizing energy systems models are, e.g., the number of regions, the number of available fuel and technology options, as well as the number of modules and feedback mechanisms incorporated in the energy flow from the primary energy extraction to the end-use technology. Table 1 show differences between some cost-minimizing energy systems models that have been used to generate insights on cost-effective fuel and technology choices in the transportation sector.

Table 1. Comparison of some published energy systems model studies analyzing long-term cost-effective fuel and technology choices in the transportation sector. Acronyms are explained on page IX.

	Grahn *et al.* (appended Paper 1)	**Takeshita & Yamaji (2008)**	**Endo (2007)**	**Gül *et al.* (2007)**	**Turton & Barreto (2007)**	**Turton (2006)**	**Gielen *et al.* (2003)**
Model	GET-RC 6.1	REDGEM70	MARKAL	MARKAL EHM/GMM	ERIS	ERIS/ ECLIPSE	BEAP
Geographic coverage	Global 10 regions	Global 70 regions	Japan only	Eur only EU-25	Global 11 regions	Global 11 regions	Global 12 regions
Time horizon	2100	2100	2050	2100	2100	2100	2050
Analyzed CO_2 targets	BAU, 400, 450, 500, 550 ppm	550 ppm and BAU	Not analyzed	≈450 ppm use reduction curve	≈550 ppm use CO_2 tax	550 ppm	≈400, 450, 550 ppm uses tax
CCS an available option?	Yes, fossil fuels and biomass	Yes, fossil fuels and biomass	Not specified	Yes	Yes	Yes, fossil fuels and biomass	Yes, fossil fuels
H_2 and FCVs included?	Yes	Yes	Yes	Yes	Yes	Yes	Yes (only fossil H_2)
HEVs, PHEVs and BEVs?	Yes	HEVs only	HEVs and BEVs only	Yes	HEVs only	HEVs only	No
Comments	Analyzes the connection between available options in the stationary energy sector and cost-effective fuel and technology choices for cars. Includes a comprehensive sensitivity analysis on vehicle cost parameters.	Focuses on the competition within the synthetic fuels.	Focuses on finding what CO_2 tax is needed to fulfill Japan's FCV goal. Assumes very optimistic FCV costs. Only fossil H_2 enters the scenario.	Focuses on the prospects for hydrogen and biofuels in the European transporttation sector.	Analyzes the role of FCVs for different CO_2 taxes.	Focuses on how to reach a long-term sustainable energy system, e.g., maintaining a fossil fuel buffer, continuing economic growth, and ensuring mobility demand is met.	Focuses on the allocation of biomass. In which sector is the limited resource biomass most cost-effectively used?

2.2 Description of the Global Energy Transition (GET) model

To analyze future transitions of the global energy system, Azar and Lindgren developed the GET 1.0 (Global Energy Transition) model[15] (Azar *et al*., 2000, 2003). It is a linear programming global energy systems model which is set up to meet exogenously given energy demand levels while meeting a specific atmospheric CO_2 concentration at the lowest global system cost. The model does not include greenhouse gases other than CO_2. 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 less detailed way.

Research done within this thesis has used further-developed model versions, i.e., GET 5.0, for the comparison with results from the BEAP model (see appended Paper IV), and GET 5.1, for the investigation of prices and costs in the GET model (see appended Paper V). The GET model has also been regionalized, GET-R 6.0, and a six region model version has been used to analyze the effect of regionally different CO_2 reduction policies (see appended Papers II and III), and a ten region model version, GET-RC 6.1,[16] has been used to analyze the effect of different technology paths in the electricity sector (see appended Paper I). In the following section, the model version GET-RC 6.1 is presented.

2.2.1 Model structure

The model is composed of three major parts: (i) the primary energy supply with the supply options: coal, oil, natural gas, nuclear, hydro, wind, biomass, and solar energy; (ii) the energy conversion system with facilities that may convert the primary energy sources into secondary energy carriers; and (iii) the exogenously given final energy demand for heat, electricity, and transportation fuels (i.e., there is no price elastic

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[15] The GET model structure is similar to the structure of the MARKAL models. That is, various costs for carbon may be generated for different levels of emission reduction constraints. Future technology configurations are generated and may be compared. If constraints are also placed on the availability of primary energy sources as well as types of technologies and rates of penetration, the configuration of the entire energy system will change. The models will produce the least-cost solution subject to the provided set of constraints. For full description of MARKAL, see Seebregts *et al.* (2002).

[16] R stands for regionalized model version and C stands for cars since this model version focuses on the light duty passenger vehicle sector, utilizing expertise from the auto industry for assumptions on future fuel and technology options.

response). The fuel demand for the transportation sector, however, depends on the choice of vehicle drive train. The energy and carbon dioxide flows in GET-RC 6.1 are shown in Figure 5.

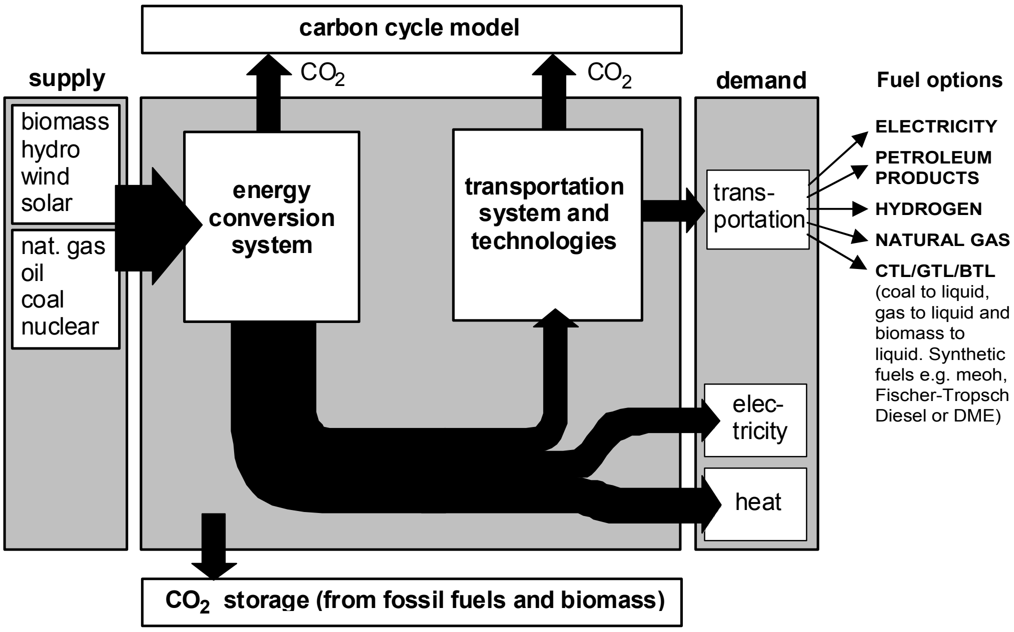

Figure 5. The main energy and carbon dioxide flows in GET-RC 6.1.

The GET-RC 6.1 model includes the following fuel (energy carrier) options for transportation: gasoline/diesel, natural gas, synthetic fuels (coal to liquid, CTL; gas to liquid, GTL; biomass to liquid, BTL), as well as hydrogen and electricity. Powertrain technologies included are: internal combustion engine vehicles, (ICEVs), fuel cell vehicles (FCVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Combinations of these fuel and vehicle technologies cover most likely options.[17]

The atmospheric CO_2 concentration is derived from the use of fossil fuels by using a carbon cycle module (Maier-Reimer & Hasselmann, 1987). The total CO_2 emissions in the model may be constrained by entering a specific atmospheric CO_2 concentration stabilization target, a specific aggregated emission cap, an emission cap per time step or by CO_2 taxes. In GET-RC 6.1, the emissions are constrained by global emission curves developed by Wigley, Richels and Edmonds (WRE) (Wigley *et al.*, 1996). The GET

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[17] However, gaseous fuels in HEVs and PHEVs are not an option in GET-RC 6.1.

model allows for carbon capture and storage technologies for the production of heat, electricity, and hydrogen, based on fossil fuels and biomass.[18]

In GET-RC 6.1, the world is treated as 10 distinct regions: North America (NAM), Europe (EUR), the Former Soviet Union (FSU), OECD countries in the Pacific Ocean (PAO), Latin America (LAM), the Middle East (MEA), Africa (AFR), Centrally Planned Asia – mainly China (CPA), South Asia – mainly India (SAS) and Pacific Asia (PAS), see Figure 6.

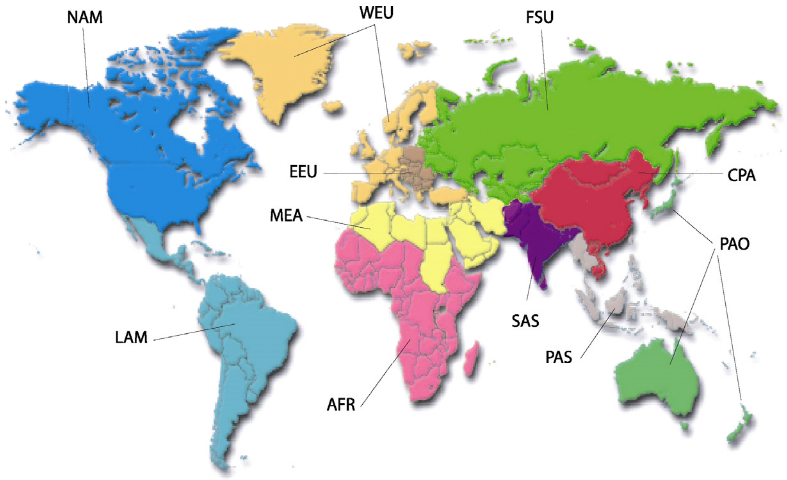

Figure 6. The regions assumed in GET-RC 6.1, except that in the model WEU (Western Europe) and EEU (Eastern Europe) are aggregated to EUR. The acronyms are explained in the text and on page IX of this thesis.

At an additional cost, most primary energy resources and fuels can be traded between regions. A cost minimization algorithm is applied to the model to generate cost-effective energy scenarios, subject to various constraints for the time period 1990–2130. Results from GET-RC 6.1 are presented for the period 2010–2100.

2.2.2 Energy demand scenarios

In 2000, the world used about 400 EJ of primary energy of which about 250 EJ were used by the roughly 1.3 billion people living in the industrialized world (roughly 200 GJ/capita/yr). Assuming that people in these countries will continue to use the same amount of energy per capita as today, and that people in developing countries increase

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[18] Biomass Energy with Carbon Capture and Storage (BECCS) has the potential to turn biomass into a continuous carbon sink, while at the same time offering carbon-free energy carriers, and may play an important role when aiming for atmospheric CO_2 stabilization targets at or below 400 ppm (Azar *et al.*, 2006).

their energy use to 200 GJ/capita, the total energy demand would be 2000 EJ/yr, assuming 10 billion people, by the end of this century. We have chosen an ecologically-driven energy demand scenario "C1" derived by IIASA/WEC (Nakicenovic *et al.,* 1998), which assumes that the energy demand of 2000 EJ/yr could be halved due to energy efficiency measures.[19] This lower energy demand is exogenously given in the model for electricity and heat (including low and high temperature heat for the residential, service, agricultural, and industrial sectors) sectors. Minor modifications from the "C1" demand scenarios were carried out so as to match actual values for the year 2000, for primary energy supplies and final energy use, with data taken from IEA (2000).

The transportation demand scenario is developed separately based on the transportation model developed by Schafer and Victor (Schafer, 1998; Schafer and Victor 1999; Schafer and Victor, 2000), assuming projections of global population from scenario "C1", which increases to 10 billion in 2050 and 11.7 billion in 2100, and assuming that an increase in the amount of person-kilometers traveled is proportional to the regional GDP growth (in PPP terms[20]) and that the choice of transportation mode changes with increased income. Transportation scenarios in GET are developed separately for passenger and freight transportation and disaggregated into trains, cars, buses, trucks, ships, and aviation. A detailed description of the GET demand development can be found in Azar *et al.* (2000). In GET-RC 6.1, the energy demand for the aviation sector has been modified, following the Sustainable Mobility Project (SMP) model developed by the World Business Council for Sustainable Development and the International Energy Agency (WBCSD, 2004).

In the original GET model, it was assumed that there is a total exogenous improvement in energy efficiency in the transportation sector by 0.7% per year. However, in GET-RC 6.1, we have split the total improvement factor in two. All cars are assumed to increase energy efficiency by 0.3% per year from improved air and rolling resistance, driving patterns, and so on. In addition, we have assumed a specific powertrain efficiency, where internal combustion and fuel cells are assumed to improve by 0.4% per year,

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[19] In sensitivity analyses and scenarios meeting less ambitious targets, we use IIASA's high-growth demand scenario "A1".

[20] The GDP expressed in PPP (purchasing power parity) terms takes the relative cost of living and the inflation rates of different countries into account, to equalize the purchasing power (Wikipedia, 2008b).

while batteries are assumed to improve by 0.12% per year, see Supporting Information for Paper I.

2.2.3 Assumptions and constraints

Primary energy supply potentials are given exogenously for each region. For the global supply potential for oil and natural gas, we have chosen approximately twice their present proved recoverable reserves in the year 1990, i.e., 12,000 and 10,000 EJ, respectively (Rogner, 1997; BP, 2007; WEA, 2000) and assumed a regional distribution following Johansson *et al.* (1993). For coal, we have chosen a global supply potential of approximately 260,000 EJ following the total resource estimates in Rogner (1997).

A detailed assessment of the biomass supply potential can be found in Berndes *et al.* (2003) and Hoogwijk (2004). Hoogwijk estimates the global supply potential to range from 130 to 439 EJ/yr (with a mean value of 253 EJ/yr) by the year 2050 from four different scenarios assuming two biomass production cost levels (lower than 2 USD/GJ and lower than 4 USD/GJ). This global potential is similar to Johansson *et al.* (1993), where estimates on regional biomass[21] supply potentials add up to a global maximum of 205 EJ per year, which we have chosen to follow in GET. The large, but nevertheless limited, biomass supply potential implies that biomass cannot completely replace fossil fuel use in all sectors. The model chooses to use biomass in the sector where it is most cost-competitive. Sensitivity analysis of primary energy supply potentials are carried out in all studies.

The supply potentials for wind and solar energy are huge and have therefore not been assigned an upper limit, but they are limited by expansion rate and intermittency constraints.

