Annex VII: Hybrid Vehicles
Overview Report 2000

Chapter 6: General trends worldwide

Worldwide developments and activities in the field of hybrid road-vehicle technology

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This report

This Overview Report on the status of Hybrid Vehicle Technologies and Programmes is the result of collaborative work carried out in phase I of Annex VII between June 1998 and June 2000. It incorporates the results of both Subtask VII/1 and Subtask VII/2 over this period. The main text is based on the information collected by the participants on the status of hybrid vehicle technology and the R&D and implementation projects and programmes in various countries. As the Topics that have been studied in Subtask VII/2 closely relate to the aspects that are analyzed in the Overview Report resulting from Subtask VII/1, the Topic Reports have been integrated into this report at the appropriate places. Whenever this is the case, authors of the Topic Report are clearly mentioned.

At the end of phase II an updated version of this Overview Report will be published, incorporating the Topic Reports on subjects studied in phase II.

The structure of the report is as follows:

Chapter 2 introduces the various hybrid drivetrain configurations which are being developed and studied by the light duty and heavy duty vehicle manufacturers in the world. Roughly spoken, one can divide hybrid drivetrain configurations using electrical storage devices into series-, parallel and combined hybrids. Furthermore, hybrids making use of a mechanical energy storage device are briefly discussed.

Chapter 3 takes a closer look at some concrete examples of hybrid vehicles that have been developed for different applications (two-wheelers, passenger cars, vans, buses and trucks) and discusses some trends. Different vehicle applications demand different hybrid configurations. On the basis of existing examples the choices made by the R&D community and automotive industry are illustrated.

Subsequently, Chapter 4 deals with the two main components that are specifically developed for hybrid vehicle applications: thermal energy sources and energy storage devices (i.e. batteries, supercapacitors and flywheels). An overview and analysis of the state-of-the-art of these components is presented and some general reflections on the latest developments are given. In a future version of this report more components for hybrid powertrains will be discussed.

Chapter 5 describes large programmes and projects on hybrid vehicles that are being carried out worldwide. These are on the one hand divided into governmental and industrial programmes and on the other hand split up for the three regions Europe, USA and Asia.

Based on the vast amount of data collected in Annex VII Chapter 6 analyses worldwide trends within the field of hybrid vehicle technology in a more statistical manner. Trends in R&D (for instance status of hybrid vehicles, components used within several hybrid vehicle configurations), market introduction and mass production are visualized. Furthermore time paths for the development and introduction of hybrid electric vehicles and fuel cell vehicles are discussed.

Chapter 7 is focused on energy and emission aspects of hybrid vehicles. This chapter is composed of various Topic Reports written by the Annex VII participants. Attention is paid to test methods for HEVs, energy consumption and emissions of hybrids and the perspectives for using alternative motor fuels in hybrid vehicles. As part of the discussion on energy aspects a comparative assessment is presented of different HEV configurations using the simulation tool ADVISOR.

The next chapter (Chapter 8) presents a study of the cost aspects of hybrids, fully based on a Topic Report devoted to this subject.

Chapter 9 concludes the report with some final remarks. A summary of the conclusions from the various chapters of this report can be found in the executive summary.

Finally in Chapter 10 a general overview is given of the information collected on hybrid vehicles (from human powered hybrid two-wheelers up to heavy duty vehicles) which are currently in the R&D or early commercial stage (prototypes, testing vehicles, concept cars). The overview is of course not complete. A selection is made of those vehicles that are attractive or illustrative by virtue of their technical innovation, or that are already in the (pre-) commercial stage. Apart from general vehicle data, some technical information of the driveline configuration is given (whenever available).

Contents

6 General trend worldwide

6.1 Introduction

As a basis for this Overview Report all Annex VII participants have collected data on hybrid vehicles and related government and industry activities in their countries. The Operating Agent has also collected information from countries and regions that are not represented in the project. For this purpose standard data collection formats have been developed by the Operating Agent. The collected data deals with information on projects, vehicles and components. An abstract of the collected vehicle data is included in chapter 10 of this report.

The collected data have been analyzed to determine general trends in hybrid vehicle R&D. In this chapter we present some cross-sections through the data and try to draw conclusions on worldwide trends in the choice for different vehicle configurations and component types (see section 6.2). Besides these analyses based on the collected data, also considerations are presented with respect to market introduction (section 6.3) and the interaction between hybrid vehicle and fuel cell vehicle development and implementation in section 6.5. Section 6.4 is a Topic Report resulting from Subtask VII/2 (see section 1.3) and deals with the trend from charge depleting to charge sustaining hybrids.

6.2 Trends in R&D

The graphs in this section present some cross-sections of the data collected in Annex VII. From these graphs some general conclusions can be drawn with regard to choices made in R&D projects worldwide. It is important to keep in mind that in the graphs all entries in the Annex VII database are weighted equally. This means that large and small projects are treated as equal. It is, however, absolutely obvious that some projects and developments are more significant than others in terms of how they reflect the worldwide trend in thinking about hybrids. Therefore one has to be careful not to go into to much detail with the interpretation of the presented results.

In Figure 6.1 the development status is presented of all HEVs for which information has been collected (commercial, pre-commercial, demonstration, testing and prototype). Counted are numbers of vehicle types / models. So, the Toyota Prius only accounts for one type (production amounts have not been included).

It is clear that most hybrid electric vehicles, for which information has been gathered, are in the prototype or demonstration stage at the moment. A clear distinction between these categories is sometimes difficult. When vehicles used in a demonstration project have been produced in small series they can be categorized as demonstrators. Often, however, prototype vehicles are also used in a demonstration phase following the initial development phase.

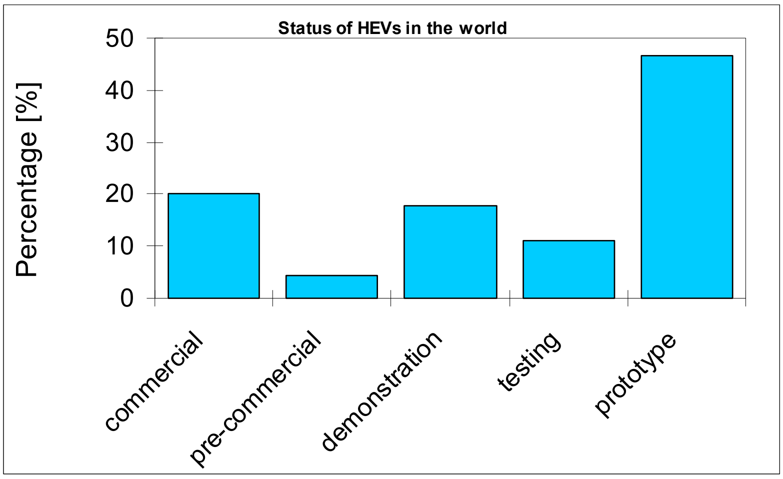

Figure 6.1 Status of the HEVs in the world (based on number of vehicle types), derived from the Annex VII database

As a remark on the "commercial" vehicles, it can be said that - apart from the Toyota Prius and the Honda Insight - these vehicles are mainly (Japanese) light trucks and buses. Such vehicles can be put forward more easy as 'commercial' compared to passenger cars, which in general require large-scale production to be really commercial. The market for trucks and buses is much smaller and consequently production volumes are smaller. Due to different manufacturing techniques innovative vehicles can be sold "commercially" on the basis of very small production series (see also sections 3.4 and 3.5).

