ResearchGate

See discussions, stats, and author profiles for this publication at:
https://www.researchgate.net/publication/222696127

A comparison of technologies for carbon-neutral passenger transport

Article *in* Transportation Research Part D Transport and Environment · May 2002

DOI: 10.1016/S1361-9209(01)00018-9

CITATIONS
36

READS
55

2 authors:


Bengt Johansson
Lund University
51 PUBLICATIONS 728 CITATIONS

SEE PROFILE


Max Åhman
Lund University
33 PUBLICATIONS 322 CITATIONS

SEE PROFILE

All in-text references underlined in blue are linked to publications on ResearchGate, letting you access and read them immediately.

Available from: Max Åhman
Retrieved on: 15 September 2016

PERGAMON

Transportation Research Part D 7 (2002) 175–196

TRANSPORTATION RESEARCH PART D

www.elsevier.com/locate/trd

A comparison of technologies for carbon-neutral passenger transport

Bengt Johansson *, Max Åhman

Department of Environmental and Energy Systems Studies, Lund University, Gerdagatan 13, SE-223 62 Lund, Sweden

Abstract

In this study, the use of energy carriers based on renewable energy sources in battery-powered electric vehicles (BPEVs), fuel-cell electric vehicles (FCEVs), hybrid electric vehicles (HEVs) and internal combustion engine vehicles (ICEVs) is compared regarding energy efficiency, emission and cost. There is the potential to double the primary energy compared with the current level by utilising vehicles with electric drivetrains. There is also major potential to increase the efficiency of conventional ICEVs. The energy and environmental cost of using a passenger car can be reduced by 50% solely by using improved ICEVs instead of ICEVs with current technical standard. All the studied vehicles with alternative powertrains (HEVs, FCEVs, and BPEVs) would have lower energy and environmental costs than the ICEV. The HEVs, FCEVs and BPEVs have, however, higher costs than the future methanol-fuelled ICEV, if the vehicle cost is added to the energy and environmental costs, even if significant cost reductions for key technologies such as fuel cells, batteries and fuel storages are assumed. The high-energy efficiency and low emissions of these vehicles cannot compensate for the high vehicle cost. The study indicates, however, that energy-efficiency improvements, combined with the use of renewable energy, would reduce the cost of CO_2 reduction by 40% compared with a strategy based on fuel substitution only. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Road transport has become one of the largest sources of pollution in society and in 1998 accounted for about 37% of the total nitrogen oxide (NO_x) emission, 38% of the non-methane volatile organic compound emission (NMVOC) and 27% of the carbon dioxide (CO_2) emission in Sweden (Statistics Sweden, 1999). Road vehicles are also important producers of particulate matter (PM). Whereas road transport emissions of NO_x, NMVOC and PM have been reduced as a result of exhaust gas treatment and improved combustion technology CO_2 emission have continued to increase.

* Corresponding author. Tel.: +46-46-222-9730; fax: +46-46-222-86-44.
E-mail address: bengt.johansson@miljo.lth.se (B. Johansson).

1361-9209/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S1361-9209(01)00018-9

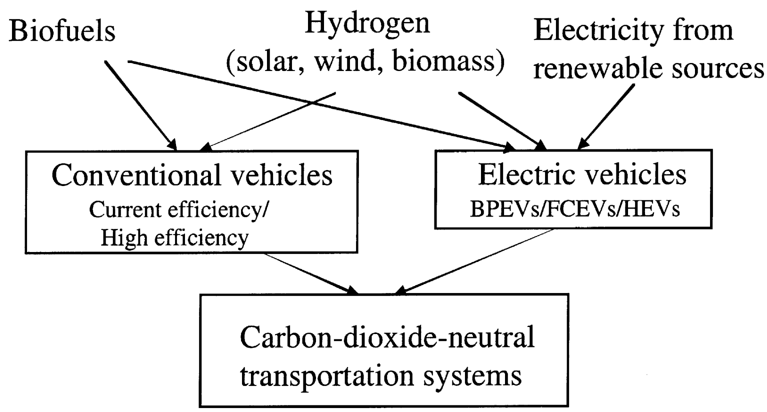

Fig. 1. Combinations of energy carriers, primary energy and vehicle technology that together form carbon dioxide neutral transportation systems based on renewable energy.

Efficient energy use and the use of renewable energy sources are main options for reducing CO_2 emission from vehicles in the future. There is the potential to increase energy efficiency significantly, both by improving conventional technology and by introducing vehicles with new powertrains such as battery-powered electric vehicles (BPEV), hybrid electric vehicles (HEVs) and fuel-cell vehicles (FCEVs) (Åhman, 1999). Renewable energy sources can be used to produce electricity and liquid or gaseous fuels, which can be used for transportation purposes.

In this study, combinations of new efficient vehicle technologies and renewable energy sources are analysed with regard to primary energy efficiency, environmental impact and cost, see Fig. 1. The aim of the study is to form a basis for long-term strategic analyses of future transportation technologies, and to identify which combinations of energy sources, energy carriers and vehicle technologies can form parts of efficient future transportation systems. Several other studies comparing new vehicles technologies and fuels with regard to efficiency, emissions and costs have been carried out (see e.g., IEA, 1993, 1999; Wang and Delucchi, 1992; Goubeau et al., 1996; Johansson, 1996; Kazimi, 1997; Metz, 2000; Lipman and DeLucchi, 1996). In these studies, however, the new technologies are usually compared with current ICEVs with little focus on the possibility for improvement in future ICEVs. Furthermore, they usually concentrate on either certain vehicle technologies (for example, BPEVs) or fuels (for example, fuels from renewable energy sources). Studies that systematically take into account the potential for improvements in all technologies and the compatibility of these technologies with renewable energy sources are lacking.

The study is carried out from a Swedish perspective. This will be apparent mainly in the choice of energy resources suitable for transportation fuels and in the valuation of the environmental impact of the analysed vehicle/fuel system.

2. Methodology

In this study primary energy efficiency, emission and the cost of using various energy carriers in ICEVs, HEVs, FCEVs and BPEVs are compared. The cost includes energy, environmental

Table 1
Cost of the environmental impact of VOC, NO_x and particulate emissions in Sweden (Carlsson and Johansson-Stenman, 2000)

	Cost of environmental damage[a] SEK/kg	Health effects[b]	
		Urban, medium-size town SEK/kg	City centre, major city SEK/kg
VOC	30	22	45
NO_x	60	49	50
Particulate matter	0	5000	7600

[a] Includes cost of acidification, eutrophication and damages to crops due to high ozone concentration.
[b] The values for a medium-sized town are based on estimates for the town of Malmö (250 000 inhabitants) whereas the value for a city centre in a major city is based on estimates for Stockholm. The cost of health damage was based on estimates of the value of reducing population doses. This value was obtained from surveys in which people were asked about their willingness to pay for pollutant dose reductions. The value of reducing population doses was then transformed into a value for reducing vehicle emissions, utilising different dispersion models, wind, climate and population data. The value of reducing the emissions was then used as the cost of the emission (Johansson, 1997). The method of using values from willingness-to-pay studies to estimate the cost of environmental impact is not unproblematic. For example, respondents have been found to refuse the whole idea of "buying" environmental quality or have been found to give unrealistic bids in relation to their budget constraints, see e.g. discussion in Spash (2000).

and vehicle costs. Future technologies are analysed for a typical mid-size passenger car which in principle has the same performance as present conventional cars in terms of speed, acceleration, size and comfort. The only exception is the BPEVs which are assumed to have a shorter driving range (≈200 km) as a consequence of the problems of carrying large batteries in the vehicle. An analysis of the future potential performance of ICEVs is included for comparison.

In order to compare the cost of using BPEVs with the cost of using other vehicles, a marginal cost perspective on the electricity supply is adopted. The cost of the electricity for a group of electric vehicles is estimated to consist of the difference between the total cost of an electricity system where these electric vehicles are supplied with electricity, and the total cost of a corresponding system where there is no supply to the electric vehicles. As the potential for some low-cost electricity supply options is restricted, the marginal cost for the introduction of electric vehicles will depend on the total electricity demand in society. Therefore, two different scenarios for future electricity demand have been defined, one assuming a low electricity demand (LD) and the other assuming a high demand (HD). The scenarios are based on Johansson and Mårtensson (2000).

The environmental cost of emissions has been calculated using the values in Table 1. These values are roughly the same as those used in official transport infrastructure planning in Sweden. It is assumed that emissions from electricity production plants have the same environmental impact as vehicle emissions in rural areas. This means that the direct health aspects of the emissions are negligible whereas the emissions would have negative effects on acidification, eutrophication and would cause damages to crops due to high ozone concentrations. The cost of

CO_2 emissions was defined as the current Swedish carbon tax, 0.36 SEK/kg CO_2 (USD 150/tonne C). [1]

Different sources of data have been used to estimate the average energy use and emission of the vehicle studied. Generally, both energy use and emissions are higher for urban than for rural traffic using ICEVs. There is little information on such differences for vehicles using alternative fuels. In this study, we assumed the same relation between urban and rural energy use and emission levels for ICEVs using alcohol fuels, as has been found for petrol-fuelled ICEVs, i.e., the NO_x emission is 1.5 times higher, VOC emissions 4 times higher, particulate emissions 1.7 times higher, and energy use 1.5 times higher in urban traffic than rural traffic (Hammarström, 1990; Solvang Jenssen, 1992; Swedish Environmental Protection Agency, 1998). Regarding the energy use of BPEVs, HEVs and FCEVs, however, we expect the same values for both urban and rural traffic (Martin and Michaelis, 1992).

