Cars and fuels of tomorrow: strategic choices and policy needs

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1. SYNOPSIS

Alternative powertrains, notably BPEV, FCEV and HEV, are assessed together with alternative fuels, notably methanol, hydrogen, and electricity. From this knowledge strategic choices and future policy needs are discussed.

2. ABSTRACT

Light duty vehicles, i.e., passenger cars and light trucks, account for approximately half of global transportation energy demand and thus a major share of carbon dioxide and other emissions from the transport sector. Energy use in the transport sector is expected to grow in the future, especially in developing countries. Cars with alternative powertrains to internal combustion engines (notably battery, hybrid and fuel cell powertrains), in combination with potentially low carbon electricity or alternative fuels (notably hydrogen and methanol), can reduce energy demand by at least 50%, and carbon dioxide and regulated emissions much further. The article presents a comparative assessment of promising future fuel/vehicle combinations. The study indicates that there are several promising technologies but no obvious winner. However, the electric drivetrain is a common denominator in the most promising alternative powertrains but continued cost reductions are important for widespread deployment in future vehicles. It appears that a flexible transition with a gradual phase-in of new vehicle technologies and alternative fuels is technically possible and, it seems, economically within reach. A shift from current supply push policies, e.g. research and development funding, towards more demand pull and market creating policies such as feebates, subsidies, certification *e.t.a.*, are needed to overcome initial barriers for the alternative technology.

3. GLOSSARY

BPEV: Battery Powered Electric Vehicle
HEV: Hybrid Electric Vehicle
FCEV: Fuel Cell Electric Vehicle
ICEV: Internal Combustion Engine Vehicle

4. INTRODUCTION

Mobility and transport play a central role in achieving social and economic development goals in most countries. The growth of the transport sector has, however, also resulted in increasing negative impacts on the environment, as a result of emissions of hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and carbon dioxide (CO_2), congestion and noise. Concerns for energy security and environmental protection have been the main driving forces for research and development efforts into new vehicle technology and new fuels, but economic restrictions and market trends have so far, in most countries, hindered the introduction and diffusion of fundamentally new vehicle technologies and alternative fuels.

While limited oil reserves have motivated the search for alternative fuels for many decades, it was the 1973 and 1979 oil crises that focused the world's attention on the issue of oil dependence. In OECD countries, 97% of the transport sector uses petroleum-based fuels. This sector alone accounts for 54% of the OECD´s overall oil use (Peake and Schipper, 1997). Light duty vehicles use 49% of the total transport energy demand, trucking uses another 30%, with the remaining 21% divided equally among air, rail and maritime transport (WEC, 1998).

In the mid-1980s, with the fall of oil prices, the focus of transport energy policy shifted somewhat from security of supply and fuel economy to environmental concerns. One manifestation of this shift is the California Air Resources Board (CARB) 1990 mandate for various low- and zero-emission vehicles in response to local air-quality concerns. The climate change issue was effectively put on the global political agenda at the 1992 Earth Summit in Rio de Janeiro and has since received increased attention. The need to reduce greenhouse gas (GHG) emissions has promoted increased efforts to develop low-carbon emitting transportation systems, although policy initiatives have occurred mainly in response to industrial competitiveness and a desire to reduce dependence on petroleum fuels (Chapman, 1998).

In the last two to three decades, the automotive industry has substantially reduced exhaust emissions in new vehicles for regulated pollutants, such as CO, HC, NO_x, PM and lead, in response to progressively tighter environmental regulations. However, these gains have been partly offset by increases in total transport demand. Thus, between 1970 and 1997, freight and passenger transport doubled in Europe (ECMT, 1999).