Figure 6.2 shows the number of HEV development activities distributed per region. Again one has to bear in mind that this figure only reflects numbers of vehicle types and does not allocate budgets or production amounts to the regions.

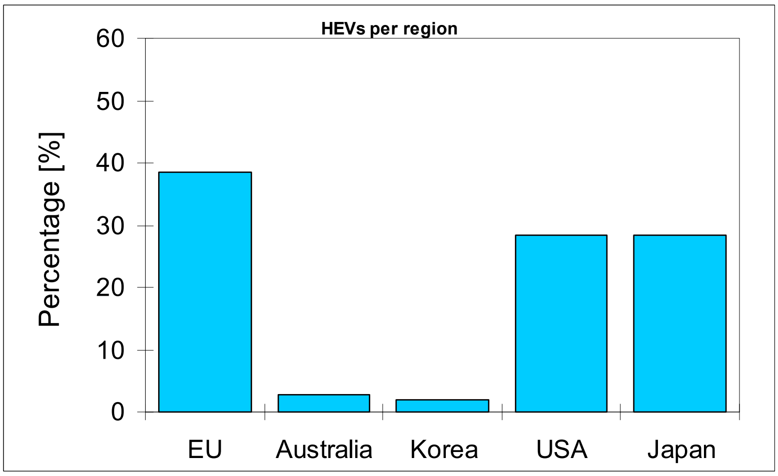

Figure 6.2 Production of HEVs divided per region (based on number of vehicle types), derived from the Annex VII database

Furthermore, the gathering of information from the USA has been limited to the major HEV programs and projects, whereas, besides HEV developments by major European car manufacturers, small European HEV development projects are reflected in these graphs as well.

6.2.1 Selection of applications

Figure 6.3 shows the vehicle types on which HEV developments are focused. By far the most R&D effort is put into light duty passenger car applications, followed by heavy duty vehicles (trucks and buses). However, considering the worldwide production amounts of passenger cars and buses/trucks, the relative share of hybrid research and developments in the last group is bigger than in the passenger car category. This could be correlated with the relative ease to convert conventional buses/trucks into hybrids compared to passenger cars.

Other types of vehicles (both light- and heavy duty) are clearly in minority as far as research and development is concerned.

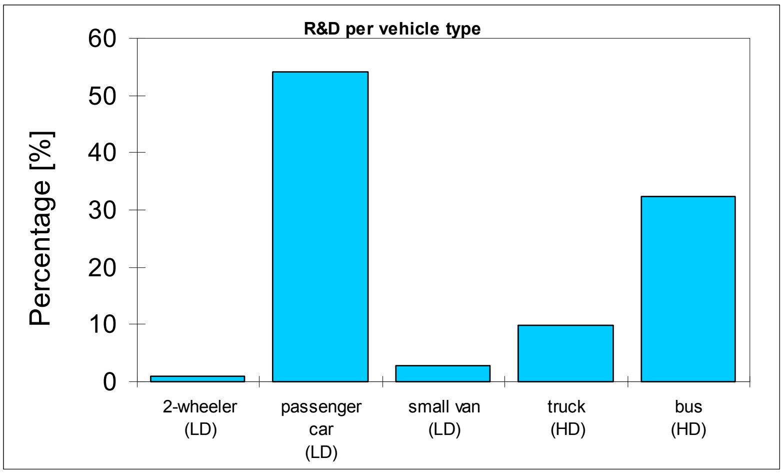

Figure 6.3 HEV research and development activities per vehicle category (based on number of vehicle types), derived from the Annex VII database

6.2.2 Selection of component technologies

Figure 6.4 depicts the types of components used within the HEVs for which information has been collected in the Annex VII database. Note that the amount of electric motors should be equal to the amount of internal combustion engines and gasturbines added up. It can be seen that most hybrids are making use of an internal combustion engine as primary energy converter. Except for the case that a hybrid vehicle makes use of more than one energy storage device (for instance a battery and a supercapacitor), the amount of electric motors should also equal the amount of batteries, flywheels and supercapacitors together. Many hybrid vehicles make use of a generator, although in some cases this function is accounted for by the electric motor itself, in that case acting both as a generator and as electric motor.

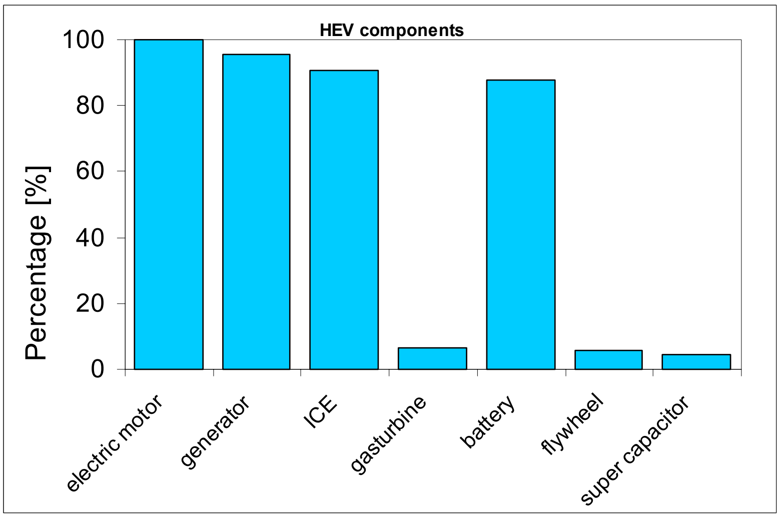

Figure 6.4 Components used in HEVs developed worldwide (based on number of vehicle types), derived from the Annex VII database

In Figure 6.5, the distribution is given of the HEV propulsion system types, based on the number of vehicles which are taken up in the Annex VII database. Most HEVs developed so far are equipped with a series or parallel hybrid powertrain, whereas the technically more complicated combined HEV configuration is clearly a minority. However, if one would weight the distribution over the actual production volumes, the combined HEV would obviously outnumber the other two configurations, because of the large production volume of the Toyota Prius (over 55,000 at the beginning of the year 2001). As the production volume of hybrid vehicles equipped with engine assist systems (as e.g. the Honda Insight) is expected to grow rapidly in the near future, the parallel HEV will most likely become more popular.