Data for most conversion plants (investment costs, conversion efficiencies, lifetimes, and capacity factors) are held constant at their "mature levels". Regionalized capacity factors for solar energy technologies give some advantages to the regions NAM, LAM,

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[21] For the biomass supply potential, we assume woody biomass and residuals in equal amounts, and the required land area for the assumed energy plantations corresponds roughly to a third of current agricultural cropland or around a tenth of total agricultural land, i.e., arable land plus pasture.

AFR, CPA, SAS, PAS and MEA. We have, further, put the global discount rate at 5% per year.

Technological change is exogenous in the GET model versions used in this study, i.e., the cost and performance, etc., are independent of previously installed capacity. We assume technology-mature costs throughout the time period considered. We checked to make sure that this does not lead to an unduly rapid adoption of technologies.[22] The impact of including endogenously technological change is judged to be limited in relation to other uncertainties in global long-term energy systems models minimizing costs under perfect foresight.[23] We further assume that technologies developed in one region are available for other regions. Global dissemination of technology is not seen as a limiting factor.

Constraints have been added to the model to prevent unrealistically fast changes in the energy system, i.e., constraints on the maximum expansion rates of new technologies (in general, these are set so that it takes at least 50 years to change the entire energy system), as well as annual or total extraction limits on the available energy sources.

The contribution of intermittent electricity sources (wind and solar PV) is limited to a maximum of 30% of electricity use. To simulate the actual situation in developing countries, a minimum of 30 EJ per year of the heat demand is required to be produced from biomass during the first decades. The total use of CCS is limited by the global carbon storage capacity, and we have generally set an upper limit of 600 GtC (IPCC, 2005).

The future role of nuclear energy is primarily a political decision and will depend on several issues such as nuclear safety, waste disposal, questions of nuclear weapons proliferation, and public acceptance. We assume that the contribution of nuclear power (in absolute numbers) is maximized at the level we have today.

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[22] Reduced investment costs are not what allow technology options to enter the scenario. Instead, conventional fuels become more and more costly as the carbon constraint gets more stringent.

[23] Endogenously technological change is included and analyzed in a GET model version run with limited foresight, see Hedenus *et al*. (2006).

Data assumptions made in GET-RC 6.1, including assumptions on battery performance and assumed driving distances in electric mode for PHEVs, are described in detail in the Supporting information for appended Paper I. Further details about data and technology assumptions are given in Azar *et al*. (2000, 2003, 2006) and appended papers.

The GET model will soon be available on-line where interested readers are welcome to study how the model results are affected by different parameter assumptions. A prototype of the web adaptation of the GET model can be found at http://129.16.11.117/.

2.3 Model limitations

It is important to remember that energy systems cost-minimizing models do not predict the future and are not designed to forecast the future development of the energy system. Instead, they provide a tool to understand system behavior, interactions and connections among energy technology options in different sectors. The description of the energy system in the models is a simplification of reality. Such simplifications include, for the GET model versions used in this thesis:

- the number of available fuels and technologies is limited;
- the demand is price-inelastic;
- decisions in the model are only based on cost considerations;
- there is no uncertainty about future costs or energy demand levels, etc.;
- the global energy system is optimized with perfect foresight and with a single global goal function.

All results obtained with energy systems models must be interpreted with care, including cost-results (model out-puts), which should not be presented as absolute numbers. A global long-term cost-minimizing model can never give an exact answer to how much a change will cost. The reason for that is first of all, that it is very hard to estimate costs (in-put data) of future technologies. Further, since models are a simplification of reality, only the most important costs are included. Also, even if all costs would have been included and estimated at the correct level, these models find the optimal solution, given perfect information. In real life, some perfect investments may be made, but less optimal choices will be made as well, and thereby the real costs will be higher than obtained in the models. Despite these difficulties, model out-puts on costs for a certain scenario are useful when comparing results between different runs assuming different developments of the energy system. The generated insights can for example be presented as rough percentage (instead of in absolute values) increases or decreases of a certain base cost-result, or in terms of reduction of baseline GDP projections, see e.g. Barker *et al*. (2002) and (Azar, 2006).

Another reason for treating GET model results with care is that the transition of the global energy systems to meet ambitious CO_2 reduction targets (subject to the constraints) is fulfilled at the lowest possible global cost. One could say that the GET model represents the energy system in an ideal market with no other policies other than CO_2 reduction. Cost-effectiveness is one important criterion for climate policy, but not the only one. In addition to the simplifications, there are other factors (factors that society may consider more important than cost-effective CO_2 reduction) not taken into account in the model. Factors not taken into account in the GET model include:

- Valuation of energy security, local pollution, and rural development
- Public acceptance of new technologies
- Alternatives may not be identical[24] for customers' purposes
- Convenience aspects[25]
- Potential technical, economical, and social barriers
- Actual oil market behavior
- Impact of lobby groups
- Current and future local and regional policy instruments for CO_2 reduction, e.g., energy and carbon taxes, tax exemptions, subsidies
- Current and future agriculture and industry policies
- Real decision-making, more complicated than cost-minimization[26]
- Political instabilities, e.g., war

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[24] For example, it is difficult to model willingness to purchase electric cars, which is an energy-efficient technology but currently not really comparable to standard cars (e.g., shorter driving range and usually lacking energy-intensive accessories).

[25] Oil and natural gas are more convenient for in-home use for heating than solid biomass. Also, industries may 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).

[26] 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.

Adding a price premium for these factors could help but would also add uncertainties. In Section 6.1, some of these factors are discussed in more detail, including how the results could be affected if some of the factors above were considered more important than cost-effective CO_2 reduction.

3. Research studies

This section presents the most important differences between the model versions used in the five research studies, as well as the main findings from each study.

3.1 Paper I: Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO_2 targets: Connections between transportation and other energy sectors

The model version used in this study, GET-RC 6.1, differs from the other model versions used in this thesis in the following way: (i) three powertrain technology options (HEV, BEV, and PHEV) and electricity as an energy carrier option for road transport have been added; (ii) the investment costs for passenger vehicle technologies have been updated to reflect current understanding and expectations; (iii) vehicle efficiency improvement has been divided in two parts, one overall fuel efficiency (e.g., aerodynamic drag and rolling friction) applied on all vehicle options and one powertrain specific fuel efficiency, where pure electric propulsion is assumed to have a lower improvement potential compared to the other propulsion options; (iv) the world has been treated as ten distinct regions,[27] and (v) the pattern of allowed global CO_2 emissions has been constrained according to the WRE emission profiles (Wigley, 2008).

3.1.1 Aim of the study

The model is used to quantify the potential impact of carbon capture and storage (CCS) technology and low CO_2 intensity electricity from renewable sources such as concentrating solar power (CSP) on cost-effective passenger vehicle fuel and technology options necessary to achieve stabilization of atmospheric CO_2 at 400–550

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[27] The ten regions are: NAM, EUR, FSU, PAO, CPA, SAS, PAS, MEA, AFR and LAM. Acronyms are explained on page IX. In the other studies, we have used either six-region or globally-aggregated GET model versions.

ppm. In addition, the model is used to assess the sensitivity of the model to assumptions on future vehicle costs. The assessment considers a cost range such that the lower bound is set at government/industry R&D targets, and the upper bound is set so that above it there are no further impacts on model results. Battery costs are varied from $150/kWh (USCAR, 2008) to $450/kWh, hydrogen storage costs from $1500/GJ (DOE, 2008) to $3500/GJ, fuel cell stack cost from $65/kW (Ballard, 2008) to $125/kW, and natural gas storage cost from $1000/GJ to $1300/GJ.

3.1.2 Main results and conclusions

Four scenarios are considered: (A) neither CCS nor CSP are available, (B) CCS is available but CSP is unavailable, (C) CSP is available but CCS is unavailable, and (D) both CCS and CSP are available. Results on cost-effective fuels and drive train technologies, chosen for the assumed global passenger vehicle fleet, in the four different scenarios are presented in Figure 7.

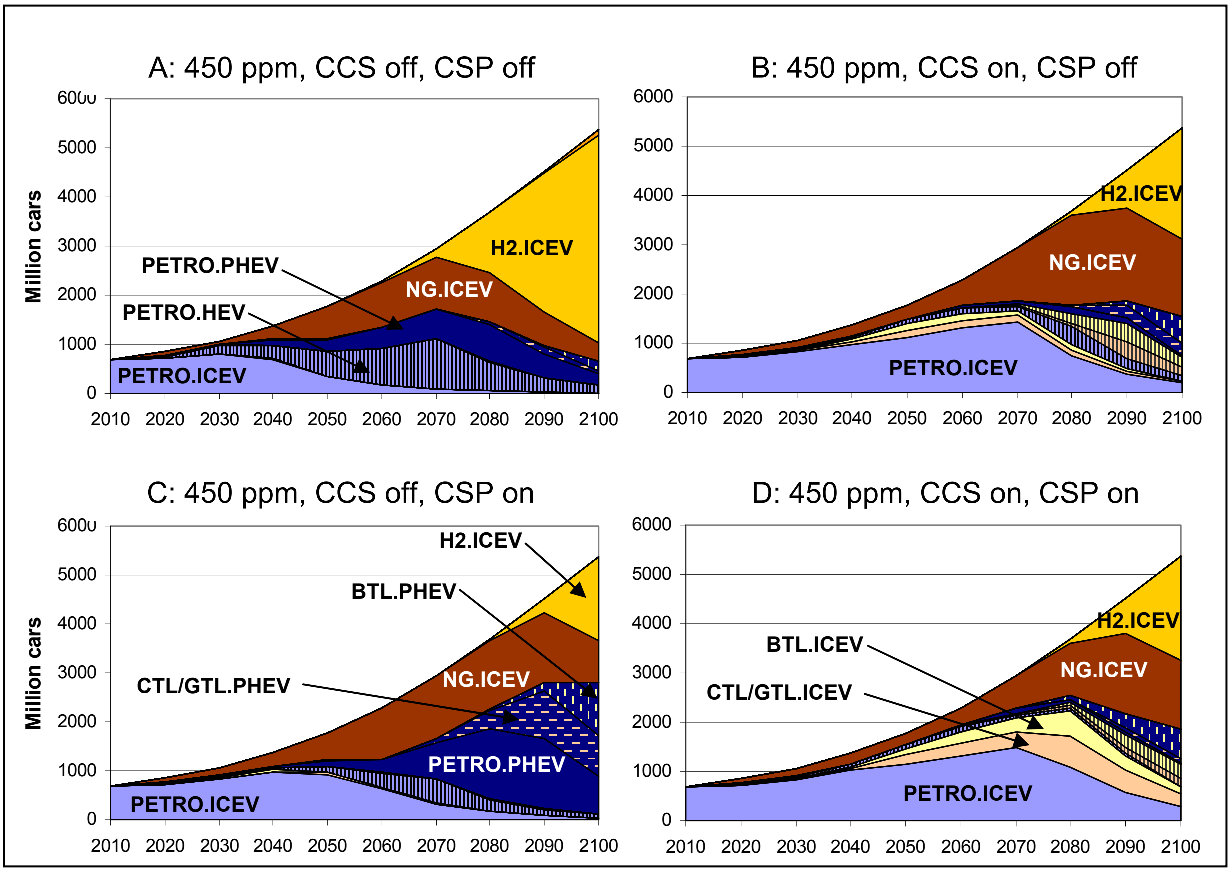

Figure 7. Global passenger vehicle fleet (millions) consistent with atmospheric CO_2 stabilization at 450 ppm, a battery cost of $300/kWh, a hydrogen storage cost of $2500/GJ, a natural gas storage cost of $1150/GJ, a fuel cell stack cost of $95/kW, and: (A) neither CCS nor CSP available, (B) only CCS available, (C) only CSP available, or (D) CCS and CSP both available.

In all scenarios, there is no single technology or fuel that dominates throughout the century. The diversity of solutions reflects: (i) differences in regional resource availability and mobility demand; (ii) changes over time in relative cost-effectiveness among fuels and technology options, due to increased carbon constraints; and (iii) oil and natural gas supply potentials become scarcer with time and this drives the introduction of alternative fuels on its own.

The availability of CCS and CSP has a substantial impact on cost-effective fuel and technology choices, and the following can be noticed: (i) in general, the introduction of CCS increases the use of coal (in the energy system) and ICEV (for transport); (ii) the introduction of CSP reduces the relative cost of electricity in relation to hydrogen and tends to increase the use of electricity for transport; and (iii) the combined introduction of CCS and CSP reduces the incentives to shift to more advanced vehicle technologies (only ICEVs are shown in these model scenarios).

In all cases, the use of coal as a primary energy source in the entire energy system increases substantially when CCS is available. Further, in all cases, except for the 550 ppm scenario, the use of solar energy (mainly solar-based hydrogen) increases when neither CCS nor CSP is available.

Sensitivity analyses in which we vary cost estimates for future vehicle technologies result in large differences in the cost-effective fuel and vehicle technology solutions. For instance, for low battery costs ($150/kWh), electrified powertrains dominate, and for higher battery costs ($450/kWh), hydrogen fueled vehicles dominate, regardless of CCS and CSP availability. Thus, our results summarized above should not be interpreted to mean that the electricity production options alone will have a decisive impact on the cost-effective fuel and vehicle options chosen.

It is too early to express firm opinions about the future cost-effectiveness of different fuel and powertrain combinations.

3.2 Paper II: The role of biofuels for transportation in CO_2 emission reduction scenarios with global versus regional carbon caps

The model version, GET-R 6.0, used in this study is a regionalized version of the global GET 6.0 model version, which in turn is an update of the initial GET 1.0 model version. In this study, we treat the world as six distinct regions,[28] and we assume that emissions reduction curves may differ between industrialized and developing regions.

Two types of different emissions reduction curves (both leading to atmospheric CO_2 stabilization at 450 ppm) are assumed. In the first emissions scenario, Global Cap (GC), all regions are assumed to start reducing their CO_2 emissions by 2010, and global emissions trading is allowed. In the second emissions scenario, Regional Caps (RC), emissions reductions are not tradable across regions, and industrialized regions take the lead in mitigating global warming by starting to reduce their CO_2 emissions by 2010, while developing regions may wait some decades.

In the GC scenario, we use the ecologically driven and energy efficient IIASA demand scenario, C1, for all regions. For the RC scenario, we use the C1 demand scenario for the industrialized regions, but for the developing regions we constructed a mixed demand scenario, which is a weighted combination of the IIASA high-growth demand scenario, denoted A1,[29] and the demand scenario C1. Fuel options available for the transportation sector are Petro, NG, BTL, GTL, CTL, and H_2. Available vehicle technology options are ICEVs and FCVs. Electric vehicles (including PHEVs) are not included in the analysis, but analyzed in the sensitivity analysis.

