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The transportation energy carrier of the future. System interactions between the transportation and stationary sectors in a carbon constrained world

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Abstract

The aim of this study is to examine how the options for producing electricity, fuels, and heat in a carbon constrained world affect cost-effective fuels and propulsion technologies in the transportation sector. GET 7.0, a global energy system model with five end-use sectors, is used for the analysis. We find that an energy system dominated by either solar thermal energy or nuclear power tends to make biofuels in plug-in hybrids cost-effective. If coal with carbon capture and storage dominates the energy system, hydrogen cars, rather than plug-in hybrids tends to become cost-effective. From a Monte Carlo analysis we conclude that the stationary energy system does not alone determine how the transportation sector develops, but that its impact on the absolute and the relative cost of energy carriers has a significant impact on the cost-effectiveness of different propulsion technologies. Thus, analyses of future energy carriers and propulsion technologies need to consider developments in the stationary energy sector.

Keywords: Energy system model, plug-in hybrids, hydrogen, climate change mitigation

1 Introduction

The future of transportation fuels in a CO_2-abating world is subject to debate. Three main alternatives are often discussed, biofuels, hydrogen, and electricity. These may be used in different combinations in four types of propulsion technologies, hybrids, plug-in hybris, electric engines and fuel cells. It has been argued that biomass globally is most cost-effectively used for industrial process heat and residential heat, rather than for transportation [1,2]. Also it is unclear whether the biomass potential is large to considerably contribute to the long term transportation demand. Thus, for near zero global carbon emission targets, carbon neutral hydrogen or electricity are likely to be attractive transportation energy carriers.

Cost-effective fuels and cars may be studied in a static analysis, such as in [3, 4, 5]. One crucial aspect in these kinds of studies is the cost of producing hydrogen and electricity.

The price of electricity, biofuels, and hydrogen will largely depend on the technology options available. Technology options have both a direct effect on the price, as some production technologies are cheaper than others, and an indirect effect as technologies available in the overall system affect the price of scarce resources such as biomass, oil, and natural gas. There are thus potentially important system interactions between the stationary energy sector (electricity generation, fuel production, and industrial and residential heat) and the transportation sector. This is of interest since uncertainties pertain to the future technology options in the stationary sector for mitigating carbon dioxide emissions. Some uncertainties are of technical nature such as the cost of producing electricity from solar energy. Other uncertainties concerns the resource base, how large are the oil and gas reserves, or how large is the carbon capture and storage potential. Finally there are political uncertainties. For instance, will the global society accept a large scale expansion of nuclear power, despite the risks of accidents and nuclear weapons proliferation?

A few system analyses of cost-effective transportation fuels have been performed. Endo [6] used a MARKAL model to investigate the future role of hybrid gasoline cars and hydrogen fuel cell vehicles in Japan. He found that with a high carbon tax, hybrid gasoline cars are cost-effective in a transient phase between 2020 and 2040 and are thereafter replaced by hydrogen fuel cells cars. Similar results were obtained by [7,8], although the transition to hydrogen fuel cells takes place at the end of the 21th century. Grahn et al [9] studied cost-effective transportation fuels in an energy system model, and found the availability of carbon capture and storage and thermal solar power to have a large impact on which fuels become cost-effective.

In this paper we analyse the long-term system effect on the road transportation sector in a carbon constrained world using a global energy system model. The aim of this paper is to investigate how different technological options in the stationary energy sector affect cost-effective choices of transportation fuels and propulsion technologies.

The paper is structured as follows. Section 2 describes the model and parameters; section 3 presents the scenarios. Section 4 contains the results and section 5 an analysis to understand the mechanisms behinds the results. In section 6 there are wider discussions of the results, and section 7 contains our conclusions.

2 The model

GET 7.0 is a global energy system model with five end-use sectors. The model finds the least cost solution given a carbon constraint, for the period 2000 to 2150, with a discount rate of 5 % per year. Technology costs and performances are assumed at a mature level. Demand projections are based on the MESSAGE B2 scenarios with stabilization level of 470 ppm in 2100 [10], whereas the transportation demand scenarios are based on [1].

Five main energy carriers are represented in the model: petroleum based fuels such as gasoline and diesel, natural gas, synthetic fuels (synfuels) such as methanol, DME and Fischer Tropsch diesel, hydrogen and electricity, see figure 1. There are four end-use stationary energy sectors with exogenous energy demand: electricity, feed-stock for chemical industry, residential and commercial heat and industrial process heat. The transportation demand, also exogenously given, is in turn divided into different modes: rail, aviation, road and sea, as well as into personal and freight transport. For details about the electricity and transportation sectors see [1,11].

In GET 7.0 we include a more detailed representation of industrial process heat, industrial feed-stock and residential heat compared to previous versions of the GET model. This influences the competition for scarce resources such as oil, natural gas and biomass and therefore affects the transportation sector.

