Hydrogen and Biofuels – A Modeling Analysis of Competing Energy Carriers for Western Europe

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Abstract
This paper deals with the prospects of hydrogen and biofuels as energy carriers in the Western European transportation sector. The assessment is done by combining the US hydrogen analysis H2A models for the design of hydrogen production and delivery chains, and the European Hydrogen Markal model EHM with a detailed representation of biofuels and the European transportation sector. The analysis shows that with CO_2 reduction target of 50% in the year 2050 for EU-29, biofuels are an option for decarbonization of personal transport and can achieve a share of 14% of total fuel consumption in this sector by 2050. Hydrogen penetration occurs in the long-run only, with the potential to dominate the personal transport market. Increasing oil prices and subsidies for biofuels and hydrogen increase the share of both fuels in personal transport. However, it takes stronger CO_2 reduction targets, i.e. 60% in 2050, in order to make hydrogen gain significant market shares already by 2050.

1. Introduction

In light of increasing greenhouse gas (GHG) emissions and oil prices, the concept of the often-called “hydrogen economy” has been discussed widely over recent years, i.e. an energy system attributing a key role to hydrogen (Ogden 1999). However, other competing energy carriers such as biofuels do exist, and seem at least equally suitable to at the same time decrease GHG emissions and decrease fossil fuel dependency, and probably even at lower cost.

This paper compares the prospects of hydrogen in the transportation sector in Western Europe (EU-29) with those of biofuels and seeks to identify market conditions that could accelerate hydrogen and biofuels market penetration. The analysis is pursued using the European Hydrogen Markal model EHM, a partial-equilibrium, technology-oriented “bottom-up” model with a detailed representation of energy technologies, which serves for the analysis of energy systems on a Western European scale by assessing the impacts of different policies.

The model and its components are further described in chapter 2. Chapter 3 describes the baseline scenario analysis, while chapter 4 presents and discusses the scenarios investigated. In chapter 5, a summary is given and conclusions are derived.

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2. The European Hydrogen Markal Model EHM

The European Hydrogen Markal model EHM is a partial-equilibrium, technology-oriented "bottom-up" model of the MARKAL family of models [1] with a detailed representation of energy technologies on a European scale (EU-25 plus Norway, Switzerland, Bulgaria and Romania). MARKAL-type of models identify least-cost solutions for the energy system under given sets of assumptions and constraints.

EHM displays the whole energy system from the extraction of energy carriers to conversion processes, their transmission/distribution and end-use in the transportation sector (personal transport, aviation, and other transport), residential/commercial sector (heat, electricity), industrial sector (heat, electricity) and feedstocks. The timeframe of EHM is 2100, divided into 10 years time steps, and the model applies exogenous learning assumptions. It is calibrated to year 2000 statistics from the IEA (2002).

In its structure and technology cost data, EHM is based on the Global Multi-Regional Markal Model GMM, a model developed at Paul Scherrer Institut in Switzerland. Further details can e.g. be found in Rafaj (2005).
EHM, however, extends GMM by three key modules, which have been designed to assess the competitiveness of hydrogen in comparison to biofuels in the transportation sector: a hydrogen module with a detailed representation of hydrogen production technologies and a hydrogen delivery infrastructure for assessing the cost of hydrogen at fueling stations; a biofuels module comprising promising biofuels production pathways and their delivery to fueling stations; and a transportation sector module reflecting existing and future personal vehicles.
The hydrogen module provides for a link to the H2A modeling analysis, which is an effort conducted under the umbrella of the US Department of Energy;[2] this module will be described in the following. Thereafter, a description of the biofuels and personal transport modules of EHM is presented.

2.1 The Hydrogen Module

The hydrogen module of EHM is composed of central hydrogen production facilities, a hydrogen delivery infrastructure and forecourt hydrogen production.

2.1.1 Central Hydrogen Production

The central hydrogen production technologies considered in this analysis comprise the fossil-based coal gasification and natural gas reforming with and without carbon capture; the prospective nuclear-based technologies nuclear sulphur-iodine (SI) cycle, nuclear high-pressure (HP) electrolysis and nuclear high-temperature (HT) electrolysis; alkaline water electrolysis (AWE) and HP electrolysis; and finally the renewable technologies

[1] See i.e. Loulou et al. (2004), Fishbone et al. (1983) and Fishbone and Abilock (1981) for details on MARKAL-type of models.
[2] See http://www.hydrogen.energy.gov/h2a_analysis.html for details.

biomass gasification, combined wind & electrolysis systems and the solar-supported coke gasification as well as the solar Zn/ZnO-Cycle.

Except for the solar-based technologies, all data has been analyzed using the H2A hydrogen production models.[3] The solar-supported coke gasification and solar Zn/ZnO-cycle are developed at Paul Scherrer Institut in Switzerland and analyzed in Felder (2007). A detailed description of the operation of all technologies is beyond the scope of this paper, but can for example be found in IEA (2005). Table 1 gives an overview on cost and efficiencies considered.[4] Note that negative electricity input represents net gains, as these technologies are designed as co-production facilities; advanced and future technologies in this table have been modeled crediting exogenous cost reductions for the individual technologies, with the future technology costs as floor costs. For future technologies, no further cost reductions were assumed.

Today, most of currently produced hydrogen is from natural gas (48%), main reason is the long-proven maturity of natural gas reforming; coal contributes only 18% to global hydrogen production, the remainder is from heavy oils and naphtha (30%) and electrolysis (4%) as a by-product of chlorine production (Source: Penner 2006, all data for 2001).

[3] Unpublished data from the H2A Project at the U.S. Department of Energy's Hydrogen Program and the National Renewable Energy Laboratory, H2A model-version 2006. Older versions of these models can be found at http://www.hydrogen.energy.gov/h2a_production.html.
[4] All calculations herein are based on an interest rate of 5%, US$ are understood as US$2000 for the entire paper. All hydrogen related data is on LHV basis. Fuel input cost assumptions for this table only: Natural Gas = 4.6 US$/GJ; Coal = 1.6 US$/GJ; Biomass = 5.1 US$/GJ; Electricity = 12 US$/GJ; Coke = 4.6 US$/GJ.