3.2.1 Aim of the study

In the initial GET study it was assumed that *all* countries take action to reduce CO_2 emissions *by 2010*. In reality, so far, not all nations have taken action, and it is not clear all countries will act by 2020, even. Thus, a key question is what will happen in the transportation sectors in the industrialized regions if emissions have to be significantly

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[28] The six regions are: NAM, EUR, FSU, PAO, LAMEC, and AFSAPA, where the latter two are considered developing regions, roughly grouped by current GDP and CO_2 emissions levels. Acronyms are explained on page IX.

[29] Note that IIASA's demand scenario A1 is one unique scenario, not to be confused with the IPCC SRES A1 family.

reduced over the coming years. The aim of this study is to analyze cost-effective fuel choices in the transportation sector given that industrialized countries take on their responsibilities and reduce emissions before developing countries start reducing their emissions.

3.2.2 Main results and conclusions

A general pattern, for all four industrialized regions and both scenarios, is a transition from petroleum-based fuels used in internal combustion engines to hydrogen used in fuel cell engines. Natural gas and synthetic fuels (BTL/CTL/GTL) are cost-effective fuel choices during a transition period. To compare the total fuel use over the century, we add up the regional results fuel by fuel, for the time period 2000–2099. We then analyze the biofuel use as share of total fuel use for road and sea-based transportation.

Results from scenario GC, towards 450 ppm, show that biofuels play a limited role in developing regions, with 4–6% of total road and sea-based fuel use. In the industrialized regions, the biofuel share is 8% in North America and 4% in PAO, whereas no biofuels are used in either Europe or the Former Soviet Union. The mean value in the four industrialized regions for biofuel use is 4.4%. Results from scenario RC show a mean value of 12%, almost three times higher than in GC.

The mean values for the use of biofuels for the four industrialized regions, from model runs toward different CO_2 concentration targets, are presented in Figure 8.

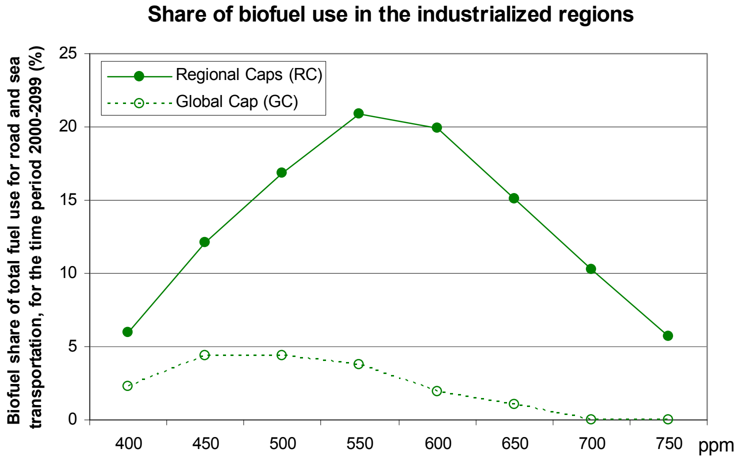

Figure 8. Mean values of cost-effective biofuel use for the four industrialized regions as share of total fuel use for road and sea-based transportation, over this century.

The average share of biofuels in the road and sea transportation sectors in the industrialized regions is significantly higher in RC than GC, for all CO_2 targets, see Figure 8. Mid-range targets yield the highest values for biofuel share. In RC, the highest value is 21%, obtained with the 550 ppm target. In scenario GC, the use of biofuels is significantly lower, below 5% for all CO_2 stabilization targets (the highest value is 4.4%, for 450 ppm). Biofuel trade between regions is not shown in GC, whereas a significant trade occurs in RC where developing regions export biofuels to industrialized regions.

Three main results emerge from our analysis: (i) the use of biofuels in the industrialized regions is significantly higher in RC than in GC; (ii) the use of biofuels in RC actually increases the weaker (i.e., higher) the CO_2 concentration target (up to 550 ppm); and (iii) biofuels never play a dominant role in the transportation sector.

The reason biofuels become more attractive in RC is that the industrialized regions have to commit to much more stringent reductions early on. This means that they cannot rely on only reducing emissions from stationary sources; they also have to address fuel choices for transportation.

The reason the use of biofuels in RC increases the weaker the CO_2 concentration target (up to 550 ppm) is that less ambitious targets allow for an increased use of fossil fuels, i.e., coal (the use of oil and natural gas remains constant). An increased share of coal (first and foremost in the electricity and heat sectors) reduces the competition for biomass, which can be used both in stationary applications and the transportation sector. If the concentration targets become even weaker, the relatively expensive biomass is needed less and less. For very ambitious CO_2 targets, on the other hand, the competition for biomass is higher and the limited supply of biomass will first and foremost be used in the heat sector, thus the use of biofuels for transportation decreases.

The reason biofuels never play a dominant role in any region's transportation system is that biomass is more cost-effectively used for heat and co-generation, in the model. Once oil starts diminishing, other fuels, such as hydrogen or natural gas, enter the transportation sector first and foremost, and biomass remains in the heat system.

We find that biofuels may play a more important role in industrialized countries if these take on their responsibilities and reduce their emissions before developing countries start reducing their emissions, compared to the case in which all countries take action under a global cap and trade emissions reduction regime.

3.3 Paper III: Will biofuels directives in industrialized regions lead to lower CO_2 emissions in non-industrialized regions – a reverse form of carbon leakage?

The model version, GET-R 6.0, used in this study is the same as in the study presented in Section 3.2. We treat the world as six distinct regions, and we assume that CO_2 emissions reductions may differ between industrialized and developing regions. When presenting results in this study, we chose to combine results from the four industrialized regions (NAM, EUR, FSU and PAO) as I-REG, and from the two developing regions (LAMEC and AFSAPA) as D-REG.

In this study, the emissions reductions are achieved by CO_2 taxes. The carbon policy scenarios analyzed range from no CO_2 emissions reduction policy to relatively high carbon taxes in both industrialized and developing regions. We have chosen to run the model under different combinations[30] of CO_2 tax levels and time lags between the introduction of carbon policies in industrialized and developing regions. Each carbon policy scenario is run with and without the assumption that all industrialized regions adopt a biofuels directive requiring a minimum 20% biofuels use, for road and sea-based transportation, over a hundred year time period, starting in 2020.

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[30] The carbon tax is always introduced in 2020 in industrialized regions and is subsequently increased by 3% per year. The initial tax level is varied in a range between $0–150/tC. For developing regions we assume the same initial tax level as in industrialized regions but vary the time delay until it is introduced, in the range of 0–100 years. From the year that the developing regions adopt CO_2 policies, the CO_2 tax is increased by 6% per year until the developing regions' tax level equals the tax level in industrialized regions, which means the taxes are the same after, about, the initial delay, times two, counting from the time that tax is introduced in industrialized regions. (In reality carbon taxes are already introduced in parts of some regions, and if strong agreements on emission reductions are established such taxes (or equivalent costs) are likely to be introduced throughout several or all industrialized regions even before 2020. However, in the model we have ten-year time steps, and we have therefore chosen to introduce a CO_2 tax for all industrialized regions in 2020).

In the majority of our analyzed cases, the industrialized regions are assumed to adopt relatively ambitious CO_2 reduction policies. Therefore, we use IIASA's ecologically driven energy efficient demand scenario, "C1", for these regions. For the developing regions, which in most of the analyzed cases are assumed to adopt CO_2 policies decades after the industrialized regions, we use IIASA's high-growth demand scenario, "A1".

3.3.1 Aim of the study

Carbon leakage occurs if policies to reduce emissions in one region lead to higher emissions in other regions of the world. Efforts to introduce biofuels in the industrialized regions may free up oil so that it can be used in developing regions. Intuitively, this seems as if it could lead to higher emissions in developing countries. However, higher oil use may also lead to a reduction in coal to liquids, in developing regions. Coal to liquids typically emits twice as much CO_2 compared to fuels based on crude oil. Under these conditions, CO_2 emissions would actually be reduced in developing regions as a result of biofuels policies introduced in the industrialized regions (a reverse form of carbon leakage).

The aim of this paper is to analyze how policy instruments aimed at increasing the use of biofuels in industrialized regions, e.g., a biofuels directive, affect CO_2 emissions in the energy and transportation sectors, of developing regions, to see if and when a reverse form of carbon leakage take place. We are also able to study the direct carbon benefits of introducing biofuels. Since oil is scarce, biofuels may in reality replace more carbon-intensive fuels and therefore lead to larger reductions (than previously thought) in both developing and industrialized regions. In addition, we are also able to study if and when the introduction of a biofuels directive will lead to globally *increased* CO_2 emissions.

3.3.2 Main results and conclusions

We have performed systematic carbon policy scenario runs covering initial CO_2 taxes in the range of 0–150 USD/tC combined with a time delay in the range of 0–100 years until developing regions adopt CO_2 taxes. We find that the introduction of a biofuels directive, affect fuel choices in all sectors in both industrialized and developing regions, in both the short and long term perspective.

Generally, at high initial CO_2 tax levels, combined with a short delay, the global demand for biomass is high, and biomass is most cost-effectively used for stationary applications. An initial CO_2 tax of $80/tC combined with a 20-year delay (which in this model results in a CO_2 concentration of 450 ppm in 2100) leads to no use of biofuels in the developing regions' transportation sectors. The CO_2 taxes are high enough to exclude fossil-based synthetic fuels from the cost-effective solution in both industrialized and developing regions. In this case, when the biofuels directive is introduced, the biomass use in the developing regions' heat sector is significantly reduced, leading to increased emissions (conventional form of carbon leakage). The avoided emissions in the industrialized regions are not high enough to compensate for the developing regions' increased emissions. In this case, the introduction of a biofuels directive leads to *globally* increased emissions.

On the other hand, when assuming low initial CO_2 tax levels combined with a long delay the global demand for biomass is low. An initial CO_2 tax of $20/tC, combined with an 80-year delay (resulting in a CO_2 concentration level over 700 ppm in 2100) leads to less use of CTL in both industrialized and developing regions, when introducing a biofuels directive. The use of gasoline/diesel decreases in industrialized regions, whereas it increases in developing regions. In this case, the introduction of a biofuels directive leads to reduced CO_2 emissions in both the developing regions (the reverse form of carbon leakage) as well as in the entire world.

We also find that introducing a biofuels directive when CO_2 policies are weak give raise to a direct carbon benefit, since biofuels replace coal-based fuels in industrialized regions leading to a larger CO_2 reduction than if biofuels replace gasoline/diesel. However, a biofuels directive does not lead to reduced emissions in developing regions, during the first 50 years.

For the key question, if and when introduction of a biofuels directive can lead to reduced emissions in the developing regions, we have aggregated avoided emissions over a hundred-year period (2020–2119). Aggregated avoided emissions for the developing regions are presented in Figure 9a. Red shades indicate that the introduction of a biofuels directive in industrialized regions leads to CO_2 emissions reduction in developing regions (the reverse form of carbon leakage). Blue shades indicate that a biofuels directive leads to *increased* CO_2 emissions in the developing regions (conventional form of carbon leakage). The reverse form of carbon leakage occur at low initial CO_2 tax levels and long. The greatest avoided emissions, 10 GtC, is found at initial tax 30 USD/tC and a 60-year delay (the developing regions' emissions are decreased from 1200 GtC to 1190 GtC; a reduction of 0.8%).

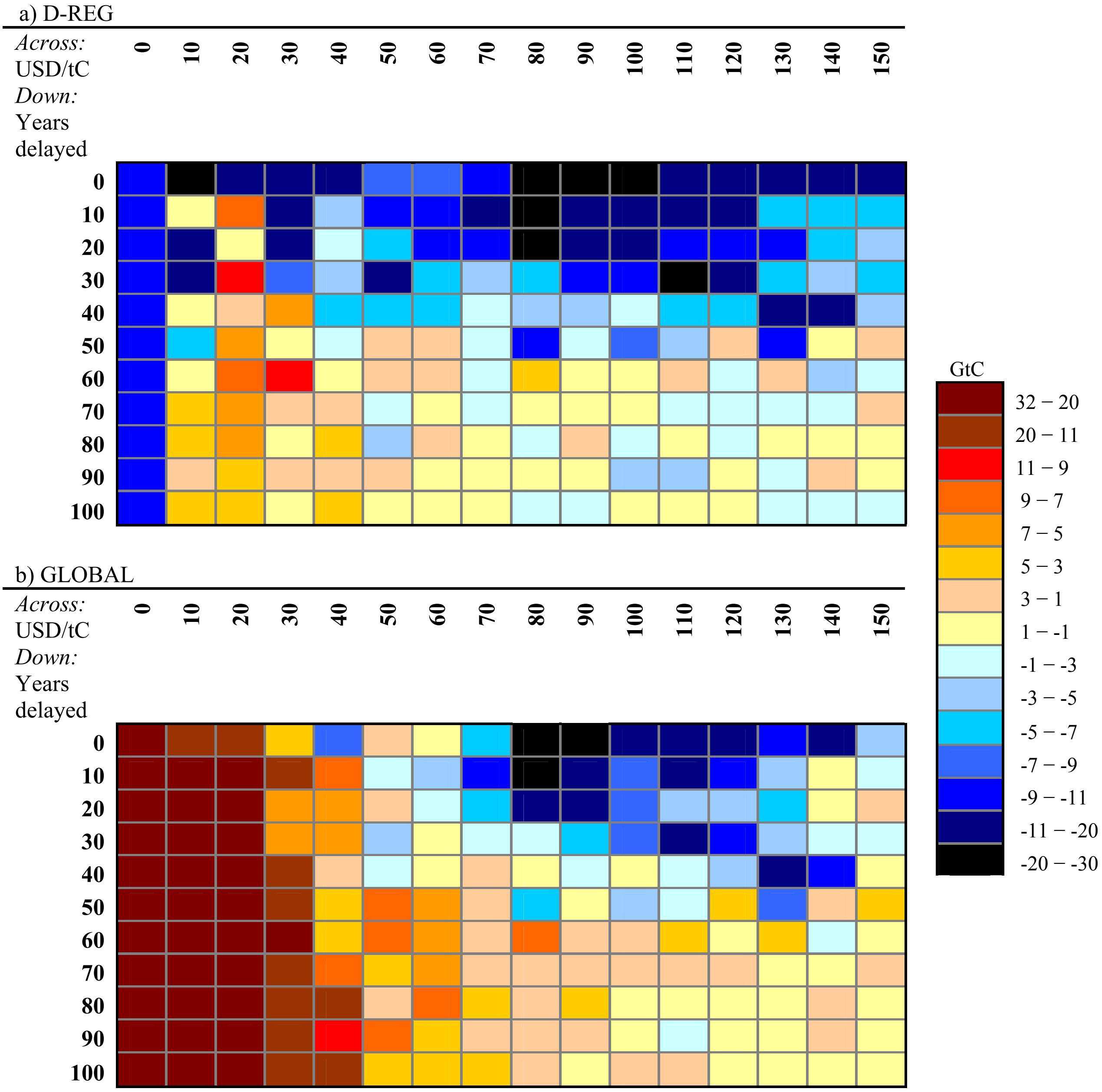

Figure 9. Avoided emissions in a) developing regions and b) the entire world, 2020–2119, stemming from the introduction of a biofuels directive in the industrialized regions. The matrix includes initial tax levels in the range of 0–150 USD/tC introduced in the industrialized regions in 2020 and in the developing regions with a delay of 0–100 years.