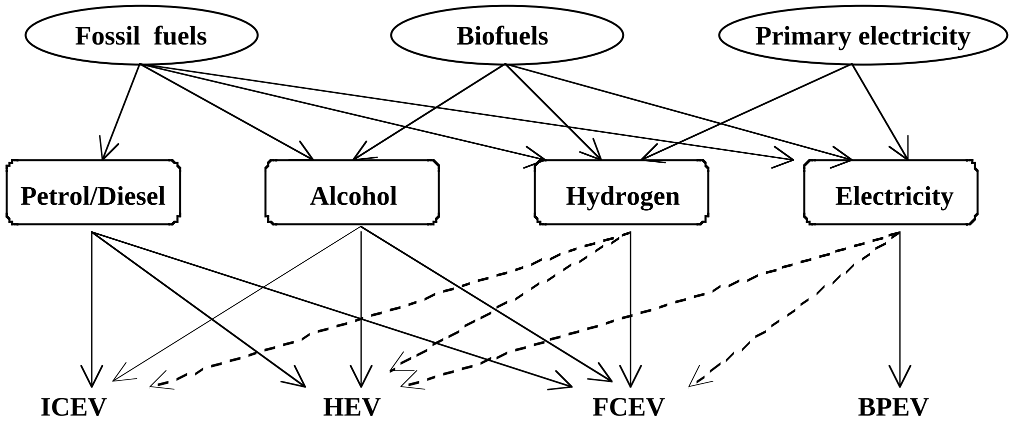
Future transportation systems must be compatible with multiple policy objectives, including reliability, safety, clean air, low-carbon emissions and affordable prices. Thus, increasingly stringent environmental regulations are to be expected, as exemplified by the forthcoming TIER II requirements issued by the U.S Environmental Protection Agency (EPA). The automotive industry must also meet consumer demands and preferences for performance and comfort.

A shift from today's internal combustion engine vehicles (ICEV) to a new generation of vehicles, including battery-powered electric vehicles (BPEV), hybrid electric vehicles (HEV) and fuel-cell electric vehicles (FCEV), in combination with low-carbon electricity and other fuels, can make a substantial contribution towards meeting these goals.

5. ANALYSING FUTURE VEHICLES AND FUELS

Several fuel-vehicle combinations are technically possible as shown in Figure 1. Options analysed should be comparable in terms of performance.

Figure 1. Possible pathways for energy from primary resource to final end use.



Note: Solid lines represent analysed vehicle and fuel combinations. Dotted lines indicate combinations that are possible but not analysed here, for example, feeding grid electricity to HEV and FCEV.

Future powertrain technologies for BPEVs, HEVs and FCEVs are analysed for typical medium-size passenger cars that, in principle, offer the same performance as present conventional cars in terms of speed, acceleration, size and comfort. An analysis of the potential future performance of ICEVs is included for comparison. The performances of the studied technologies assumed in this study are those attainable within 10 to 20 years. The stated performances (notably for energy efficiency) indicates what *could* be achieved, not what *will* be achieved in the future.

It is assumed that alternative powertrains will only come on the market if they meet commercial cost criteria. Cited cost targets for crucial components, such as fuel cell- and electric battery drivetrains, used in this analysis are mainly those stated by PNGV[1] and USABC[2]. The commercialisation targets are cost reductions considered necessary by auto manufacturers and analysts in order to make market introduction possible. Long-term cost targets are based on life-cycle cost analysis considering that the higher purchase price is off-set by a lower per mile energy price (see NRC, 1998b). However, the cost targets have been criticised for not being ambitious enough, thus making further cost reductions necessary in order for alternative vehicles to become fully competitive (Delucchi, 1999).

6. VEHICLES AND FUELS OF TOMORROW

Primary energy and conversion technologies

The shift away from oil as the dominant primary resource for transportation fuels is not likely to be driven by resource constraints. A reserve to consumption ratio of about 45 years is often cited, but if the total resource base is taken into account, including oil shale, tar sands and heavy crude oil, and divided by present consumption, the ratio is about 230 years. Thus, occurrences of oil already known and under exploitation can cover the total global demand likely to occur in the 21st century (Rogner, 2000). Although oil is the primary resource for nearly all transportation fuels today, natural gas and coal can also be used. A shift away from these fuels is not likely to be resource driven either. The total resource base divided by present consumption is close to 600 years for gas and more than 2000 years for coal. Although these potentials may be reduced by economic, security and environmental considerations, they start out at a high level.