Table 1. Discounted Central Hydrogen Production Costs and Efficiencies.[5]

Process	Start Year	Feedstock In / H_2 Out	Net ELC In	INV. COST	FIXOM	VAROM	Feedstock Cost	ELC Cost	AF	H_2 Cost
		[GJ / GJ]	[GJ_{ELC} / GJ_{H2}]	[US$/GJ]					[-]	[US$ / GJ]
Coal Gasification										
Current	2005	1.84	-0.09	1.98	1.80	0.27	2.94	-1.13	0.9	**5.85**
Current w/ CCS[6]	2005	1.69	0.01	2.28	1.85	0.66	2.71	0.10	0.9	**7.60**
Advanced	2015	1.65	-0.01	1.55	1.51	0.16	2.64	-0.08	0.9	**5.78**
Advanced w/ CCS[5]	2015	1.65	0.00	1.57	1.52	0.58	2.64	0.00	0.9	**6.31**
Future	2025	2.12	-0.45	2.61	2.43	0.19	3.38	-5.37	0.9	**3.25**
Future w/ CCS[5]	2025	2.12	-0.44	2.80	2.50	0.73	3.38	-5.27	0.9	**4.15**
Biomass Gasification										
Current	2005	2.21	0.05	1.24	1.46	1.60	11.28	0.56	0.9	**16.14**
Advanced	2015	1.94	0.03	1.19	1.39	1.43	9.87	0.34	0.9	**14.23**
Future	2025	1.81	0.03	1.05	1.28	1.27	9.24	0.34	0.9	**13.18**
Natural Gas Reforming										
Current	2005	1.36	0.02	0.61	0.40	0.22	6.32	0.20	0.9	**7.76**
Current w/ CCS[5]	2005	1.36	0.05	0.77	0.51	0.57	6.30	0.62	0.9	**8.76**
Advanced	2015	1.36	0.02	0.46	0.34	0.22	6.32	0.20	0.9	**7.54**
Advanced w/ CCS[5]	2015	1.36	0.05	0.62	0.44	0.57	6.30	0.62	0.9	**8.54**
Future	2025	1.36	0.02	0.46	0.34	0.22	6.32	0.20	0.9	**7.54**
Future w/ CCS[5]	2025	1.36	0.05	0.62	0.44	0.57	6.30	0.62	0.9	**8.54**
Nuclear SI cycle										
Future	2025	0.00	0.05	3.12	3.41	2.26	0.00	0.61	0.9	**9.40**
Electrolysis										
Current AWE	2005	0.00	1.59	2.52	2.18	0.24	0.00	19.07	0.9	**24.00**
Advanced AWE	2015	0.00	1.43	1.36	1.23	0.26	0.00	17.10	0.9	**19.96**
Future AWE	2025	0.00	1.33	0.95	0.90	0.27	0.00	15.96	0.9	**18.09**
HP Electrolysis	2015	0.00	1.43	1.30	1.58	0.03	0.00	17.20	0.9	**20.10**
Other Electrolysis Options										
Nuclear HP	2015	0.00	0.00	4.22	5.57	2.18	0.00	0.00	0.9	**11.96**
Nuclear HT	2025	0.00	0.00	3.84	3.69	2.43	0.00	0.00	0.9	**9.96**
Wind + AWE Current	2005	0.00	0.00	11.38	8.96	0.24	0.00	0.00	0.4	**20.59**
Wind + AWE Advanced	2015	0.00	0.00	6.66	4.49	0.26	0.00	0.00	0.5	**11.41**
Wind + AWE Future	2025	0.00	0.00	4.91	3.33	0.27	0.00	0.00	0.5	**8.51**
Solar Technologies										
Solar Zn/ZnO	2025	0.00	0.00	32.08	37.46	0.00	0.00	0.00	0.23	**69.5**
Solar & Coke	2025	0.87	0.00	22.51	26.48	0.00	0.67	0.00	0.23	**49.7**

[5] INVCOST = Investment Cost, FIXOM = Fixed O&M Cost, VAROM = Variable O&M Cost, ELC = Electricity, AF = Availability Factor; CCS = Carbon Capture for Sequestration.

[6] Note that all carbon capture technology cost in this table do not include the cost for transporting and sequestering hydrogen. In the modeling analysis, CO2 storage costs are considered as 10 US$/t CO2.

2.1.2 Hydrogen Delivery Infrastructures

This section describes the infrastructure for delivering hydrogen from central production facilities to hydrogen fueling stations. As a general remark, there is a wide range of literature available on the delivery of hydrogen, and, thus, a lot of different viewpoints. In absence of existing projects on delivering hydrogen at the scale required in a hydrogen economy, this is probably mainly due to a lack of experience. In particular, there is some disagreement on the cost of delivering hydrogen by pipeline, which the H2A components model considers to be in the order of a factor 1.1 more costly than for natural gas pipelines according to Parker (2005). Moreover, delivering hydrogen in a liquid state by truck is widely debated, some authors are more (i.e. Simbeck and Chang (2002)), some less optimistic. Generally, approaches to calculating hydrogen delivery costs differ.

The analysis conducted here has been based on the assumptions of the H2A components model[7] as this analysis was deemed very consistent and transparent, and provides for a lot of flexibility in terms of underlying assumptions and design of delivery networks. For the analysis, it has been assumed that the design city demand for hydrogen is 250'000 kg of hydrogen per day. This could equal a city size of about around 1 million inhabitants, if all hydrogen demand was from personal vehicles, and all personal vehicles were hydrogen fuelled vehicles.
Moreover, a total delivery distance of 80 km has been depicted. This number may naturally differ in real-life applications; however, for the analysis with EHM, it seems sufficient though to assess this distance as a European average number. Figure 1 depicts the hydrogen infrastructure systems as considered in EHM.

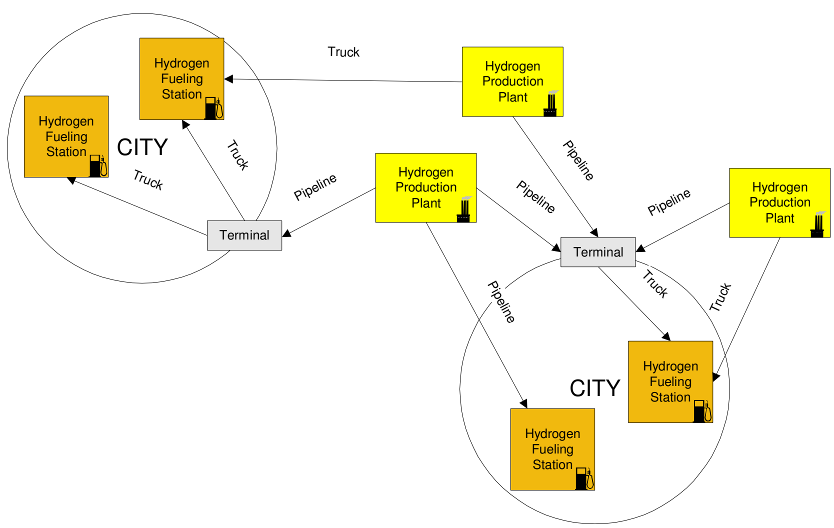

Figure 1. Hydrogen Delivery Infrastructures in EHM.

Five different possibilities for hydrogen delivery from central production facilities are considered: delivery by truck in gaseous (option 1) or liquid form (option 2); delivery by pipeline using a system of transmission, trunk and delivery pipelines (option 3); and

[7] Version 10 July 2006. Available on the web: http://www.hydrogen.energy.gov/h2a_delivery.html

combined systems with pipeline delivery to a terminal at city boundaries, and delivery by truck from the terminal in gaseous (option 4) or liquid state (option 5) to the fueling stations.
Table 2 shows the total cost of these options as designed for coal gasification. Two sizes of hydrogen fueling stations were considered: small fueling stations with a peak demand of 100 kg/day, and large fueling stations with a peak demand of 1'500 kg/day. For option 1, only small fueling stations were considered as one truck in H2A can carry only 9 tubes of hydrogen with a capacity of 31.15 kg/day each. For option 2, both options were considered as one liquid hydrogen truck delivers net 3'650 kg of hydrogen per trip. The drawback is that the economic competitiveness depends considerably on the number of fueling stations served per trip. H2A provides for the possibility of serving up to 3 stations per trip only, which means in turn that if liquid truck delivery to small-size fueling stations is desired, then the number of trips per year per truck becomes very low.

