Hybrid Electric Vehicles

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** A hybrid electrical vehicle (HEV) is a vehicle equipped with either an internal combustion engine (ICE) and an electrical motor powered by electrical batteries. In 1997, Toyota sold in Japan the first modern hybrid electric car, the Toyota Prius. Today's HEVs are an emerging technology in the automotive market, with manufacturers designing and producing hybrid systems for passenger cars, light-duty vehicles, heavy duty vehicles, and even locomotives. The improved efficiency of HEVs over conventional (i.e. non-hybrid) vehicle is achieved by operating a smaller (more efficient) ICE within a narrower, more efficient operational speed/power band and using an electric engine and electrical storage (i.e. the battery) to balance the performance energy requirements. In general, in the current-generation HEVs, the combustion engine provides the main power during long-distance drive while the electrical motor can either complement the ICE or power the vehicle in electric-only mode (as long as energy is available from the battery) during the urban service, where the ICE is less efficient. The battery charge is provided by regenerative braking and excess energy from the ICE (stored when the vehicle has lower power requirements). There are however different grades of hybridization and many configurations of hybrid vehicles, including micro, mild, full hybrids, with different role for the electric motor. Currently, only hybrids combining a petrol or diesel combustion engine with an electric motor are commercially available. Improving battery capacity and technology may enable longer electric drive range and reduce the need for the ICE contribution. New-generation HEVs include batteries rechargeable from the grid (known as plug-in hybrid electrical vehicles, PHEVs, see also ETSAP TB05).

■ **PERFORMANCE AND COSTS –** The hybrid vehicles can benefit from the best features of both conventional ICE vehicles and electric vehicles. Hybrids offer drive range and rapid refuelling the same as conventional vehicles, and provide high efficiency at low loads, potentially better acceleration, environmental benefits and 25-40% CO_2 emissions saving as compared to conventional vehicles [1]. The HEVs cost however is higher. This is largely due to the high price of the battery. Currently most hybrids use NiMH battery packs, although Lithium-ion is the most promising battery technology for the future. Li-ion offers better performance and much greater power density (gravimetric 120+ Wh/kg, volumetric 300 Wh/litre), compared to NiMH (~70 Wh/kg and 150+ Wh/litre respectively). Smaller and lighter battery packs are therefore possible with Li-ion (around half the size/weight of NiMH). However, further developments are needed to improve capacity and lifetime, reduce volume and costs (currently around €250-€500/kWh for NiMH and €700-€1,400/kWh for Li-ion), and to be abuse-tolerant, safe and reliable.

■ **POTENTIAL AND BARRIERS –** Costs and technical bottlenecks still restrain the full deployment of both hybrid and full electrical vehicles. Various countries such as the US, Spain and Japan have set ambitious targets for the future deployment of hybrids. These targets form a major component of national and international policies for tackling climate change. In particular, Europe is subject to an array of regulations that restrict the emissions of the automotive sector and it is anticipated that HEVs will benefit. The future deployment of hybrid vehicles essentially depends upon substantial improvements in battery technology, electric motors and power electronics. Of particular importance is battery cost reduction as the single largest incremental cost component over conventional ICEs. Word-wide sales of hybrid vehicles currently account for less than 1% of all vehicle sales. However, recent research has suggested that the annual uptake of hybrid vehicles could increase by 20% in the next few years, with as much as 13% of global vehicle sales being hybrids by 2020 (and almost 20% of sales in the US).

TECHNOLOGY STATUS AND PERFORMANCE - The first hybrid electric vehicles (HEVs) were sold in Japan in 1997 and two years later in the United States. It has taken more than ten years for HEVs to achieve 1% of the global car market, and 2.5% of the US market [3]. Nowadays, several producers offer new generations HEVs. This is largely due to the advances made in battery technology. Hybrid electric vehicles (HEVs) are powered by the combination of a conventional petrol or diesel internal combustion engine (ICE) and an electric motor with battery storage charged by regenerative braking and excess energy from the ICE (available when the vehicle has lower power requirements). There are a wide range of possible configurations for an HEV, depending on the role and capability of the battery and the electric motor. ■ **Micro Hybrids -** This technology has a starter-generator system coupled to a conventional engine. An electric motor provides stop-start operation of the engine, plus (usually) regenerative braking to charge the battery. The electric motor does not supply additional torque when the engine is running, and the cost of this type of hybrid is comparatively low due to the use of conventional batteries and drivelines. Compared to conventional vehicles, micro hybrids return fuel savings of up to 10% in city driving [1]. They are currently only found on light vehicles, and are most suited to urban applications where they can benefit from duty cycle [6]. ■ **Mild Hybrids** - An electric motor is

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still not a sole source of driving power, but provides supplementary torque to the internal combustion engine when peak power is needed. Like a micro-hybrid, the system also features start/stop technology and regenerative breaking. Most current HEVs are mild hybrids [13]; the Honda Civic Hybrid is an example. Mild hybrids provide a 10-20% fuel efficiency gain [1]. ■ **Full Hybrids** - For short periods the electric motor can be used as the sole source of propulsion for the vehicle. For this reason full HEVs require larger capacity batteries and larger electric motors than other hybrid vehicles. Full hybrids have the ability to deliver 25-40% better fuel efficiency than conventional vehicles [1]. An example of a full hybrid is the Toyota Prius, which can operate in electric-only mode. ■ **Plug-in Hybrid Electric Vehicles (PHEV)**, or range extended hybrids (RE-HEV), are hybrid vehicles that can be plugged into the national grid to recharge batteries. Their battery is smaller than those installed in pure battery electric vehicles (BEV), therefore they require a conventional petrol or diesel engine to extend their range, yet larger batteries than other hybrid electric vehicles. PHEVs could provide a 40-55% improvement in fuel economy [1] (see ETSAP TB05).