Fossil fuels can be converted to attractive energy carriers (such as dimethyl ether, methane, methanol, hydrogen and electricity) for future vehicles, facilitating near zero or zero tail pipe emissions of regulated pollutants. In particular, near-zero emission of both regulated pollutants and greenhouse gases can be achieved with electricity and hydrogen as energy carriers in BPEVs and FCEVs respectively. Although several uncertainties remain, it is technically possible to recover and use the energy content of fossil fuels while preventing carbon dioxide from being released into the atmosphere. This can be done by separating out the carbon dioxide and sequestering it, for example, in geological formations or in the deep ocean (Williams, 2000). There are still 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).

The most promising renewable source of primary energy for fluid transportation fuels is biomass. The potential long-term contribution from biomass to world energy term is high: on the order of 300 exajoules per year, corresponding to 75% of present global energy use or more (Rogner, 2000). Biomass can be converted into electricity, and various liquid and gaseous hydrocarbons suitable for transportation.

In order to be competitive, biomass-based transportation fuels should be produced with efficient processes that use, as a feedstock, residues or biomass produced with high yields per hectare and low inputs of energy in cultivation and harvesting. Further, the fuel produced should be suitable for use in highly efficient and low polluting powertrains. Low or negative cost biomass in various waste streams are likely to be used first, before more costly dedicated energy plantations are widely used. In temperate climate, cellulosic biomass seem to have both efficiency and cost advantages compared to annual crops. In addition, cultivating perennial cellulosic energy crops typically results in lesser environmental impacts than annual crop cultivation, and may even offer environmental benefits in terms of reducing nitrogen run-off, etc. (Börjesson, 1998).

Thermal gasification offers a relatively high efficiency conversion route from cellulosic biomass to methanol and hydrogen; fuels that can be used in efficient and low-polluting thermal engines or fuel cells. The gasification process is relatively insensitive to the quality of the feedstock. Methanol and hydrogen are perhaps the most promising biomass-based fluid transportation fuels that can be considered and are the only ones included in the present analysis. In addition, they can be produced from a variety of feedstock, including fossil fuels, offering the advantage of flexibility concerning primary resource, thus facilitating a gradual phase-in process.

Biogas (i.e. methane from anaerobic digestion) from various organic wastes is a promising fuel, but it depends on the availability of relatively limited waste-streams since using dedicated crops for Biogas production is less efficient and less economical than pursuing other conversion routes.

Ethanol from sugar cane in favourable climate conditions is more promising, as illustrated by the Brazilian PRO-ALCOOL programme. Ethanol production from cellulosic biomass (e.g. wood) through hydrolysis techniques may also become cost competitive in the future (Wyman, Bain *et al.*, 1993).

The potential for using primary electricity from hydro, wind or solar power for transportation is dependent on the total consumption of electricity in society, see e.g. (Johansson and Mårtensson 1999) and on the possibilities for BPEVs to come to market. The potential for new marginal power dedicated to passenger cars from hydro or wind power is limited by potential land use conflicts, see e.g. (Naturvårdsverket 2000) and the limited electric energy storage capacity in BPEVs is a major constraint (see below). The future outlook for solar power is dependent on the long term and highly uncertain development of low-cost solar cells. Conversion of solar energy to electricity in photovoltaics and electrolysis of water to produce hydrogen is often advanced as a promising option. However, producing hydrogen through electrolysis of water using primary electricity from solar power, is likely to be more expensive, at least in the foreseeable future, than producing it from fossil fuels, even with carbon sequestration and biomass (Williams 2000; Johansson and Åhman 2001). One reason is that electrolysis and subsequent transport and storage involves considerable conversion losses.

Vehicle technology

Internal combustion engine vehicles (ICEV)

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

Alternative powertrains

The common denominator for all alternative powertrains studied here is the electric drivetrain, consisting of an electric motor and power electronics for control. The electric drivetrain offers the benefit of high mean efficiency during partial load compared to the conventional drivetrain. The electric drivetrain has attained the technical requirements for market introduction, but its cost remains a major barrier (Chan and Chau, 1997; Xu, 1999).