For options 3 to 5, only large fueling stations were considered. This is due to the fact that these elaborated systems will require significant hydrogen demand for their implementation. Thus, large-scale fueling stations will rather be chosen.

Note that for hydrogen delivery infrastructures, no explicit cost reductions were assumed.

Table 2. Discounted Cost of Hydrogen Delivery Infrastructures for Coal Gasification.[8]

Infrastructure Option[9]	Efficiency	Investment Cost	Fixed O&M	Variable O&M	Electricity / Fuel Cost	Hydrogen Cost
	[%]	[US$/GJ]				
Option 1, small fueling station	98.9	16.86	16.43	5.50	1.23	**40.03**
Option 2, small fueling station	82.2	24.16	15.25	2.97	3.00	**45.38**
Option 2, large fueling station	85.7	6.33	4.22	1.11	3.00	**14.66**
Option 3, large fueling station	98.5	5.27	3.23	0.40	0.96	**9.86**
Option 4, large fueling station	97.9	8.34	7.14	1.26	0.70	**17.46**
Option 5, large fueling station	84.8	6.80	4.78	1.02	3.15	**15.76**

The data shows a cost advantage for the delivery of hydrogen by pipeline ring systems to large hydrogen fueling stations. However, this delivery option will not be available without a significant hydrogen demand. Therefore, truck delivery has its merits. Moreover, it needs to be noted that direct truck delivery as well as combined pipeline and truck delivery systems are comparatively easier to implement and extend with increasing demand than is direct pipeline delivery.

[8] Interest rate: 5%.
[9] Options 1: delivery by truck in gaseous form; Option 2: delivery by truck in liquid form; Option 3: delivery by pipeline; Option 4: combined system terminal and delivery by truck in gaseous state; Option 5: combined system terminal and delivery by truck in liquid state.

The comparison of data also clearly reveals a general cost advantage for large fueling stations. For gaseous hydrogen fueling stations, the reason is significant scale economies for the cost of hydrogen compressors, which are relatively cheaper if designed for larger flowrate. For the case of liquid hydrogen fueling stations, the case is similar: scale economies do exist in particular for liquid hydrogen cryogenic storage and high-pressure cryogenic pumps. As O&M costs in the H2A components model are calculated in percent of capital investment, the impact of these scale economies is further pronounced.

Figure 2 displays the full chain of hydrogen costs for the example of future coal gasification, i.e. for the year 2025. In doing so, it further separates the costs of delivering hydrogen into its different components, i.e. compression, liquefaction, terminals, etc, as considered in the analysis. A detailed description was deemed too extensive for the scope of this paper, but is inherent to the model.[10]
For comparison of data presented, if the cost of gasoline at fueling stations were US$ 0.5/litre, this converts to US$ 14.8/GJ.

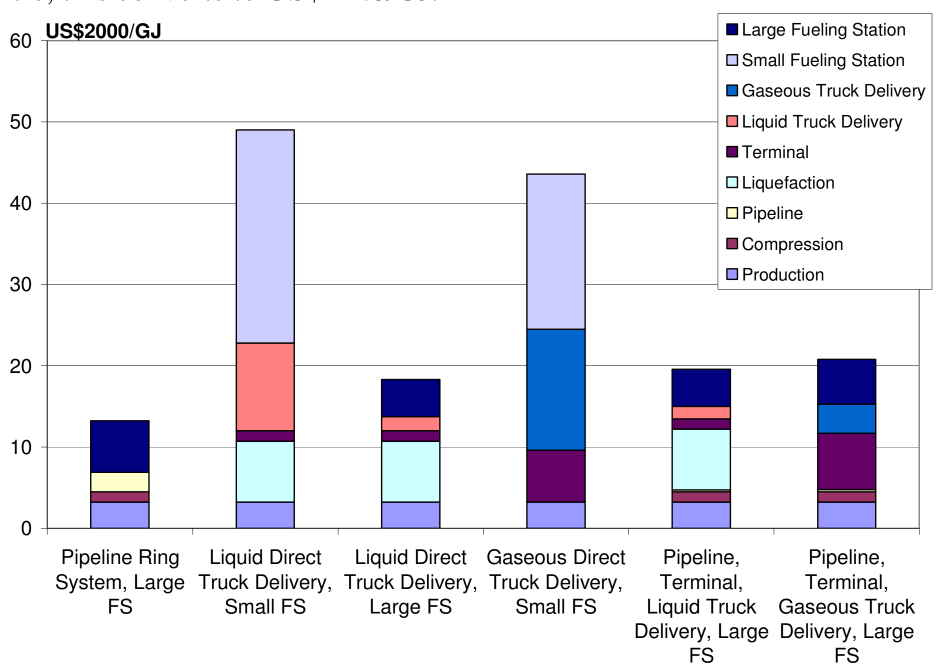

Figure 2. Comparison of Hydrogen Cost Chains for Coal Gasification in 2025.

.2.1.3 Forecourt Hydrogen Production

Forecourt hydrogen production provides an alternative to central hydrogen production facilities, and may be important in particular in early phases of hydrogen penetration when demand for hydrogen is still low. Forecourt hydrogen refers to the production of hydrogen onsite of the demand spot, which could be a point of industrial hydrogen use, but in the context of this analysis is a fueling station.

[10] More information can be obtained by the author.

Forecourt hydrogen production facilities have been modeled with the H2A forecourt hydrogen production models (electrolysis and natural gas reforming)[11], and are complemented by a study of Simbeck and Chang (2002) for methanol and gasoline reforming. Electrolysis and natural gas reforming are, thus, available at two capacities related to the available fueling stations in H2A, i.e. 100 kg/day or 1'500 kg/day production rate. Steam reforming of methanol and gasoline are designed for an output of 470 kg/day of hydrogen.

Table 3. Discounted Cost and Performance of Forecourt Hydrogen Production Options.[12]

Process	Start Year	Feed In / H_2 Out	ELC In	Investment Cost	Fixed O&M	Variable O&M	Feedstock Cost	Electricity Cost	Hydrogen Cost
		[GJ/GJ]	[GJ_{ELC}/GJ_{H2}]	[US$/GJ]					
Natural Gas Reforming									
100 kg/day Current	2005	1.47	0.14	10.81	13.57	0.17	10. 75	1.65	**36.96**
100 kg/day Advanced	2015	1.37	0.12	9.06	12.16	0.17	10.02	1.42	**32.84**
100 kg/day Future	2025	1.30	0.12	8.61	11.79	0.17	9.5	1.42	**31.49**
1500 kg/day Current	2005	1.38	0.11	4.91	4.15	0.07	10.07	1.33	**20.54**
1500 kg/day Advanced	2015	1.25	0.11	3.32	3.34	0.07	9.14	1.26	**17.14**
1500 kg/day Future	2025	1.18	0.11	3.12	3.21	0.07	8.58	1.26	**16.25**
Electrolysis									
100 kg/day Current	2005	0.00	1.66	14.70	17.53	0.00	0	19.86	**52.40**
100 kg/day Advanced	2015	0.00	1.49	10.07	13.12	0.00	0	17.90	**41.41**
100 kg/day Future	2025	0.00	1.40	8.51	11.60	0.00	0	16.76	**37.17**
1500 kg/day Current	2005	0.00	1.66	6.84	5.67	0.00	0	19.86	**32.59**
1500 kg/day Advanced	2015	0.00	1.49	3.87	3.76	0.00	0	17.90	**25.74**
1500 kg/day Future	2025	0.00	1.40	3.15	3.19	0.00	0	16.76	**23.32**
Methanol Reforming									
470 kg/day	2005	1.33	0.01	8.34	5.20	0.73	8.7	1.19	**24.13**
Gasoline Reforming									
470 kg/day	2005	1.54	0.01	9.38	5.85	0.82	9.2	1.25	**26.54**