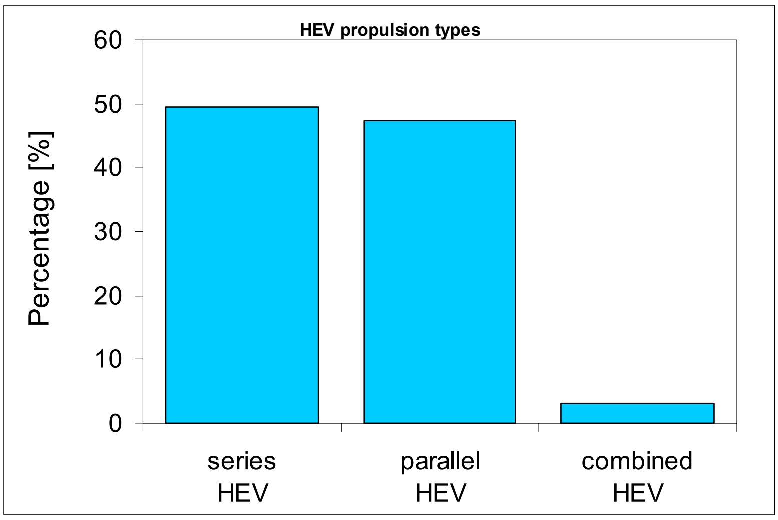

Figure 6.5 HEV propulsion types worldwide (based on number of vehicle types), derived from the Annex VII database

In Figure 6.5 both Light Duty and Heavy Duty vehicles are presented in the same figure. There is however a big difference between these two. When these categories are separated the Light Duty HEV propulsion types presented in Figure 6.6 show that most of these vehicles are equipped with a parallel hybrid powertrain.

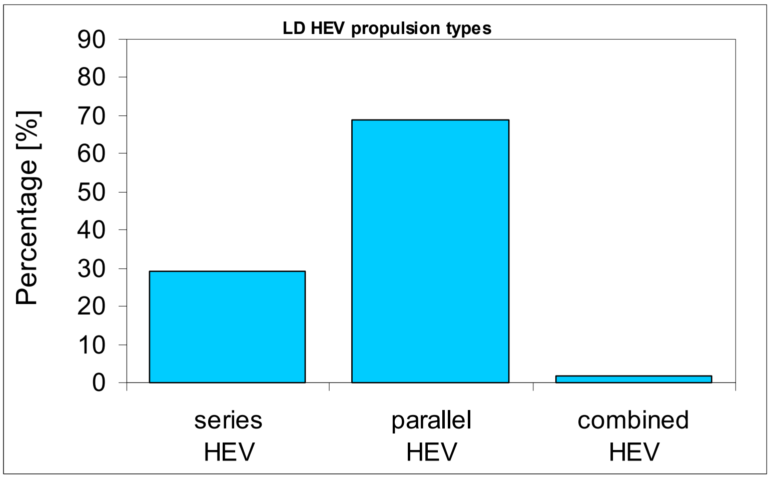

Figure 6.6 Light Duty HEV propulsion types worldwide (based on number of vehicle types), derived from the Annex VII database

The Heavy Duty HEV propulsion types presented in Figure 6.7 show that most of these vehicles are equipped with a series hybrid powertrain. Most of these Heavy Duty series hybrid vehicles are buses (see Figure 6.3).

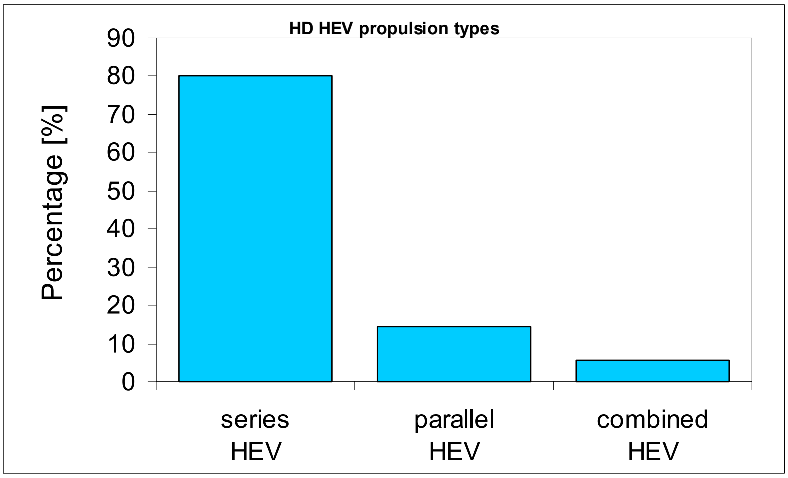

Figure 6.7 Heavy Duty HEV propulsion types worldwide (based on number of vehicle types), derived from the Annex VII database

The contradiction between the distribution of Light Duty HEV propulsion systems as reflected in Figure 6.6 and the actual (or expected near future) production amounts of hybrid vehicles with different HEV propulsion systems can possibly be ascribed to the changing insights concerning the use of the various hybrid configurations. When Toyota developed its Prius some years ago, hybrid research still largely focussed on the series hybrid approach. This configuration seemed most elegant and most promising because of the drastic uncoupling of road and engine load. Designing a series hybrid to meet the performance standards of modern passenger cars, however, was found possible only at high costs and at the expense of emissions and fuel economy benefits. Toyota's combined hybrid approach was from a technical point of view more complex and more advanced than most of the series or parallel HEV approaches attempted to that date. After the commercial launch of the Toyota Prius in Japan, no other passenger car manufacturer seemed to be able to cope with the technical progressiveness of the Prius in terms of mass production. However, with the arrival of the engine assist systems (falling into the parallel hybrid category), car manufacturers have been given a relatively cheap way to introduce hybrid vehicles. The share of parallel and combined hybrids is therefore expected to increase even further.

6.3 Market introduction and mass production

In the 30 days following the launch in December 1997 of the Toyota Prius in Japan, Toyota received about 3,500 orders for this vehicle. This amount appeared to be even more than the marketeers within Toyota had expected. In 2000 Toyota has sold about 12,511 Priuses totaling 45,730 Priuses in Japan by the end of 2000. Toyota even had to stop selling the Prius for some time in 1998 as the amount of orders surmounted the production capacity of about 2,000 a month. Although the commercial viability of the Toyota Prius is still questionable (no body knows exactly how much money Toyota is loosing on the Prius), the sales success of the Toyota Prius in Japan has been inspiring other car manufacturers in thinking even more seriously about a commercially produced hybrid vehicle. This is further encouraged by Toyota's development of a version of the Prius specifically for the European and US market. Halfway the year 2000 this model has been launched in Europe and the US. Specific countries are listed in Table 6.1.

Table 6.1 Countries where the Toyota Prius was available in 2000

Continent	*Country*		*Continent*	*Country*
North America	USA (excluding Guam)		Europe	Germany
	Canada			France
Asia	Japan			U.K.
				Italy
				Spain
				Netherlands
				Belgium
				Portugal
				Ireland
				Sweden
				Austria
				Switzerland
				Norway

In 2000 Toyota has exported 9,927 Priuses of which 5,562 were sold in the USA. The Prius production in 2000 was 20,875 vehicles totaling 57,291 vehicles by the end of 2000 since production started in 1997. In France Toyota sold 75 Priuses by the end of may 2001. Toyota plans to sell 20,000 Priuses per year in North America and Europe, of which 12,000 in the USA.