Conventional form of carbon leakage occur when assuming a short delay prior to developing regions adopt CO_2 policies. The greatest increase in emissions, 29 GtC, is observed for an initial tax of 80 USD/tC and zero delay (the developing regions' emissions are increased from 396 GtC to 425 GtC; an increase by 7.2%).

Figure 9b illustrates how a biofuels directive affects the *global* CO_2 emissions for different combinations of CO_2 tax and delay. If the main purpose of the biofuels directive is to reduce CO_2 emissions, a resulting increase in global emissions clearly shows that the directive is counterproductive. Red shades again indicate that an introduction of a biofuels directive result in global CO_2 emission reduction. These are found at low initial CO_2 tax levels, with highest avoided emissions, 32 GtC, at initial tax \$20/tC and a 30-year delay (the global emissions are decreased from 1337 GtC to 1305 GtC; a reduction of 2.4%). Blue shades indicate *increased* global emissions. These are found at high initial CO_2 taxes and short delays, with highest increase of emissions, 26 GtC, found at initial tax \$90/tC and zero delay (the global emissions are increased from 547 GtC to 573 GtC; an increase by 4.7%).

A biofuels directive may have both direct effects on CO_2 emissions and effects occurring later. Globally avoided emissions are first and foremost observed during the first 50 years and originate in the industrialized regions. The globally increased CO_2 emissions occur toward the end of this century and mainly originate in the developing regions. Almost no avoided emissions are observed for the developing regions during the first 50 years, but a long-term effect arises when assuming low carbon taxes and a long delay.

Four main results emerge from our analysis: the introduction of a biofuels directive in the industrialized regions (i) leads to avoided CO_2 emissions in the industrialized regions in most carbon policy scenarios, especially during the first 50 years; (ii) leads to a direct carbon benefit (CTL instead of gasoline/diesel is replaced) for low carbon taxes; (iii) tends to reduce the emissions from developing regions when assuming low carbon taxes and a long delay prior to developing regions adopting carbon policies; and (iv) tends to increase global emissions when assuming high carbon taxes and a short delay.

Thus, a biofuels directive in the industrialized regions may lead to a direct carbon benefit if biofuels are used to replace coal-based fuels (instead of oil-based fuels) in the industrialized regions. It may, further, lead to a reverse form of carbon leakage, but only under certain conditions. None of these specific cases are consistent with ambitious CO_2 reduction targets. Thus, the reverse form of carbon leakage seems to occur only in cases leading to CO_2 concentration levels significantly higher than those discussed in international climate policy agreements aiming for a "2 °C target"[31]. In almost all of the cases leading to CO_2 concentration levels below 450 ppm, the introduction of a biofuels directive is counterproductive and leads to globally increased emissions. In most of the analyzed cases, conventional carbon leakage takes place.

The introduction of a biofuels directive in industrialized regions may lead to increased CO_2 emissions in the developing regions as well as globally; therefore, such a directive needs to be motivated by other considerations than ambitious global CO_2 emissions reduction.

3.4 Paper IV: Biomass for heat or as transportation fuel? A comparison between two model-based studies

The GET model version used in this study, GET 5.0, is an update of the initial globally aggregated version, GET 1.0. In this study, we have also used the BEAP (Biomass Environmental Assessment Program) model developed by Gielen *et al.* (2002, 2003). The GET model is run under constraints on CO_2 emissions corresponding to a stabilization target of 400 ppm by 2100, and the BEAP model (in the GLOB scenario) is run with a CO_2 tax that roughly leads to the same CO_2 concentration target.

One difference between the two models' restrictions is that in the BEAP model some of the heat processes are constrained, i.e., no investments can take place in gas- and biomass-fueled industrial heat boilers before 2020. Also, urban heat produced from biomass is limited to very low levels (or even zero) for all industrialized regions.

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[31] The 2007 Bali Climate Declaration, prepared at the Climate Change Research Centre in Sydney and signed by more than 200 scientists worldwide, states that the primary goal must be to limit global warming to no more than 2°C above the pre-industrial temperature (Allan *et al.*, 2007). This limit has already been formally adopted by the European Union (European Council, 2005).

Another difference between the models are the fuel options available in the transportation sector, see Table 2.

Table 2. The energy carriers assumed available in the transportation sector in both models.

	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-based)	X	X
Hydrogen (CO_2 neutral)	-	X
Gaseous natural gas	-	X

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 exogenously included in the heat, electricity, and transportation demand scenario (IIASA's C1 scenario).

3.4.1 Aim of the study

Azar *et al.* (2003) find that it is more cost-effective to substitute biomass for fossil fuels in 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. This study aims to explain the difference in results.

3.4.2 Main results and conclusions

We found four reasons that explain the differences between the two models' results on biomass allocation: (i) a correction of a data input error;[32] (ii) the method used to

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[32] The capital costs for all industrial heat plants were too high in the BEAP model. After correction, the production of biofuels decreased by 26 and 39 percent by 2020 and 2050, respectively, and the use of "bio-heat" increased.

constrain CO_2 emissions;[33] (iii) assumptions on how much biomass can be used for heat production;[34] and (iv) long-run fuel options for the transportation sector, see Table 2.

To find out more about the biomass allocation between GET and BEAP, we performed 13 runs with a fixed CO_2 tax over the period 2005–2100, in the range 0–300 USD/tC in steps of 25 USD/tC. Results for 2020 are presented in Figure 10.

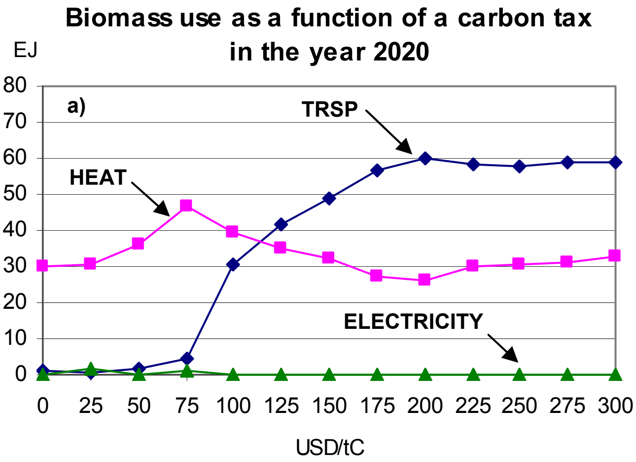

Figure 10. The biomass use (primary energy) in the BEAP model for various CO_2 taxes. The taxes have been fixed during each run, and the figure includes 13 runs.

Figure 10 shows that in the BEAP model, no biofuels are produced but 30 EJ of biomass is used for heat production by 2020 when no carbon tax is applied. When the tax is increased, 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 annual biomass supply potential is limited,[35] the biomass for heat production slightly decreases when the use of biofuels increases.

In the BEAP scenario, the CO_2 tax reaches 300 USD/tC by 2020; at that tax, as shown in Figure 10, most of the biomass is used for the production of biofuels. Since Gielen *et*

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[33] The BEAP tax profile increases rapidly early in the century, whereas the implicit GET tax profile (shadow price on carbon) increases by approximately 5% per year, i.e., has low tax levels during the initial decades of the century. In a run where we used the "GET tax profile" in the BEAP model, the use of bio-heat increased, and the production of biofuels almost disappeared in 2020 and was halved by 2050 (compared to the corrected BEAP scenario).

[34] The use of biomass for urban heat in industrialized regions is constrained in the BEAP model. When releasing this constraint, the use of bio-heat increased and the production of biofuels dropped by around 40% (compared to the corrected BEAP scenario).

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

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 that biomass is most cost-effectively used for heat, when the carbon tax is low (in 2020, below 75 USD/tC).

For higher taxes, there is a difference between GET and BEAP. Biomass is used most cost-effectively for biofuels production in the BEAP model, but in the GET model, biomass remains used most cost-effectively for heat production. The key reason for this 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, the transportation sector has to be almost CO_2 free toward the end of this century, and biofuels are the only available option in the BEAP model for reaching almost zero emissions levels.[36] Both GET and BEAP have carbon-free options in the two other sectors.

Analyzing the reasons for the different biomass allocation in the BEAP and the GET models, we conclude that (i) biomass is used most cost-effectively for heat production 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 focused on higher carbon taxes, and (ii) the sector in which biomass is used most cost-effectively 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.

Thus the assumptions about the availability of CO_2 neutral hydrogen and/or electricity as a fuel option in the transportation sector was a key factor whether biomass will be used for transportation in a carbon constrained world. If hydrogen is assumed to have widespread use as an energy carrier in the transportation sector, then cost assumptions on fuel cells, storage options, infrastructure, and supply will determine in which sector

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[36] If the costs of hydrogen vehicles are lowered in the BEAP model, hydrogen from natural gas enters the transportation sector.

the biomass will be used. Clearly, these cost numbers are very uncertain, so the long-run future is still open.

3.5 Paper V: Biomass for heat or transport? An investigation of prices and costs in the GET model

The model version used in this study, GET 5.1, is a further developed global version of GET 5.0. There are two main new features in the GET 5.1 model, compared to GET 5.0: (i) the primary energy oil has been divided into two oil sources, conventional and heavy oils; and (ii) the refinery process has been further developed.

The main difference after including the 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 oil could be converted into transportation fuels, at a certain cost. Now, only 60% of the conventional oil can be transportation fuels, at that cost. In this model version we have also changed the energy efficiency of fuel cells, compared to internal combustion engines, from a factor of 2.2 more efficient down to a factor of 1.5, following Åhman (2001). Hence, a transition into hydrogen in fuel cell vehicles is less favorable than in earlier versions of the GET model. The primary energy cost of conventional oil is taken from Azar *et al.* (2006), and the new primary energy cost of heavy oils is estimated following EIA (2002) and in the model set to 3.5 USD/GJ and 5 USD/GJ respectively. The CO_2 emissions are constrained by letting the carbon cycle module stabilize the atmospheric concentration at 450 ppm in 2100.

3.5.1 Aim of the study

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

3.5.2 Main results and conclusions

The overall results, on cost-effective fuel choices in the transportation sector, are the same as in previous GET 1.0 and GET 5.0 model studies. That is, gasoline/diesel (now from both conventional and heavy oils) remain for some decades in the transportation sector, until the carbon constraint becomes increasingly stringent, and solar-based hydrogen dominates by the end of this century. Biofuels do not appear as a cost-effective fuel choice. However, one significant exception to the GET 1.0 model results is that natural gas takes a larger share of the transportation fuels, which first and foremost is a result of the assumption that fuel cells are less efficient.

One important observation for the understanding of the price mechanism in the GET model is that the primary energy price, P, (USD/GJ) consists of two parts, as

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

where P_C is the primary energy cost (which we set in the model) including the extraction costs and distribution and P_{SR} is a scarcity rent[37] generated in the model as a shadow price for each time step.

To analyze the underlying price mechanism in GET 5.1, we calculate costs and prices separately. We have used the data and the equations in the GET 5.1 model together with scarcity prices generated by the model to calculate the costs per km for all fuel and vehicle choices. These costs (USD/km) are then plotted as a function of the carbon tax (USD/tC) to illustrate how the relationship between the costs per km changes with higher carbon taxes. Plots for time steps 2030, 2050, 2070, and 2090 are presented in Figure 11. The vertical dotted line in each graph marks the generated carbon tax for the specific time step. Note that the scarcity rents generated in the run for a specific time step are kept constant in each plot, i.e, it is not possible to foresee any other GET results from the plots outside the intersection with the dotted vertical carbon tax curve.

Figure 11 shows that in 2030 (a) and 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, at which points cars run on BTL take over as the least-cost option. Figure 11c shows that in 2070, fossil fuel options, i.e., CTL, 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, at which point cars run on

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[37] Scarcity rent is the economic term for the additional cost due to the fact that the price on an item increases as a result of its relatively low supply, e.g., an exhaustible resource or raw materials in high demand. Scarcity rents were generated on natural gas, conventional oil, and biomass in the GET 5.1 model. Scarcity rents are generated on biomass since the demand for biomass exceeds the supply potential, especially at high carbon taxes.

BTL take over as the least-cost option. Note that two other carbon-neutral alternatives (hydrogen-based on either biomass or solar) are close to BTL in 2070. Figure 11d shows that in 2090 solar-based hydrogen used in fuel cell vehicles is the least-cost option, at a carbon tax level of 930 USD/tC and higher. Note that the cost per km for BTL now is higher than solar-based hydrogen, which is due to a high scarcity rent on biomass (the primary energy price, *P,* on biomass is here 37 USD/GJ, compared to 2 USD/GJ).