All costs are given in SEK at the price level of January 2000 when 1 USD = 8.8 SEK. The energy cost is calculated excluding taxes. Investment costs are annualised using a 6% real discount rate, assuming vehicle lifetimes of 13 yr and annual driving distances of 15 000 km.

3. Renewable energy for transportation

Liquid and gaseous fuels as well as electricity can be produced from biomass and other renewable sources such as wind, solar and hydro. Biomass-based transportation fuels are in use today in several countries around the world, with the largest amount being used in Brazil. Alcohol fuels are well suited for use in internal combustion engines and, especially methanol, also as energy carriers in FCEVs. In Sweden the attention has been focused on ethanol, which is currently used mostly in buses. A new plant producing approximately 50 000 m^3 ethanol/yr from grain has been taken into production. This ethanol will mainly be used as a 5% blend in petrol. In Sweden, and other countries with similar geographic characteristics, cellulosic feedstock is the most cost-effective biomass alternative in a CO_2 reduction strategy (Johansson, 1996). There is also a major local environmental advantage in growing cellulosic biomass instead of grain, see e.g. (Börjesson, 1999). Methanol seems to have economic advantages compared with ethanol (see e.g. Johansson, 1996; IEA, 1999), [2] at least in the medium term and is the preferred fuel by many vehicle manufacturers for use in FCEVs. Dimethylether is another alternative fuel produced with technology similar to that for methanol and this fuel may play an important role in the future as a low-polluting fuel (Williams, 2000).

Hydrogen can be produced both from biomass through gasification and synthetisation and from electricity through hydrolysis. The cost of biomass-based hydrogen is, however, expected to be significantly lower than the cost of hydrogen produced from wind or solar electricity through hydrolysis (Ogden and Nitsch, 1993; Gröndalen, 1998). Although the production cost of biomass-

[1] The estimation of the cost of damage due to CO_2 emission is very sensitive to the assumptions made, such as interest rate, see e.g. Azar and Sterner (1996). In this study, we assumed that the valuation, by society, of CO_2 damage is reflected in the carbon dioxide tax.

[2] Some sources, for example (Wyman et al., 1993), assume that with major breakthroughs in the development of enzymatic hydrolysis ethanol may become competitive to biomass-based methanol in the long run.

based hydrogen is lower than the cost of biomass-based alcohol, the total cost of using hydrogen in ICEVs is higher as a result of costly vehicle hydrogen storage (Johansson, 1996). The development of a new infrastructure will also pose a challenge to the introduction of hydrogen in the transport sector.

From a long-term resource perspective the production of hydrogen from solar electricity might be of interest. It is, however, expected to cost 2–3 times more than hydrogen from biomass, even assuming considerable cost reductions in solar cell technology (Ogden and Nitsch, 1993; Johansson, 1996; Gröndalen, 1998). Biomass prices may increase if biomass resources become scarce as a result of an increased demand for food, materials and energy. This would make solar hydrogen more competitive. In the analysis below only biomass-based hydrogen is included.

Renewable energy sources (mainly hydro) currently contribute about half of the Swedish electricity supply (Swedish National Energy Administration, 1999). There is great potential to increase the renewable electricity supply through wind-power and biomass-based plants, however, at somewhat higher costs than new fossil-fuel-based plants. Johansson and Mårtensson (2000) have analysed the cost and environmental impact of using electricity from theoretical Swedish electricity systems based on renewable energy sources in the future. In these systems hydro, wind and biomass are used. The cost and environmental impact of the marginal electricity of the system depend on the general electricity demand in the system and the need for grid upgrading due to this demand. In the low-demand scenario of Johansson and Mårtensson (2000) marginal electricity in Sweden would be based on wind-power and biomass cogeneration. In their high-demand scenario, marginal electricity has to be produced in biomass-based condensing plants, as the potential for cogeneration and low-cost wind-power in this scenario is already utilised for purposes other than transport.

Although there is, technically, no problem in assuming an electricity system based solely on renewable resources, its implementation would require policy instruments that compensate for the higher cost compared with, for example, natural-gas-based power plants.

A large-scale use of BPEVs would require the build-up of home charging appliances and public fast charging stations and there might be a need for grid upgrading. It is not probable that any grid upgrading will be necessary in the scenario with a low electricity demand as the general electricity demand would be much lower than today as a result of reduced use of electric heating (which today consumes about one-third of Swedish electricity) and efficiency improvements. In

Table 2
Estimated costs of electricity for electric vehicles (Johansson and Mårtensson, 200). All costs are based on electricity from renewable energy sources

Distribution scenario	No new distribution		New distribution	
Electricity demand scenario	Low electricity demand	High electricity demand	Low electricity demand	High electricity demand
	SEK/kWh (cents/kWh)	SEK/kWh (cents/kWh)	SEK/kWh (cents/kWh)	SEK/kWh (cents/kWh)
Production cost	0.40 (5.3)	0.57 (7.6)	0.40 (5.3)	0.57 (7.6)
Distribution cost	0.11 (1.5)	0.12 (1.6)	0.30 (4.0)	0.31 (4.1)
Charging cost	0.07 (0.9)	0.07 (0.9)	0.07 (0.9)	0.07 (0.9)
Total cost	0.58 (7.7)	0.76 (10)	0.77 (10)	0.95 (13)

the scenario with high electricity demand the requirement for grid upgrading may be somewhat larger.

The cost of electricity in a system totally based on renewable energy would depend on general electricity demand and the need for grid upgrading, according to Table 2.

4. Energy-efficient and low-polluting vehicles

Several studies have shown that there is considerable potential to improve energy efficiency in ICEVs, see e.g. (DeCicco and Ross, 1993; DeCicco and Mark, 1998; Duleep, 1997). Efficiency improvements can be achieved through reductions of the road load (air resistance, rolling resistance and energy for acceleration) and by using more efficient powertrains. From the studies referred to above, it appears to be possible to reduce energy use in conventional vehicles by at least 40% compared with vehicles from the beginning of the 1990s by combining more efficient powertrains and reductions in road loads.

There are a number of possible options for improving the mean efficiency of an ICEV such as variable valve timing, shut-off during idling, higher compression ratio, variable displacement and a continuously variable transmission (DeCicco and Ross, 1993). HEVs with an internal combustion engine can also benefit from most of these efficiency gains. The only option not to be fully utilised in a HEV is variable displacement, aimed at improving the efficiency at partial load. Most of the improvements listed above involve well-known technologies that could become available in the next generation of vehicles.

The common denominator for all alternative powertrains studied here is the electric drivetrain [3] consisting of an electric motor, a generator and power electronics for control. The electric drivetrain has attained the technical requirements for a market introduction, and the major problem remaining is the cost (Chan and Chau, 1997; Xu, 1999). Cost targets for market introduction differ between 11 and 20 USD/kW (National Research Council, 1999; Dönitz, 1998). Attaining more stringent cost targets seems unrealistic without technical breakthroughs and new production technology (National Research Council, 1999) as projections for large-scale production of current advanced electric drivetrain technology indicate costs of 20–25 USD/kW (Delucchi, 1999; National Research Council, 1999).

The BPEV consists of an electric drivetrain with a battery for energy storage. Current battery technology offers too short range at too high a cost to become commercially competitive. New battery technology, e.g. lithium-ion, lithium metal-polymer and nickel metalhydride (NiMH) batteries, could give the BPEV sufficient range, 150 miles (240 km), for introduction onto the open market, but the question remains of whether the cost of batteries will fall to the target of 150 USD/kWh set by the United States Advanced Batteries Consortium (USABC) for a market introduction (National Research Council, 1998a). Lead/acid batteries have a relatively low cost but have a poor energy storing capacity, and can be regarded as a transitional battery to long-term

[3] The term drivetrain typically refers to the transmission system from engine output shaft to driven road wheels. In the term alternative powertrain we include both the electric drivetrain, energy storage (e.g. batteries and hydrogen storage), and possibly, a prime mover (ICE or fuel cell).

lithium or NiMH batteries. Today, projection for NiMH batteries gives a large-scale production cost of 200–250 USD/kWh (Lipman, 1999). The only batteries believed to have a *possible* long-term potential below 150 USD/kWh are lead/acid and lithium metal-polymer batteries (Rand et al., 1998; Pierre et al., 1999), but the potential is highly uncertain.

In the HEV, an electric drivetrain and a battery are combined with an internal combustion (IC) engine and a fuel tank. The IC engine charges the battery, or takes over the drive from the electric drivetrain, when the battery is discharged. HEVs with advanced, energy-efficient IC engines are available on the market today (Toyota Prius and Honda Insight). New IC engines will have to provide both low emissions and high efficiency. The cost of HEVs is not disclosed, but a fair assumption is that the HEVs currently on the market are not profitable for the companies producing them. Toyota claims that they will make no loss at the end of the Prius production series, but admits initial losses of 15 000–20 000 USD/vehicle (Amstock, 2000). The HEVs of today use petrol, but can easily use methanol or ethanol and, with some effort, also hydrogen. This fuel flexibility and the fact that the vehicle uses the same fuel infrastructure as the ICEVs is an advantage.