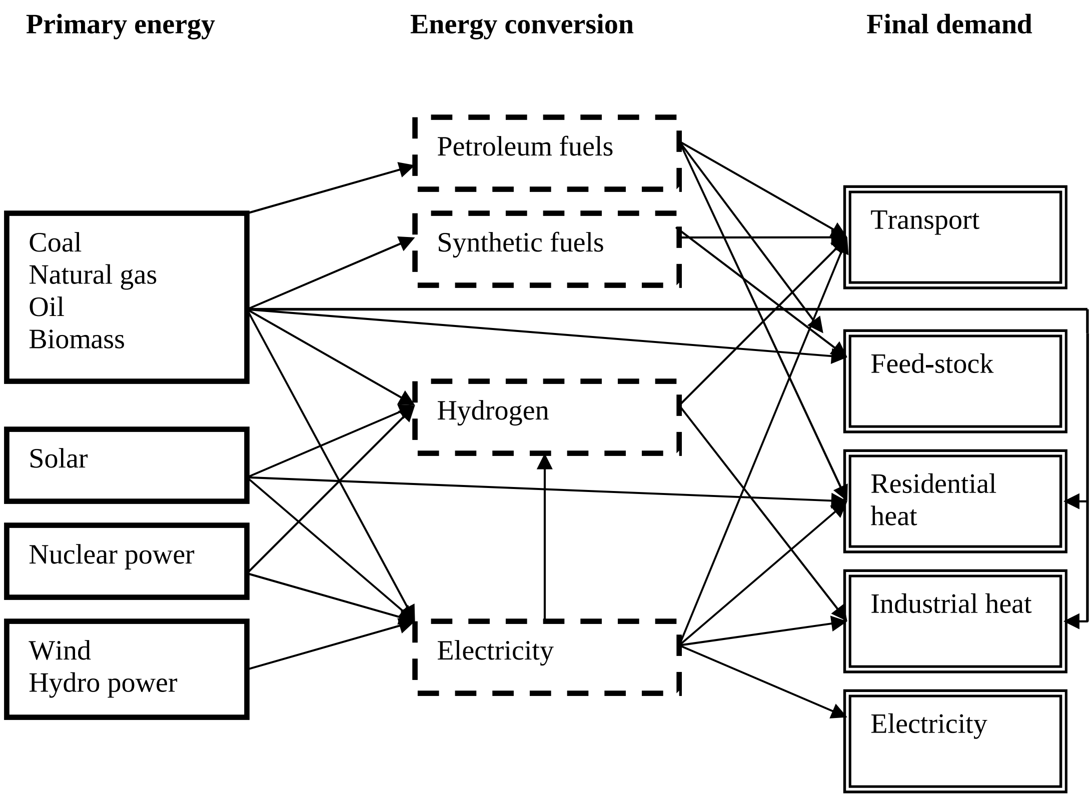

Figure 1. Structure of GET 7.0. Supply of primary fuels and energy carriers to end-use sectors.

2.1 Transportation sector

Cars, trucks, buses, trains, sea transportation and aviation are modeled; of these, cars, busses and trucks are modeled in greater detail. As we are primarily interested in the development for cars, busses and trucks, we prescribe that petroleum fuels are used in aviation and sea transportation to 2040, thereafter there is a transition to hydrogen use only.

2.1.1 Passenger cars

Five kinds of propulsion technologies are represented in the model, internal combustion engines, hybrids, plug-in hybrids, electric engines, and fuel cells. There are also five energy carriers that may be used for transport, gasoline/diesel, synfuels, hydrogen, natural gas, and electricity.

The internal combustion engine (IC) is assumed to be further developed over the century, from an average power train efficiency of 20% to 30%. All fuels can be used in the internal combustion engine.

Hybrid Electric Vehicles (HEV) have an internal combustion engine and a larger generator and battery. The battery stores energy from braking, which is released during acceleration. Further, hybridization enables the engine to work in more efficient modes, which improves the overall efficiency.

Plug-in hybrids (PHEV) have an even larger battery than the HEV and can be charged from the electric grid. The battery allows for 65% of the driving distance to be supplied by electricity from the grid. Plug-in hybrids enable further optimization of the internal combustion engine which gives even larger fuel efficiency than for hybrids.

Electric vehicles (EV) can only be charged from the grid, and have a limited range of 150 km. They are thus limited to urban use, and are therefore restricted to a maximum 30 % of the total number of cars.

Finally, Fuel Cell Vehicles (FCV), convert the fuel directly to electricity with high efficiency using a fuel cell. For fuels other than hydrogen a reformer is used, which increases the cost and decreases the efficiency.

We relate the efficiency of the other engines to the gasoline internal combustion engine, see Table 1. The estimates are based on [9], but we use a weight factor for batteries and hydrogen and natural gas storage to adjust the efficiencies. In addition, hybrid electric vehicles with gaseous fuels are included. Weight data for different energy storage options were found in [12].