Battery powered electric vehicle (BPEV)

The main barrier to introduction of the BPEV is that the range attained with currently available batteries is too small and the price is too high for this technology to be competitive on the market. New battery technology, e.g. lithium-ion, lithium metal-polymer and NiMH batteries, could give the BPEV enough range, 150 miles, for introduction on the market, but the question remains whether batteries will reach the cost target of US$150/kWh (NRC, 1998a). Medium term cost assessments suggest large scale production costs for NiMH and lithium batteries between 160 – 350 dollars/kWh (Lipman 1999; Anderman et al 2000), while theoretical reasoning indicates that lithium batteries may have a long term potential of attaining USABC´s cost target of 100 – 150 dollars/kWh (NRC 1998; Rand *et al.* 1997). Large-scale use of BPEVs would require a new electric infrastructure, such as home charging appliances and public fast-charging stations. The cost of this infrastructure could be high, but it can be introduced gradually; CARB (2000) does not consider cost a major obstacle to an eventual large-scale BPEV deployment in California. BPEVs may also be integrated into the electricity grid and used for load management (Kempton, 1997).

Hybrid electric vehicle (HEV)

The technology for HEVs with advanced and energy efficient IC-engines is available on the market today, examples are Toyota Prius and Honda Insight. New IC-engines will have to manage both low emissions and high efficiency which might, in the future, exclude diesel engines as an alternative (NRC, 2000). The actual cost of HEVs are not disclosed, but it is a fair assumption that the HEVs available on the market today are not yet profitable for the companies producing them. Toyota claims that the company will make no loss at the end of the Prius production series, but admits initial losses of US$15,000 – 20,000 per vehicle (Amstock, 1999). The HEV uses petrol, but can easily use methanol or ethanol, and with some effort also hydrogen. This fuel flexibility is a benefit as is the fact that the vehicle uses the same fuel infrastructure as the ICEVs. However, large-scale use of methanol or ethanol would require a partly new fuel infrastructure (Wang, Stork *et al.*, 1997).

Fuel cell electric vehicle (FCEV)

Advances in recent years have made the PEM fuel cell technically competitive; however, some further development is needed to integrate the system (Kalhammer, Prokopius *et al.*, 1998). Serial production based on current state-of-the-art FCEVs will begin at the earliest in 2004 (Daimler-Chrysler, 1999), but serial production of developed FCEVs, fully exploiting their potential, could probably not start until 2010. An important barrier to FCEV development is the long-term cost of the fuel cell itself. The fuel cell still needs considerable development in order to bring costs down to a competitive level of US$50/kW (NRC, 1998a; Appleby, 1999). Long term cost assessments suggest that it is possible to reach a competitive cost, provided that critical technical improvements or breakthroughs are made, such as reducing the need for platinum, see e.g. (James *et al.* 1997; Kalhammer *et al*. 1998). An important feature of the fuel cell system is that it uses pure hydrogen for fuel, which requires a new fuel infrastructure and a complicated hydrogen storage facility on-board the vehicle. In order to be able to use existing infrastructure and storage technology, a 'hydrogen carrier', like methanol or even petrol, can be reformed and used on-board the vehicle instead. Using a 'hydrogen carrier' lowers the energy efficiency and adds to the weight and cost of the vehicle. So far, auto manufacturers prefer reforming methanol or petrol on-board the vehicle instead of using hydrogen directly (see conclusions in Kalhammer *et al.*, 1998). Petrol, methanol or natural gas can be used as transitional 'hydrogen carriers' during the interim before a hydrogen infrastructure has been established[3].