The advantage of the FCEV is the potential for high-energy efficiency and tail-pipe emissions consisting only of water vapour. The most interesting fuel cell for automotive purposes is the Proton Exchange Membrane (PEM) fuel cell. Technical advancements in recent years have made the PEM fuel cell technically competitive, however, further development is needed to integrate the fuel-cell system (Kalhammer et al., 1998). Series production based on the current state-of-the-art FCEVs will, at the earliest, begin in the year 2004 (Daimler-Chrysler, 1999), but series production of FCEVs that fully exploit their potential will probably not start before 2010. The fuel cell still needs much development in order to bring the costs down to a competitive level of 50 USD/kW (National Research Council, 1998a; Appleby, 1999). Long-term cost projections for the fuel-cell system, assuming large-scale production, result in cost estimates between 50 and 300 USD/kW (see e.g. James et al., 1997; Kalhammer et al., 1998; Ronger, 1998; National Research Council, 2000).

One major feature of the fuel-cell system is the requirement of pure hydrogen as a fuel which demands a new fuel infrastructure and a complicated hydrogen storage system on board the vehicle. In order to be able to use existing infrastructure and storage technology, a "hydrogen carrier", such as methanol or even petrol, can be reformed to hydrogen on board the vehicle and used instead. The use of hydrogen carrier reduces the efficiency and adds to the weight and cost of the vehicle. So far, vehicle manufactures prefer reforming methanol or petrol on board the vehicle instead of using gaseous hydrogen, see the conclusions of Kalhammer et al. (1998).

According to Åhman (1999) new vehicle powertrains could achieve vehicle efficiencies that are four times higher for BPEVs and two times higher for FCEVs or HEVs compared with current ICEVs, see Fig. 2.

Primary energy efficiency, where energy loss in energy extraction, conversion and distribution is included can be twice as high for BPEVs, HEVs and FCEVs compared with today's ICEVs, Tables 3 and 4. The potential for improvement in ICEVs could allow an increase in primary energy efficiency of 30–40%.

According to Åhman (1999) it should be possible to reduce the total energy use by at least 60% compared with today's ICEVs when combining energy-efficient powertrains and reduced road loads. In these estimates no breakthrough in the technology of producing safe lightweight composite vehicles and no performance reductions were assumed.

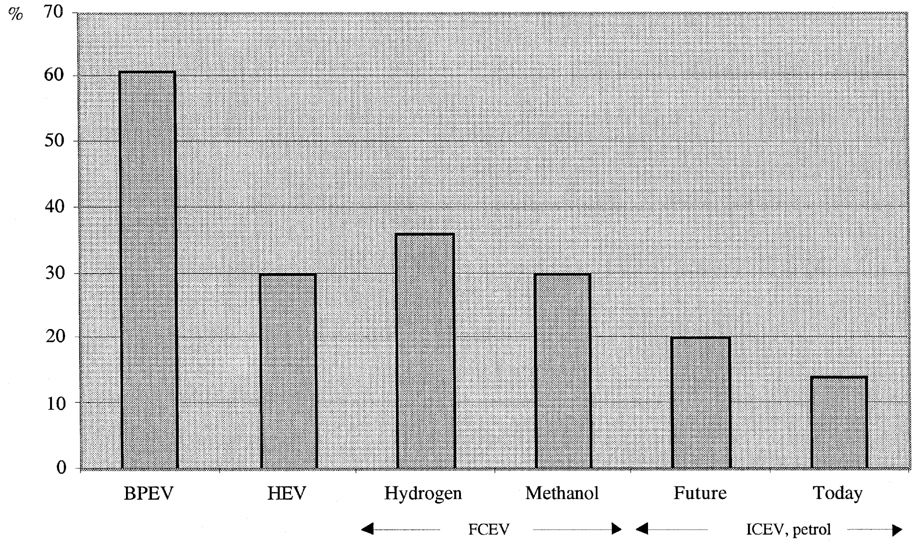

Fig. 2. Vehicle efficiency calculated as energy consumed at the wheels divided by total energy supplied to the vehicle (Åhman, 1999). The vehicle efficiency was calculated from the powertrain efficiency by correcting for the energy saved due to regenerative braking, energy use when idling and energy for extra loads.

Table 3
Primary energy efficiency with a fossil-fuel primary energy source

Vehicle	Primary energy source	Energy carrier	Primary energy to energy carrier (%)	Distribution (%)	Vehicle efficiency from Fig. 2 (%)	Primary energy efficiency (%)
BPEV	Coal	Electricity	40[a]	93[b]	61	23
BPEV	Natural gas	Electricity	55[c]	93[b]	61	31
HEV	Crude oil	Diesel	95.3[d]	99.8[d]	30	28
FCEV	Natural gas	Hydrogen (350 bar)	85[e]	86[f]	36	26
FCEV	Natural gas	Methanol	72[e]	99.6[d]	30	21
ICEV, future	Crude oil	Petrol	91.5[d]	99.8[d]	20	19
ICEV, today	Crude oil	Petrol	91.5[d]	99.8[d]	14	13

[a] Relates to Danish coal power with an efficiency ranging between 36% and 47%.
[b] Based on Gustavsson et al. (1995).
[c] Based on Official Report of the Swedish Government (1995).
[d] Based on Blinge et al. (1997).
[e] Based on Katofsky (1993).
[f] Own calculations based on Ogden et al. (1995).

The emission of NO_x, VOC and CO has been significantly reduced in passenger cars during recent decades as a result of the introduction of catalytic converters. There is, however, potential to reduce these emissions further by employing exhaust gas recirculation (EGR) and improved technology for reducing cold-start emission (Egebäck et al., 1997), see Table 5. The cost of an

Table 4
Primary energy efficiency with biomass as primary energy source

Vehicle	Primary energy source	Energy carrier	Primary energy to energy carrier (%)	Distribution/ storage (%)	Vehicle efficiency from Fig. 2 (%)	Primary energy efficiency (%)
BPEV	Biomass	Electricity	45[a]	93[a]	61	25
HEV	Biomass	Methanol	63[b]	99.6[c]	30	19
FCEV	Biomass	Hydrogen (350 bar)	69[b]	86[d]	36	21
FCEV	Biomass	Methanol	63[b]	99.6[c]	30	19
ICEV, future	Biomass	Methanol	63[b]	99.6[c]	22[e]	14
ICEV, today	Biomass	Methanol	63[b]	99.6[c]	15[f]	10

[a] Based on Gustavsson et al. (1995).
[b] Based on Katofsky (1993).
[c] Based on Blinge et al. (1997)
[d] Own calculations based on Ogden et al. (1995).
[e] Efficiency is assumed to be 10% higher than for petrol (Olsson, 1996).
[f] Efficiency is assumed to be 6% higher than for petrol (Olsson, 1996).

Table 5
Emission of VOC, NO_x, and PM from passenger cars (ICEVs) of 1988 and 1996 models and estimated potential for model in the year 2010 (Egebäck et al., 1997)

	VOC (g/km)	NO_x (g/km)	PM (mg/km)
Petrol-fuelled passenger cars			
1988	2.5	1.5	37
1996	0.89	0.26	13
2010	0.08	0.04	1.2
Alcohol-fuelled passenger cars			
1988	4.2	1.4	n.a.
1996	0.82	0.07	n.a.
2010	0.03	0.01	n.a.

emission reduction corresponding to the difference between the 1996 and 2010 levels in Table 5 can be estimated from State of California Air Resources Board (1996, 1998) to about 220 USD/ vehicle. BPEVs will produce no emission from the vehicle itself and the total emission is determined by the emission from the electricity production plant. Both HEVs and FCEVs have the potential for emission lower than that could be expected for future ICEVs (Patil and Zegers, 1994; Hermance and Sasakai, 1998; Egebäck and Bucksch, 2000).

5. System comparison

In this section, combinations of vehicles and fuels are analysed regarding life-cycle emissions and cost. The technologies compared are summarised in Table 6. Methanol and hydrogen are the biomass-based fuels analysed, as methanol is assumed to be the most promising liquid fuel in the medium-term perspective and methanol and hydrogen have special advantages when used in

Table 6
Studied vehicle technologies

Vehicle type	Technology level	Energy carrier	Primary energy source
ICEV	Current	Petrol	Crude oil
ICEV	Future	Petrol	Crude oil
ICEV	Current	Methanol	Cellulosic biomass
ICEV	Future	Methanol	Cellulosic biomass
HEV	Future, low-cost vehicle	Methanol	Cellulosic biomass
HEV	Future, high-cost vehicle	Methanol	Cellulosic biomass
FCEV	Future, low-cost vehicle	Methanol	Cellulosic biomass
FCEV	Future, high-cost vehicle	Methanol	Cellulosic biomass
FCEV	Future, low-cost vehicle	Hydrogen	Cellulosic biomass
FCEV	Future, high-cost vehicle	Hydrogen	Cellulosic biomass
BPEV	Future, low-cost battery	Electricity	According to low-demand scenario (LD)
BPEV	Future, high-cost battery	Electricity	According to low-demand scenario (HD)

FCEVs. Two vehicle cost estimates for HEVs, FCEVs and BPEVs are used (low and high). Two cost estimates for electricity, based on the low- and high-demand scenarios discussed above, are also included in the analysis. The assumed characteristics of the vehicle are given in Table 7 and the characteristics of the energy carriers in Table 8.