Table 3 gives an overview of the designed forecourt production options. Note that the data presented here includes not only the production of hydrogen, but also compression, storage and dispension of hydrogen at 430.6 bar. It thus represents the cost of hydrogen at the fueling station to the individual consumer. Again and as for central hydrogen, advanced and future technologies in this table have been modeled as exogenous cost reductions, with the future technology costs as floor costs.

[11] Unpublished data from the H2A Project at the U.S. Department of Energy's Hydrogen Program and the National Renewable Energy Laboratory, H2A model-version 2006. Older versions of these models can be found at http://www.hydrogen.energy.gov/h2a_production.html.

[12] Prices assumed for forecourt applications in this table only: Natural gas 7.29 US$/GJ, Gasoline 6.01 US$/GJ, 6.51 US$/GJ. Interest rate: 5%.

2.1.4 Discussion

The above analysis revealed a general cost advantage for centrally produced hydrogen delivered by pipeline; depending on the source of hydrogen it can be expected that hydrogen cost at the fueling station can be competitive to other fuels within the coming decades. In reality though, this cost advantage is likely to be utilized in the long-run only: a pipeline ring system will not be implemented unless significant hydrogen demand has developed (neither will be a large central production facility) – this situation is usually referred to as the chicken-or-egg problem, which is seen as an obstacle for a hydrogen economy.
For early phases of hydrogen, therefore, hydrogen produced onsite of the fueling station – forecourt hydrogen – is expected to play a dominant role. This will increase the cost of hydrogen for the consumer, but could help facilitate large-scale hydrogen penetration from pilot project scale to demand levels that could justify central hydrogen production facilities and pipeline ring system delivery.

2.2 The Biofuels Module

The European Commission intends to replace 10% of liquid fossil fuels with biofuels by 2020. Several countries in Europe have, thus, already adopted different incentives to promote the use of biofuels.

The economics and prospects of biofuels production have been assessed within a literature review in the context of a Master thesis at Paul Scherrer Institute and ETH Zürich (Ragettli 2007). The analysis comprises "first generation" biofuels as well as "second generation biofuels", which are expected to be available on the market around 2015-2020.

Table 4 provides an overview on estimated biofuels cost at the fueling station. Biomass prices for Europe used were derived from FAOSTAT as average values for 2000-2003 (FAO 2006), and are producer prices including biomass production, harvesting, pre-treatment, transport and storage of the biomass, as well as the farmer's margin.[13] Efficiencies given as well as investment and O&M costs refer to the biofuels production facility, which is complemented by the cost of delivery to the fueling stations according to the individual biofuels (IEA 1999). Negative variable O&M cost occur as a result of by-product credits such as animal feed, which have not been considered independently for this analysis. Negative electricity inputs are due to the fact that these products are designed as coupled production processes.

[13] Transport of biomass is assumed to take place by truck over a distance of 50 km, costs of 10 $/t were assumed and added to the producer prices of biomass. For details, see Ragettli (2007).

Table 4. Cost of Biofuels at Fueling Stations.

Process		Feed In / Fuel Out	ELC In / Fuel Out	Investment Cost[14]	Fixed O&M	Net Variable O&M	Feedstock Cost	Energy Cost[15]	Distribution Cost	Biofuels Cost
		[GJ/GJ]		[US$/GJ]						
1st Generation Biofuels										
Sugar Beet-to-EtOH	Fermentation	1.84	0.11	1.23	6.52	1.04	18.99	2.71	5.27	**35.76**
Corn-to-EtOH	Fermentation	2.27	0.03	1.85	1.61	-2.34	15.22	4.53	5.27	**26.13**
Waste-to-SNG	Anaerobic digestion	1.94	-0.19	3.83	5.40	2.20	6.23	-2.26	8.40	**23.80**
Oil crops-to-biodiesel	Esterification	1.61	0.00	0.53	0.23	-3.08	13.55	0.33	3.49	**15.05**
2nd Generation Biofuels										
LC-to-DME	Gasification	2.00	0.05	3.94	2.50	0.23	6.22	0.58	8.40	**21.86**
LC-to-MeOH	Gasification	3.45	-0.93	4.91	2.07	0.69	10.73	-11.15	6.06	**13.31**
LC-to-Biodiesel	Pyrolysis	1.73	0.00	1.94	2.07	1.55	5.38	-0.01	3.49	**14.43**
LC-to-EtOH	Fermentation	2.29	-0.10	2.84	1.34	3.93	7.23	1.06	5.27	**21.67**
LC-to-FT diesel	Gasification	3.25	-0.84	7.36	3.42	0.31	10.12	-10.03	3.49	**14.68**
LC-to-SNG	Gasification	1.83	0.01	3.87	1.91	0.01	5.70	0.10	8.40	**19.99**

2.3 Personal Transportation Module

Personal transportation in EHM is treated using "generic" vehicles, i.e. no distinction is made between different vehicle sizes, and an average annual mileage of 15'000 km is assumed for all vehicles. The reason is that the intention of this analysis is to assess the efficacy of policies to support market penetration of biofuels and hydrogen only rather than to identify market segments for these fuels.

The cost of vehicles is divided into learning and non-learning components. Learning components are those which are expected to encounter significant cost reductions after their initial commercialization, whereas cost reductions of non-learning components are deemed less pronounced. All cost data is based on Kromer and Heywood (2007), Kasseris and Heywood (2006) and Turton (2006). Table 5 summarizes the cost of non-learning components.

[14] Discounted investment cost, interest rate 5% chosen for all technologies.
[15] Includes electricity, natural gas and steam.