7. ENERGY EFFICIENCY AND EMISSIONS

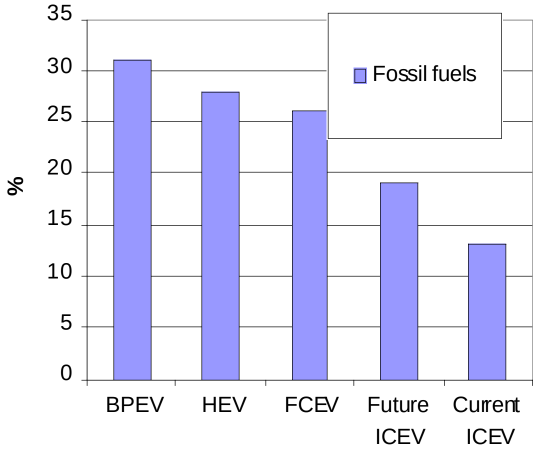
Studies show that future vehicles can meet more stringent emission standards, such as Tier II (Egebäck, Ahlvik et al., 1997; EEA, 1997). The standard of the California zero-emission vehicle (ZEV) can only be met by BPEVs and FCEVs. It is reasonable to assume that all vehicles studied here can meet future standards as exemplified by Tier II, and therefore controlling CO_2 emissions will be the key challenge to developing a sustainable transportation system. Regardless the choice of future energy carrier for passenger cars, renewable primary energy resources that can be allocated to the transport sector will be limited and will put a constraint on primary energy use, see e.g. (Steen *et al.* 1997). Limiting factors can be available land (biomass), scarce materials (solar cells), or conflict with other land-use-related interests (wind power). Thus primary energy efficiency becomes a critical part of a strategy for mitigating CO_2 emissions.

Primary energy efficiency

Primary energy efficiencies attainable for future vehicles using energy carriers based on fossil fuels are given in Figure 2. The fossil fuels used are assumed to be crude oil or natural gas for fluid fuels and natural gas for marginal electricity generation.

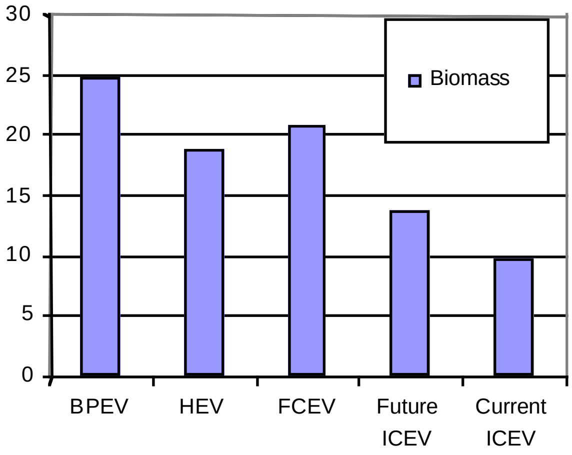
Of the alternatives studied, the BPEV will have the highest primary energy efficiency, which is partly due to the fact that we use a marginal perspective calculating energy efficiency for electricity production from new natural gas power plants. The advantage with regard to the emission of CO_2 is even higher due to lower carbon content per unit of energy for natural gas compared to petrol. HEVs with advanced IC-engines are twice as efficient as the conventional vehicles of today. FCEVs have lower efficiencies than HEVs due to losses when converting natural gas to hydrogen or methanol.

Figure 2. Primary energy efficiency attainable for future vehicles using fossil fuels. BPEV fuelled with electricity from natural gas power plant, HEV and FCEV with hydrogen derived from natural gas. Derived from Åhman (1999)



The primary energy efficiencies attainable for vehicles using energy carriers based on biomass (notably methanol or hydrogen) are given in Figure 3. The BPEV has the highest potential for primary energy efficiency. One reason for this is the conversion loss when producing liquid and gaseous fuels from biomass. The various HEVs and FCEVs all have similar efficiencies.