In the last two decades nearly every car manufacturer has been involved in hybrid vehicle development activities of some sort. These activities have resulted in quite a number of prototypes, in varying states of technical progressiveness, from concept cars to pre-commercial vehicles. So far, however, apart from the Toyota Prius, the Honda Insight and to a lesser extent the Nissan Tino Hybrid, no hybrid electric light duty vehicle has been sold on a commercial basis in significant amounts.

With the start of the new millennium the Honda Insight has been introduced on markets outside Japan. The Honda Insight is sold on de US market since the beginning of the year 2000, and Honda has started the introduction of the Insight in some European countries as well. Currently, within Europe the Honda is sold in the UK only.

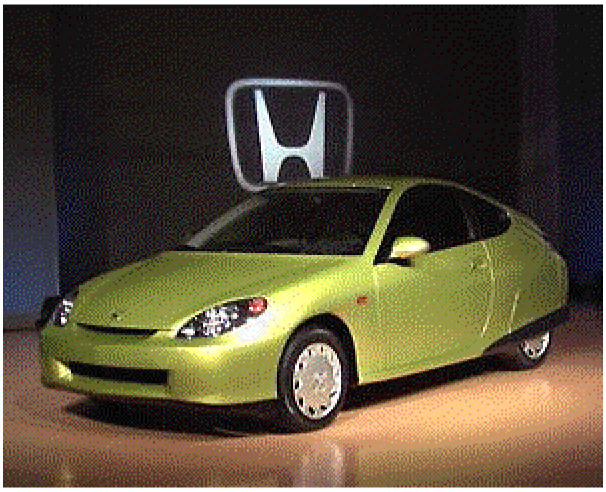

Figure 6.8 Honda Insight

Furthermore, in Europe the launch of the Fiat Multipla Ibrida has been announced since 1999. It is not sure whether this vehicle will actually appear on the market. Since its presentation no visible steps towards market introduction have been taken. The vehicle seems technically prepared for market introduction as it uses many mass produced components, but other motives are apparently discouraging the Fiat management from actually going ahead with the introduction process.

Figure 6.9 Fiat Multipla Ibrida

In the USA the "Big Three" have announced the commercial introduction of hybrid SUVs (Sport Utility Vehicles) by the year 2003. Fuel economy improvements of a factor 2 are claimed for these heavy vehicles. It seems that in the USA this market segment is considered the most attractive for early introduction of HEVs.

Concluding it can be stated that today the Toyota Prius and the Honda Insight are the only hybrid electric passenger cars that are sold on a commercial base and -especially in case of the Prius- in considerable amounts (about 2000 per month in case of the Prius and about 500 per month in case of the Insight). However, the situation nowadays differs from 1997, the year of the launch of the Prius, in the sense that the chances that other car manufacturers will release a commercial HEV have grown considerably due to the selling success of the Prius in Japan. Already several manufacturers have stated their intention to build and sell hybrid electric vehicles in both Europe, Japan and the US. Although the technical progressiveness of some of these vehicles may be less than that of the Prius, the interest in building HEVs in mass-production seems increasing, although the selling initiatives will also depend on the tax regulations and incentives within the different countries.

Literature

1. FT Automotive Environment analysis, issue 37, February 1998, page 7
2. FT Automotive Environment analysis, issue 39, April 1998, page 9
3. http://www.calstart.com/

6.4 Analysis of the trend from charge depleting to charge sustaining hybrids

Topic Report

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Charge-sustaining hybrids are also referred to as non-grid-connected or non-plug-in hybrids. This means that the vehicle can not be connected to the grid for recharging, but all electricity consumed is generated on-board by an internal combustion engine (ICE), or possibly by another energy converter, e.g. from gasoline. The batteries are recharged only by the on-board ICE and by capturing energy during braking (regeneration). Typically these vehicles use specific high power batteries, which are capable of storing a relatively small amount of energy, but can deliver high peak power.

6.4.1 Charge-depleting hybrids

Charge-depleting hybrids are also referred to as grid-connected or plug-in hybrids. In this case the batteries can be (and mainly are) recharged from the grid. Usually, they can also be partly recharged by an internal combustion engine and through regenerative braking. These vehicles are often derived from pure electric vehicles and are equipped with batteries with high energy-storage capacity. They can also be considered as electric vehicles with a range extender.

6.4.2 Is there a trend towards charge sustaining hybrids?

The first mass production hybrid vehicle on the commercial market, the Toyota Prius, cannot be recharged from the grid. A Toyota News Release on the World Wide Web dated on July 14, 1998 states as follows: “Because of the system's design, Prius is capable of recharging its battery by routing power from the gasoline engine to an on-board electric generator and never needs to be plugged in.”

The first hybrid vehicle in the US market is the Honda Insight. Honda calls the propulsion system “Integrated Motor Assist” (IMA). Also in the case of this vehicle no external power supply is needed for recharging.

The hybrid vehicle data stored on the Annex VII database contains information about over 75 light-duty hybrid vehicles. Most of these are concept cars or prototype vehicles with only a few being at commercial stage. Most of the newer ones feature charge-sustaining systems. It looks like there is a trend towards the charge-sustaining configuration in many markets. However, at least some of the European car manufacturers seem to have activities also in the field of charge-depleting hybrids.

Besides other factors that will be discussed later in this paper, the trend towards the charge-sustaining configuration may be due to the fact that the vehicle manufacturers want to distinguish hybrids from battery electric vehicles (BEV). This is because many consumers consider the relatively short range of BEVs as unacceptable, and the manufacturers want to indicate that range is not a problem that should be associated with charge-sustaining hybrids.

Currently there is a strong focus on engine-assist like systems as the IMA of the Honda Insight, which is a clear first example of such a vehicle. Other OEM's, such as for instance Ford has also announced to sell engine-assist SUV vehicles in 2004 (Ford explorer). These vehicles could be seen as a 'transition' from conventional vehicles to 'real' hybrids. Technically, engine assist vehicles are not as complicated as real hybrids and the additional costs seem (having reasonable production amounts) limited compared to conventional vehicles. Moreover, customers do not need to be 'instructed' to drive such vehicles: the way of using these vehicles is nearly the same as driving conventional vehicles.

6.4.3 Sustaining or depleting - different stakeholders have different points of view

Vehicle manufacturers

The car manufacturers are naturally very concerned about their product liability and warranty costs. They want to take every possible effort to make things work as reliably as possible to avoid loss of reputation, costly repairs or part replacements. They are especially concerned about recalls, because in those cases they would have to fix every single vehicle of a certain batch manufactured.

In the case of electric vehicles, including hybrids, the batteries contribute to a great amount of the total cost of the vehicle, especially, if the battery pack is large or if the batteries are of an advanced technology type. Having to replace the batteries of a great number of vehicles under warranty would be a nightmare for any vehicle manufacturer.