The emissions of NO_x, VOC and PM are significantly lower for all the future vehicles studied compared with the current petrol-fuelled car, Table 9. Future petrol-fuelled ICEVs are also expected to have higher emissions than most of the other future vehicles studied. The only expectation is the BPEV using electricity in accordance with the high-demand scenario. This vehicle has higher emissions of NO_x and PM than any of the other future vehicles. This is a result of the higher emissions from biomass combustion. It should be noted that the emission from the electricity plant is not produced at ground level where many people are exposed to it. The most significant differences in emission are found for CO_2, for which the petrol-fuelled car emits significantly more CO_2 than the other alternatives.

The energy and environmental cost of vehicles used as the average Swedish vehicle is summarised in Fig. 3. Compared with the current situation, the environmental and energy costs can be reduced by 50%, even with the continued use of ICEVs if they are developed according to our assumptions. FCEVs using hydrogen and BPEVs are the only vehicles using renewable energy sources that will have lower energy and environmental costs than future petrol-fuelled ICEV. HEVs, FCEVs and BPEVs all have lower energy and environmental costs than the ICEV using biomass-based methanol. The cost advantage for the HEVs, FCEVs and BPEVs compared with the methanol-fuelled ICEV using future technology is 0.4–1.2 SEK/10 km, which corresponds to 600–1800 SEK (USD 70–200) annually.

In urban traffic, the cost advantage of the HEVs, FCEVs and BPEVs compared with ICEVs increases, see Fig. 4, partly because of a higher economic valuation of the emissions, but mainly because of the relatively high efficiency of vehicles with electric drivetrains in urban traffic.

All the HEV, FCEV and BPEV alternatives have a higher total cost than the future methanol-fuelled ICEV, if the vehicle cost is added to the energy and environmental costs, Fig. 5. The

Table 7
Assumed energy use, vehicle cost and tail-pipe emissions for the analysed vehicles

	Energy use (kWh/10 km)[a]	Vehicle cost (SEK/vehicle)[b]	NO_x (g/10 km)[c]	PM (mg/10 km)[c]	VOC (g/10 km)[c]
ICEV					
Petrol, current technology	7.2	140 000	2.6	130	8.9
Petrol, future technology	4.4	148 000	0.4	12	0.8
Methanol, current technology	6.5	144 000	0.7	0	8.2
Methanol, future technology	4.0	152 000	0.1	0	0.3
HEV					
Methanol, low-cost vehicle	3.0	167 000	0.1	0	0.2
Methanol, high-cost vehicle	3.0	187 000	0.1	0	0.2
FCEV					
Methanol, low-cost vehicle	3.2	163 000	0.01	0	0.01
Methanol, high-cost vehicle	3.2	200 000	0.01	0	0.01
Hydrogen, low-cost vehicle	2.6	163 000	0	0	0
Hydrogen, high-cost vehicle	2.6	198 000	0	0	0
BPEV					
Electricity, low-cost vehicle	1.7	143 000 + batteries (USD 100/kWh)	0	0	0
Electricity, high-cost vehicle	1.7	143 000 + batteries (USD 200/kWh)	0	0	0

[a] Energy use estimates for all vehicles are based on an average new petrol-fuelled ICEV. The 40% efficiency improvement between the future and the current ICEV is assumed to result from a reduction in road load (15%) and improvements in the powertrain (25%), cf. (DeCicco and Ross, 1993). This reduction of the road load was applied to all the vehicles studied. A methanol-fuelled ICEV is assumed to be 10% more efficient than its petrol-fuelled counterpart, see e.g. (Olsson, 1996). The difference in efficiency between the alternative and conventional powertrains is taken from Fig. 2. Additional energy use as a result of higher vehicle weight (300 kg, for a BPEV, 250 kg for a methanol-fuelled FCEV, 200 kg for the hydrogen-fuelled FCEV and 50 kg for the HEV) has been taken into account.

[b] The extra costs for future ICEVs compared with current vehicles are based on DeCicco and Ross (1993), DeCicco and Mark (1998), State of California Air Resources Board (1996, 1998) and Johansson (1996). 3500 SEK/vehicle of this extra cost is assumed to be associated with reducing the road load, measures which it is assumed, are also applied to the other vehicle types. The cost interval for HEVs was based on Duleep (2000), Sperling and Lipman (2000) and Egebäck and Bucksch (2000). The cost interval for FCEVs was estimated from Ogden et al. (1998) and Jung (1999). The most important assumption are a fuel cell cost of 50–100 USD/kW, a motor and control cost of 13–26 USD/kW, a battery cost of 500–1000 USD/vehicle, a hydrogen storage cost of 1000–1500 USD/vehicle and methanol reformer cost of 20–30 USD/kW. Furthermore, we assume that the costs of BPEVs and ICEVs are the same if batteries are excluded (cf. Delucchi et al., 1989; National Research Council, 1988b). It is assumed that the BPEVs use a battery package with a storage capacity of 30 kWh, which has to be replaced once during the vehicle lifetime.

[c] Emissions for ICEVs are based on Egebäck et al. (1997) and for HEVs and FCEVs on discussions in Patil and Zegers (1994) and Hermance and Sasakai (1998).

difference is very small, however, between the ICEVs, HEVs and the FCEVs in the cases where we assumed low vehicle costs. The cost of BPEVs is in both the low-cost and the high-cost alternatives significantly higher than the cost of the future methanol-fuelled ICEV. With optimistic assumptions for FCEVs and HEVs, the vehicle, energy and environmental costs for these vehicles are lower than the corresponding costs of *current* petrol-fuelled ICEVs.

Table 8
Cost and assumed emissions from fuel extraction, conversion and distribution (pre-vehicle emissions, PVE)/MWh for the energy carriers studied. End-use emissions of NO_x, VOC, and PM are given in Table 7. End-use emissions of CO_2 are assumed to be zero for the energy carriers produced from renewable sources and 74 g/MJ for petrol

	Cost[a] (SEK/MWh)	PVE-CO_2[b] (kg/MWh)	PVE–NO_x[b] (g/MWh)	PVE–VOC[b] (g/MWh)	PVE–PM[b] (g/MWh)
Petrol	260	18	114	140	5
Methanol(bio)	550	30	200(130)[c]	33	3
Hydrogen(bio)	550	30	200(130)[c]	33	3
Electricity (LD)	600	8	210	8	15
Electricity (HD)	850	25	750	34	70

[a] Costs are based on Johansson (1996) and Table 2.
[b] Pre-vehicle emissions for the fuels are based on Blinge et al. (1997) and for electricity on Brännström-Norberg et al. (1996). In the low-demand case (LD) a combination of wind-power and biomass-based cogeneration is assumed, whereas in the high-demand case (HD), emission factors for biomass-based condensing plants are assumed.
[c] Lower emissions of NO_x are assumed for the biomass-based fuels in the future (in parentheses) as the current very high emission factors for agricultural machinery are expected to be reduced as result of the introduction of modern diesel technology.

Table 9
Life-cycle emission (tail-pipe emission plus pre-vehicle emission) of NO_x VOC, PM and CO_2 for the vehicles studied

Technology	NO_x (g/km)	VOC (g/km)	PM (g/km)	CO_2 (g/km)
1988 Level (end-use only)	1.6	2.6	40	–
Petrol, current	0.34	0.99	17	214
Petrol, future	0.09	0.14	3.4	125
Methanol, ICEV, current	0.20	0.84	2.0	20
Methanol, ICEV, future	0.06	0.043	1.2	12
HEV, methanol	0.04	0.010	0.90	9
FCEV, methanol	0.04	0.010	0.96	9.6
FCEV, hydrogen	0.03	0.008	0.78	7.8
BPEV, electricity, LD-scenario	0.04	0.001	2.5	1.5
BPEV, electricity, HD-scenario	0.13	0.0006	11.9	4.2

It can be estimated from the data in Tables 7 and 8 that the CO_2 valuation should be increased from the current Swedish level of 0.36 SEK/kg CO_2 (≈150 USD/tonne C) to about 1.10 SEK/kg CO_2 (≈450 USD/tonne C) if the biomass-based fuels are to compete with petrol. It can also be estimated that a combination of substituting biomass-based methanol for petrol and the utilisation of more energy-efficient technology (future technology instead of current technology) would reduce this cost to approximately 0.65 SEK/kg CO_2 (≈270 USD/tonne C).

The vehicle and energy costs of using the most competitive of the vehicles using biomass-based fuels are estimated to be 1.2 SEK/10 km higher than the corresponding cost of using a petrol-fuelled passenger car of today. This is equivalent to an increase in vehicle and energy costs of about 10%. As these costs are only part of the total cost of using a vehicle, the relative effect on the total cost would be even lower for the consumer. [4]

[4] In the calculations in Fig. 5, taxes, service and maintenance costs, and insurance are excluded.