Fuel storage and motor costs are also based on estimates in [9], but some adjustments are made for storage costs for hydrogen and natural gas. We assume a battery cost of 300 USD/kWh, and a fuel cell cost of 65 USD/kW. Further all vehicles except the electric vehicles have a range of 500 km. The costs of the engines are related to the cost of a gasoline internal combustion engine, see Table 2.

2.1.2 Trucks

The costs of trucks are based on up-scaling of the component (motor, battery, fuel storage etc) costs of cars. For efficiencies of trucks some adjustments are made compared to cars. The efficiency gain for hybrids is assumed to be only 5 % [13], since most trucks are used for long-distance travels, where hybridization gives less efficiency gain. Plug-in hybrids will only be cost-effective to use in specific situations such as city traffic and are therefore limited to a maximum 20 % of the truck transportation.

The range of the trucks is assumed to be 700 km rather than 500 km as for cars. This constitute a potential problem for hydrogen and natural gas as truck fuels since the fuel storage is rather spacious. For these fuels we assume a 10 % energy penalty per km due to potential space for cargo being used for fuel storage.

2.1.3 Distribution of transportation fuels

The distribution of transportation fuel to the end consumer means both an economic cost and in some cases an energy cost. The distribution of hydrogen in a large scale system with pipelines is estimated to cost between 6 and 9 USD/GJ with losses of around 10% of the energy content for compression [8, 14,15].

The cost of distribution of electricity varies a lot between distribution to households, 10-16 GJ/USD, and industries 3-6 GJ/USD, see the Appendix. We estimate the energy losses at 5 %. However, it is unclear what the extra cost would be for distribution of electricity to plug-in hybrid or electric vehicles, since those vehicles to a large extent can be slowly charged during nights. In that case it is reasonable not to assume any additional infrastructure cost since the load on the system is low during those hours, and the power needed to charge the battery is small.

Table 1. Efficiency estimates (in HHV) for different combinations of propulsion technologies and fuels compared to a gasoline/diesel IC car.

Propulsion technology	**Acronym**	**Liquid fuels**	**Natural gas**	**Hydrogen**	**Electricity**
Internal combustion engine	IC	1.00	0.97	1.03	
Hybrid	HEV	1.33	1.30	1.40	
Plug-in hybrid	PHEV	1.42	1.39	1.50	2.7
Fuel cell	FCV	1.25		1.60	
Electric	EV				2.8

Sources: [9, 12], for details see main text

Table 2. Incremental cost in USD compared to a gasoline/diesel IC car for different cars.

Engine	**Acronym**	**Liquid fuels**	**Natural gas**	**Hydrogen**	**Electricity**
Internal combustion engine	IC	0	1000	2700	
Hybrid	HEV	1800	2700	4200	
Plug-in hybrid	PHEV	6000	6700	8000	
Fuel cell	FCV	5500		6200	
Electric	EV				15000

Source: [9]

Otherwise the batteries may be charged rapidly at refueling stations. In that case, the distribution cost would be similar to the cost of distribution electricity to industries. Thus, the typical distribution cost of electricity to households is probably not applicable for distribution of electricity to vehicles.

For natural gas for transportation use we estimate the energy losses at 5% of the energy content [16]. Estimates used in the model for all fuels can be found in table 3. For more details on the cost estimates for energy carriers other than electricity, see [1].

Table 3 Distribution cost and energy losses for distribution of fuels for transportation use assumed in the model.

	Distribution cost (USD/GJ)	Energy losses
Gasoline	2	0 %
Synfuel	3	0 %
Natural gas	5	5 %
Hydrogen	7	10 %
Electricity	3	5 %

Source: See main text

2.2 Hydrogen and electricity production

Hydrogen and particularly electricity may be produced in a variety of ways. However, in the hundred year perspective there are only a few options that are not strictly limited by resource constraints, and those are solar energy, nuclear energy, and coal with carbon capture and storage. Those options also differ in characteristics, and therefore influence the overall energy system in different ways.

Thermal Solar Energy (TSE) may be used to either produce hydrogen in a chemical reactor or electricity through a steam turbine. By using thermal storage, heat generated during the day can be used during the night to produce electricity, which means that intermittency becomes less of a problem. There are two main technologies for concentrating solar energy. Parabolic troughs that concentrate solar heat to oil pipes is one, electricity is thereafter produced in a steam generator. A solar tower is the other, where a large field of heliostats concentrates solar energy to a tower, where steam is generated. Here higher temperatures are generated and solar towers are therefore the only viable option for hydrogen production. Estimates in [17] show that the solar tower technologies in the long run have a cost advantage over the parabolic trough; therefore we base our estimates for both electricity and hydrogen production on the solar tower technology.