One possible way to ruin the batteries is to recharge them improperly. If the end-user of the vehicle is the one who controls the recharging process, there always is the possibility that the batteries will not be handled properly. This makes the charge-depleting option somewhat unwanted in the manufacturers' eyes. In other words, the manufacturers want to be in control of the way the batteries are being recharged. This desire can be fulfilled best in the case of charge-sustaining hybrids, because the control strategy of the recharging process is completely designed by the manufacturer, programmed in the computer system of the vehicle, and the end-user can not tamper with it.

Utility companies

The business of the utility companies is to sell electricity. Their interest is to try to enhance the use of electricity in all functions of the modern society. They see the electric vehicle market as a completely new segment of business. Their vision is to be able to see a significant drift from conventional fuels to the use of electricity in the transportation sector. From this development, the utility business strives to get new revenues that have until now been directed to the oil industry.

The charge-depleting hybrids use electricity from the grid. In the case of these vehicles, the party who gets paid for the energy consumed is the utilities, not the oil companies. Because of this, the utilities' wish in many cases is to go for the charge-depleting option. The utilities willingly point out the advantages of this configuration.

6.4.4 Charge sustaining hybrids - reasons behind current development

In the case of a charge-sustaining hybrid vehicle, the operator can refuel the vehicle just as any other car. He or she does not even need to know that the vehicle is powered by a hybrid propulsion system. This is a marketing advantage in many regions, because most of the customers usually are more or less not technically oriented and want to use a new vehicle like other vehicles they have operated previously. A vehicle that should be plugged in for recharging would seem less familiar to those customers.

This advantage of the charge-sustaining hybrid perfectly matches the trend that can be seen in present commercial cars and prototypes displayed at auto shows. Service intervals are becoming longer, and vehicle users need and are able to do less for the regular check-up and maintenance of the vehicle. In some recent prototypes, the manufacturers have actually made it impossible for the user to open the hood to gain access to the engine. Instead, behind the grill there is only a small panel with a set of filler ports that allow the user to fill up e.g. brake fluid, windshield-wiper fluid and coolant.

Another benefit of the charge-sustaining option is that there is no need for time-consuming slow charging, neither the need for infrastructure for special fast charging. Also, there is no fear for electric shock, which sometimes is, at least in some customers' minds, related to powerful fast charging systems.

Because there are no common standards for recharging, finding suitable recharging locations away from home, workplace or depot can be difficult for one particular vehicle type. This problem is eliminated with non-plug-in type of vehicles.

Independence of the electric grid is an advantage in some geographical areas, where people can have remote vacation homes or other places to spend their leisure time, where there is no grid available.

On-board charging provides the driver also with a feeling of certainty about the available range, because gauges for liquid fuels are generally more accurate than the battery state-of-charge (SOC) indicators.

The charge-sustaining systems have generally no range problems. Because the ICE is used for power generation, it can be operated at its optimal operating range in terms of efficiency.

The weight and volume needed to store energy on-board a vehicle are at the lowest in the case of vehicles powered with conventional liquid fuels. This means higher fuel efficiency and more payload space in a vehicle. It also means ease of storing the energy (low-cost fuels tanks) and ease of refueling.

The ICE-based on-board charging system enables the use of small, specifically designed high power batteries, which leads to lower vehicle mass and lower energy consumption. It also decreases the problems related to the possible limited worldwide capacity to manufacture enough batteries to fulfill the demand.

Smaller battery pack of a charge-sustaining vehicle means lower battery costs than in the case of the charge-depleting configuration. The charge-sustaining system needs a more powerful combustion engine, though, but still the total cost of a vehicle is lower compared to a charge-depleting hybrid, because engines are less expensive than batteries.

One possibility related to charge-sustaining hybrids is that they could be used to generate electric power for use outside of the vehicle itself. This could be useful in remote areas that the grid does not reach, because in many cases it is too expensive to have power lines built up for just a few houses. This kind of local power generation could be utilized also at vacation homes and campgrounds.

Market Area Related Issues

USA

Most BEVs on the US market (if there are any left) have no on-board charger due to the will to save manufacturing costs and both space and weight on the vehicle. They have to be recharged with an external charger (slow or fast). The low voltage level (110 V) makes it impossible to fast-charge BEVs by just plugging into a household outlet. Hence, to meet the customers needs regarding charging time, special fast charging stations utilizing higher voltage have to be built, if there is a desire to expand the use of charge-depleting or pure battery electric vehicles.

The need for a special charging station does not apply for charge-sustaining hybrid vehicles. This gives the operators of these vehicles the freedom from having to ponder where to have the vehicle recharged. This means also that if charge-sustaining hybrids were utilized instead of BEVs, there would be no need to build the recharging infrastructure.

The low taxation on conventional liquid fuels in the US makes it very alluring to use hybrids to generate the electricity on-board with an ICE. The cost per kilometer or mile would stay low. Another advantage is that gasoline is abundantly available everywhere.

Most of the customers in the USA are not willing to change their driving related habits. They do not want to know about the details under the hood, either. In this regard, the use of a charge-sustaining hybrid would be an ideal solution, because it would free the customers from having to change habits or putting any special thinking on how to operate the vehicle.

All new types of industrial products create liability concerns for the manufacturer, because the compensations that may have to be paid may be of gigantic magnitude, when someone dies or hurts himself or herself when using a technical product. In the case of recharging a vehicle from the grid, there is a danger of accidents because ignorant and reckless vehicle users always exist. A charge-sustaining vehicle lowers the manufacturer’s risk in this respect, because the risks, which inevitably exist also when carrying gasoline in a vehicle, seem to be commonly accepted.

Japan

Like in the case of the US, low household voltage makes it unfeasible to charge vehicles at homes. Home charging would need a completely new infrastructure. It is not easy to build publicly available recharging stations, either, because the country is very densely populated and land space is scarce in all inhabited areas. It would be very difficult and extremely costly to acquire land for recharging stations. Charge-sustaining hybrids eliminate the problems related to both home charging and public recharging stations.

Electricity is fairly expensive in Japan. This makes on-board charging by an ICE more attractive. On the other hand, gasoline is not very cheap, either. Japanese gasoline is of good quality, which lowers the emissions. This fact also enhances the competitiveness of on-board charging by an ICE.

Europe

In Europe, there seems to be more activity around charge-depleting vehicles than in the US or in Japan. One reason might be that in most European countries the liquid fuel prices are fairly high. Because of this, recharging the vehicle from the grid is less expensive for many European vehicle operators. Another reason is probably the 220 V voltage, which makes it easier to recharge the batteries relatively quickly from the grid. Also, the European customers might not be as concerned about having to change some driving related habits as are their American counterparts.

6.4.5 Charge depleting hybrids -another alternative

Charge-depleting hybrids are not beaten in all respects by the charge-sustaining type, but also have advantages over their counterparts. There is no clear winner in this competition, and the decisive factors vary between different types of vehicles, different types of vehicle use and between different markets.

In general, charge-depleting hybrids can be much less dependent on crude oil products. This derives from the fact that electricity can be produced from renewable energy sources. If a charge-depleting vehicle is recharged using electricity produced e.g. by hydro, wind or solar power, there unquestionably is an environmental advantage over on-board charging using an oil-derived product. In cases like this, when the ICE of the charge-depleting hybrid vehicle is switched off, the car could be considered as a real zero or near-zero emission vehicle.