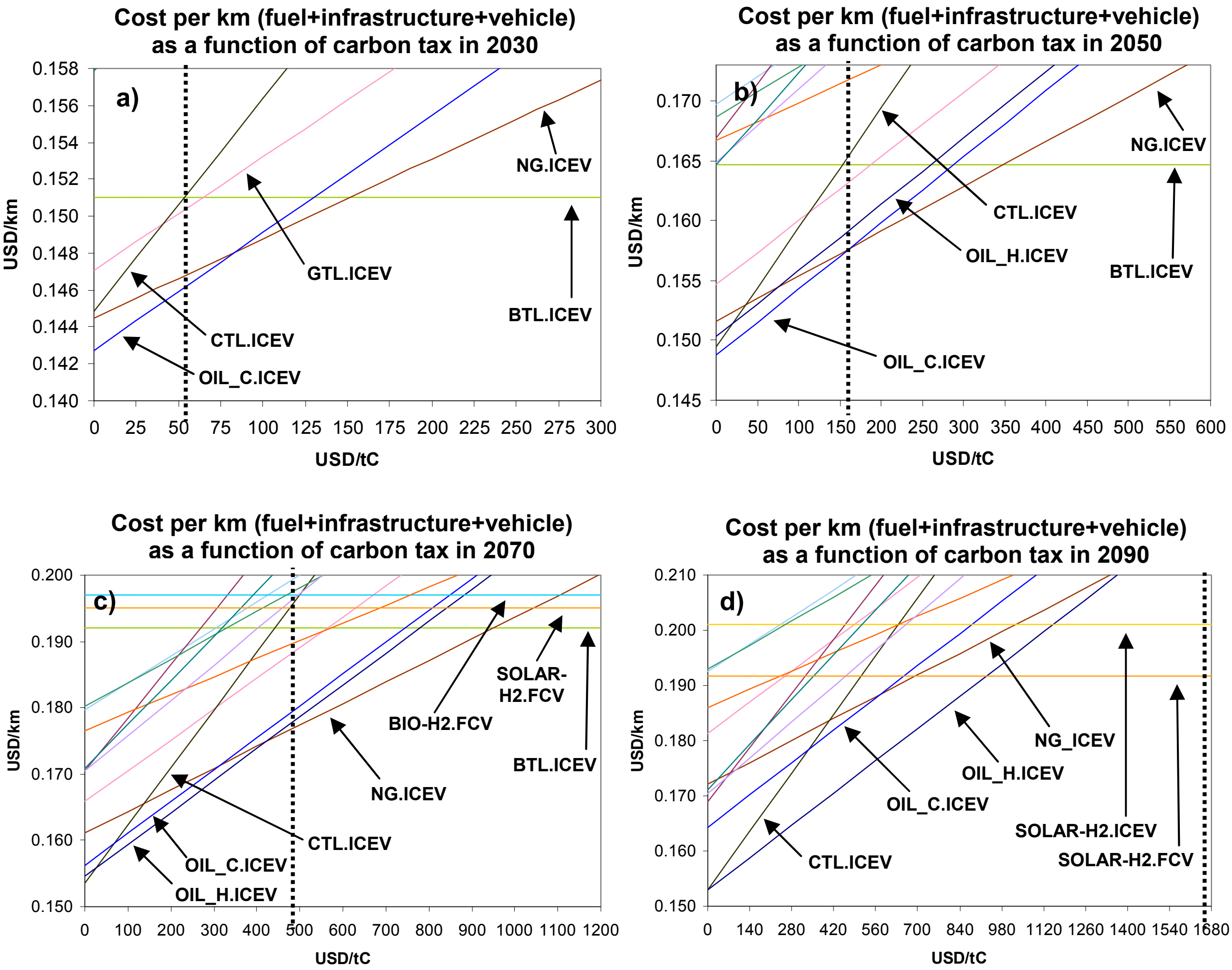

Figure 11. Costs per km (subgroup Cars only) generated in GET 5.1 when aiming for 450 ppm. Graphs for the time steps 2030, 2050, 2070, and 2090 are presented and the vertical dotted line marks the generated carbon tax, which is in a) 52 USD/tC, b) 157 USD/tC, c) 490 USD/tC, and d) 1673 USD/tC. Note that the scarcity rents generated in each time step are kept constant in each plot.

From the plots presented in Figure 11 (but for all time steps between 2000–2100), we identify the intervals where a certain fuel is shown as the least-cost alternative. The identified intervals are then presented in bars where the carbon tax generated in the GET 5.1 is also plotted as a line curve across the bars, see Figure 12.

The fuel option that crosses the carbon tax line curve will first and foremost be chosen in a linear optimization model. However, since the model has expansion rate constraints, a technology may 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 but crosses the carbon tax line curve in 2080, in Figure 12. The model also has constraints on the rate at which a fuel can be phased out, which 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.

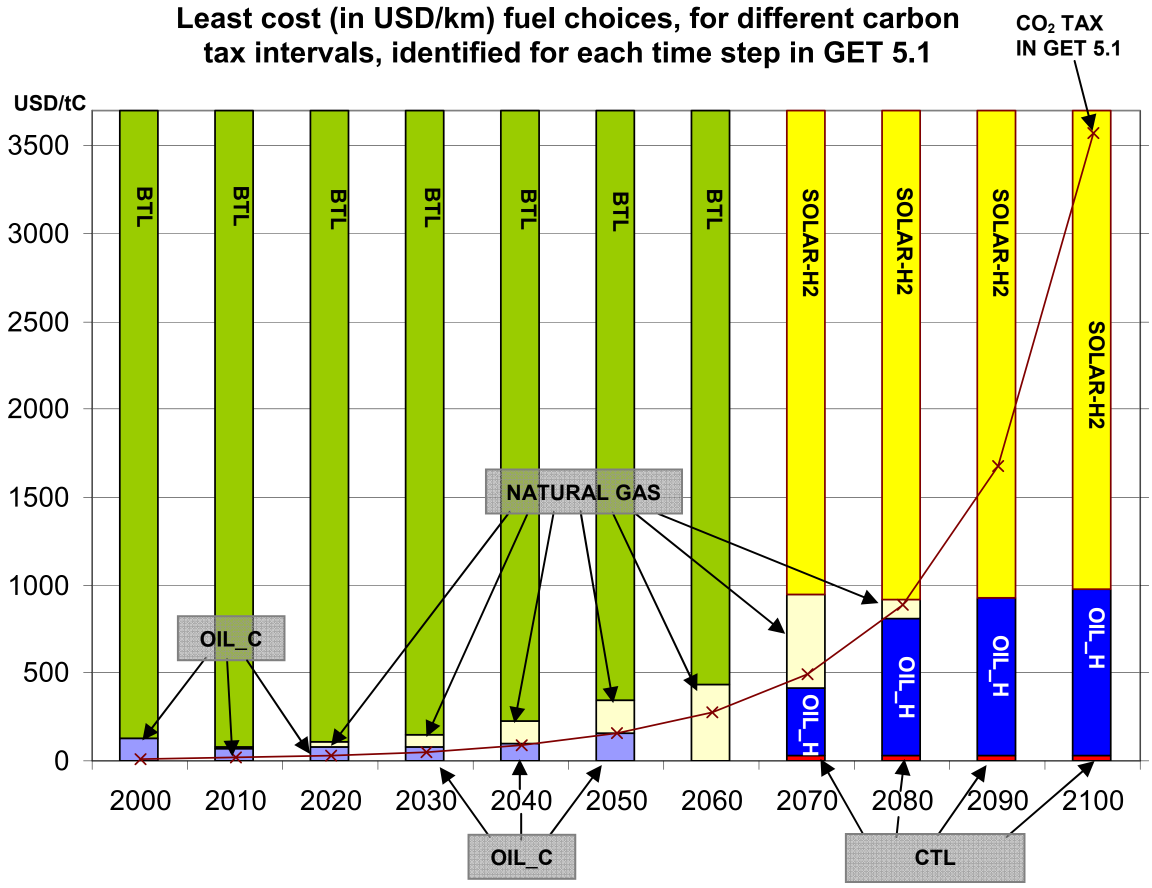

Figure 12. Fuel choices in the transportation sector (subgroup Cars only) for different carbon tax intervals, when running GET 5.1 toward 450 ppm. For each time step, the lowest fuel cost per km for a certain range of carbon taxes is identified and plotted in bars. The carbon tax generated in the run is plotted as a line curve in front of the bars, with the tax values marked with an x. Acronyms used in the figure are: OIL_C= conventional oil, OIL_H= heavy oils, BTL, CTL= synthetic fuels derived from biomass and coal, respectively, and SOLAR-H2= solar-based hydrogen.

By studying Figures 11 and 12 it is tempting to interpret the carbon tax intervals to suggest that biofuels become a cost-effective fuel choice when the carbon tax is higher than, e.g., 150 USD/tC in 2030, but this is not the case. A run where the carbon tax is locked into 160 USD/tC for 2010–2030, does not introduce any biofuels. Instead, the primary energy price, *P*, on biomass increases to 4.4 USD/GJ compared with 2.3 USD/GJ in the first case, which increases the cost on BTL to 0.161 USD/km compared with 0.151 USD/km in the first case. Natural gas and conventional oil options are still options with lower costs per km than BTL.

This elusive quality of the carbon tax level at which biofuels become cost-effective, compared to fossil-based fuels, results from the underlying price mechanisms in the optimization model. The tax level moves upward with increasing carbon taxes, since increased taxes lead to an increased biomass primary energy price in the model. In the GET 5.1 model, the biofuels interval never coincides with the generated carbon taxes.

That biofuels never enter the scenarios in this cost-minimizing model 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 (here compared without scarcity rents and carbon taxes). In the transportation sector, by going from BTL 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 the total energy system cost is minimized if biomass (instead of solar) is used for heat production.

We have illustrated that in a carbon constrained world, the demand for bioenergy leads to a scarcity rent making the biofuels option more costly than gasoline/diesel, natural gas, and later in the century, also more costly than solar-based hydrogen. This gives a deeper understanding of why biofuels generally are not found to be a cost-effective option for ambitious CO_2 reductions in the GET 1.0, GET 5.0, and GET 5.1 model versions.

4. Main findings

Conclusions drawn in earlier GET model studies and re-confirmed in this thesis include: (i) carbon dioxide emissions can be reduced at the same time as the demand for energy services increases; (ii) to reach ambitious CO_2 stabilization levels, a radical change of the energy system is needed; (iii) biomass is generally allocated to the heat sector; and (iv) the general pattern for cost-effective fuel choices in the transportation sector involves a transition from petroleum-based fuels used in internal combustion engines to hydrogen used in fuel cell engines (or electricity used in PHEVs). Natural gas and synthetic fuels (BTL/CTL/GTL) are cost-effective fuel choices during a transition period.

New conclusions, drawn within the scope of this thesis, further refine the picture of earlier conclusions, e.g., that the results differ for the short and the long term, as well as for low and high carbon taxes, industrialized and developing regions, and assumptions on future technology costs.

4.1 The role of biofuels

In globally aggregated model versions, biofuels are generally not a cost-effective strategy to reduce CO_2 emissions (again shown in Papers IV and V using GET 5.0 and GET 5.1). When assuming regionally different CO_2 reduction policies (as in Papers II and III) a more refined role of biofuels arises. Generally, assuming stronger CO_2 reduction policies for the industrialized regions (compared to the developing regions), means a flow of biofuels from the developing regions. For instance, in Paper III biofuels dominate the industrialized regions' transportation sector when assuming high carbon taxes for the industrialized regions and a long delay until developing regions adopt CO_2 policies. Paper II shows that biofuels may play a more important role in industrialized regions if these take on their responsibilities and reduce their emissions before developing regions start reducing their emissions, compared to the case in which all countries take action under a global cap and trade emissions reduction regime. Paper II also finds that the role of biofuels is larger when assuming CO_2 concentration targets around 500–600 ppm, compared to both higher and lower targets. Paper I shows that biofuels in conventional ICEVs are seen over the entire century (however, they never take on a dominant share) when assuming that both CCS and CSP are available options in the electricity sector. Biofuels may also play an important role in PHEVs in scenarios that favor the use of electricity.

4.2 Biomass allocation

The analysis of biomass allocation in Paper IV shows that biomass is most cost-effectively used for heat production at low CO_2 taxes in both the GET 5.0 and BEAP models. Biomass allocation at higher CO_2 taxes may depend on assumed possible energy carriers in the transportation sector, e.g., hydrogen and/or electricity. Paper III shows that policy instruments aimed at increasing the use of biofuels in industrialized regions (a forced biomass allocation) may lead to avoided emissions in the industrialized regions, especially during the first 50 years, and in the developing regions in a few specific cases, but in the majority of cases the introduction of a biofuels directive leads to increased emissions in the developing regions (a reverse form of carbon leakage).

4.3 Impact of cost-uncertainty

Paper I concluded that the uncertainty in future technology costs has a large impact on the modeling results; e.g., low battery costs ($150/kWh) lead to dominance of electric powered vehicles, while high battery costs ($450/kWh) lead to dominance of hydrogen powered vehicles. In Paper IV, we concluded that cost assumptions on hydrogen production, fuel cells, storage options, and infrastructure will determine in which sector biomass is used. In both Papers I and IV, we highlighted that future technology costs currently are very uncertain and that it is too early to express firm opinions about the future cost-effectiveness of different fuel and powertrain combinations.

5. Comparison with other studies

In this section I have summarized and compared results from other studies analyzing questions close to ours, especially studies based on cost-minimizing energy systems modeling.

5.1 Studies analyzing long-term development of the global energy system

During the 1970s, Nordhaus developed the three energy systems model versions, "the Efficient Model," "the OPEC Model," and "the Market Model," all linearly programmed to generate scenarios over 120 years (1970–2090) in ten year time steps. The aim was to analyze the future role of different energy sources. Nordhaus saw a competition between three groups of energy sources: (i) inexpensive but limited oil and gas resources; (ii) less attractive environmental risky sources such as coal, high-cost oil and gas, and high-grade uranium; and (iii) expensive abundant resources, unproven for large-scale use, such as advanced fission, fusion, solar, and unknown. One general model result for the transportation sector is that oil is first replaced by synthetic fuels and thereafter by electricity. He concludes that we are probably heading for major climatic changes over the next 200 years if market forces are uncontrolled. He suggests that a carbon tax on the combustion of fossil fuels is the most efficient control strategy (Nordhaus, 1979). These results and conclusions are similar to what we find in our GET model studies.

Maybe the most well-known GHG and energy systems model analysis is the IPCC Special Report Emissions Scenarios (SRES). Four qualitative storylines (A1, A2, B1, and B2) yield 40 SRES scenarios.[38] Energy systems models are then used to explore the transition of the energy systems and carbon dioxide emissions in the different scenarios, to generate insights on, e.g., the potential of different energy technologies and primary energy sources (IPCC, 2000). An overview of the models AIM,[39] ASF,[40]

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[38] The 40 scenarios differ by, e.g., assumptions on global population, regional GDP developments, alternative directions of technological change, as well as different ambitions regarding environmental protection and social equity. The distribution of the scenarios provides a useful context for understanding the relative position of a scenario but does not represent the likelihood of its occurrence.

[39] AIM stands for Asian pacific Integrated Model.

[40] ASF stands for Atmospheric Stabilization Framework.