A large part of the cost of a solar tower comes from the heliostats, the tower, and the receiver, and those are approximately the same whether electricity or hydrogen is produced. The part that differs is the generator and thermal storage in the case of electricity production and the thermo-chemical reactor in the case of hydrogen production. There are many different potential thermo-chemical cycles for producing hydrogen from solar energy even though none are commercially available [18]. Cost data on the thermo-chemical reactors are based on [19], and the cost of heliostats and power generator is based on mid level estimates in [17]. For estimates used in the model see Table 4.

Nuclear energy can be used to produce both electricity and hydrogen. Rothwell et al [20] examine the cost of producing electricity and hydrogen from modular helium reactors. Hydrogen is produced using a sulphur-iodine cycle where higher temperatures are required than generated in a light water reactor. Therefore helium reactors are suggested, those are, however, not yet proven, but we assume they may be available from 2030 and onward; cost estimates can be found in Table 4. The main difference between solar thermal energy and nuclear energy is that nuclear power provide base-load, so less back-up supply capacity is needed.

The additional cost of Carbon Capture and Storage (CCS) equipment is lower for hydrogen production and synfuel production than for electricity generation. The investment cost of producing hydrogen as well as synthetic fuels from coal with CCS is based on [21,22,23], whereas the electricity generation cost is based on [11]. Different from both thermal solar energy and nuclear energy CCS may be used in synfuel production and large industries.

Table 4. Investment cost, load factor and efficiency for production of electricity and hydrogen.

	Hydrogen				Electricity			
	Capital ($/kW)	Efficiency HHV (%)	Load factor (%)	Cost[1] ($/GJ)	Capital ($/kW)	Efficiency HHV (%)	Load factor (%)	Cost[1] ($/GJ)
Nuclear	2100	42	90	12	1500	48	80	10
Thermal solar power	1500[2]	n.a	22	24	4200[2]	n.a	70	21
Coal CCS	900	60	80	7	1500	35	70	13

[1]The cost in USD/GJ is calculated given an annual operation and maintenance costs of 4% of the capital investment, a life length of 25 years of the capital and the fuel costs 2 USD/GJ coal and 1 USD/GJ uranium.

[2] The capital cost is per kW produced hydrogen, whereas the capital cost for electricity is per kW generated electricity. As electricity is generated also during nights due to energy storage, the capital cost is higher.

2.3 Industrial process heat and residential and commercial heat

Industrial process heat can be supplied by fossil fuels, synthetic fuels, electricity, biomass and hydrogen. Due to process requirements and temperature restrictions only 50% of the total industrial energy demand may be supplied by solid biomass. If larger quantities of biomass are to be used, the biomass must be transformed to hydrogen or synthetic fuels. CCS may also be applied to large scale industrial plants, we assume that 50% of the demand for industrial process heat can be supplied with fossil fuels or biomass with CCS. The capture rate in the CCS facilities is set to 85%.

Residential and commercial heat may be supplied in a variety of ways. Heat can be generated from natural gas, fuel oil or pellets locally, or waste heat and centrally generated heat may be supplied by a district heating system. Further, solar heat may be used as well as heat pumps. The potential for heat pumps and solar heat is also very climate dependent. In cold regions 20%

of the demand may be covered with solar heat, and in warm regions 70%. The potential for heat pumps is assumed to be 60% of the residential and commercial heat demand.

3 Scenarios

We use on carbon dioxide emission trajectory reaching 400 ppm atmospheric CO_2 concentration at the year 2100, see Figure 2..

We develop three scenarios for the stationary sector to investigate the development in the transportation sector, see Table 5. In the base scenario, neither CCS nor nuclear energy can expand. Thus, the only large-scale carbon-free energy available is renewable energy. In the nuclear scenario nuclear power is allowed to expand but there is no CCS. In the CCS scenario, on the other hand, we assume that CCS is available at large scale but nuclear power is frozen at the current level.

The main constraint for electricity generation in the base scenario is intermittency, since wind and solar power dominate the supply. Wind power together with solar PV are assumed to cover a maximum of 30% of the electricity supply due to intermittency. Thermal Solar Energy (TSE) systems allow for 12-hour thermal storage, which enables power production at nights, too. Still,
TSE is only a reliable energy source in solar rich regions, and even there, a cloudy day could result in a black-out if there are no back-up systems. It is unclear to which extent TSE, solar PV and wind power together can dominate electricity generation without backup systems with hydrogen or natural gas. Tried and Muller-Steinhagen [24] estimate that 80% of the electricity demand in Europe, North Africa, and the Middle East could be supplied by renewables (including hydro and tidal energy) by 2050. They sketch a system with high-voltage DC transmission lines connecting Europe to the solar rich-regions of North Africa and the Middle East. Based on this, we assume that wind and solar energy together can supply 75 % of the global electricity demand.

