Regionalized Global Energy Scenarios Meeting Stringent Climate Targets – cost effective fuel choices in the transportation sector

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Abstract

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

1 Introduction

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

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

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

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

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

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

2 Model and scenario assumptions

2.1 Model description

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

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

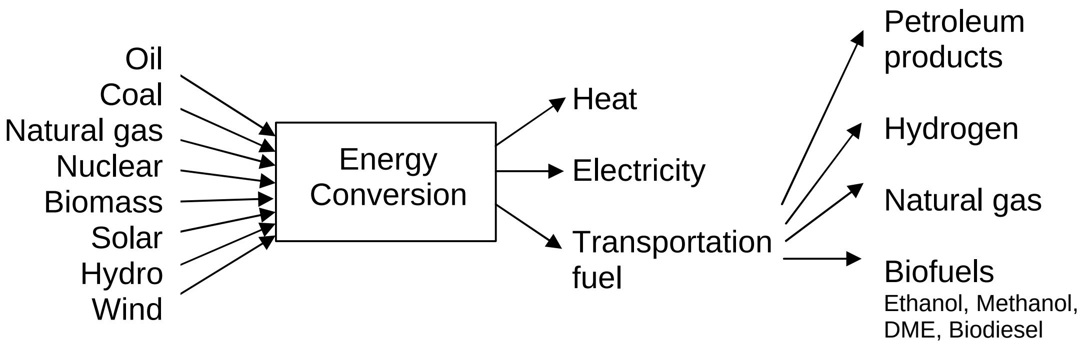

Figure 1: The basic flow chart of supply and fuel choices in the energy system model.

2.2 Scenario assumptions

2.2.1 Energy demand

Regional population, heat and electricity demand are assumed to follow an "ecologically driven" scenario developed by International Institute for Applied Systems Analysis (IIASA) in Austria. In this scenario, titled "C1", it is assumed that technological development leads to energy efficiency improvements, so that per capita heat and electricity demands in industrialized countries are reduced. In some regions, strong economic development will increase the per capita demand even if efficiency improvements are taken into account (Nakicenovic et al, 1995).

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

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

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

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

2.2.2 Energy availability

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

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

2.3 Maximum expansion rate

In reality, it takes time to make profound changes in the energy system of the world. This inertia is sometimes difficult to capture in energy system models. In our model, inertia is introduced in several ways. First, it takes time before the capital stock is replaced and therefore it becomes more expensive to introduce new technologies. Second, we have also introduced exogenous constraints on how fast new technologies might enter. When the total supply from a specific technology is set, then the maximum level of supply in the following decade is set so that a complete transformation of the energy system would take at least 50 years.

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

3 Results

3.1 Global results

Due to space limitations, it is only possible to present a short summary of our results here. A more complete description can be found in (Grahn et al, 2003).

3.1.1 Primary Energy Supply

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

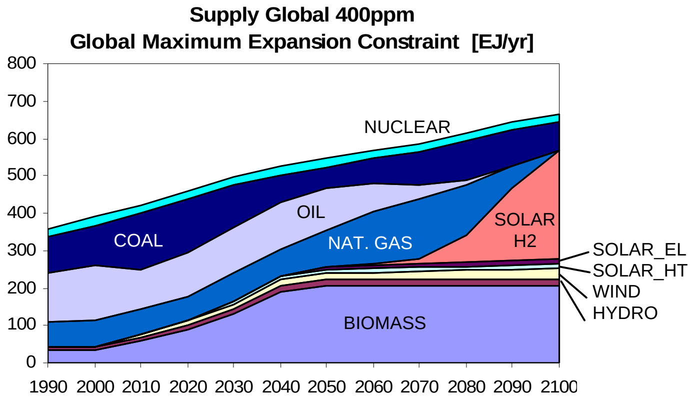

Figure 2: Primary energy sources required to supply the world's energy system, if atmospheric CO_2 concentrations are stabilized at 400 ppm. The eleven regional results have been added to produce this global figure.

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

3.1.2 Transportation

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

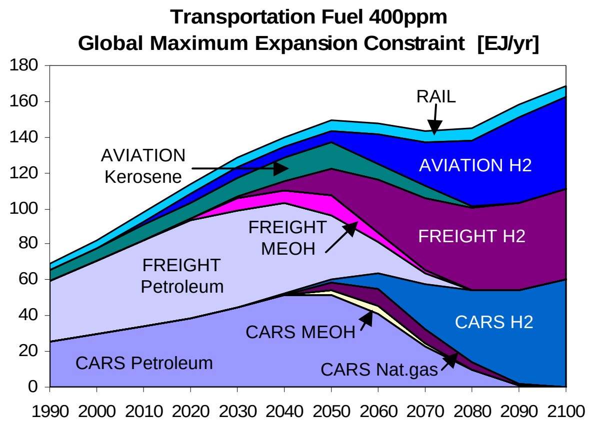

Figure 3: Projected transportation fuels requirements, if atmospheric CO_2 concentrations are stabilized at 400 ppm. Note that regional results are added to give a global figure.