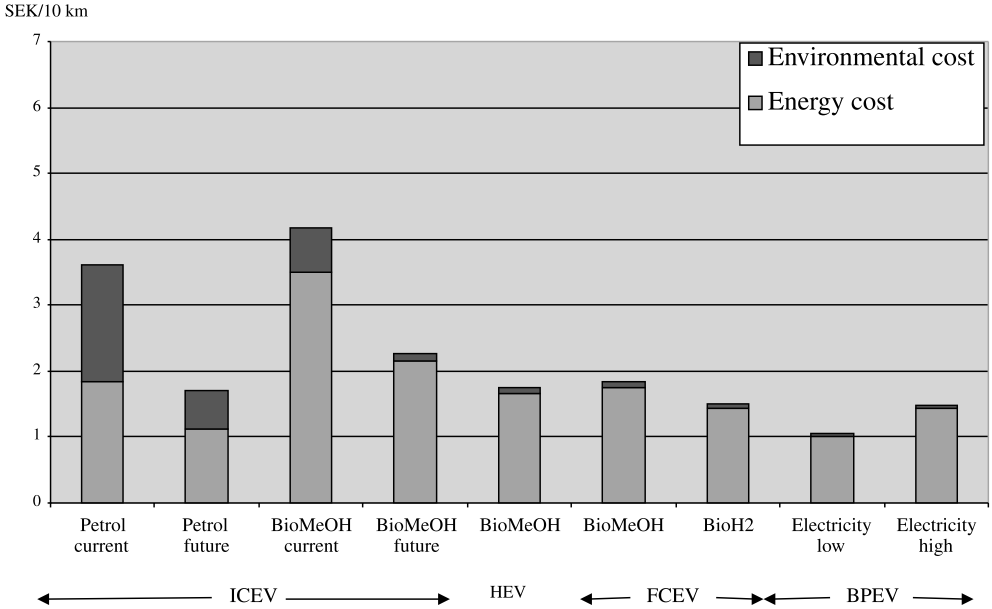

Fig. 3. Energy and environmental costs for vehicles used as the average Swedish vehicle (70% rural, 30% urban). The low alternative for BPEVs is based on the electricity cost from the LD-scenario and the high alternative on the electricity cost from the HD-scenario, see Table 8.

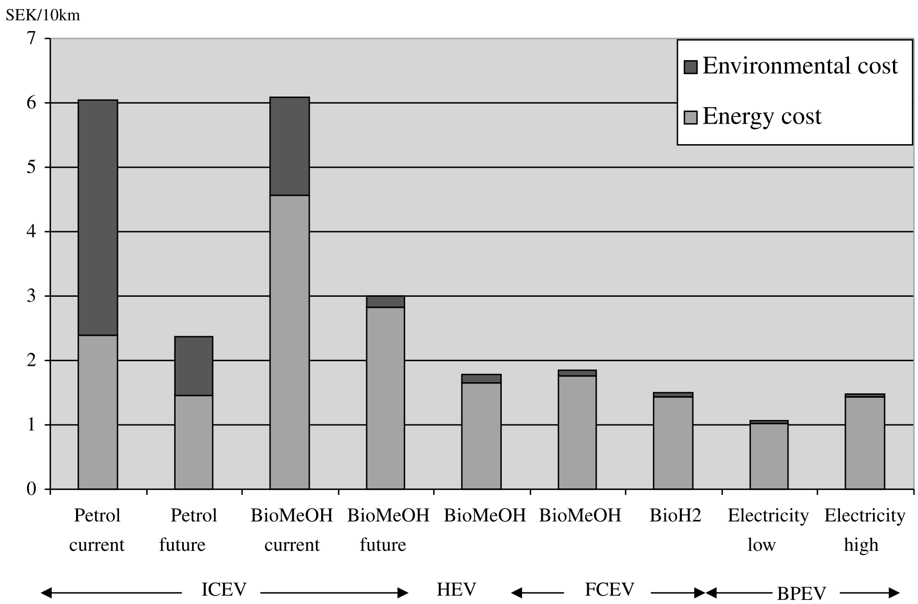

Fig. 4. Energy and environmental costs for vehicle used in urban traffic in a medium sized city. The low alternative for BPEVs is based on the electricity cost from the LD-scenario and the high alternative on the electricity cost from the HD-scenario, see Table 8.

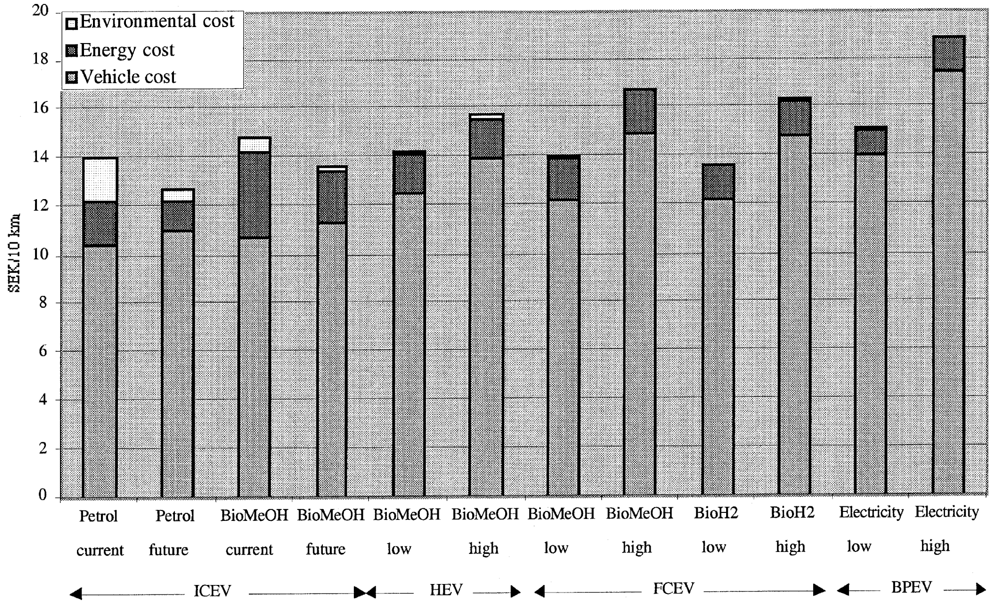

Fig. 5. The vehicle, energy and environmental costs of current and future vehicles used as the average Swedish vehicle (70% rural, 30% urban). The low alternative for BPEVs is based on the electricity cost from the LD-scenario and low-cost batteries the high alternative on the electricity cost from the HD-scenario and high-cost batteries, cf. Table 6.

It is important to note that major cost reductions for fuel cells, batteries and hydrogen storage were assumed in the calculations. For example, we assumed a fuel-cell cost of 50–1000 USD/kW which can be compared with current costs which lie somewhere between 2500 and 5000 USD/kW (Ronger, 1998; Lipman, 1999; Ekdunge and Råberg, 1998; Thomas, 1998). Battery costs are assumed to be somewhere between 100 and 200 USD/kWh, which can be compared with the current cost of NiMH batteries of about 1000 USD/kWh (National Research Council, 2000).

As expected, vehicles with electric drivetrains will be more competitive when used in urban traffic, Fig. 6. Here both HEVs and FCEVs exhibit lower costs than ICEVs using biomass-based methanol, mainly because the efficiency gains of the alternative powertrains are more noticeable in urban traffic.

There may be other cost advantages in using vehicles with electric drivetrains such as lower service and maintenance cost, but this is uncertain as there is still too little experience of this technology in everyday use. Some sources claim that the maintenance cost of electric vehicles would be half that of an ICEV (see, e.g. Delucchi and Ogden, 1993). This would correspond to approximately 1300–2000 SEK/yr [5] (150–230 USD/yr), a level that is of the same magnitude as the differences in energy and environmental costs between the electric vehicles and ICEVs. Thus, this is a factor that might have significant impact on the economy of vehicles with electric drivetrains.

Swedish studies indicate that CO_2 taxes would have to be increased significantly from the current level to reach even rather modest medium-term CO_2 reduction targets. For example, Swedish

[5] Based on current approximate levels according to the National Swedish Board of Consumer Policies (1999).

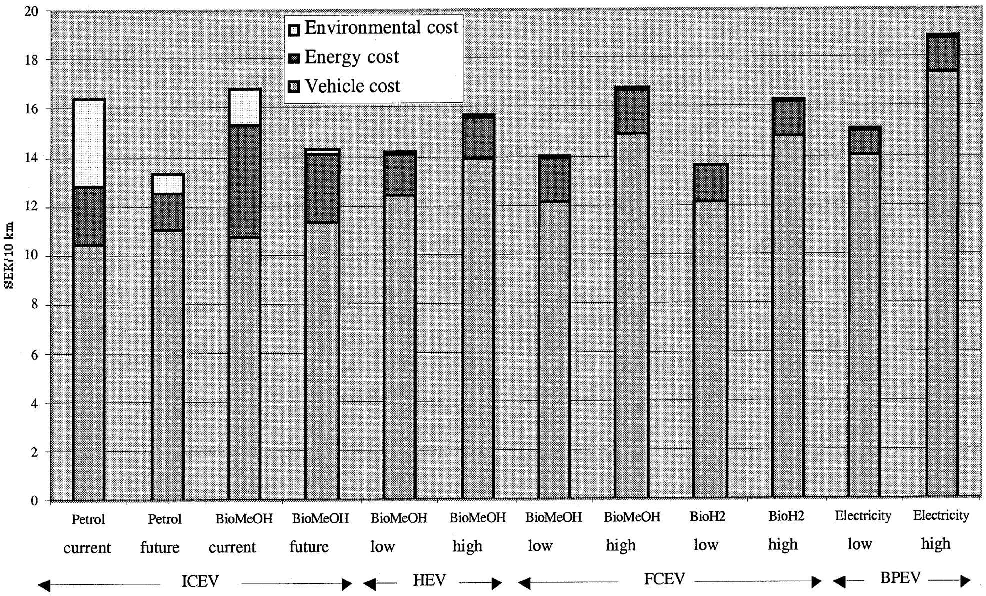

Fig. 6. The vehicle, energy and environmental costs of current and future vehicles when used in urban traffic only. The low alternative for BPEVs is based on the electricity cost from the LD-scenario and low-cost batteries the high alternative on the electricity cost from the HD-scenario and high-cost batteries, cf. Table 6.