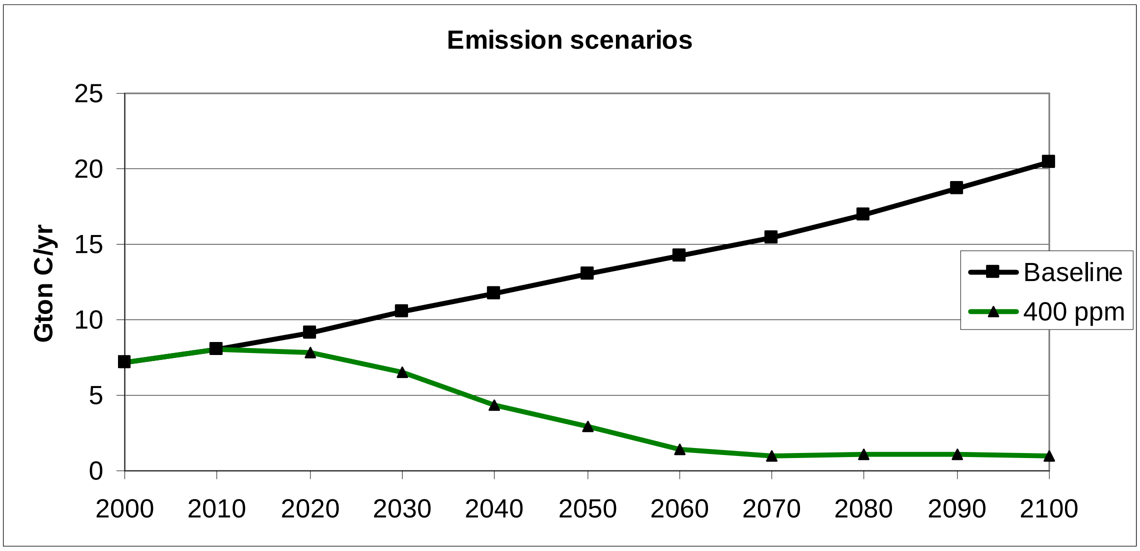

Figure 2. Carbon dioxide emission trajectories for baseline and 400 ppm stabilization scenario.

Table 5. Scenario names and technology options in the different scenarios.

Scenario	Nuclear energy	CCS potential (Gton C)
Base	Fixed at the present level	0
Nuclear	Unlimited	0
CCS	Fixed at the present level	3000

In the scenario where nuclear energy is allowed we assume both a large resource base and that advanced nuclear technologies are developed. The reserves of uranium for a price below 130 USD/kg uranium (0.2 USD/GJ thermal energy) are estimated at 25,000 EJ, whereas resource base including undiscovered resources is estimated at around 200,000 EJ [25]. We assume a resource base of 80,000 EJ thermal energy at a price of 1 USD/GJ, including the cost of waste management.

The global carbon storage potential is still poorly investigated. IPCC [22] estimate the CCS potential at between 1700 Gton C and 10 000 Gton C. We assume that the CCS storage potential is 3000 Gton C which means that the use of CCS is not limited by storage capacity for the time horizon studied in the model. Carbon capture and storage from biomass BECCS is limited to 20 % of the biomass use, we relax this constraint in the sensitivity analysis.

4 Results

We here present global results from the different scenarios with a atmospheric stabilization level of 400 ppm CO_2 in the year 2100.

4.1 Base scenario

In the base scenario nuclear energy and CCS are not available; therefore relatively expensive solar thermal energy dominates the electricity system as well as hydrogen production. Industrial process heat is supplied by solid biomass and electricity. Biomass is also used for production of synthetic fuel, which is used for road transportation and as industrial feed-stock. Further biomass is used to provide base load electricity. In this scenario the carbon price is high, above 1400 USD/ton C after 2050, due to limited low cost-abatement options.

In the passenger car sector hybrids with natural gas and gasoline are introduced around 2020. Around 2040 biofuel PHEVs are introduced and dominate the sector after 2070, see Figure 3. For road freight there is a shift from diesel trucks to hydrogen fuel cell trucks around 2050. These dominate the sector for the rest of the century.

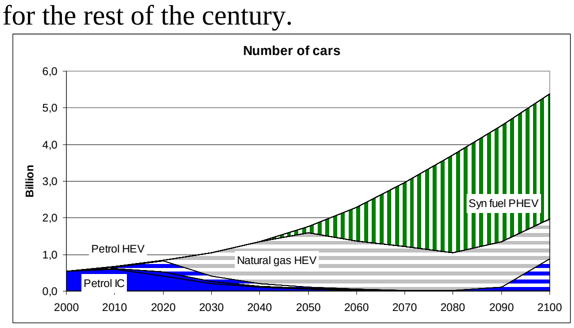

Figure 3 Passenger cars in the 400 ppm base scenario

4.2 Nuclear scenario

In this scenario nuclear energy dominates both electricity generation and hydrogen production. Biomass is used for industrial process heat and synfuel production. The remaining energy demand for industrial process heat is supplied by electricity in the later part of the century. The carbon price is lower in this scenario, compared to the base scenario, around 750 USD/ton C in the long run.