Furthermore, a charge-depleting vehicle, utilizing electricity produced by renewable sources, does not contribute to global warming when driving on electricity, because no CO_2 or other greenhouse gas emissions are produced.

However, electricity can also be produced by less advanced technologies. For example, oil products or coal can be used as energy sources for electricity generation. Especially coal is not considered as an environmental-friendly raw-energy source. In cases like these, the environmental benefits of charge-depleting hybrids are doubtful.

A feasible charge-depleting vehicle, meaning that the range is sufficient, has to have a significantly large battery pack. That will likely result in a considerable cost difference compared to a charge-sustaining vehicle, which works fine with much smaller batteries.

The high weight of the battery pack causes also concern related to crashes. Even if they were mounted very tightly to the frame of the vehicle, they could come loose in crashes and cause excessive injuries. In any case, they will influence dynamics and crash behavior of the vehicle. Also, the rescue people are concerned about how to handle the situation, when an electric vehicle has ended up in an accident.

However, the worries about electric shock and about the safety issue in crashes originate from insufficient knowledge about the technology used and can be eventually diminished by educating the public.

Another thing worth mentioning is that the performance of a charge-depleting vehicle may be affected by the state-of-charge (SOC) of the batteries. When the SOC is low, acceleration could be slower and hill climbing capacity lower than usual. If the operator of the vehicle is aware of these limitations, keeps them in mind and accepts them, they do not constitute a major problem. However, especially for a temporary user of a vehicle, it may be an unpleasant surprise, if the vehicle does not accelerate normally when merging into heavy traffic or driving up a ramp.

In general, charge-depleting vehicles may be seen as an attempt of manufacturers to avoid range problems encountered with BEVs. Thus, charge-depleting hybrids can be considered as electric vehicles incorporating a range extender. One possible market for these vehicles could be like the market for electric delivery vans, which, until now, has been very narrow. These vans have been only in fleet use around city centers utilizing night charging. A charge-depleting hybrid delivery van could run on battery electricity in city centers and switch to hybrid propulsion to extend the range in order to reach outskirts of the city.

Issues related to different market areas

Charge-depleting vehicles can be recharged conveniently e.g. at home or office utilizing hours when the vehicle is not in use. However, sufficient electric voltage (preferably at least 220 V) and current must be available at outdoor outlets, like it is at many homes, offices and parking lots in the Nordic countries (the reason being the use of engine block pre-heaters).

Alternatively, there must be an adequate special recharging infrastructure in place. If the possibility of home or office charging can be utilized in full, there very seldom occurs the need to make stops or drive specific trips or routes to refuel the vehicle. This undoubtedly is a time saving benefit for the vehicle operator. The infrastructure needed for recharging already exists, to some extent, in certain regions. These areas can be found e.g. in California and, as already mentioned, in Northern Europe. It would be reasonable to utilize this potential as much as possible.

The voltage has to be at least 220 V to obtain a short enough recharging time for a charge-depleting vehicle. This constitutes additional infrastructure costs especially in the US and parts of Japan. However, if the society puts emphasis on building the recharging network for hybrids, this would also facilitate the market introduction of pure battery electric vehicles.

In regions where fuel taxes are high (Europe, Japan), it is usually less expensive to use electricity than gasoline to power a vehicle. In many European countries, one liter of gasoline costs over one Euro (or a dollar). Knowing that a liter of gasoline contains about 9 kWh of energy, the cost for gasoline in these countries is in the order of €0.12 per kWh. Electricity price is lower than this in many areas. Moreover, the high efficiency of the electric motor compared to the ICE increases the economical benefit caused by electric propulsion. A charge-depleting hybrid vehicle can utilize the savings caused by both cheap electricity and high efficiency of the electric motor.

Electricity is lower-priced at night than during the day in many areas. These systems are established to promote night-use of electricity in order to make the consumption as stable as possible over each 24-hour period. For a charge-depleting hybrid vehicle owner, this gives an opportunity to lower fuel costs even more by utilizing cheap night-electricity. Additionally, large amounts of vehicles recharging at night would increase the desired load stability for electric power generating plants.

However, some consumers do not like the idea of plugging in the vehicle because of fear of an electric shock. This applies especially in countries, where people are not accustomed to dealing with electric cords outdoors like is the case in regions where engine block heaters are used. People might be worried what happens, if they are standing in a water puddle while plugging in the vehicle. The relevance of this question and the actual risk of an electric shock probably varies from country to country, because the regulations how the electric outlets have to be wired and protected varies in different regions.

6.4.6 Summary

The general trend at least in the US market seems to be towards charge-sustaining hybrids. The two mass-produced commercial hybrid vehicles on the market (Toyota Prius and Honda Insight) are both of charge-sustaining type.

The vehicle manufacturers want to be in control of the recharging strategy of the batteries to avoid possible warranty costs originated by incorrect charging of the batteries by the customer. From their viewpoint, the charge-sustaining option fulfills this desire better. On the other hand, the utility companies want to find new segments in society to sell electricity for. They are lobbying for the charge-depleting option.

For the manufacturers, the critical issue of a vehicle is marketability. In many cases it overrides other factors like energy efficiency or the possibility to utilize renewable energy sources. Because most consumers are happiest when not having to change their driving or refueling habits, charge-sustaining hybrids obviously appear to have the greatest marketing potential.

In many markets, the lack of vehicle recharging infrastructure drives the development towards the charge-sustaining option. It is much easier to find locations to refuel a vehicle with conventional liquid fuels than to find places to recharge it with electricity.

However, charge-depleting hybrids have several advantages over the other alternative. They can be much less dependent on crude oil products, and they can utilize energy from renewable sources. In this case, they contribute less to global warming. Especially in those regions, where gasoline prices are high and electricity price is low, it can be much cheaper to operate charge-depleting type of vehicle. Also, with the charge-depleting configuration, it is relatively easy to create vehicles with a significant zero emission range.

There is no clear winner in the competition between these two alternatives. The decisive factors vary between different types of vehicles, different types of vehicle use and between different market areas. One possibility to combine the advantages of the two types might be a flexible hybrid that would have the capability of both, meaning that it could be recharged either from the grid or by the ICE. However, this might be a costly solution, and the batteries available now would probably not have the characteristics needed for both types of use.

Because hybrid vehicles use two propulsion systems for one vehicle, they are an expensive solution as such. When engineering a hybrid, all possible factors should be utilized to increase the fuel economy in order to justify the higher expenses of the vehicle itself.