Institute for Transportation and Communications Analysis (1999) estimated that CO_2 emission would have to be charged at 1.50 SEK/kg CO_2 ($\approx$625 USD/tonne C) for the Swedish transport sector to meet the target that CO_2 emission in 2010 should not be higher than in 1990. The economic valuation of health and environmental effects might change in the future. As a result of better knowledge of the impact of different pollutants the economic valuation of emission may change. Furthermore, growing incomes may increase the willingness to pay to avoid negative environmental impact.

The effect of increased valuations of CO_2, NO_x VOC and PM emissions is shown in Fig. 7. If the valuation of carbon dioxide emission is increased to 1.50 SEK/kg CO_2 (high CO_2), this could make biomass-based fuels used in ICEVs HEVs and FCEVs competitive with petrol. Also increasing the valuation of the NO_x VOC and PM emissions (high CO_2/environ) by 120% [6] would not affect the rank order of the alternatives, but would further motivate the development of low-emitting vehicles in the future.

Higher CO_2 valuation would not directly make energy-efficient vehicles more competitive if they used carbon-neutral renewable energy sources. Indirectly, however, an increased CO_2 valuation in society could increase biomass demand which, in turn, could result in increased biomass prices, thus favouring energy efficiency.

In Fig. 8, the effect of an increase in biomass cost on the total cost is illustrated. More energy-efficient vehicles will be more competitive with increasing biomass costs. The sensitivity of the fuel

[6] An increase in the economic valuation by 120% may be the result of an economic growth of 2.0% under a period of 20 yr if the income of environmental goods is 2.

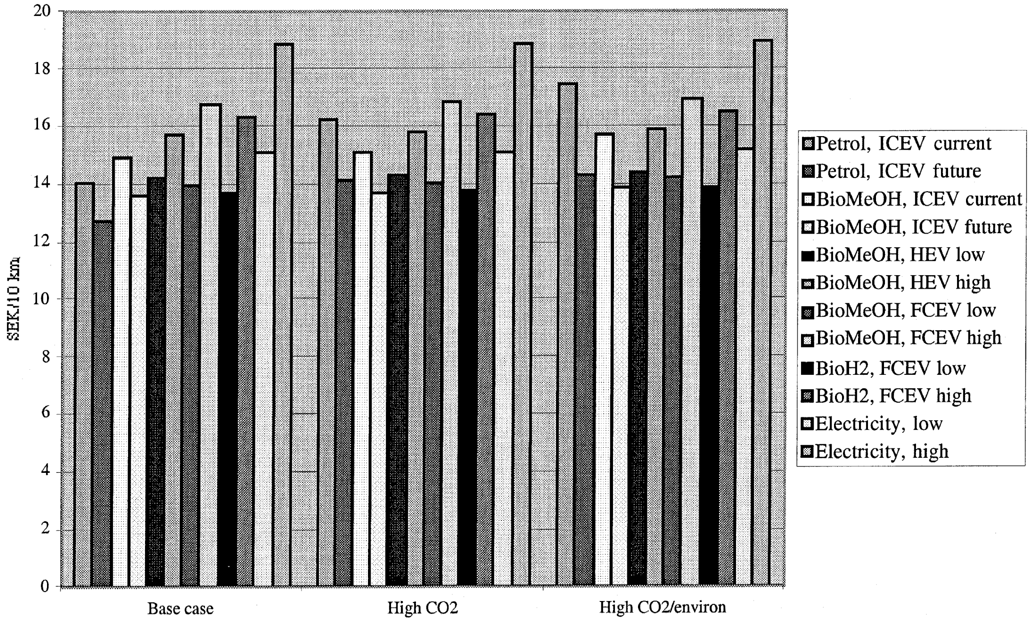

Fig. 7. The sum of vehicle, energy and environmental costs in the base case, when CO_2 emission is valued at 1.5 SEK/kg CO_2 (High CO_2), and when CO_2 emission is valued at 1.5 SEK/CO_2 and NO_x , VOC and PM are valued 120% higher than in Table 1 (High CO_2/environ).

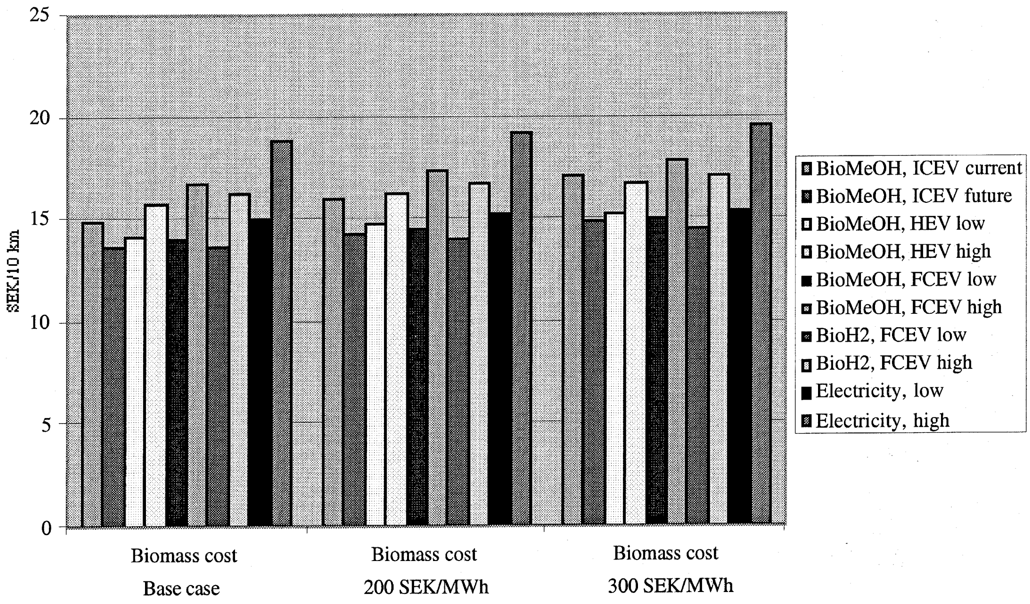

Fig. 8. Total cost in the base case (biomass cost 100 SEK/MWh (11 USD/MWh) and with assumed biomass costs of 200 SEK/MWh and 300 SEK MWh).

cost, however, is rather small for all the future vehicles studied as their energy use in relatively low. The methanol-fuelled ICEV with current technology, however, strongly loses in competitiveness in the biomass cost increases.

Rather conservative assumptions regarding battery weight and the vehicle efficiency of BPEVs have been used above. A vehicle efficiency of 70% instead of the 61% we used in the calculations above and a specific battery weight of 200 Wh/kg instead of 100 Wh/kg would reduce energy use by about 20%. This would reduce vehicle energy costs by approximately 300–400 SEK/yr. This cost reduction would be insufficient to make BPEVs competitive. A reduction in energy cost of 300–400 SEK/yr would have the same effect on the total cost of BPEVs as a reduction in battery cost of 10 USD/kWh. The uncertainties in battery costs will thus be much more important than the uncertainties in weight and efficiency of BPEVs.

Also, some of the assumptions regarding the cost of the electricity supply are uncertain. This is, however, also of much less importance than the battery cost. An increase in the electricity distribution cost of 0.1 SEK/kWh (1.1 cents/kWh), cf. Table 2, and a doubling of the assumed cost of vehicle charging would increase the total cost of using a BPEV to the same degree as would an increase in battery cost by 10 USD/kWh.

6. Discussion

This study gives an indication of the potential competitiveness of different vehicle technologies in a future carbon-neutral transportation system. It is clear that vehicles with electric drivertrains have the potential for higher efficiency and lower emissions than ICEVs, but these advantages can only, to a certain extent, compensate for higher vehicle costs. It is not clear whether the cost reductions for FCEVs, BPEVs and HEVs in the future will be sufficiently large to economically motivate their introduction even if environmental costs are considered. Many of the cost assumptions in this study are highly uncertain although the uncertainty is lower for ICEVs and HEVs than for FCEVs and BPEVs. At this stage, no certain winner for the future can be proclaimed. BPEVs are however, rather unlikely to compete successfully with the other alternatives if costs are a key issue in the choice of vehicle.

The gradual shift from oil to renewable energy as a dominant source of fuel for transportation involves phasing in new fuels and new vehicles at the same time. Preferably, fuels should be flexible with respect to primary energy source and suitable for use in vehicles developed in both the near- and long-term, thereby avoiding lock-in effects determined by fuel characteristics. Methanol and hydrogen are fuels that can be used both in ICEVs and in many thermal engines for HEVs as well as in FCEVs. Both methanol and hydrogen can be produced from biomass using the same gasification technology.