Even if the energy supply in the stationary sector changes compared to the base scenario, the fuel supply for road transportation does not. The passenger car transportation system is very similar to the base scenario, see Figure 4, whereas for road freight transportation biofuels and diesel to large extent replace hydrogen.

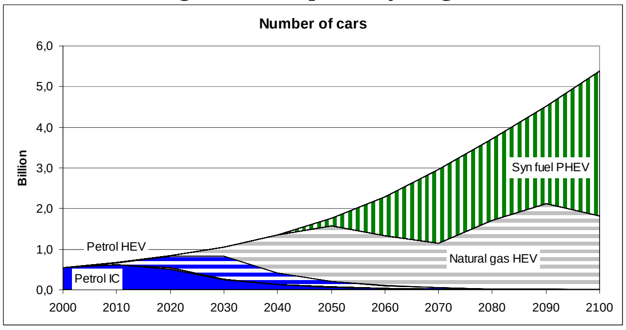

Figure 4. Passenger cars in the 400 ppm nuclear scenario

4.3 CCS scenario

In the CCS scenario carbon capture and storage is used for electricity and hydrogen production as well as to a limited extent for industrial process heat. Biomass is used for industrial process heat, hydrogen and synfuel production. Since CCS can be applied to industrial processes besides electricity and hydrogen production, and since hydrogen is cheaper to produce than in the nuclear scenario, the carbon price in this scenario in the long run is even lower, 500-600 USD/ton C

In this scenario gasoline/diesel IC and hybrid cars dominate passenger transportation until 2060. Thereafter hydrogen hybrid cars are introduced, see Figure 5, and to some extent natural gas hybrids. For trucks, diesel is used for the first 50 years and is thereafter replaced by biofuel IC trucks.

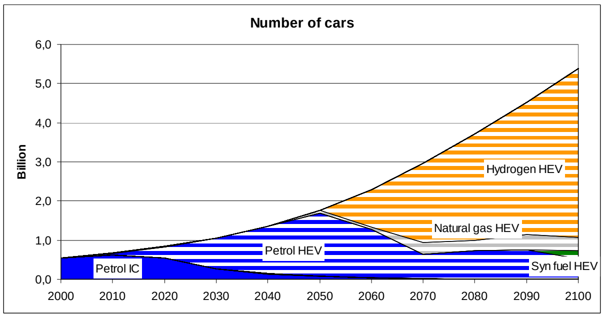

Figure 5 Passenger cars in the 400 ppm CCS scenario

4.4 Energy efficiency and energy prices

Figure 6 shows the energy used for road transportation (cars and trucks) on average for the time 2060-2099 for the 400 ppm scenarios. To the right the amount of energy required to supply the transportation demand using only gasoline/diesel IC vehicles is shown. The degree of improved end-use efficiency in the different scenarios can thus be related to the Gasoline/Diesel IC scenario as the total distance driven is the same in all scenarios.

Below the bars the price of electricity and hydrogen per unit of energy are showed. In the base scenario the electricity price is somewhat higher than the hydrogen price as hydrogen is used to provide base-load electricity at the margin. In the nuclear scenario, electricity has lower production costs than hydrogen production from nuclear energy, which results in somewhat lower electricity price, whereas the reverse solution holds for the CCS scenario.

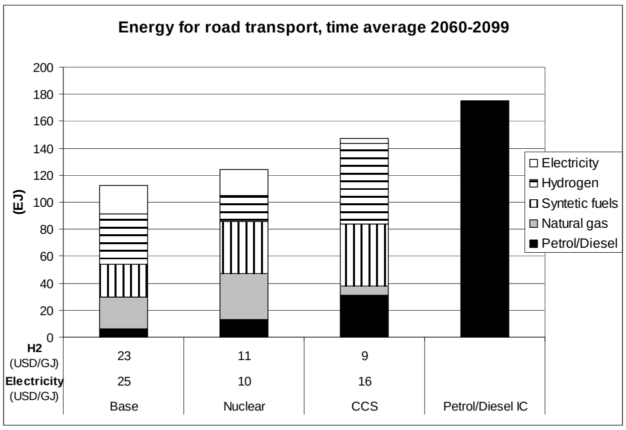

Figure 6. The energy for different fuels used for trucks and passenger cars in the 400 ppm case; and the average hydrogen and electricity prices for the period.