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

3.1.3 Heat and Electricity Production

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

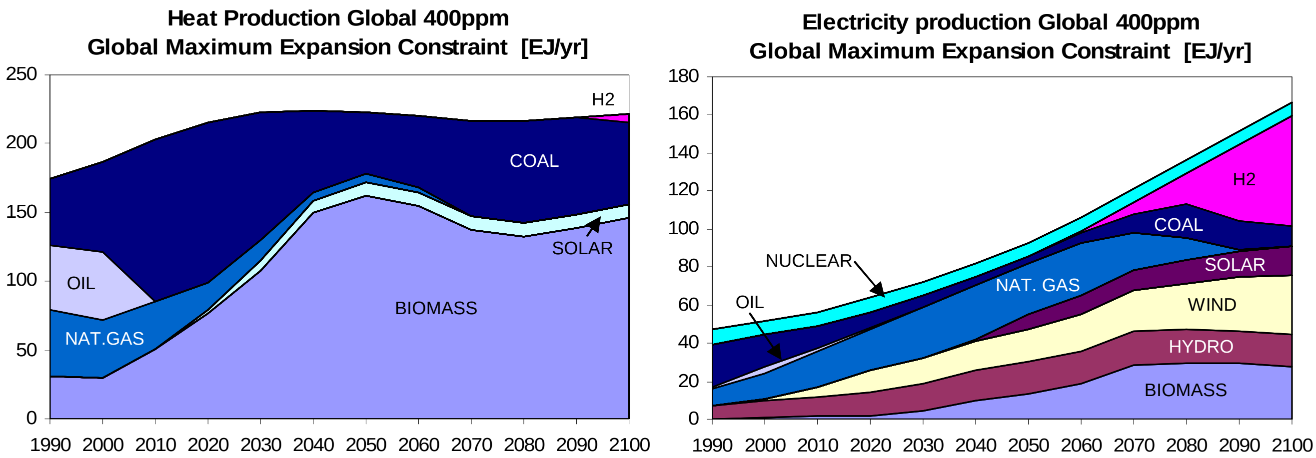

Figure 4: Primary energy sources used to supply households and industries global demand for heat as well as primary energy sources to supply the world's demand of electricity, given that atmospheric CO_2 concentrations are stabilized at 400 ppm. These graphs are produced using the global maximum expansion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

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

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

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

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

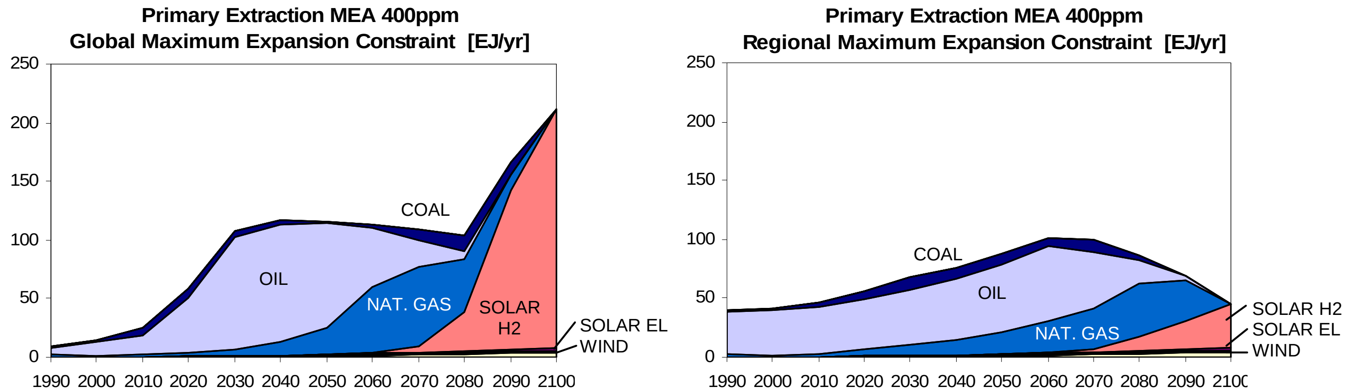

Figure 5: Primary energy extracted in region Middle East and North Africa, MEA. Solar produced hydrogen will be exported in the case of a global maximum expansion rate.