Advantages of the charge-sustaining configuration over the charge-depleting option:

1. Can be refueled quickly like any conventional car
2. No need for fast-charging infrastructure
3. No need to use time-consuming slow-charging
4. No need to look for a (specific type of) recharging location
5. No fear of electric shock (no need to be plugged in)
6. Generally no range problems
7. Better information on remaining range: fuel gauge is fairly accurate compared to SOC indicators
8. Lower energy storage need and more room for payload because a liquid fuel tank is smaller and weighs less than batteries for the same range
9. Vehicle (battery pack) is cheaper than in the charge-depleting option
10. Can be used in remote areas where there is no electric grid
11. Can be utilized to generate electric power for use out of the vehicle itself (campgrounds, summer homes etc.)
12. Operating costs low in areas where fuel prices are low and electricity is expensive

Advantages of the charge-depleting configuration over the charge-sustaining option:

1. Less dependant on oil-derived energy sources
2. Possibility to have a real zero-emission range
3. Does not contribute to the global CO_2 balance if renewable energy sources are used for generating the electricity
4. Can be recharged when being parked. No need to make stops for refueling
5. The efficiency of the electric motor is higher than that of the ICE
6. Energy costs are low in areas where electricity is priced low and fuels are expensive
7. Energy costs can be lowered by utilizing even lower-priced night electricity
8. Recharging at night provides desired load stability for electric power plants

6.5 Time paths for development and introduction of fuel cell vehicles and HEVs

The development of fuel cell technology and fuel cell vehicles proceeds faster than expected. In the early 1990s it was generally believed that the fuel cell could eventually replace the internal combustion engine, but a technically mature and commercially viable fuel cell car was thought to be impossible until 2015-2020. In 1999, however, DaimlerChrysler and other manufacturers announced that they would start producing and selling fuel cell electric vehicles by the year 2003. By now various manufacturers have demonstrated generations of fuel cell vehicle prototypes and the progress made in fuel cell system size and weight reduction and in performance has been astonishing. Reaching the technical goals defined by various manufacturers in combination with the cost reductions required for commercialization before 2003, however, still seems a tremendous task.

In order to speed up this process, the California Fuel Cell Partnership was formed. The California Fuel Cell Partnership is a collaboration in which several companies (automobile companies and fuel suppliers) and government entities are independent participants. These participants will join together to demonstrate fuel cell vehicles under real day-to-day driving conditions. The California Fuel Cell Partnership will place about 70 fuel cell passenger cars and fuel cell buses on the road between 2000 and 2003. In addition to testing the fuel cell vehicles, the Partnership will also identify fuel infrastructure issues and prepare the California market for this new technology.

Specifically, the Partnership seeks to achieve four main goals:

1. Demonstrate vehicle technology by operating and testing the vehicles under real-world conditions in California;
2. Demonstrate the viability of alternative fuel infrastructure technology, including hydrogen and methanol stations;
3. Explore the path to commercialization, from identifying potential problems to developing solutions; and
4. Increase public awareness and enhance opinion about fuel cell electric vehicles, preparing the market for commercialization.

The rapid pace of fuel cell development could have a big influence on manufacturers' commitment to the development of other alternatives such as hybrid-electric vehicles. Manufacturers may not be willing to invest large amounts of money in the development of components or systems which might be outdated in just ten years time, like for example a dedicated IC engine for use in hybrid applications.

At the time Toyota introduced the Prius to the market, it was obvious that all other manufacturers would not be able to catch up technically with Toyota within a few years. The earliest reasonable time frame for mass introduction of hybrids by American and European manufacturers therefore coincides with the claimed date for the first market introduction of fuel cell vehicles. Developing both hybrid vehicle and fuel cell vehicle technology in the R&D and prototype stage seems feasible for most large manufacturers. That they would also set up production facilities and sell significant numbers of both vehicle types at the same time, however, seems a less probable scenario. This either calls for choices or cooperation with other manufacturers.

6.5.1 Development strategies

If you can't beat them, join them. On the 19th of April 1999 General Motors Corp. and Toyota announced a partnership to cooperate on electric, hybrid-electric and fuel cell vehicles. Both hinted they might eventually build such vehicles together. As stated before, Toyota is the world leader in hybrid vehicle technology and is known to be skeptical about the short-term chances for automotive fuel cell applications.

DaimlerChrysler has stopped the development of both the hybrid-electric Smart microcar and the hybrid-electric and battery electric Mercedes-Benz A-class. There could be various reasons for this termination, such as the limited success of the Smart. DaimlerChrysler's partner in the Smart project, Swiss watchmaker Swatch, disagreed with the canceling of the hybrid Smart. This disagreement eventually led to DaimlerChrysler buying out its partner. Meanwhile, through the dbb partnership DaimlerChrysler achieved a world leading position in the development of fuel cell vehicles, with well-known prototypes like the NeCars I, II, III and IV. It may be the case that DaimlerChrysler is focussing more on the introduction of fuel cell vehicles, rather than launching hybrids on a short term. On the other hand, Daimler's partner Chrysler still continues its effort within the PNGV-project for developing a fuel efficient hybrid electric vehicle. Also Daimler itself is developing a combined hybrid configuration for its large Mercedes cars (S-class). Although Daimler has only brought out a single prototype of the hybrid S-class, it does indicate that Daimler is still interested in hybrid technology.

In Table 6.2 a small overview has been given of some recent fuel cell vehicles (test- and prototype stadium). The Ballard company plays a key role in this development by delivering fuel cell systems for most of the fuel cell vehicles listed. In this list of developers Toyota and Renault are researching both hybrid electric and (hybrid) fuel cell vehicles extensively. Other companies in this list seem to focus more specifically on fuel cell vehicles and limit the R&D on hybrid electric vehicles.

Table 6.2 Key demonstrations of fuel cell powered vehicles. Source: Scientific American / TNO Automotive

Date	*Developer*	*Vehicle*	*Technology*	*Fuel, range*
1990 (operational since 4/94)	H Power, Georgetown University, US Government	Three 9.1 meter buses	50 kW Fuji Electric, phosphoric acid *	Reformed methanol (RM) supplies hydrogen
1991 (operational since 2/93)	Ballard Power Systems	9.8 meter bus	120 kW Ballard Mk 5, PEM	Compressed hydrogen (CH)
Oct. 1993	Energy Partners	'Green Car' sports car	15 kW, PEM	CH, 100 km
April 1994	Daimler-Benz	Necar (V-class)	60 kW, Ballard Mk 5, PEM	CH
May 1996	Daimler-Benz	Necar 2 (A-class)	50 kW, Ballard Mk 7, PEM	CH, 250 km
Sept. 1997	Daimler-Benz	Necar 3 (A-class)	50 kW, Ballard Mk 7, PEM	RM, 400 km
July 1998	Daimler-Benz	Necar 4 (A-class)	50 kW, Ballard Mk 7, PEM	Liquid H2 (LH), 400 km
1994 – 1997	Ballard	Six 12.2 buses	205 kW, Ballard Mk6, PEM	CH
Nov. 1996	Toyota	RAV4	10 kW, PEM*	H2 in metal hydride (MH), 250 km
Sept. 1997	Toyota	RAV4	25 kW, PEM*	RM, 500 km
May 1997	Daimler-Benz	Nebus 12 meter O 405N	190 kW Ballard, PEM	CH, 250 km
Aug. 1997	Renault	Laguna	30 kW, De Nora, PEM	LH, 500 km
Dec. 1997	Mazda	Demio	25 kW, PEM*	MH, 170 km
May 1998	Georgetown University, Nova bus, US DoT	12 meter bus	100 kW, International Fuel Cells, phosphoric acid *	RM, 550 km
July 1998	Zevco	Millennium London taxi	5 kW, alkaline*	CH, 150 km
Oct. 1998	Opel (GM)	Zafira	50 kW, PEM*	RM
	PSA (Hydro-Gen project)	Berlingo	30 kW fuel cell and 20 kW NiMH battery	H2, 300 km
	GM	EV1 Fuel Cell	102 kW 3 phase AC induction electric motor	Methanol
	Ford	P2000 FCEV	67 kW	H2
	Ford	P2000 SUV		Methanol
	Ford	P2000 FC5	PEMFC (Ballard)	
	Honda	FCX-V1	60 kW PEFC Ballard fuel cell	H2
	Honda	FCX-V2	60 kW PEFC Honda fuel cell	Methanol
	Nissan	Altra FCV	30 kW PEM-FC	Methanol