4.5 Monte Carlo Analysis

The future costs of batteries, fuel cells, and hydrogen storage are very uncertain. We have seen that the stationary energy system has an impact on the cost-effectiveness of fuel and propulsion technologies for one set of vehicle cost assumptions. The question remains whether this qualitative result holds for other vehicle costs. We therefore perform a Monte Carlo analysis, randomly varying important parameters, and study the outcome. We use a normal distribution for the battery cost, fuel cell cost, and gas storage cost, and assume a standard deviation of 25% of the respective costs. We ran the three scenarios for 100 different sets of vehicle costs. In Figure 8 the results for passenger cars are shown as the time average for the period 2060-2099 for a 400 ppm scenario. On average the base scenario holds the largest shares of plug-in hybrids, and the lowest share of hydrogen cars. The opposite holds for the CCS scenario, whereas the nuclear scenario is in the vicinity of the base scenario.

In figure 7 we can also see that there are several sets of vehicle costs that give very different results from the averages. In some cases hydrogen is used to a large extent in the nuclear scenario, whereas no hydrogen is used in the CCS scenario. The stationary system has a large impact on the cost-effective choice of vehicles, but the impact is not conclusive.

5 Analysis

The stationary energy system affects the cost-effectiveness of transportation fuels and propulsion technologies primarily through its impact on relative and absolute prices of energy carriers. The prices of different energy carriers are not only determined by the investment costs, interest rates, extraction costs for different fuels and operation and maintenance costs, but also by the availability of the fuels. Scarcity rents are generated in the model, and help to determine in which sectors certain fuels, e.g., biomass and oil, are used most cost-effectively. The effect of different technology options in the stationary energy sector can thus not be reduced to a single mechanism.

In a partial analysis without scarcity rents the cost of using biofuels in an IC or hybrid vehicle is lower than both plug-in hybrids (independent of engine fuel) and hydrogen vehicles. However, biomass is even more cost-effectively used for industrial process heat and electricity generation. As biomass is a scarce resource, biomass is, in our model, allocated to the sector where the cost advantages compared to the alternatives are the greatest, in order to achieve cost-effectiveness. For this reason biofuel seldom dominates the road transportation sector in our scenarios.

In the base scenario, dominated by solar thermal energy and with an emission trajectory reaching a concentration 400 ppm CO_2 by the end of the century, biomass is primarily allocated to the industrial sector and for synfuel production. In the passenger transportation sector plug-in hybrids, with biofuels as a complementary fuel, tend to be cost-effective beyond 2050. Still, our Monte Carlo analysis shows that for low hydrogen storage costs together with high battery costs, hydrogen instead of electricity becomes cost-effective.

In the nuclear scenario, both the electricity and hydrogen prices decrease compared to the base case, this also affect the biomass and synfuels prices which decreases compared to the base scenario. The lower energy prices make end-use efficiency less cost-effective, which can be seen in figure 6. Further the relative price between electricity and hydrogen makes plug-in hybrid more cost-effective than hydrogen vehicles. On average somewhat less plug-in hybrids are used compared to the base scenario on average.

In the CCS scenario the prices of hydrogen and electricity again decrease, but here the hydrogen price is reduced more, to roughly half the electricity price. Again end-use efficiency becomes less cost-effective, but the relative price of hydrogen and electricity tend to make hydrogen hybrids cost-effective.

Fuel cells for passenger vehicles seldom become cost-effective in our scenarios. When fueling them with liquid fuels the same or greater efficiency can be obtained by hybridization, but to a lower cost in most cases. For hydrogen there are some efficiency gains with fuel cells. Still, in the CCS scenario, as the price of hydrogen is relatively low, hydrogen is used in hybrids rather than fuel cell cars in all runs in the Monte Carlo analysis. Fuel cell passenger cars become cost effective in around 5 % of the runs in the Monte Carlo analysis in the base scenario. In this scenario the energy prices are