IMAGE/TIMER,[41] MARIA,[42] MESSAGE,[43] and MiniCAM,[44] which all analyze long-term energy systems developments connected to the IPCC/SRES scenarios, is, e.g., given in van Ruijven *et al*. (2008) and Barker *et al*. (2002). Results on energy sources used in the 40 SRES scenarios, analyzed with the six energy systems models, are presented at SRES OPEN PROCESS (2009); this summary shows that the overall model results[45] on global primary energy choices are similar to results we see in our GET model runs.

5.2 Studies analyzing the effect of regional CO_2 reduction policies

A study using the cost-minimizing MESSAGE model analyzes how delayed participation by regions can affect a long-term international climate mitigation regime. The authors conclude that non-participation *always* leads to an increase in mitigation costs on the global-scale emissions reductions (up to 40% higher cost). Their main finding is that the use of coal, especially in the electricity sector, is greatly increased through non-participation, which takes several decades to overcome after the region has joined the mitigation regime. The authors stress the importance of establishing international climate regimes that involve a large number of players from the beginning (Keppo & Rao, 2007). The importance of avoiding a delayed participation is also found in Papers II and III in this thesis.

A study using the MiniCAM cost-minimizing energy systems model analyzes economic implications from the assumption that some regions will have delayed CO_2 emission reduction targets. Delays in the year by which non-Annex I regions begin to reduce emissions raise the price of carbon in Annex I regions for any given CO_2 concentration limit. The incremental cost for reaching 450–650 ppm is found to be in the range of 8% to almost 400%. Generally, the longer the delay, the greater the incremental cost for reaching any CO_2 reduction goal. For long delays, 450 ppm stabilization levels become

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[41] IMAGE stands for Integrated Model to Assess the Global Environment. A simulation model developed by RIVM, the Netherlands.

[42] MARIA stands for Multiregional Approach for Resource and Industry. The origin of the model is the DICE model, developed by Nordhaus.

[43] MESSAGE stands for Model for Energy Supply Strategy Alternatives and their General Environmental Impact. A model developed by IIASA, Austria.

[44] MiniCAM stands for Mini Climate Assessment Model.

[45] For SRES scenarios that have similar assumptions regarding global population and technology development as those made in the GET model. Nuclear expansion usually differs, however.

infeasible (Edmonds *et al*., 2007). Papers II and III in this thesis also find it difficult to reach low CO_2 concentration levels when developing regions have delayed CO_2 targets.

No papers were identified that analyzed how regionally different CO_2 reduction targets would affect cost-effective fuel and technology choices in the transportation sector or a "reverse form" of carbon leakage.

5.3 Studies analyzing biomass allocation

In a report edited by Lysen and van Egmond (2008), Londo, Mozaffarian and Smekens compare bioenergy allocations in different energy systems models results. The global models included in the survey are the EPPA[46] model, our GET 1.0 model, the WEM[47] model, the Timer[48] model, the Message model, and the BEAP[49] model. The model results differ widely on the sector in which biomass is most cost-effectively used. The extremes, regarding the share of total biomass that is allocated to the transportation sector, are the GET 1.0 model (lowest) and the BEAP model (highest). All studies show a significant share of biomass-based heat. The authors conclude that the two main factors influencing the allocation of biomass are (i) differences in techno-economic assumptions; and (ii) differences in policy assumptions. With a stringent CO_2 policy, or when specific subtargets are defined for each sector, biomass may be allocated more to transportation, since this sector hardly has any other climate-neutral options (in a short-term perspective), while the other sectors do (Lysen and van Egmond, 2008). Other studies (not analyzed in Lysen and van Egmond's report) finding that biomass first and foremost is allocated to the stationary sector are, e.g., Berndes and Hansson (2007), Gül *et al*. (2007), and Turton and Barreto (2007).

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[46] EPPA stands for Emissions Prediction and Policy Analysis, developed by MIT.
[47] WEM stands for World Energy Model, developed by IEA.
[48] Timer stands for Targets-IMage Energy Regional model, developed by RIVM/MNP.
[49] BEAP stands for Biomass Environmental Assessment Program (only the most stringent CO_2 reduction scenario - GLOB - is included).

5.4 Studies analyzing cost-effective fuel and technology choices in the transportation sector

Most modeling studies analyzing long-term fuel and technology choices in the global transportation sector treat synfuels such as methanol, DME, and Fischer-Tropsch (FT) fuels in aggregate, as one fuel option. However, Takeshita and Yamaji (2008) have analyzed the role of FT synfuels in competition with other synfuel options. They run their linear cost-minimizing model toward a CO_2 stabilization target of 550 ppm, by 2100. They find that methanol is barely introduced, and that DME is introduced only as an LPG replacement. FT products derived from coal resources play a major role in compensating for the scarcity of conventional crude oil assuming no CO_2 reduction policy; those derived from woody biomass also play a role (up to approximately 25% of global transportation fuel use in 2100) in the 550 ppm scenario. The authors conclude that FT products (naphta, diesel, gasoline, and kerosene) could contribute to securing transportation fuel supplies from diversified sources regardless of CO_2 abatement policy. Takeshita and Yamaji's results are to some extent similar to what we find using the GET model. In a no policy scenario, we also see coal-based synthetic fuels replacing oil in the transportation sector. In runs toward 550 ppm, we also see biofuels taking a significant share very similar in size (at most around 20% of global transportation fuel use), see, e.g., results in Paper II.

Yeh *et al.* (2008) use a US EPA national MARKAL model to analyze the role the transportation sector could play under economy-wide CO_2 constraints in the US, in the short- to medium-term perspective (up to 2050). In two of their analyzed CO_2 reduction scenarios, they assume ambitious CO_2 reductions without biofuel policy. Results from these scenarios show that gasoline will continue to dominate over the studied decades, first in ICEVs and then in HEVs and PHEVs. In one of these scenarios it is assumed that cellulosic ethanol will become economical viable, large-scale, which leads to HEVs and PHEVs being fueled with both gasoline and ethanol. Corn ethanol is not seen in these scenarios. In all scenarios assuming an ethanol target of minimum 36 Ggallons (approximately 4 EJ) per year, the results show ethanol flexifuel cars and fewer PHEVs. Hydrogen-fueled FCVs do not show penetration in any of the analyzed scenarios, and the authors note that this result is sensitive to the cost of fuel cell technology. These results are similar to what we see using the GET model. Hydrogen is very seldom seen before 2050, oil-based fuels dominate, and biofuels, used in HEVs and PHEVs, can be a cost-effective strategy to reduce emissions, see Paper I.

Endo (2007) uses a MARKAL based energy systems model to analyze what carbon tax is needed to achieve the targeted number of hydrogen FCVs in Japan (6% and 20% of total vehicles in 2020 and 2030 respectively). The author finds that conventional gasoline, diesel, and LPG constitute the full market until gasoline HEVs start to take market shares around 2010. At carbon taxes around 2400 JPY/tC (Approximately 22 USD/tC) gasoline HEVs dominate the market 2030–2050, and no other technology is introduced; but at a carbon tax of 10,000 JPY/tC (91 USD/tC) fossil-based hydrogen FCVs are introduced as early as 2020 and dominate the market by 2040 and onwards. Endo concludes that to achieve the targeted number of introduced hydrogen FCVs requires a carbon tax above 10,000 JPY/tC. Endo's conclusion differs from what we find using the GET model, where a carbon tax of 300 USD/tC or higher is needed before more advanced drive trains can compete with conventional ICEVs. Endo has not presented any sensitivity analyses, on, e.g., FCV costs, and he has assumed fairly optimistic costs on hydrogen vehicles, taken from a Japanese hydrogen energy roadmap from 2004. By using these data, the cost of hydrogen fuel cell cars drops to the same level as gasoline HEVs and diesel ICEVs in 2020. Also methanol FCVs drop to the same level as methanol ICEVs in 2020, which may explain the differing results.

Van Ruijven *et al.* (2007) use the global system-dynamics simulation energy model, Timer 2.0, to explore the role of hydrogen. They analyze three different hydrogen technology development paths, for a no CO_2 policy scenario and a climate policy scenario meeting 450 ppm CO_2-equivalents. Their results on primary energy use are similar to what we see in the GET model. When assuming ambitious CO_2 reduction targets, the primary energy use reaches about 900 EJ in 2100, biomass takes a significant share, oil and natural gas remain over the entire century, and the use of coal (without CCS) is almost phased out. Van Ruijven *et al.*'s results on hydrogen use in the no policy scenario, however, differ from what we see in the GET model. In their intermediate case (where they assume the same energy taxes on hydrogen as on other fuels), 150 EJ of hydrogen is used in the transportation sector (mainly based on coal). This result can never be seen in the GET model since we assume that the total cost (including the cost for infrastructure and vehicles) always is lower for coal-based liquid fuels compared to coal-based hydrogen.

Gül *et al*. (2007) use a MARKAL based energy systems model to analyze competing energy carriers for Western Europe's transportation sector. The authors have extended the Global Multi-Regional Markal model GMM, with three new key modules: (i) a hydrogen module; (ii) a biofuels module; and (iii) a transportation sector module reflecting existing and future personal vehicles. The model is then called the European Hydrogen Markal model, EHM, including EU-25 plus Norway, Switzerland, Bulgaria, and Romania. They find that in their CO_2 reduction scenario (minus 50% compared to 1990 in 2050 and minus 75% in 2100) the car sector is dominated by gasoline/diesel (first in ICEVs, then HEVs, and to a small extent also PHEVs) until hydrogen in FCVs takes over and dominates the market in the end of the century. Strips of biofuels (at most 14% of the market in 2050) and natural gas are seen in between petroleum and hydrogen. In a sensitivity analysis it is revealed that it takes very high subsidy levels of more than US$ 10/GJ to increase the share of biofuels to levels above 30% (but still below 5% in 2100). Toward the end of the century hydrogen is a too strong competitor for biofuels, in reaching CO_2 reduction targets, and biomass is predominantly utilized in other sectors. Gül *et al*.'s overall results are similar to what we see in our GET-runs.

Turton and Barreto (2007) use the global ERIS energy systems model to investigate how including a cost on greenhouse gas emissions affects the fuel and technology choices in the passenger car sector. The model has been developed to include non-CO_2 GHG gas emissions, forest sinks, and CCS. Energy demand[50] and population projections are assumed to follow the SRES B2 scenario. Results, assuming a carbon tax of 150 USD/tC-eq, show that petroleum ICEVs dominate the first half of the century and are then replaced by first and foremost natural gas HEVs (more than 60% of the global market in 2070). Strips of petroleum HEVs, natural gas ICEVs, and alcohol HEVs are also shown. FCVs do not play a significant role. The share of hydrogen FCVs, however, increases to around 60% in a sensitivity analysis, assuming a carbon tax of

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[50] One interesting difference regarding the future energy demand is the assumption on global car ownership, which in this study is projected to increase from approximately 100 to 250 cars per 1000 persons over the century, whereas it in the GET model is assumed that global car ownership will increase to 500 cars per 1000 persons, which is the level we have in Western Europe today (Eurostat, 2006; Regionfakta, 2007). Regarding the space required for almost 6 billion cars, note that even in densely populated European areas, e.g. Germany and the Netherlands there currently is one car per two persons.

1000 USD/tC-eq (leading to an atmospheric CO_2 concentration of approximately 550 ppm). The authors argue that even though biofuels are considered a possible future transportation fuel, the limited availability of biomass means that greater economic and environmental benefits can be derived by using biomass in other sectors. Turton and Barreto's results for fuel choices in the transportation sector are similar to what we see in the GET model. Oil- and natural-gas-based fuels dominate while there is a limited use of biofuels. Hydrogen dominates at the end of the century when assuming more stringent CO_2 policies.

Turton (2006) analyzes cost-effective fuel and technology choices in the transportation sector by using the ERIS model combined with the ECLIPSE model. Three aspects of long-term sustainable development are combined: (i) continued economic growth with reduced income disparities between different world regions; (ii) climate change mitigation; and (iii) security of energy supply. The first sustainable aspect is fulfilled by choosing the SRES B2 scenario where the global Gini index[51] improves from around 71.5 in 2000 to 36.7 by 2100. The second and third aspects are modeled by assuming an upper limit on atmospheric CO_2 concentrations of 550 ppm and that the resources-to-production ratio (R/P) for oil and gas is maintained above 30 years throughout the 21st century. It is found that petroleum products remain in the transportation sector during the whole century, and not until 2080 does the combined production of biofuels and hydrogen become larger than petroleum production. Fuel and technology choices shown are petro-HEVs, gas-HEVs, biofuel-HEVs, and an increasing share of H_2 FCVs at the end of the century (PHEVs and BEVs are not available options in the model). Turton's results regarding cost-effective fuel choices in the transportation sector are similar to what we see in the GET model. Oil-based fuels remain for many decades, and hydrogen is the fastest growing fuel option at the end of the century. The results on electricity production are, however, different. In the GET model, we have constrained nuclear contribution to current level, whereas approximately 225 EJ nuclear is shown in

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[51] The Gini index is a measure of the inequality of income distribution with values between 0 and 100, where 0 corresponds to perfect equality (everyone having exactly the same income), and 100 corresponds to perfect inequality (where one has all the income, while everyone else has zero income) (Wikipedia, 2008a).

Turton's study. Assuming reactors of 1 GW, 225 EJ correspond to more than 10,000 reactors, which can be questioned from a sustainability perspective.[52]

Gielen *et al*. (2002, 2003) use the BEAP energy systems model to study the optimal use of biomass for greenhouse gas emissions reductions. Results show that the majority of the biomass used in the model is allocated for the production of transportation fuels. The use of biofuels increases with more stringent CO_2 reduction scenarios. In the most stringent scenario (corresponding to approximately 400 ppm), there is an increasing use of biofuels (ethanol, methanol and biomass-based diesel/gasoline via HTU oil) and natural-gas-based methanol replacing conventional gasoline/diesel. Results for 2020 show approximately 45% gasoline/diesel, 35% biofuels, and 20% methanol (based on natural gas). The significant biofuel use shown in BEAP model results differs from what is seen in GET model results. This differing result, on how to allocate the scarce biomass resource, inspired us to carry out the analysis in Paper III of this thesis.

From this summary of different energy systems models results we can observe that conventional gasoline/diesel is a cost-effective fuel option for decades to come, in all studies. Most studies also find hydrogen the dominating option at the end of this century. Other fuel options are generally seen in a transient period. The role of biofuels varies but will never dominate the transportation sector (generally less than 20%, except for in the BEAP model). These results agree with the outcome from the GET model. Among these studies presented here, not many studies include electricity as an energy carrier option for passenger vehicles, at least not in a global energy systems perspective. Most studies also lack comprehensive sensitivity analyses.