Table 5. Cost of Non-learning Components of Personal Vehicles in EHM [US$ / vehicle].[16]

		Drive Train		Storage			Miscellaneous		
Vehicles in MARKAL	**Base cost: Engine / Transmission**	**Motor / Controller**	**Engine / Transmission additional**	**Fuel Tank System**	**Exhaust**	**Wiring etc.**	**Charger**	**Fuel Cell Premium**	**Processor Premium**
Gasoline ICEV - Year 2010	3000			100					
Gasoline Advanced ICEV - Year 2030	3700			100					
Diesel ICEV - Year 2010	3000		1400	100	500				
Diesel Advanced ICEV - Year 2030	3700		700	100	500				
Natural Gas ICEV - Year 2030	3700			500					
Biofuels ICEV - Year 2030	3700		800	100					
Gasoline ICE & Electric Hybrid	3700	600	200	100	0	200			
Gas ICE & Electric Hybrid	3700	600	200	300	0	200			
Biofuels ICE & Electric Hybrid	3700	600	250	100	0	200			
Hydrogen ICE & Electric Hybrid	3700	600	200	2290	0	200			
Direct H2 Fuel Cell & Battery Hybrid	0	1400	200	1800	-300	200			
Petroleum ATR-FC & Battery Hybrid	0	1400	200	100	0	200		1000	800
Plug-In Hybrid	3700	800	100	100	0	200	400		
Battery Electric	0		200	0	-300	200	400		

In Table 6, initial costs of learning components as well as anticipated floor costs are presented. These cost assumptions are exogenous to the model, and floor costs are reached 50 years after market launch of the vehicle.

Table 6. Cost of Learning Components of Personal Vehicles in EHM.

	Size	Initial Cost	Floor Cost	
Fuel Cell	40 kW	250	40	US$/kW
Reformer	40 kW	90	25	US$/kW
Hybrid Battery System	28 kW	2’500	800	US$/vehicle
Battery Electric	48 kWh	16’250	12’000	US$/vehicle
Plug-in Hybrid	8.2 kWh	6’500	2’800	US$/vehicle

The costs of the hydrogen fuel cell here assume mass production. Kromer and Heywood (2007) suggest that fuel cell stack costs have decreased by 50% within the last 5 years largely as a side-effect of reducing stack size and weight. The US Department of Energy short-term commercialization target for the fuel cell is US$ 30/kW; achieving this target, however, requires dramatic breakthroughs in membrane technology and an order of magnitude reduction in platinum loading (Kromer and Heywood 2007). The floor cost chosen here, thus, are deemed optimistic, but not unrealistic in the long-run.

Tank-to-wheel efficiency improvements of new vehicles in EHM were derived from CONCAWE (Edwards et al., 2007), Kromer and Heywood (2007), Kasseris and Heywood (2006) and Turton (2006) and are depicted in Table 7. It is assumed that most significant efficiency improvements take place until 2030; thereafter, all efficiencies have been kept constant.

As all vehicle efficiencies found in above literature are driving-cycle efficiencies, a factor of 1.195 was used following Smokers, Vermeulen et al. (2006) to adjust them to real-life efficiencies. After 2030, no further efficiency improvements are assumed.

[16] Base cost common to all vehicles assumed US$ 15’000 per vehicle. Biofuels vehicles were designed similar to diesel vehicles with an additional US$ 50 to account for flex-fuel, but less need for exhaust system.

Table 7. Efficiency Improvements of Personal Vehicles in EHM [MJ/vehicle-km].

Vehicles in EHM	Fuel Input	2000	2010	2020	2030
Gasoline ICEV Advanced	Gasoline		2.27	2.14	2.01
Diesel ICEV Advanced	Diesel		2.11	1.92	1.72
Natural Gas ICEV	Gas	2.23	2.24	2.12	2.01
Biofuels ICEV	Biofuels	2.19	2.11	1.96	1.72
Gasoline Hybrid	Gasoline		1.93	1.53	1.12
CNG Hybrid	Gas		1.67	1.32	0.97
Biofuels Hybrid	Biofuels		1.74	1.38	1.01
Hydrogen Hybrid	Hydrogen		1.77	1.40	1.03
H2 Fuel Cell & Battery Hybrid	Hydrogen			1.00	0.88
Gasoline ATR-FC & Battery Hybrid	Gasoline			1.94	1.72
Plug-In Hybrid	Electricity			0.23	0.17
	Gasoline			0.59	0.43
Battery Electric Vehicle	Electricity		0.65	0.61	0.57

The existing fleet was calibrated using TREMOVE (2007) and IEA statistics (IEA 2002). Its efficiency is assumed to improve by 2% per decade until 2030. Thereafter, the efficiency is again kept constant just as for all new vehicles.

3. Baseline Scenario

The baseline scenario is based on an updated IPCC-SRES B2 scenario, and can, thus, be interpreted as a „middle-of-the-road” development of the European energy and transportation system. The demand for personal transport was derived from IEA/WBCSD (2004) until 2050 and extrapolated to 2100 assuming a further growth of 0.1% per year.

3.1 Baseline Assumptions

For the analysis, it has been assumed that the oil price increases linearly from US$35/bbl in the year 2000 to US$ 52.5/bbl in 2050 and US$ 70/bbl in 2100.[17] The price for natural gas price is coupled to the oil price with a factor of 0.625 and increases accordingly.

For biomass, it needs to be emphasized that this analysis uses European biomass potential only, i.e. no imports of biomass or biofuels allowed. The potentials were derived from the CONCAWE-study (Edwards et al. 2007) and IEA (2005) and amount to 7.2 PJ in total per year. The costs of biomass were assumed constant over time.

In personal transport, all new vehicles are allowed to obtain a maximum share of 1% of all vehicles on the market at market launch. Together with a maximum annual growth rate of 10%, all new vehicles have the possibility to make a significant contribution within few decades, and take over the entire market by the end of the time horizon.

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[17] Note again that all costs and prices in this paper are US$2000. The oil price in the year 2050, thus, corresponds to the projection of the IEA’s World Energy Outlook 2006, IEA (2006).

For the calibration of the model, renewable energy potentials were derived from WEC (2001), Hoogwijk et al. (2004) and IEA (2003). It was assumed that intermittent renewable power sources such as wind power or solar photovoltaic would not contribute to more than 25% of electricity production due to intermittency reasons.

Another important element of the analysis is the role of nuclear power. It must be recognized that the future role of nuclear energy in Europe is primarily a political decision and will depend on several issues such as nuclear safety, waste disposal, questions of proliferation and consequently public acceptance. In absence of a consistent European strategy, this analysis assumes only modest increases in nuclear power plant capacities.

3.2 Baseline Results

Figure 3 illustrates the development of primary energy consumption in the base case. Primary energy consumption increases from 76.6 EJ in 2000 to 111.6 EJ in 2050 and 131.3 EJ in 2100. In this analysis, coal almost doubles its share in primary energy consumption to 27.1% in 2100, up from 14% in the year 2000. Renewables extend their share, primarily due to residential and commercial thermal uses and increased utilization in the power sector. Total electricity production in EU-29 is growing by a factor of more than 3 until 2100 in the baseline case.
The use of oil is reduced in the long-run. One key reason apart from the increasing oil price is the gradual replacement of inefficient current technology with high-efficient other technology, for example in the transport sector. This is reflected in the share of personal transport in final energy consumption, which is not presented here: the share is gradually decreasing from 15.3% in 2000 to 10.5% in 2100.