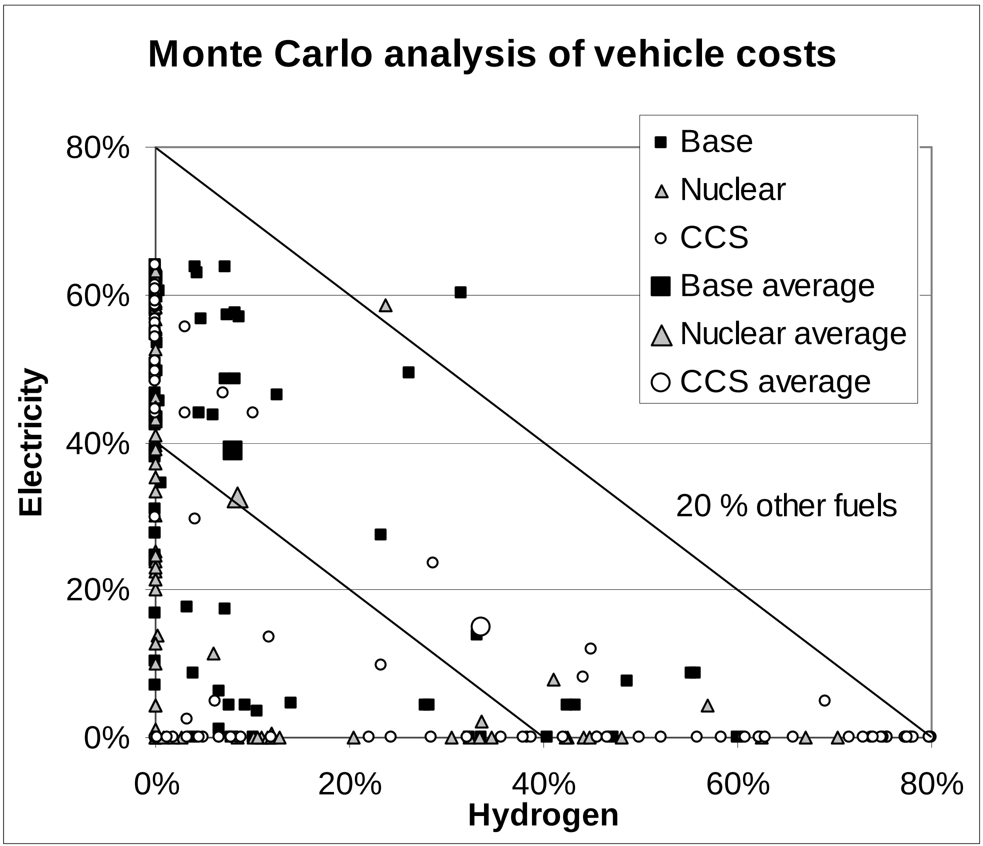

Figure 7. Monte Carlo analysis of 100 sets of vehicle costs in the 400 ppm CO_2 case. The cost of batteries, natural gas and hydrogen storage, and fuel cells are varied. The fraction of passenger car transportation distance using electricity and hydrogen are shown as the time average for the period 2060-2099.

higher compared to the CCS scenario, which tend to make increased efficiency more profitable.

6 Discussion

A hydrogen economy is often linked to a future of renewable, or sometimes nuclear, energy. Our results indicate, on the contrary, that hydrogen primarily tends to become cost-effective in a world with extensive use of coal with carbon capture and storage and an emission trajectory resembling our 400 ppm case. But, as stated earlier, hydrogen may also be cost-effective in other scenarios (assuming high battery prices).

To produce hydrogen from coal with steam reforming is a relatively well-established technology, and it is likely that the cost will be relatively low compared to electricity generated from coal. When it comes to renewables and nuclear energy we have assumed that thermo-chemical cycles for the production of hydrogen will be technologically feasible, even though this is still uncertain. Thermo-chemical cycles would mean that electricity and hydrogen would cost roughly the same. If thermo-chemical cycles are not available, hydrogen would have to be produced with electrolysis, which would significantly increase the price of hydrogen, and give electricity an even larger advantage as transportation fuel.

A major uncertainty, not included in the model, is consumer preferences. Vehicle types are not directly comparable from a consumer perspective. A natural gas car today takes longer time to refuel, the current hydrogen storage requirements are demanding, and an electric vehicle takes some hours to recharge and has a shorter driving range. If any of these aspects is considered to be a large problem among consumers, that vehicle may not be used despite a possible cost-advantage.

Around 80 % of the global population is expected to live in urban areas at the end of the century. In this analysis we have assumed a fairly high car density, around two persons per car. In urban areas people might accept cars with a shorter range and may consider reduction of local pollutants an important objective. In that case battery electric vehicles may be attractive. On the other hand, efficient and convenient mass transit systems may enable the car density to be considerably lower than assumed in this modeling exercise. Thus, there are factors in the transportation sector not included in the analysis that may be of large importance.

7 Conclusions

We have studied how the development of the stationary energy sector in a carbon constrained world influences the cost-effectiveness of fuels and propulsion technologies in the transportation sector. We conclude:

The stationary sector mainly influences the transportation sector through the absolute and relative price of energy carriers. These price in turn are determined both by the generation cost of different technology options, but also by the competition for scarce resources such as biomass and oil.

Our results show that plug-in hybrids rather than hydrogen cars tend to become cost-effective if the stationary energy sector is dominated by relatively expensive solar energy. This tendency also holds if the system is dominated by nuclear energy. However, if coal with carbon capture and storage dominates the energy supply, hydrogen tends to become the cost-effective transportation fuel in a 400 ppm CO_2 case.

Due to the uncertainty in vehicle cost technologies the long-term cost-effective transportation fuels and propulsion technologies in a carbon constrained world remain uncertain. However, we have shown that the potential for different propulsion technologies and fuels can not be analyzed separately, but must be based on a comprehensive analysis that includes both the stationary energy system and the different fuels and propulsion technologies.

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