5.5 Studies analyzing carbon leakage

If policies to reduce emissions in one country lead to higher emissions in other regions of the world, we define that as carbon leakage. There are two key mechanisms that may cause carbon leakage: (i) industrial production may relocate from regions with CO_2 reduction policies to other countries where such carbon policies are not in place; and (ii) reduced use of fossil fuels in regions with carbon policies may depress global oil prices

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[52] Before fission technology can be considered an option for sustainable development it must deal with challenges such as: safety, waste management, public acceptance, and nuclear weapons proliferation.

so that more oil is used in other (non-abating regions). Both mechanisms would reduce the global carbon benefit of the actions taken in the abating region. So far there has been very little empirical evidence about the extent to which carbon leakage has occurred, primarily since carbon policies have been too weak and short-lived so far to have had measureable impacts (Reinaud, 2008).

Grubb *et al*. (2002) and Persson *et al*. (2007) have made the case that a reverse form of carbon leakage could take place. For instance, if European countries set standards for CO_2 emissions from cars or electric appliances, this would form the norm for products being sold to other regions of the world regardless of their climate ambitions. This would, in turn, lead to reductions in carbon emissions in these other countries, defined as spillover. Grubb *et al.* note that it is common to discuss carbon leakage but not equally common to discuss spillover. Grubb *et al.* find that the spillover effect is larger than the carbon leakage. A reverse form of carbon leakage is found in some of our studied cases, in Paper III, but in most of the analyzed cases carbon leakage takes place. However, we have only studied carbon leakage from a cost-minimizing aspect, whereas Grubb *et al*. have studied other aspects.

Gielen *et al.* (2002, 2003) have looked at the impact of a large scale introduction of biomass in industrialized regions and found that this would depress oil prices and trigger an increased oil demand in developing countries. They find that around 20% of the emissions reductions in the industrialized regions is offset by increased emissions in developing regions in the scenarios they analyze. The largest leakage is found in policy scenarios with limited CO_2 reduction ambition. This is the opposite of what we find in our study. For cases when CO_2 taxes are low, we find the reverse form of carbon leakage (although small). Cases showing the largest carbon leakage are found when assuming high carbon taxes and a short delay prior to developing regions adopting carbon policies, in our study. The differing results can be explained by the time frame for which the models are run. Gielen *et al.* only present results until 2040, and at that time frame we also find carbon leakage (however, not that large as described in the study of Gielen *et al.*). That the carbon leakage is larger in Gielen *et al*., compared to our study, is likely connected to that they assume price elasticities on their energy demand levels.

No papers were identified that analyzed the reverse form of carbon leakage in an energy systems modeling framework nor specifically analyzed carbon leakage in a long-term perspective assuming limited primary energy supply.

6. Discussion and implications for policy

The main objective of this thesis is to analyze cost-effective fuel and technology choices in the transportation sector, typically under stringent CO_2 reduction targets. All five studies use the linearly programmed global energy systems GET model. The solution is based on cost-minimization. Our GET model results should be treated with care, as stated in Section 2.3; cost-effectiveness is one important criterion for CO_2 reduction policies, but not the only one. In Section 6.1, I discuss other factors that could be considered more important than cost-effective CO_2 reduction. I also discuss potential barriers to a cost-effective transition of the energy system.

I will also take the opportunity to summarize some of my personal reflections. These reflections have grown from numerous discussions with, e.g., local, national, and EU decision makers, Swedish authorities, strategists within the auto industry, farmers, media, the general public, and my colleagues, see Section 6.2. The world is certainly much more complex, and includes many more dilemmas and uncertainties, than can be handled in modeling studies.

6.1 Factors not included in the model that may impact results

In the following subsections I attempt to discuss some factors not taken into account in the model that may influence the results.

6.1.1 Biofuels in the transportation sector for other reasons than cost-effectiveness

A general result from the GET model is that biofuels never dominate among the fuel options in the transportation sector. In reality, biofuels may, however, be chosen for reasons other than cost-effective CO_2 reductions. Most countries wish to become less dependent on imported oil. If energy security is regarded an important objective, biofuels have a greater potential than hydrogen or electricity to be introduced in the transportation sector in a short-term scenario.[53] For studies discussing the role of biofuels from a European energy security perspective, see, e.g., Berndes and Hansson (2007) and Hedenus *et al*. (2009a). Rural development is another objective that could be considered more important than cost-effective CO_2 abatement. Regions that have land set aside (to avoid the overproduction of traditional agricultural products) now generally see biofuels as an additional agricultural product improving farming's profitability. Biofuel production in rural areas (as a part of rural development) is generally welcome in many regions. Finally, if technical, economical, and/or social barriers to using hydrogen or electricity in the transportation sector prove to be too difficult to overcome, biofuels will be a very important alternative when we run out of conventional oil.

6.1.2 Barriers for biomass in the heat sector

A general result from the GET model is that biomass first and foremost is used for heat production. In reality, biomass might not be well suited for all processes. The heat sector, in the GET model, has been refined in Hedenus *et al.* (2009b), resulting in less biomass being allocated for heat. Also when solid biomass *is* well suited, there may be barriers to introducing solid biomass for heat production on a large scale. One barrier for urban heat may have to do with logistic challenges. It may be difficult to transport large amounts of solid biomass into cities. Another barrier has to do with the inconvenience of using solid fuels. A switch from solid fuels to natural gas has occurred during the last decades in many regions where gas is available. 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 be large enough to make this argument invalid.

6.1.3 Stringent policy measures for industry may be politically difficult

GET model results generally show that actions first and foremost are seen in the stationary energy sectors. To realize these results it is necessary for politicians to also

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[53] One should also recall that measures aimed at reducing fuel demand may be equally or even more cost-effective in terms of improving energy security, than domestic biofuels production.

put pressure on industries competing on the international market. If it proves to be politically difficult to implement carbon reduction policies in the stationary energy sector, an earlier phase-out of fossil fuels in the transportation sector will be necessary, compared to what is shown in our GET model results. Moreover, if the stationary energy sector fails to reduce carbon emissions as much as shown in our results, biomass will to a larger extent be available for the transportation sector.

6.1.4 Barriers for large-scale electricity and hydrogen use

Biofuels are generally not seen as a cost-effective strategy to reduce CO_2 emissions as long as CO_2 neutral hydrogen and/or electricity are available at sufficiently low costs. Currently, it is very difficult to judge how reasonable these assumptions about the future are. Batteries used in mobile phones and laptops are constantly improving, and there are currently high expectations that Li-ion batteries soon will be available for the car industry. From scientific conferences on the other hand one realizes that a lot of research still is needed before it is possible to scale up Li-ion battery production, e.g., improvements are needed in the areas of capacity, effect, life time, production cost, safety, and environmental impact (Thomas *et al.*, 2008).

Fuel cells have been around since the 19th century and have been used successfully for decades for power generation in spacecraft. Automakers have produced hundreds of prototype hydrogen internal combustion and fuel cell vehicles[54] including cars, buses, bikes, and utility vehicles (e.g., fork lifters, mining locomotives, and golf carts) since the 1950s (Service, 2004; H2mobility, 2008). However, hydrogen still faces huge barriers as a large scale energy carrier, and it is not obvious that it will be available in a future transportation sector, at a reasonable cost. Barriers for large-scale hydrogen and fuel cell use include difficulties in the following four areas: (i) large-scale CO_2 neutral hydrogen production;[55] (ii) hydrogen storage for on-board applications;[56] (iii) fuel

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[54] Photos and descriptions of more than 400 hydrogen vehicles and more than 200 hydrogen filling stations are presented at www.netinform.net/h2/H2Mobility/Default.aspx (H2Mobility, 2008).

[55] Renewable electricity for hydrogen production via electrolysis is still not available at sufficiently low cost, e.g., solar PV still very expensive and/or includes scarce metals, gasification of biomass, as well as CCS from gasification of coal, not yet commercial available.

[56] At room temperature and atmospheric pressure, hydrogen takes up roughly 3000 times as much space as gasoline containing the same amount of energy. This 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

cells;[57] and (iv) hydrogen safety and infrastructure.[58] Each of the barriers is challenging on its own but for a hydrogen economy to succeed, all must be solved. One loose end could block a broad-based changeover (Service, 2004). Hydrogen, in either FCVs, ICEVs, HEVs, or PHEVs is, however, still discussed among vehicle manufacturer as an attractive long-term solution (FCCJ, 2008). Clearly, the long run future is still in the open. Again, if technical, economical, and/or social barriers to using hydrogen, or electricity, in the transportation sector prove to be too difficult to overcome, biofuels will be a very important alternative when we run out of conventional oil.

6.1.5 Future transportation systems may differ from what we know of today

The GET model assumes that car density will increase to a global mean of 500 cars per 1000 persons. The future energy and transportation system may, however, be totally different from what we know today. In fact, the transportation system will most likely undergo major developments during this century. Thus, it is not obvious that individual cars will be running in future cities. Many cities have today reached the maximum of vehicle capacity on roads above ground. One option is that future city vehicles instead may run on elevated tracks.[59] These vehicles may also be more safe and efficient compared to conventional cars (DN, 2004; SIKA 2008).

If cars, as we know them, remain in society, future citizens may be interested in flexible access to different types of cars. Today, a general car buyer chooses a car for her maximum needs, including daily commuting, shopping, and long vacations. Future car buyers may choose a car based on their median needs (most likely short driving distances), and for that purpose a small energy efficient car is appropriate. When buying

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promising, but some still have severe drawbacks, e.g., too heavy, too large, releasing the hydrogen too slowly, requiring high temperature or pressures or a time-consuming materials recycling (Service, 2004).

[57] The production costs of fuel cells are still high and material choices are not yet sufficiently optimized, e.g., improvements are needed in life time and replacement of scarce metals before scaling up the production.

[58] Read more about the challenges of hydrogen distribution, including leakage and embrittlement problems, in Björck and Grahn (1999). Further, hydrogen pipeline grids are costly, and investments will most likely not take place until the demand is large enough (chicken and egg problem).

[59] A podcar system consists of fully automatic car-sized vehicles located a few meters above ground. Propulsion, braking, switching, control and scheduling could all be done by using electromagnetic power and computer technologies. The vehicles may run non-stop from their point of origin to their destination freeing the driver from traffic responsibilities and at the same time virtually eliminating the risk of accidents. Vehicles can automatically connect to each other, to minimize congestion and maximize capacity and aerodynamics. When not in use, the vehicles automatically find parking spaces, either at an empty station or in a special parking garage (SIKA, 2008).

such cars, access to large or luxury cars, during weekends or for special occasions, may be included in the deal (Rishi *et al*., 2008).

Clearly, it is very difficult to know what direction the future transportation system will develop. Within this thesis we have not analyzed how the fuel and technology choices would have been affected by assuming different future transportation systems.

6.1.6 Future biofuel production may be significantly improved

In the GET model, we assume that the amount of crops that can be produced for the energy system is limited by the availability of land, given a certain yield. However, discussions on how to improve the yield from energy crops and the conversion efficiency are ongoing. Craig Venter argues: "The ability to construct synthetic genomes may lead to extraordinary advances in our ability to engineer microorganisms for many vital energy and environmental purposes" (Venter, 2003). Synthetically produced organisms (cell level bio-factories) will enable new direct methods of bio-engineered industrial production, such as the production of bioenergy, including ethanol and hydrogen as alternative fuels or substitutes for petrochemicals (Synthetic Genomics, 2008).

Researchers within forest biotechnology have used poplar to reveal key genes in the wood forming process. Recent work has focused on the genes and proteins involved in wood cell expansion (Mellerowicz and Sundberg, 2008), with the goal of increasing the cellulose content in energy crops. In the real world, a plant sometimes spontaneously produces 75% cellulose instead of normally approximately 45%. When this gene is identified, it may be possible to use biotechnology on energy crops, increase the crop's cellulose biosynthesis, and thereby improve the area efficiency of for instance cellulosic ethanol (Sundberg, 2002). Thus, radical developments, in biomass and biofuels production, that may occur in the future are not taken into account in the model. In sensitivity analyses, we have assessed higher biomass supply potentials; generally, these lead to an increased share of biofuels in the transportation sector.

6.1.7 Difficult to model oil and natural gas prices

All energy systems modelers face the same problem regarding how to model oil and natural gas prices. Nordhaus (1979) discussed the difficulty of what oil price that was appropriate to included in his energy systems model and found, by doing extensive sensitivity analysis, that a reasonable value for the initial oil price in the model was in the range of \$2 to \$4 per barrel (1975 year prices) – well below the market price at that time. The primary energy cost of oil in GET (\$3/GJ corresponding to \$18/barrel), is chosen as to be lower than the market price but higher than most conventional oil extraction costs. This is similar to the oil price in the BEAP model, which was set to \$1.6–5.2/GJ for different oil qualities (Gielen *et al*., 2002, 2003). In any approach (market price or extraction cost), it is likely that the price will rise over time and this feature is captured in the model. When the model is running, a scarcity rent is generated for all primary energy sources facing a demand higher than the availability. In sensitivity runs, we find that when doubling the oil and natural gas costs both sources are still used until depletion.

6.2 Personal reflections

In this section I have taken the opportunity to summarize some of my personal reflections. I have concluded that: (i) to reach near-term CO_2 reductions in the transportation sector, increased fuel efficiency is more important than switching fuels; (ii) the less bioenergy we need in the energy system transition the better; and (iii) we should not wait to implement policies for radical CO_2 emissions reductions, i.e., we should not gamble with our one and only planet Earth.

6.2.1 Energy efficiency more important than switching fuels, for near-term CO_2 reductions

A wide range of fuel options are currently commercially available or being developed, e.g., biogas, RME, ethanol, methanol, DME, FT-petroleum, biomethane, hydrogen, and electricity. Since the fuels can be produced from a variety of different crops, as well as from fossil fuels, we have a flexible matrix of fuel options solving many problems at the same time. Switching fuels from gasoline/diesel into biofuels might seem like it would solve the problems of CO_2 emissions, energy security, and rural development all at once.

It is also tempting to think that if we switch to a fuel that emits less CO_2 than present oil-based fuels, we can continue using the same energy-consuming vehicles and travelling patterns as before.