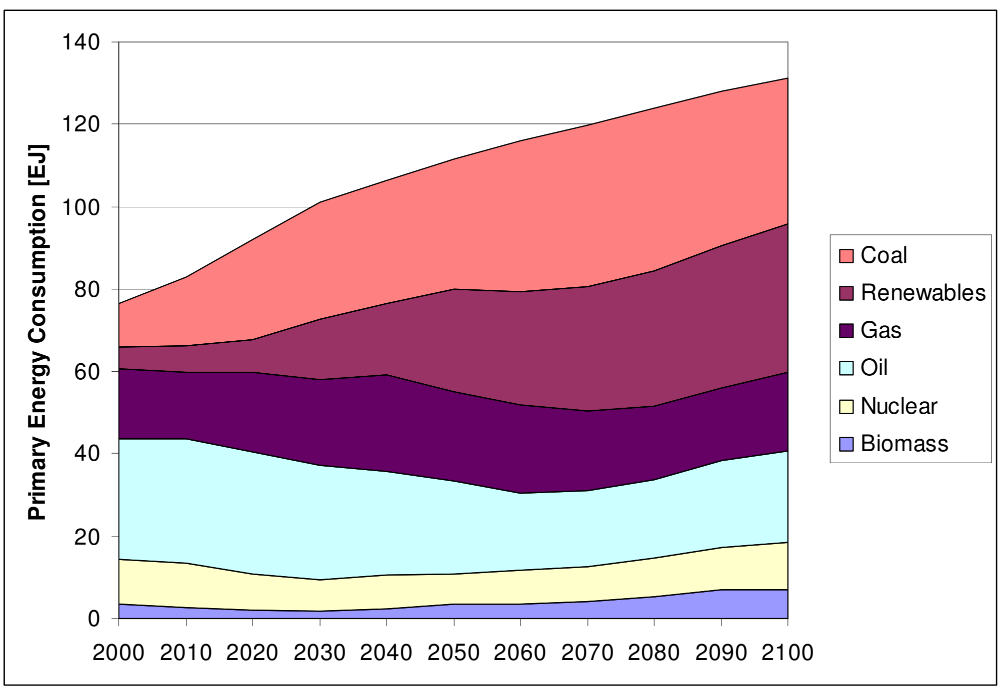

Figure 3. Primary Energy Consumption in EU-29 in the Base Case.

The results of the baseline analysis of personal transport are presented in Figure 4. The analysis suggests that in absence of corresponding policies and with the given modest oil price increase, the market shares of vehicles are not likely to change in a cost-optimization framework as EHM; only in the very long-run, other fuels than oil products can contribute due to the assumed increase in oil and gas prices.

It needs to be noted though that this model does not account for recent developments in personal transport such as the trend towards higher market share for diesel-fuelled cars in Europe. One reason is that the model assumes a generic personal vehicle sector rather than distinguishing different vehicle sizes and, thus, a common mileage to all vehicles. Diesel ICE vehicles (ICEVs) stand to benefit from their higher annual utilization despite their higher total costs. This aspect has been neglected in this analysis, and the share of diesel cars was bounded to at least 20% of gasoline use in order to avoid an early phase out due to cost-optimization.

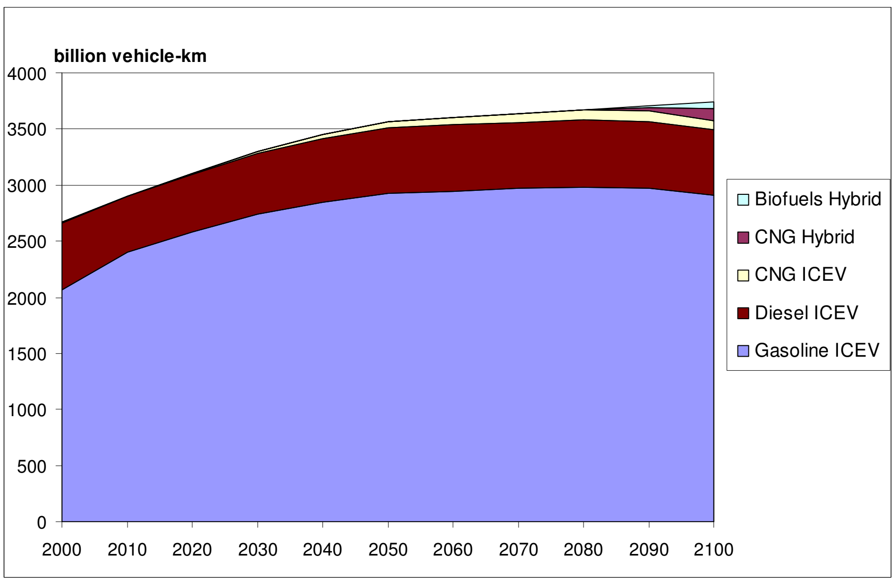

Figure 4. Share of Vehicles in EU-29 Personal Transport Baseline Scenario.[18]

4. Scenario Analysis

In the scenario analysis, it was intended to assess the role of CO_2 reduction targets on the penetration of hydrogen and biofuels in personal transport. Therefore, an assessment has been made imposing a CO_2 constraint of 20% reduction by 2020, and 50% reduction by 2050 in comparison to 1990 levels on the entire energy system. The CO_2 target is extrapolated to 2100 by assuming a further reduction of 5% per decade after 2050.

[18] ICEV = Internal Combustion Engine Vehicle.

The assessment of this policy is then complemented by an analysis of the impact of oil price variations and subsidies on either biofuels or hydrogen in personal transport. The chapter is finally concluded with a discussion of the sensitivity of results.

4.1 Case: CO_2 Reduction 50%

The results of this analysis are presented in Figure 5. The analysis reveals that under a CO_2 reduction regime biofuels can make a significant contribution to personal transport in the medium-term, in particular as hybrids; the share of biofuels in the year 2050 is at 14% of total fuel consumption, and biofuels-fuelled vehicles make up for 18.7% of all vehicles on the market.

Hydrogen fuel cell vehicles (FCVs) gain market share only in the very long run, i.e. towards the end of the century, when it becomes the dominating fuel and accounts for 78.9% of total fuel consumption, and 82.4% of all vehicles on the market. The key reason for the late penetration of hydrogen FCVs is the assumption that floor costs of the fuel cell are reached 50 years after their market launch in 2020, making the fuel cell cost-optimal only as of then.

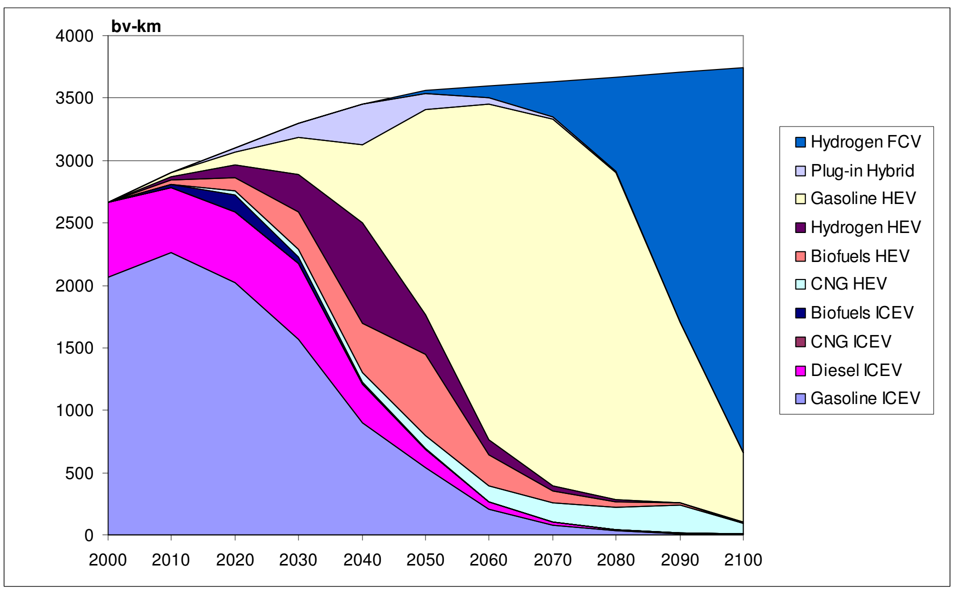

Figure 5. Contribution of Different Vehicles to Personal Transport in EU-29 under a 50% CO_2 Reduction Target for 2050.