* Hybrid system including battery or other storage device

6.5.2 Market introduction strategies

Besides the technical feasibility and economical viability of the fuel cell vehicle and the hybrid vehicle, also the infrastructure and marketing aspects need to be taken into account. On both these aspects hybrid vehicles may have an advantage over fuel cell vehicles in the 2005 – 2015 time frame.

It is clear that (charge sustaining) hybrids will not require a new fuel infrastructure. Fuel cell vehicles with reformers may also be able to operate on conventional fuels, but at the expense of a cost increase and efficiency decrease on the vehicle side. Fuel cell vehicles on hydrogen require large investments in fuel infrastructure so that it may be expected that in the early stages of introduction hydrogen will not be available everywhere. This of course limits the use of the vehicles. Also, dependent on the hydrogen storage technology applied, the refueling time will be longer than with conventional fuels.

In terms of marketing, hybrid systems, and especially engine assists, can be introduced as more or less incremental improvements to the conventional car to meet future emission standards or to contribute to reaching fuel efficiency goals set out in government directives (e.g. CAFE) or in covenants between government and industry (e.g. between EU and European manufacturers). Depending on the technical choices made the cost implications may be limited.

Fuel cell vehicles will have two marketing problems in the 2005 – 2015 time frame: They will be much cleaner than what is required by future emission standards (e.g. EURO 4), but the fuel efficiency improvements attainable in the mentioned time frame are not yet evident. Vehicles on hydrogen are very efficient on the vehicle level, but the energy chain that produces hydrogen will have significant energy losses and will for long time still be based on conventional energy sources. On the other hand fuel cell vehicles with a reformer will not easily defeat conventional or power assist vehicles with direct injection diesel engines in terms of fuel economy. The question therefore is whether consumers are willing to pay for such a clean vehicle, when there is no significant reduction of fuel costs to balance the increased vehicle costs.

However, the successful market introduction of hybrids may also have benefits for the introduction of fuel cell vehicles at a later stage. On the one hand they may reduce component costs that are also relevant for fuel cell vehicles, and on the other hand they may help to “warm up” the consumer for the new technologies that are to come.

6.5.2.1 Series hybrids
The incompatibility between fuel cell and hybrid electric vehicle development and introduction, as described in the introduction, becomes less apparent when one looks at series-hybrid arrangements. Components developed for series hybrids can also be used in fuel cell vehicles. It is relatively easy to convert an ICE powered series electric-hybrid vehicle into a fuel cell vehicle. This is especially interesting for heavy-duty vehicles since the life span of such model lines is usually longer then for light duty vehicles. Mercedes-Benz introduced the Cito city-bus a few years ago with a diesel-electric drivetrain. Mercedes says that this configuration should not be seen as their final solution but as a ‘stepping stone’ on the way to fuel cell propulsion. The Cito enables Mercedes to field-test drivetrain components like electric motors, batteries and control strategies. Experiences made with the Cito will be incorporated in the fuel cell bus ‘Citaro’ that will be built in limited amounts (about 30) in Europe by 2002. Among others Iveco and Volvo have also built series-hybrid buses.

6.5.2.2 Engine assists
Another way to cope with the choice between developing a completely new dedicated HEV powertrain or to focus entirely on fuel cell vehicles is to develop hybrid electric vehicles that make use of relatively many standard components. The HEVs that are equipped with an engine assist (see section 2.3 and 3.2.4) are examples of this philosophy. Several car and component manufacturers are working on such systems. The first commercial example in this category is the Honda Insight. It is

possible to view engine assist vehicles as a relatively cheap way to introduce hybrid electric technology and to accustom consumers to the concept of hybrid vehicles in particular or vehicles with advanced powertrains in general. In fact, engine-assist or starter-alternator vehicles can be marketed as advanced conventional vehicles offering various user benefits when the advantages of e.g. having a high voltage level are utilized.

6.5.3 Different views

It remains to be seen whether the fuel cell will live up to the expectations, especially for the short term. If problems concerning fuel choice, fuel infrastructure, consumer acceptance, reformer size, starting time, fuel efficiency, cost effectiveness and safety can not be solved adequately then the fuel cell might either be delayed or find a place in history next to the gas turbine and the Wankel engine.

Mr. Wada, Toyota's executive vice-president, has said that he does not expect more than a small market for automotive fuel cells before 2010-2020, despite the fact that Toyota has built working fuel cell prototypes. If he is right, then the Prius and its descendants, perhaps also built by GM, could have a bright (near) future ahead of them. On the other hand Mr. Panik, DaimlerChrysler's director of fuel cell development, has said that fuel cell cars can be produced for competitive prices in 2004. DaimlerChrysler has recently teamed up with Ford for the development of fuel cell vehicles. DaimlerChrysler & Ford and Toyota & General Motors both account for approximately 25 percent of the world's car and truck production. All manufacturers need to take important strategic decisions; the ones that make a mistake can see their competitiveness being seriously reduced in a few years time.

6.5.4 Conclusions

Manufacturers need to divide their limited development resources between hybrid-electric and fuel cell vehicles. Toyota, a big global player that already has a working hybrid-electric technology, says that fuel cells won't become a serious alternative in the near future. DaimlerChrysler on the other hand has cancelled most of its development work on (parallel-) hybrids and is concentrating on increasing its leading position in fuel cell development. One way to cope with R&D on both hybrid technology and fuel cells is to regard the introduction stages as a continuum: hybrid technology within the near future and fuel cell technology for the long term. As R&D on hybrid technology is partly overlapping with fuel cell vehicle R&D, this seems to give manufacturers opportunities to use spin-off of hybrid vehicle research for fuel cell vehicle development. Furthermore, joint ventures or mergers between OEMs (for example DaimlerChrysler) offer the ability to finance profound efforts on both hybrid and fuel cell research at the same time. Other companies, on the other hand, seem more reluctant to invest large amounts of money in dedicated technology for hybrid-electric and fuel cell vehicles. Instead, they construct hybrids with relatively many standard components to meet the increasingly stringent consumption and pollution emission standards and await the market demands for innovative technologies within the (near) future.

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