In an energy systems perspective this is, however, not the case. All energy sectors are competing for the same primary energy sources. By grouping the fuel options there are only three main energy carrier options: biofuels, hydrogen, and electricity and they all have limitations. Biomass for biofuel production is a limited energy source, and there will not be biomass enough to replace all fossil fuels currently used in the energy system. Both electricity and hydrogen need to be produced from low CO_2 emitting sources, which currently have high costs or are still in the demonstration stage. Fuel cells and batteries are currently too expensive and require technology breakthroughs before they can become commercially viable for large scale vehicle applications. If these options do not become available at large scale, at sufficiently low costs, then biomass will be needed to bring down overall energy- and transport-related emissions to low levels.

Thus, it is too early to choose (or rule out) either of these three energy carrier options. This leads us to my first personal insight: I see energy efficiency as more important than switching fuels for near-term CO_2 reductions. By reducing the demand for transportation fuels, no matter the fuel, it is possible to both reduce CO_2 emissions and reduce the dependency on oil. Such energy efficiency measures can be done using current technology. The average fuel consumption in 2007 in Sweden was 7.8 l/100 km for gasoline cars and 6.6 l/100 km for diesel cars[60] (Naturvårdsverket, 2008). But there are cars available on the market that only consume 3–4 l/100 km, see Miljofordon (2009) for an overview.

I want to stress the importance of continuous energy efficiency measures in the transportation sector and suggest that policies for near-term CO_2 reductions should aim for a reduction of fuel use rather than switching fuels. Simultaneous support for continued research and development of more advanced and efficient biofuels, as well as

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[60] This is a reduction from 1995 when the Swedish gasoline cars showed a mean value of 9.4 l/100 km and diesel cars 7.5 l/100 km.

hydrogen and electricity solutions, is needed to solve long-term CO_2 reduction challenges.

6.2.2 The less bioenergy needed the better

Biomass has the potential to replace fossil fuels in all possible energy applications, as well as replace currently fossil-based chemicals and feedstock usage. If grown wisely, biomass can contribute to a significant CO_2 reduction, and it can be produced in almost all countries around the world. Energy crop plantations can also be used to protect sensitive land areas from erosion, and some energy crops are good at absorbing heavy metals, e.g., cadmium and can thereby be used for the purpose of cleaning up polluted soil (Berndes *et al*., 2004). However, biomass suffers from several disadvantages. The amount of bioenergy that can be produced is first and foremost globally limited by water and land availability. There is also a risk of negative environmental impacts from bioenergy plantations, e.g., loss of biodiversity and nitrogen leakage. If tropical forests are cleared to make way for bioenergy plantations, or if these are established on peat lands, this can give rise to large GHG emissions several times higher (per energy unit) than from the combustion of fossil fuels (Hooijer *et al*., 2006).

Furthermore, land areas used for energy plantations compete with areas needed for the production of food, timber, pulp, and paper, providing recreation and wildlife habitat, and protecting sensitive ecosystems. Increased demand for land areas may lead to increased pressure on tropical forests, both direct and indirect.[61] If the competition for land intensifies,[62] it will drive up prices on land in the long term, and thereby also the cost of food production (Johansson *et al*. 2007, Azar 2005). Producing bioenergy from non-eatable crops reduces, but does not eliminate, the problem of increasing food prices, since non-edible crops compete to some degree for the same land. Other effects from increased land prices are that farmers in developing regions, who sometimes lack documented property rights, risk being driven away from their fields. This has already happened in rural areas of Colombia, where local farmers have been forced to move,

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[61] An example of indirect pressure on tropical forests already seen, is that an increased corn production (due to generous government subsidies intended to promote biofuel production) in the US leads to that less soy is produced there. To meet the soy demand, more soy has been produced in Brazil, and there is a strong link between Amazonian deforestation and soy demand (Laurance, 2007).

[62] Competition for land can arise from, e.g., increased fossil fuel prices. Increased energy prices increase the profit from producing energy crops, which will drive up prices on land areas.

and vast areas of Colombia's tropical forest have been cleared for palm tree plantations (Allen-Mills, 2007). Recent massive debate[63] regarding the drawbacks of bioenergy has been focused on the connection to current soaring food prices[64] affecting the poorest most[65] leading to numerous protests around the world.[66] However, bioenergy production is not the dominant reason for current increased food prices. The immediate reasons include floods and droughts in major wheat-producing countries, low grain reserves, high oil prices, and a doubling of per-capita meat consumption in some developing countries. The biofuel industry also contributes by using sugar, corn, cassava, oilseeds, and palm oil (The Economist, 2007; Holt-Giménez and Peabody, 2008; FAO, 2008).

The world currently uses about 50 EJ biomass per year. Some researchers argue that it will be possible to produce as much as 400–800 EJ per year by the middle of this century (Berndes *et al.*, 2003). In the GET model, we generally assume that 200 EJ biomass can be produced alongside food for 10 billion people. Such an increase in biomass production will most likely have an environmental impact and contribute to the competition for land leading to increased food prices. It may be possible to handle[67] the

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[63] Voices heard in the debate 2007-2008 include, e.g., the United Nations special rapporteur on the Right to Food, Jean Ziegler. He demanded an international five-year ban on producing biofuels to combat soaring food prices. He used the striking argument: "232 kg of corn is needed to make 50 litres of bioethanol - a child could live on that amount of corn for a year. It's a total disaster for those who are starving." (Swissinfo, 2007). A five year moratorium was also suggested by Monbiot (2007). Fidel Castro called the biofuel demand in Europe and the US "the internationalization of genocide" (Castro, 2007). IFPRI, the US National Food Administration in Washington, said that children in Africa will die if we continue to use biofuels. Andreas Carlgren, the Swedish Minister for the environment, said that reports suggesting that ethanol kills African children only profit the oil industry, not African children (NyTeknik, 2008). Ban Ki-moon, United Nations Secretary General, said higher food prices risk wiping out progress towards reducing poverty and, if allowed to escalate, could hurt global growth and security (Reuters, 2008a). Robert Zoellick, World Bank President, warned that rising food prices could push at least 100 million people in low-income countries into poverty (Reuters, 2008a). Brazil's President Lula da Silva rejected any link between rising global food prices and increased biofuel production and encouraged the whole world to produce more food (APF, 2008).

[64] Agricultural commodity prices rose sharply in 2006 and 2007 and continued to rise even more sharply in the first three months of 2008. The increase for the first three months of 2008 compared to the same three months in 2007 stands at 53%. Vegetable oils have on average increased by more than 97%, grains by 87%, dairy products by 58%, and rice by 46% (FAO, 2008).

[65] The world does not lack food. The poorest can simply not afford to buy the food there is. Rising food prices mean they eat even less. Josette Sheeran, the head of the United Nations' World Food Programme (WFP) states that "The world's most vulnerable who spend 60% of their income on food have been priced out of the food market." Today, about 850 million people remain chronically hungry, while 1.1 billion are overweight (The Economist, 2007).

[66] Demonstrations against increased food prices have occurred in, e.g., Mexico City (NYtimes, 2007), Haiti (CBN, 2008), India (Reuters, 2008b), Uzbekistan (IRIN, 2007), Burkina Faso (Reuters, 2008c), Cameroon and Johannesburg (EnergyNews, 2008), as well as in Rome and Milano (The Economist, 2007).

[67] Azar, 2008 contains an insightful chapter considering policy issues regarding food and poverty, pp.105–108.

higher food prices, the poverty issues, and the environmental impacts, but it is certainly a challenging task.

Hence my second personal insight is: “The less bioenergy needed in the transition of the energy system toward near-zero CO_2 emissions the better”. The more we can rely on energy efficiency measures and other renewable sources, especially solar energy, the better. When using bioenergy, I want to stress the importance of continued efficiency measures in biomass and biofuel production, to minimize the land needed for energy plantations.

6.2.3 Why gamble with our one and only planet Earth?

My third personal insight is directed to those who are skeptical about the importance of radical global CO_2 reductions. To those who hold that the Earth’s natural systems will take care of the increasing concentration of CO_2 in the atmosphere or suppose that increased atmospheric CO_2 levels have nothing to do with the well documented increased global average surface temperature, I fully agree with the following citation from Smalley (2005): “It might turn out that there is no causal connection between CO_2 and the warming of Earth – that if we wait long enough we will see this warming trend go back down, even though CO_2 levels keep going up. On the other hand, most likely there is a causal connection. Even if you were a conservative businessperson, you would probably agree that if a vice president of your corporation told you that there is no need to worry about CO_2 in the atmosphere, you would consider that too risky a belief on which to base the future of your company – let alone the future of the world.” So, why gamble with our one and only planet Earth?

Acknowledgments

This is a story about a person who liked to do puzzles and solve problems as a small child. She liked school, especially science and mathematics but also art. Upon choosing a track for upper secondary school, she thought it would be fun to develop skills like calligraphy, layout, and decoration. For more than ten years, she enjoyed working in the marketing and advertising business and did a lot of calligraphy, layout, and conference slides. During this period she did not have any contact with science or mathematics, but she continued to do puzzles and solve problems in her spare time. In the 1990's she was working at the Lennart Larsson advertising agency, with Volvo as her main account. She was fascinated by all the new concept vehicles running on new engine technologies and alternative fuels. She would never have guessed then that, about fifteen years later, she would be defending her doctoral dissertation analyzing the role of these new engine technologies and alternative fuels. There are of course a lot of people who need to be acknowledged. People who have had an impact on decisions and people giving support along the way, from the ad agency to the finished dissertation.

Starting from the beginning at the advertising agency: Thank you *Carina Möller-Liderfors, Lisa Andersson*, and *Anna Järvholm* for your support when I decided to totally change careers. Submitting my resignation was the first, and maybe the most difficult, step. I would also like to express my gratitude to *Lena Gustafsson*, professor of Biotechnology at Chalmers (currently at Vinnova). You gave an inspiring public lecture at Vetenskapsfestivalen, 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 the future. That lecture made me want to be involved in energy research, preferably with a connection to transportation fuels.

After two years of municipal adult education and one additional preparatory year in science, I started the four-year interdisciplinary university program "Problem solving in science." During my first year, I came in contact with the department of Physical Resource Theory. Thank you *Björn Sandén*, for being a fantastic supervisor in the course "Thermodynamics and energy models" and Christian Azar for not just being an

inspiring teacher in that course but also for asking me to work for you while a student; this work was very interesting and highly instructive. Further, thanks to all other brilliant teachers I met during the university period, especially *Maj Hansson, Jana Madjarova, Ann-Marie Pendrill*, and *Maria Sundin*, your knowledge and enthusiasm made a deep impression on me. Thanks also 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 field trip to the Ruhr-area in Germany where we took a close look at hydrogen pipelines. Great fun.

Since modeling and optimizing theory turned out to be the most enjoyable parts in these studies, I choose to continue to study these subjects for one year at Royal Melbourne Institute of Technology (RMIT) in Melbourne, Australia, leading to a Postgraduate Diploma in Statistics and Operation Research. A special thanks to *Denise* and *David Andrews* who became, and still are, dear 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 the progress of my PhD thesis. Astrid, I admire your energy, your hard work and your fabulous results. *Torbjörn* and *Susanne Bladby*, our friendship was also born during the year in Australia and means a lot to me. Susanne, are you ready for a game of Rummy?

When 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, those currently as well as those 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, Ingrid Råde, Björn Sandén, Pia Sundh, Johan Swahn, Elin Löwendahl, Tobias Persson, Anders Eriksson* and *Olof Görnerup* for your contribution to the FRT atmosphere during my first years at the department. 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.

Further, thank you *Jonas Nässén, Daniel Johansson, Martin Jacobi, Claes Andersson, Kolbjørn Tunstrøm, Johan Nyström, Larry Deschaine, Jörgen Larsson, Johan Torén, Anders Åhlen* and *David Bryngelsson* for your support, friendship and laughter. A special thanks to *Sandra Malentacchi*, your true Gothenburg humor is highly appreciated. Thank you, *Fredrik Hedenus*, for inspiring GET discussions, for reviewing drafts, as well as for your curiosity and critical feedback. Thank you, *Frances Sprei*, for your sharp questions at every seminar and for being my Jiminy Cricket, continuously checking how I prioritize my time, *Martin Persson*, for always giving sharp pedagogical answers, *Andrea Egeskog*, for creating a cheerful atmosphere and for driving us around in Brazil, *Wathanyu Amatayakul*, for teaching me how to take real tourist photos (pointing at the attraction) and the important count-down, *Stefan Wirsenius*, for your knowledge of the global food system and taking care of our computers and back up routines, *Madelene Ostwald*, for brightening up the daily life at FRT, *Sten Karlsson*, for your tough and straight arguments, for your interest in all subjects and for your passionate competitive instinct in FRT competitions, *John Holmberg*, for being a great head of the department for the first years of my doctoral studies and for offering Sten resistance in the FRT competitions, and *Ulrika Lundqvist*, for your support, heavy commitments, and for being an excellent head of the department. You all contribute to an inspiring environment.

A special thanks to *Julia Hansson*, for being the best conceivable office mate during virtually this whole period. You are always in a good mood and loaded with good arguments on every topic of conversation. I'm so glad that we also work on similar issues leading, so that we often attend the same conferences. I really enjoy the times we "appear in pair" and develop our networks together. Thank you for spending time reviewing my drafts, as well as for your support and friendship.

I would like to offer special thanks to my supervisors and co-authors. Thank you *Mats Williander*, for your genuine environmental commitment and for all interesting discussions, *Tim Wallington*, for your amazingly high work capacity, *Jim Anderson*, for your thorough calculations, and *Sherry Mueller*, for careful review. Further thanks to

Dolf Gielen, for your quick responses to my many questions, *Per Kågeson*, for your clear-sighted views on policy instruments in the transportation sector, *Göran Berndes*, for believing in me and my capacity, as well as for all support and encouragement, and *Kristian Lindgren*, for your support and for not hesitating shouldering the main responsibility when needed, as well as for your modeling expertise and for developing GET, the basic tool in most of my research. Last but not least, thank you *Christian Azar*, for all inspiration and encouraging support. You entrusted me with teaching and public speeches very early on. Your intellect, humor, ambition, knowledge, and salsa moves have made a deep impression on me. You inspire me.

Many thanks to *Paulina Essunger*, for critical review.

Financial support from Swedish Agency for Innovation Systems, Vinnova, and Swedish Energy Agency is gratefully acknowledged. Without your funding, this thesis would not have 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*. You have all been incredible patient. You have been listening to the same apology for a very long time now: "I'm sorry. I have to work this weekend. I'm in the final phase of my thesis work and need to focus." *Emma* and *Viktor*, you have enriched 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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