The cost of hydrogen at fueling stations, however, is considered low enough to make hydrogen as a fuel competitive even in 2050. This is reflected by the fact that hydrogen HEVs make up for 8.7% of all vehicles on the market; Hydrogen FCVs are responsible for only about 0.7% of all vehicles at this point in time. This reveals a total hydrogen fuel consumption of about 342.6 PJ, or 7 % of total fuel consumption in 2050.

4.2 The Role of Oil Prices and Fuel Subsidies

In a second step, a variation of oil prices has been investigated on top of the 50% CO_2 reduction case. This is motivated by the fact that oil price levels in recent years have already reached levels that in the above analyses have been treated as long-term projections for the year 2100, i.e. US$ 70/bbl.

The analysis is complemented by an assessment of the role of subsidies on the penetration of hydrogen and biofuels. Increasing the share of hydrogen or biofuels could be of strategic interest for EU-29 for other reasons than CO_2 reduction only. Such reasons could for example include energy security concerns.

Subsidies seem an appropriate measure to increase the market share of either fuel. Here, subsidies have been assessed individually, i.e. it is thought that governments would rather choose one of the fuel options than to subsidize both at a time. For assessing the impact on hydrogen and biofuels share in personal transport fuel consumption, the subsidy has been applied solely to this sector, starting as of the year 2010 and constant until the end of the time horizon.

4.2.1 Oil Price Variations and Hydrogen Subsidies

For the assessment of oil prices and hydrogen subsidies, the years 2050 and 2100 were analyzed in detail. The market shares of hydrogen in fuel consumption in personal transport are presented in the following graphs.

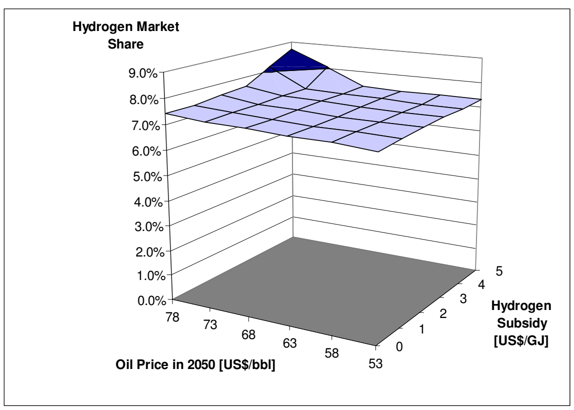

Figure 6. Hydrogen Share in Fuel Consumption in 2050.

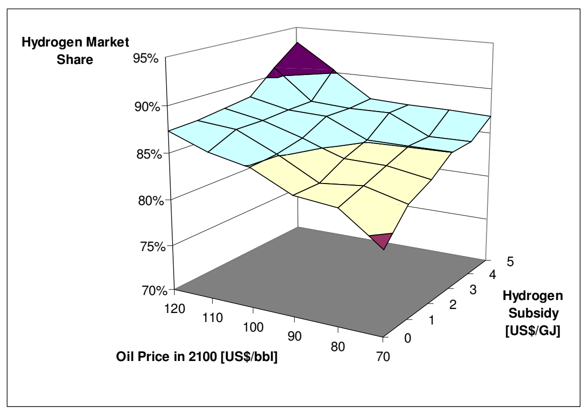

Figure 7. Hydrogen Share in Fuel Consumption in 2100.

The results suggest

- for the year 2050 that the contribution of hydrogen to personal transport fuel consumption can be increased only modestly above the value of 7% obtained in the 50% CO_2 reduction case. An analysis of the sensitivity of the subsidy level and oil price, which is not further presented here, revealed only slight further improvements with even higher subsidies.

- for the year 2100 that the dominance of hydrogen in personal transport fuel consumption can be further extended above the value of 78.9% obtained in the 50% CO_2 reduction case. High oil price levels and fuel subsidies have the same impact in the long run, as both spur the market share of hydrogen.

A closer look at the share of hydrogen FCVs in 2050 shows that in the most optimistic of the above variations, the increased share of hydrogen in fuel consumption is due to a larger number of hydrogen FCVs on the market. Their share in total vehicles increases from 0.7% in the CO_2 reduction-only case to 3.1% at high oil prices and a subsidy level of US$ 5/GJ, while the share of hydrogen HEVs remains constant at 8.7%.

4.2.2 Oil Price Variations and Biofuels Subsidies

For the assessment of oil prices and biofuels subsidies, the years 2050 and 2100 were again analyzed in detail. The market shares of biofuels in fuel consumption in personal transport are presented in the following graphs.

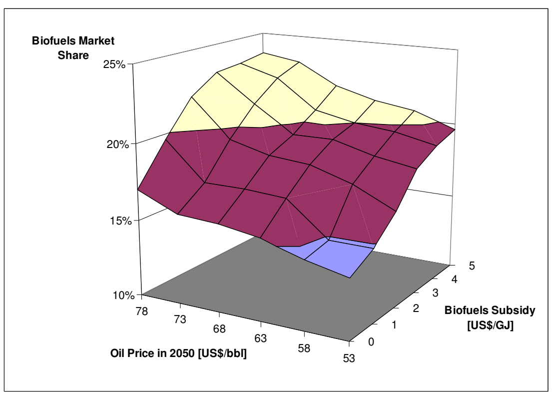

Figure 8. Biofuels Share in Fuel Consumption in 2050.

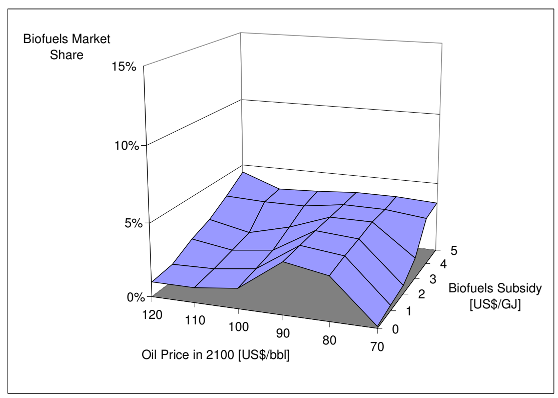

Figure 9. Biofuels Share in Fuel Consumption in 2100.