A shift from the dominating vehicle design (ICEV) and from an established fuel (petrol) will not occur spontaneously. Government efforts have so far mostly been dedicated towards research and development of alternative technologies (notably fuel cells, batteries, and thermal gasification) and currently several of the key technologies are on the verge of becoming technically competitive. However, the alternative technologies are not likely to penetrate the market due to high initial costs and competition from entrenched conventional technologies. Current supply-push policies, notably RD&D funding, needs to be complemented with demand-pull policies that can create niche-markets for buying down costs and to start developing the industrial infrastructure for these technologies. Here, market-creating policies targeted at alternative powertrains, such as feebates, subsidies, tax-exemptions, certification, etc., can play an important role for overcoming initial market barriers (Åhman et al., 2001).

Strategies aiming at major reductions of CO_2 can result in increasing fuel prices, for both fossil fuels and renewable energy sources. Fossil fuel prices would increase as a result of increasing carbon taxes or other policy instruments. The cost of biomass and other renewable energy sources increases as the prices of fossil fuels increase. This would make the more energy-efficient vehicles more competitive.

Increasing the cost of biomass might also make room for alternatives such as solar-based hydrogen in transport sector. For example, in Azar et al. (2000) solar-based hydrogen was found to be preferable to biomass-based transportation fuels. If this alternative is to be realised, significant cost reductions for solar cells would be necessary and the cost of other energy sources would have to increase significantly. Furthermore, it must be possible to motivate the high energy and cost penalties of transforming high-quality electricity into hydrogen by, for example, technical or economic restrictions for integrating high fractions of solar electricity in the electricity system due to the high distribution, storage, and system integration costs. It is today impossible to draw any final conclusion as to whether solar hydrogen would be preferable to biomass-based transportation fuels in the very long term.

We have based our analysis on the premise of a carbon-neutral-transportation system and we have therefore focused on energy carriers from renewable energy sources. In the shorter run, all the vehicle alternatives will probably also use energy carriers from fossil fuels. Most of the conclusions regarding the technical solutions drawn in this article will be valid also for a fossil-fuel based system. The total cost will, however, be lower if fossil fuels are used as long as CO_2 emissions are not valued higher than today. An environmental-economic analysis in which alternative fossil fuels, such as natural gas or fossil-based methanol, are compared with biomass-based fuels and petrol can be found in Johansson (1999).

There are other alternatives for achieving carbon-neutral transport than the use of renewable energy. Nuclear power and fossil fuels in combination with carbon sequestration could provide near-CO_2-neutral transport. There are still, however, uncertainties regarding the global potential for carbon deposition and the environmental consequences of, for example, ocean deposition. Further research in this area is therefore needed (Williams, 2000). Nuclear power is also associated with special environmental issues and its compatibility with sustainability is often challenged.

In this study much attention has been devoted to economy. There are, however, several other issues that determine the choice of vehicle technology, both from the production side and the consumer. The existing industrial structure, consumer preferences and industry's expectations of the future all have significant effects on the technological development.

The focus of this study has been on technical measures to reduce CO_2 emission. Technical measures are expected to be key options in any far-reaching strategy for CO_2 reduction in the transport sector. An efficient climate strategy would, however, involve other measures that affect the demand for transport, the choice of transportation mode, the way vehicles are utilised, etc. Unless the trend of increasing transport demand is not curbed there will be major difficulties in attaining long-term environmental goals, even if far-reaching technical improvements are assumed (see e.g. Johansson, 1998).

In this study light-duty passenger cars were considered which contribute about 48% of the global transport CO_2 emission (World Energy Council, 1998). It is believed that this fraction will decrease in the future and a CO_2 reduction strategy must involve other modes of transport as well.

Most of the conclusions in this study are relevant also for transportation systems outside Sweden. There might, however, be certain renewable energy sources that are of main interest in other countries but which have been excluded in this study due to specific Swedish climate conditions. The issue of local air pollution will also be more important for the technology choice in more densely populated countries than has been indicated for Sweden in this study.

7. Conclusions

There is potential to double the primary energy efficiency compared with the current level by utilising vehicles with electric drivetrains. There is also major potential to increase the efficiency of conventional ICEVs. Combining electric powertrains in HEVs, BPEVs and FVEVs with measures that reduce the road load can reduce the primary energy use of vehicles by 60%, without making any radical changes in, for example, vehicle construction materials.

Energy and environmental costs can be reduced by 50% merely by improving ICEVs. All the alternatives studied using electric drivetrains (HEVs, FCEVs, and BPEVs) and renewable energy sources would have lower energy and environmental costs than ICEVs. On the other hand, all the HEV, FCEV and BPEV alternatives have a higher total cost than future methanol-fuelled ICEVs, if the vehicle cost is added to the energy and environmental costs, even if significant cost reductions for key technologies such as fuel-cell batteries and fuel storages are assumed.

There is no clear winner among future vehicle technologies as the cost differences are relatively small in comparison with the uncertainties in future costs of key technologies, such as fuel cells, batteries and hydrogen storage. BPEVs are, however, unlikely to compete successfully with the other alternatives if costs are a key issue in vehicle choice.

The study indicates, however, that energy-efficiency improvement is a key area in a strategy for carbon-neutral transportation. Replacing petrol with biomass-based methanol would result in a reduction cost of about 1.10 SEK/kg CO_2 ($\approx$450 USD/tonne C). A combination of replacing petrol with biomass-based methanol and the utilisation of more energy-efficient technology (future technology instead of current technology) would reduce this cost to approximately 0.65 SEK/kg CO_2 ($\approx$270 USD/tonne C).

Acknowledgements

We gratefully acknowledge the economic support provided by the Swedish Transport and Communication Research Board.

References

Amstock, M., 2000. Behind the scenes of Prius launch – an interview with Mark Amstock, Bill More. http://evworld.com/interviews2/amstock.html. 2000-11-28.

Appleby, A., 1999. The electrochemical engine for vehicles. Scientific American 281, 74–79.

Azar, C., Sterner, T., 1996. Discounting and distributional considerations in the context of global warming. Ecological Economics 19, 169–185.

Azar, C., Lindgren, K., Andersson, B.A., 2000. Hydrogen or methanol in the transportation sector?. Department of Physical Resources Theory, Chalmers University of Technology, Göteborg.

Blinge, M., Arnäs, P.-O., Bäckström, S., Furnander, Å., Hovelius, K., 1997. Livscykelanalys (LCA) av drivmedal. The Swedish Transport and Communications Research Board, Stockholm.

Brännström-Norberg, B.-M., Dethlefsen, U., Johansson, R., Setterwall, C., Tunbrant, S., 1996. Livscykelanalys för elproduktion. Sammanfattande rapport. Vattenfall AB, Stockholm.

Börjesson, P., 1999. Environmental effects of energy crop cultivation in Sweden – I: Identification and quantification. Biomass and Bioenergy 16, 137–154.

State of California Air Resources Board., 1996. Staff report. Low-emission vehicle and zero-emission vehicle program review. Mobile Source Control Division, 9528 Telstar Avenue, El Monte, CA 91731.

State of California Air Resources Board., 1998. Staff report. Initial statement of reasons. Proposed amandments to California exhaust and evaporative emission standards and test procedures for passenger cars, light-duty trucks and medium-duty vehicles LEV II and proposed amandments to California motor vehicle certification, assembly-line and in-use test requirements Cap 2000. Mobile Source Control Division, 9528 Telstar Avenue, El Monte, CA 91731.

Carlsson, F., Johansson-Stenman, O., 2000. The cost and benefits of electric vehicles. Should battery, hybrid and fuel-cell vehicles be publicly supported in Sweden?. KFB-report 2000:46. The Swedish Transport and Communications Research Board Box 5706, Stockholm.

Chan, C.C., Chau, K.T., 1997. An overview of power electronics in electric vehicles. IEEE Transactions on Industrial Electronics 44, 3–17.

Daimler-Chrysler, 1999. http://www3.daimlerchrysler.com 1999-05-17.

DeCicco, J., Ross, M., 1993. An Updated Assessment of the Near-term Potential for Improving Automotive Fuel Economy. American Council for an Energy-Efficient Economy, Washington, DC.

DeCicco, J., Mark, J., 1998. Meeting the energy and climate challenge for transportation in the US. Energy Policy 1998, 395–412.

Delucchi, M.A., Wang, Q., Sperling, D., 1989. Electric vehicles: performance, life-cycle costs, emissions and recharging requirements. Transportation Research A 23, 255–278.

Delucchi, M.A., Ogden, J.M., 1993. Solar-hydrogen fuel-cell vehicles. Transportation Research A 27, 255–275.

Delucchi, M.A., 1999. Motor vehicle lifecycle costs and energy use model/draft. Final report. University of California, Davis.

Duleep, K.G., 1997. Evolutionary and revolutionary technologies for improving fuel economy. In: DeCicco, J., Delucchi, M. (Eds.), Transportation, Energy and Environment: How Far Can Technology Take Us? American Council for an Energy-Efficient Economy, Washington, DC.

Duleep, K.G., 2000. Cost and fuel efficiency of 2010 cars. In: Carlsson, F., Johansson-Stenman, O. (Eds.), The Costs and Benefits of Electric Vehicles. Should Battery, Hybrid and Fuel-Cell Vehicles be Publicly Supported in Sweden? KFB-report 2000:46. The Sweden. Transport and Communications Research Board Box 5706, Stockholm, Sweden.