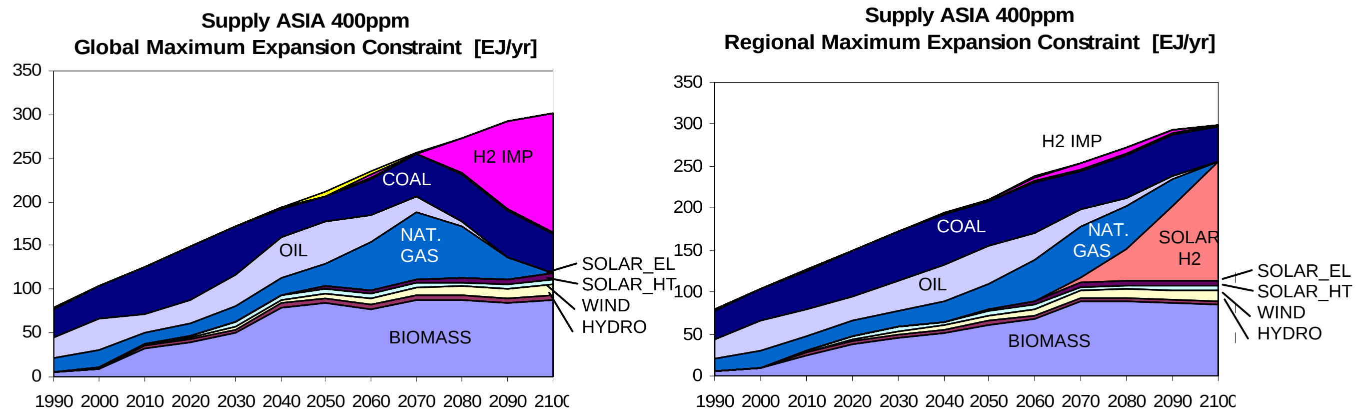

Figure 6: Primary energy sources to supply the energy demand in the Asian regions. No solar produced hydrogen will be developed in the case of a global maximum expansion rate. Instead hydrogen will be imported mainly from MEA. In the case of a regional maximum expansion rate the Asian regions will produce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

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

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

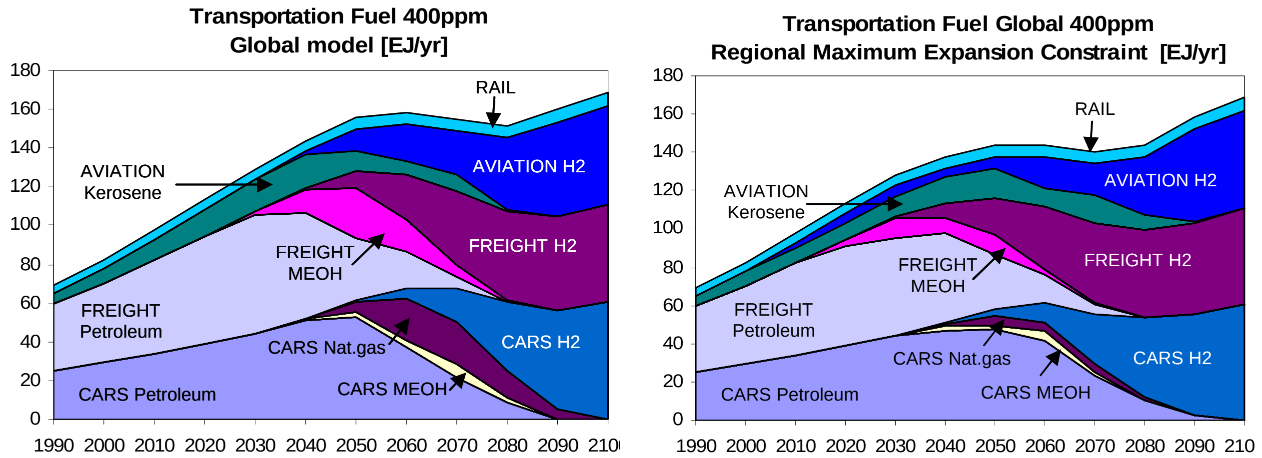

Figure 7: Fuel choices in the transportation sector will show the same over all pattern no matter global or regionalized model.

4 Discussion and Conclusions

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

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

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

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

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

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

4.3 A global but regionalized model versus a globally aggregated model

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

4.4 Affects of the two methods of regionalization

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

4.5 Model results are not a prediction of the future

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

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

5 Future Work

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

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

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

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

Acknowledgement

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