The results suggest

- for the year 2050 that the share of biofuels increases with higher oil prices and biofuels subsidies above the value of 14% obtained in the 50% CO_2 reduction case. An analysis of the sensitivity of the subsidy level revealed that it takes very high subsidy levels of more than US$ 10/GJ to increase the share of biofuels to levels above 30% without oil price increases. Alternatively, significantly higher oil prices could increase the share of biofuels as well.
- for the year 2100 that hydrogen is a too strong competitor for biofuels in reaching CO_2 reduction targets. Neither increasing oil prices, nor fuel subsidies in a reasonable range make biofuels gain significant market shares by 2100. Rather, the European biomass potential is used for decarbonization of other sectors instead.

4.3 Discussion and Sensitivity of Assumptions

The analysis points to one general trend: biofuels can act as a bridging technology towards hydrogen. Biofuels are considered competitive in the short- to medium-term, and can support reaching CO_2 reduction targets by the year 2050 in a cost-effective manner, together with gasoline hybrid vehicles. Hydrogen is a long-term option for decarbonization of personal transport, the key factor for hydrogen penetration being the cost of the fuel cell. The costs of hydrogen at fueling stations are expected to be of lower importance for the penetration of hydrogen, if efforts on a large-scale are put into practice.[19]

The market share of either fuel obtained in the cost-optimization framework of EHM has been investigated as sensitive to both oil price and fuel subsidies. Subsidies seem an appropriate tool to push the market shares, the level required depends on the oil price assumptions. For hydrogen, though, oil prices and subsidies have a large impact on the hydrogen market share in the long-run only under the given assumption of a 50% CO_2 reduction target.

In order to understand the sensitivity of these results to the CO_2 reduction target, a 60% CO_2 reduction case has been run, i.e. 60% CO_2 reduction by 2050 compared to 1990 levels, further extrapolated by assuming additional 5% reduction per decade thereafter. The result is presented in Figure 10 and shows that indeed the penetration of hydrogen is further spurred by more stringent CO_2 policy already by 2050; market shares of 23% in personal fuel consumption have been obtained for hydrogen under the assumption of baseline oil price development. Even more stringent targets, which have been analyzed but are not presented here, lead to even higher market penetration.

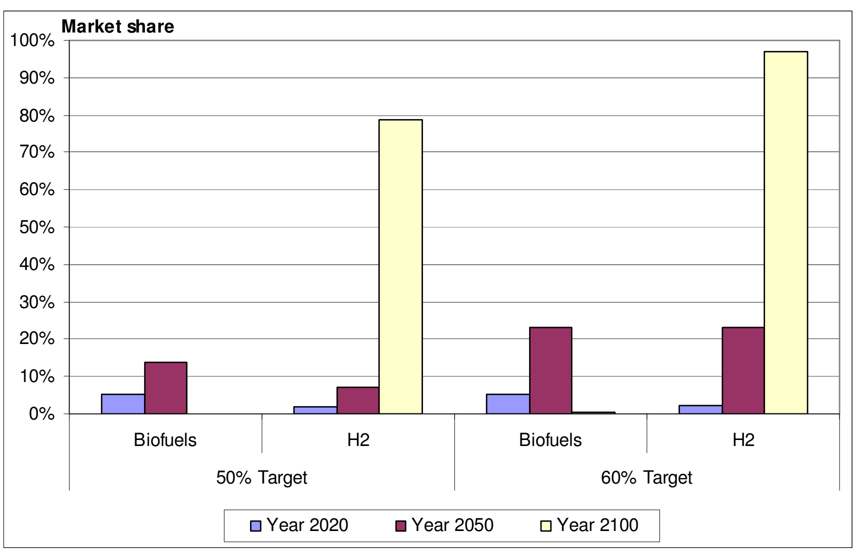

Figure 10. Market Share of Hydrogen and Biofuels in Personal Transport Fuel Consumption under different CO_2 Reduction Targets.

[19] Of course, the chicken-or-egg problem is important in this respect, a discussion is, however, beyond the scope of this paper.

The analysis of stronger CO_2 constraints also indicates that more stringent CO_2 targets do not specifically support the penetration of biofuels in 2050; even though a 60% reduction target promotes the use of biofuels in 2050, targets more rigorous than those discussed here can eventually lead to a reduction of biofuels shares due to higher utilization of hydrogen and more cost-effective use of biomass in other sectors.[20]

5. Summary and Conclusions

This paper discussed the impact of CO_2 policies, oil prices and fuel subsidies on the market penetration of hydrogen and biofuels in personal transport. The analysis was conducted using the cost-optimization European Hydrogen Markal model EHM.

The analysis revealed that hydrogen and biofuels can gain significant market shares when a 50% reduction of total CO_2 emissions compared to 1990 levels by the entire energy system is envisaged. While biofuels could contribute with 14% to total fuel consumption in personal transport in 2050, hydrogen can unfold its merits in the long-run only under a 50% CO_2 reduction target. However, towards the end of the century, hydrogen could become the dominant fuel, making up for 78.9% of the entire fuel market.

The share of either fuel can be further augmented either by fuel subsidies or by higher oil prices. Towards the end of the century, however, hydrogen is a too strong competitor for biofuels, and biomass will be predominantly utilized in other sectors.

An analysis of the sensitivity of the anticipated CO_2 reduction target, however, also showed that more rigorous targets act in favor of hydrogen and stimulate its market penetration towards earlier points in time; it suggests market shares of almost 23% as feasible even without oil price variations under a 60% CO_2 reduction target for 2050. As no level of subsidies and oil price increases investigated had a similar impact, it is apparent that CO_2 reduction targets are a more effective tool in stimulating hydrogen market introduction.

Critical to this analysis is the question whether chicken-or-egg problems for hydrogen can be overcome and whether hydrogen can develop out of niche applications towards large-scale production and distribution facilities. Even more critical towards the use of hydrogen in personal transport is the cost of the fuel cell: target costs of around US$ 40/kW as assumed in this analysis due to learning and mass production will certainly be required to make hydrogen competitive. Achieving this cost level is, thus, a prerequisite for the success of hydrogen in personal transport.

The analysis also suggests that biofuels could act as a bridging fuel towards a hydrogen economy, in particular under a 50% to 60% CO_2 reduction target. This is plausible on the one hand due to their short-to medium-term cost competitiveness; on the other hand, it

[20] Note that EHM uses European biomass potential only, and imports of biofuels are not allowed. With imports of biomass or biofuels, the competitiveness of biofuels in transport could potentially be increased. An analysis, though, is beyond the scope of this paper.

requires efforts to bring either biofuels or hydrogen into the market, as substantial infrastructure investments will be required. Interpreting biofuels as a transition fuel, thus, requires first investments in biofuels infrastructure, in order to then implement large-scale hydrogen infrastructures when cost-competitiveness is reached. It seems, thus, desirable to make early choices on either fuel to avoid double investments.

6. Acknowledgements

The authors would like to thank Prof. Alexander Wokaun, head of the General Energy Research Department at Paul Scherrer Institute in Switzerland for his guidance on this analysis. Moreover, we would like to express our gratitude to the staff of the US National Renewable Energy Laboratory in Boulder/Colorado for their support in this analysis and their hospitality during a research stay in July 2006.
Finally, the financial support of the Swiss National Centre of Competence in Research on Climate (NCCR Climate) is gratefully acknowledged.

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