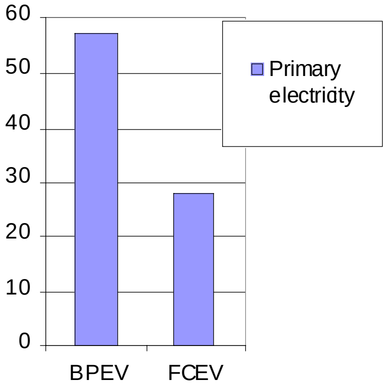
Figure 3. Primary energy efficiency attainable for future vehicles using biomass (in %). HEVs fuelled with methanol and FCEVs fuelled with hydrogen derived from biomass. Derived from Åhman (1999)



Finally, the primary energy efficiencies attainable for vehicles using primary electricity are given in Figure 4. In this case only BPEVs and FCEVs were considered. Hydrogen for the fuel cell is produced through electrolysis of water. The efficiency of producing primary electricity is set to 100% for all the alternatives.

About 30% of the energy is lost when converting electricity to hydrogen and back to electricity again in the FCEV. For this reason, the most efficient alternative would be to use the electricity directly in a BPEV. Hydrogen is, however, easier to store than electricity and may be a more practical energy carrier than electricity in a very long-term scenario, using hydrogen produced with solar energy.

Figure 4. Primary energy efficiencies attainable for vehicles using primary electricity (in %). FCEV fuelled with hydrogen derived from electrolysis of water. Derived from Åhman (1999)



Further efficiency improvements, not affecting the choice of future fuel-vehicle combinations, can be achieved by reducing road loads. The principal strategies for this involve diminishing the vehicle's frontal area and the use of aerodynamic designs, slimmer wheels, and lighter vehicle overall weight. Such measures can reduce road loads by roughly 30-40% compared to standard ICEVs today, while maintaining overall comfort and vehicle performance, resulting in approximately the same reductions in fuel consumption (Åhman, 1999). Much larger reductions may be possible in the longer term (Lovins, 1996).

8. COST EFFECTIVENESS

Alternative fossil fuels, such as natural gas, are already economically competitive to petrol and diesel today in city traffic, if environmental costs are considered (see e.g. Johansson, 1999).

The future cost of biofuels is principally governed by the price of the feedstock (Pilo, 1996). The most competitive, for most OECD countries, are cellulosic feedstock (see Reddy *et al.*, 1997; IEA/AFIS, 1999). However, in order for biomass-based fuels from cellulosic feedstock to become really competitive, an increased valuation of CO_2 emissions in combination with the development of more cost-effective fuel production will be required (Johansson, 1999; IEA/AFIS, 1999). In countries where biomass can be produced at a lower cost, the cost-effectiveness of renewable fuels is generally better and other feedstock can compete with cellulose[4]. For energy carriers derived from renewables, energy efficiency becomes crucial for reducing the cost per passenger-km (Johansson and Åhman 2000).

Renewable electricity in BPEVs provides an opportunity to lower energy and environmental costs (Johansson and Mårtensson, 2000), but the high battery cost is a major barrier. Even with major cost reductions, it seems very difficult for BPEVs to compete economically with ICEVs or HEVs (Johansson and Åhman, 2000).

Both HEVs and FCEVs will have lower energy and environmental costs than ICEVs, as their energy efficiency and emissions are significantly lower. The value of these lower costs is, however, not sufficient to allow for more than a few percent (less than 10%) increase in investment costs for such vehicles (Johansson and Åhman, 2000). Thus, cost reductions are necessary for all alternative powertrains today. Maintenance costs and length of serviceable life are other important factors that affect life-cycle costs. Some studies suggest that these factors will act to the advantage of HEVs, BPEVs and FCEVs (Delucchi and Ogden, 1993). However, final conclusions regarding these effects are difficult to draw at present since only a small number of alternative powertrain vehicles are on the road in normal use.

9. DEVELOPMENT PATHS

The rationale for developing alternative powertrains is the search for high-energy efficiency, low or even zero tail-pipe emissions, and energy resource flexibility. The ICEV does not have the same potential for high energy efficiency, but it can achieve very low tail-pipe emissions and it is relatively flexible with respect to fuels. Future cost reductions, and to some extent technical breakthroughs (notably for the BPEV), will determine whether alternative powertrains will become competitive with the ICEV.