Dönitz, W., 1998. Fuel cells for mobile applications, status, requirements and future application potential. International Journal of Hydrogen Energy 23, 611–615.

Egebäck, K.-E., Ahilvik, P., Westerholm, R., 1997. Emissionsfaktorer för fordon drivna med fossila respektive alternativa bränslen. The Swedish Transport and Communications Research Board, Stockholm.

Egebäck, K.E., Bucksch, S., 2000. Hybridfordon. Ett alternativ för den svenska bilparken. KFB-report 2000:24, The Swedish Transport and Communications Research Board Box 5706, Stockholm, Sweden.

Ekdunge, P., berg, M., 1998. The fuel cell vehicle. Analysis of energy use, emissions and costs. International Journal of Hydrogen Energy 23, 381–385.

Goubeau, A., Heuser, R., Metz, N., Nierhauve, B., Sporckmann, B.H., 1996. Energieverbrauch and Emissionen zukünftiger Pkw-Antriebe. Ein Vergleich für das Jahr 2000. Energiwirtschaftliche Tagesfragen 46, 798–804.

Gröndalen, O., 1998. Väte – framtidens energibärare? Elforsk Report 98:19. Elforsk, Stockholm, Sweden.

Gustavsson, L., Börjesson, P., Johansson, B., Svenningsson, P., 1995. Reducing CO_2 emissions by substituting biomass for fossil fuels. Energy – The International Journal 20, 1097–1113.

Hammarström, U., 1990. Trafik-och avgasutsläpp- en utblick mot 2015. Emissions-och bränslefaktorer för vägtrafik. Swedish Road and Transport Research Institute, Linköping, Sweden.

Hermance, D., Sasakai, S., 1998. Hybrid electric vehicles take to the streets. IEEE Spectrum.

International Energy Agency. 1993. Electric vehicles: Technology, Performance and Potential. OECD, Paris.

International Energy Agency, 1999. Automotive Fuels for the Future. The Search of Alternatives. International Energy Agency, Paris.

James, B.D., Lomax Jr., F.D., Thomas, C.E., Colella, W.G., 1997. PEM Fuel Cell Power System Cost Estimates: Sulpur-Free Gasoline Partial Oxidation and Compressed Direct Hydrogen. Ford Directed Technologies Inc., Arlington, Virginia.

Johansson, B., 1996. Transportation fuels from Swedish biomass-environmental and cost aspects. Transportation Research D 1, 47–62.

Johansson, B., 1998. Will new technology be sufficient to solve the problem of air pollution caused by Swedish transport. Transportation Policy 5, 213–222.

Johansson, B., 1999. The economy of alternative fuels when including the cost of air pollution. Transportation Research D 4, 91–108.

Johansson, B., Mårtensson, A., 2000. Energy and environmental costs for electric vehicles using CO_2-neutral electricity in Sweden. Energy – The International Journal 25, 777–792.

Johansson, O., 1997. Kan minskade hälso- och naturskadekostnader motivera en satsning på biodrivmedel? The Swedish Transport and Communications Research Board, Stockholm.

Jung, P., 1999. Technical and economic assessment of hydrogen and methanol powered fuel cell electric vehicles. Master of Science Thesis. Department of Physical Resources Theory, Chalmers University of Technology, Göteborg.

Kalhammer, F.R., Prokopius, P.R., Roan, V.P., Voecks, G.E., 1998. Status and Prospects of Fuel Cells as Automobile Engines. State of California Air Resources Board, Sacramento.

Katofsky, R.E., 1993. Production of Fluid Fuels from Biomass. Center for Energy and Environmental Studies, Princeton University, New Jersey.

Kazimi, C., 1997. Evaluating the environmental impact of alternative-fuel vehicles. Journal of Environmental Economics and Management 33, 163–185.

Lipman, T., 1999. The Cost of Manufacturing Electric Vehicle Batteries. ITS, University of California, USA.

Lipman, T.E., DeLucchi, M.A., 1996. Hydrogen fueled vehicles. International Journal of Vehicle Design 17, 562–589.

Martin, D., Michaelis, L., 1992. The environmental impact of electric vehicles. In: The Urban Electric Vehicle-Policy Options, Technology Trends and Market Prospects. OECD, Paris, pp. 159–170.

Metz, N., 1997. Comparison of the energy consumption and emissions of future drive trains for passenger cars at the year 2000. In: Proceedings of the 14th Symposium on Electric Vehicle. Orlando, Florida.

National Research Council, 1998a. Review of the partnership for a new generation of vehicles. Fourth report. Washington, DC.

National Research Council, 1998b. Effectiveness of the United States Advanced Battery Consortium as a Government–Industry Partnership. National Academy Press, Washington, DC.

National Research Council., 1999. Review of the research program of the partnership for a new generation of vehicles. Fifth report. Washington, DC.

National Research Council, 2000. Review of the partnership for a new generation of vehicles. Sixth report. Washington, DC.

National Swedish Board of Consumer Policies, 1999. Konsumentverket – allt om att köpa och äga bil. http://195.163.107.208/. 1999-04-30.

Ogden, J.M., Nitsch, J., 1993. Solar hydrogen. In: Johansson, T.B., Kelly, H., Reddy, A.K., Williams, R.H. (Eds.), Renewable Energy, Sources for Fuels and Electricity. Island Press, Washington, DC.

Ogden, J.M., Dennis, E., Steinbugler, M., Strohbehn, J.W., 1995. Hydrogen Energy Systems Studies. Center for Energy and Environmental Studies, Princeton University.

Ogden, J.M., Kreutz, T.G., Steinbugler, M., 1998. Fuels for fuel cell vehicles: vehicle design and infrastructure issues. SAE Technical Paper Series 982500. SAE 400 Commonwealth Drive, Warrendale, PA 15096-0001.

Official Report of the Swedish Government, 1995. Omställning av energisystemet. SOU 1995:140, Allmänna Förlaget, Stockholm.

Olsson, L.-O., 1996. Fordonskostnadens påverkan vid användande av biodrivmedel. Kommunikationsforskningsberedningen. Box 5706, 114 87 Stockholm.
Patil, P., och Zegers, P., 1994. Fuel cell road traction: an option for a clean global society. Journal of Power Sources 49, 169–184.
Rand, D.A.J., Woods, R., Dell, R.M., 1998. Batteries for Electric Vehicles. Research Studies Press, Taunton, England.
Ronger, H.-H., 1998. Hydrogen technologies and the technology learning curve. International Journal of Hydrogen Energy 23, 833–840.
Spash, C.L., 2000. Multiple value expression in contigent valuation: economics and ethics. Environmental Science & Technology 34, 1433–1438.
Swedish Institute for Transportation and Communications Analysis., 1999. Översyn av samhällsekonomiska kalkylprinciper och kalkylvärden på transportområdet. SIKA Rapport 1999: 6. Box 17213, S-104 62 Stockholm.
Solvang Jenssen, S., 1992. Køremønstre og luftforurening – i provinsen. VDL-report 105. Vejdatalaboratoriet. Herlev, Kanmark.
Sperling, D., Lipman, T., 2000. International assessement of electric-drive vehicles. policies, markets, and technologies, KFB-report 2000:30, The Swedish Transport and Communications Research Board Box 5706, Stockholm, Sweden.
Statistics Sweden, 1999. Emissions to air in Sweden – sulphur dioxide, carbon dioxide, methane, nitrous oxide and carbon monoxide, volatile organic compounds 1998. Stockholm, Sweden.
Pierre, S.-T.C., Rouillard R., Belanger A., Kapfer B., Simoneau M., Choquette Y., Gastonguay L., Heiti R. and Behun C., 1999. Lithium polymer battery for electric vehicle and hybrid vehicle applications. In: Electric vehicle symposium 16. Beijing.
Swedish Environmental Protection Agency, 1998. Vad blir konsekvenserna för miljö och hälsa av en ökad andel dieselbilar i den svenska bilparken?. Stockholm.
Swedish National Energy Administration. 1999. Energy in Sweden. Eskilstuna.
Thomas, C.E., James, B.D., Lomax Jr., F.D, 1998. Market penetration scenarios for fuel cell vehicles. International Journal of Hydrogen Energy 23, 949–966.
Wang, Q., Delucchi, M.A., 1992. Impacts of electric vehicles on primary energy consumption and petroleum displacement. Energy – The International Journal 17, 351–366.
Williams, R.H., 2000. Advanced Energy Supply Technologies, in *Energy and the challenge of sustainability* World Energy Assessement. United Nations Development Programme, NY, USA.
World Energy Council, 1998. Global Transport and Energy Development. The scope for Change. World Energy Council, London, UK.
Wyman, C.E., Bain, R.L., Hinman, N.D., Stevens, D.J., 1993. Ethanol and methanol from cellulosic biomass. In: Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H. (Eds.), Renewable Energy Sources for Fuels and Electricity. Island Press, Washington DC.
Xu, X., 1999. Automotive power electronics – opportunities and challenges. In: International Conference on Electric Machines and Drives IMED'99, 9–12 May. IEEE, Seattle, Washington.
Åhman M., 1999. Teknik för energieffektiva personbilar. KFB-meddelande 1999: 22, Stockholm.
Åhman, M., Nilsson, L.J., Johansson, B., 2001. Cars and fuels of tomorrow: strategic choices and policy needs. ECEEE Summer Study June 2001.