The buy-down of cost for the electric drivetrain, the common denominator for these alternative powertrains, through development and deployment, is the key factor to the success of alternative vehicles. Currently, the least costly way of deploying the electric drivetrain is in HEVs with IC-engines. Major battery manufacturers today are shifting their focus away from BPEV batteries to HEV batteries, as they see a greater and more immediate market potential (Anderman *et al.*, 2000).

For HEVs, lead/acid batteries could be the lowest-cost alternative, with NiMH, lithium-ion or lithium-polymer batteries as long-term options. NiMH can fulfil the requirements of an HEV, but it is not an attractive long-term option for a BPEV and has only small benefits over lead/acid as a HEV battery in the medium term. However, lead/acid, NiMH or lithium batteries may well fulfil the requirements for smaller sized BPEVs with limited range, e.g. neighbourhood electric vehicles (NEVs), which would provide a start-up market for batteries (CARB, 2000).

HEVs with petrol or alcohol fuels can meet California's SULEV[5] requirements (e.g. Honda Insight), but zero tail-pipe emission can only be met by BPEVs and FCEVs. If California and other states maintain the ZEV (zero-emission vehicle) mandate, this may force BPEVs or FCEVs onto the market. BPEVs have a somewhat higher overall primary energy efficiency than FCEVs, but the difference is small except when energy comes from primary electricity (see Figure 4).

It is uncertain whether any of these two technologies, BPEVs or FCEVs, will have a potential for market breakthrough. Both the FCEV and the BPEV need further research before wide-scale market introduction will be possible. It is thus reasonable to keep the door open for both alternatives. For commercial competitiveness, the BPEV depends on a low-cost battery with high specific energy. Developing such a battery requires further basic research. The only batteries that at present seem likely are the lithium based ones, in particular the lithium-polymer battery. The FCEV is in a slightly different position. The PEM fuel cell is expected to be technically competitive within a couple of years, with a major challenge being cost reduction.

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.

The different powertrains will compete with each other but can also be seen as complementary, sharing critical components, on a trajectory towards new vehicles with high primary energy efficiency, low emissions and resource and technological flexibility.

10. DISCUSSION AND POLICY IMPLICATIONS

Combinations of new vehicle technologies and fuels, as analysed here, represent a nexus of technical measures that can reduce air pollution and energy use in the transport sector. Electricity or alternative fuels such as methanol or hydrogen, from either renewable or fossil sources, are promising energy carriers for future vehicles. Vehicles with new powertrains using alternative fuels can cut energy use in half and reach low or near-zero emissions of carbon dioxide and regulated pollutants. It appears that a flexible transition with a gradual phase-in of new vehicle technologies and alternative fuels is technically possible and, it seems, economically within reach.

No certain winner can be seen among the different technical options today. Several alternatives are dependent on the development of common core technologies such as the electric drive train, thermal gasification, improved internal combustion engines, and batteries. HEVs fuelled with methanol or hydrogen derived from either fossil or biomass feedstocks could provide a first bridging technology that will enable the core technologies to develop and reduce cost. Maintaining flexibility regarding technical choice today seems reasonable in a long-term strategy. Eventually FCEVs, HEVs, BPEVs or even ICEVs may prove to be the most competitive solution from a combined environmental and economic perspective, depending on which cost reductions for the alternatives are realised. Methanol or hydrogen produced from thermal gasification of cellulosic biomass seems to be the most competitive renewable fuels for passenger cars and both methanol and hydrogen can be derived from fossil sources such as natural gas. It is, however, important to combine alternative fuels and energy efficiency in a coherent strategy.

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.

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12. END NOTES

[1] PNGV: Partnership for a New Generation of Vehicles.

[2] USABC: United States Advanced Battery Consortium.

[3] See Ogden (1999) for a more elaborate discussion of this aspect.

[4] For production of ethanol from sugar cane in Brazil, see e.g. Reddy *et al.* (1997).

[5] SULEV: Super Ultra Low Emission Vehicle.