Hybrid vehicles can also be defined on the basis of their drivetrain structure. ■ **Series Hybrids** – Series HEVs are battery electric vehicles that have support from a small ICE. The ICE drives an alternator which generates electricity. This then flows to the electric motor or a battery, and thus only the electric motor propels the vehicle [2]. The absence of a mechanical link between the combustion engine and the wheels enables the engine to run at a more constant and efficient rate than other hybrids. ■ **Parallel Hybrids** – In 'parallel' HEVs, both an electric motor and the ICE can generate the power to directly drive the wheels [2]. The electric motor cuts in and independently powers the vehicle at lower speeds, and can increase the power available to the small ICE. Parallel hybrids rely heavily on regenerative braking to keep the battery recharged as they can use a smaller battery pack than series hybrids. ■ **Series-Parallel Hybrids** - This type of vehicle can operate as a series or parallel hybrid. This allows the ICE to drive the wheels directly when at high speeds, as a parallel hybrid would do, whilst at lower speeds the engine can be disconnected from the wheels that are powered by the electric motor only. The dual drivetrain enables the vehicle to run efficiently as it operates differently on user demand [2]. However, the need for a generator, large battery pack and complex computer control system makes these hybrids more expensive than pure parallel hybrid.

Other potential hybrid vehicles are being investigated by the automotive industry; they are not yet commercially available. For example, fuel cell vehicles (FCVs) - including the much discussed hydrogen FCVs. These are advanced series hybrids, where a separate power source (fuel cell) generates the electricity that either drives the motor or is stored for later use (see ETSAP TB07).

TECHNICAL BOTTLENECKS AND POTENTIAL - The technical bottleneck that is faced by all HEVs is the development of low-cost, light-weight, high-capacity batteries with durable and reliable operation to enable longer drive range and abuse-tolerance (overcharge, cold weather, etc.). While Nickel-Metal Hydride (NiMH) batteries have reduced their weight by half in the past 10 years and have been used so far in current commercial HEVs, Lithium-ion batteries are the emerging technology, with potential for further improvements [4]. For a given weight or size, Li-ion batteries provide up to 2x more power and energy than NiMH. The reduced weight does also mean far less power used for moving the battery own mass. New variants of Li-ion batteries with e.g. new iron-phosphate cathodes (instead of costly cobalt oxide cathodes) or Li-titanate anodes, are expected to improve the battery performance further. In addition to batteries, regenerative braking is used in all hybrid configurations to capture the energy that is usually dissipated during braking and use it to provide useful traction power. Regenerative braking is also used in electric railway vehicles. Hybrid vehicles usually recover roughly half the total braking energy [4]. Regenerative braking offers significant efficiency and emissions benefits in the urban use of the vehicles involving many acceleration\braking cycles. In this regard supercapacitors have the capability to supply and recover high values of electric power in a very short time. This characteristic makes possible the future use of supercapacitor systems combined with battery pack to improve the energy efficiency during the regenerative braking. Hybrid vehicles are often equipped with "stop & go" devices. In the urban cycle, these devices may enable further reduction of energy use and emissions in the order of 6% (average) [6]. In general, HEVs offer more efficiency benefits in city driving rather than in long-distance motorway use. Full hybrids can reduce CO_2 emissions for urban applications by up to 40% depending on the vehicle. For long haul driving (i.e. mainly on high-speed roads) an average of 7% is reported as more typical [6].

The reduction of the CO_2 emissions in the transport sector is a strong argument in favour of HEVs. While HEVs offer higher efficiency and lower emissions than conventional vehicles in particular in the urban use, the associated reductions are difficult to predict as they vary significantly with the drive cycles and the user behaviour (i.e. the amount of stop-start driving and how aggressively the user accelerates and brakes the vehicle). The UK Committee on Climate Change has recognised the importance of eco-driving education. Along with the use of low-carbon vehicles, this could enable emissions reduction in surface transport by up to 32 $MtCO_2$ in 2020 [5]. If compared to ICE vehicles, HEVs are still an immature technology. However, during

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the past decade, HEVs (e.g. Toyota Prius) have demonstrated durability (up to 12 years) and reliability, with battery performance maintained at the original level for 5 to 8 years [4].

CURRENT COSTS AND PROJECTIONS – Current commercial HEVs must compete against the mature technologies of conventional vehicles. In Europe, the competition with advanced, highly-efficient diesel technology - which has a growing market share in the automotive sector – has proved to be particularly hard. The current costs of NiMH batteries are in the region of €250-€550/kWh and the current cost for a 35kWh battery for a medium-sized car may be still in the order of €18,800 [5]. NiMH batteries still account for roughly half of the extra cost of a hybrid vehicle, despite their cost have been almost halving over the last 10 years [4]. The battery cost is expected to level during the next 5 years, as the production benefits from economies of scale and large volumes, but the levelling process may be offset by the rising cost of nickel [4]. The new Li-ion batteries use cheaper raw materials and offer the same economies of scale as production volumes increase. The two battery technologies are expected to be the same price by 2010; however Li-ion has the advantage of low temperature performance, with better energy and power density [4]. For example, the gravimetric density for Li-ion (120+ Wh/kg) is around double that of NiMH (around 70 Wh/kg) with a similar differential for the volumetric density (300 Wh/litre vs 150+ Wh/litre respectively). For this reason, Li-ion is widely believed to be the technology with the most potential for hybrid and electric vehicles [5]. However, it should be noted that despite the possibility of high production volumes, the requirement for additional powertrain components will mean that hybrid vehicles are likely to remain as a more expensive option than their competitors [4]. According to a 2008 study by Cenex/Arup [11] the current cost of Li-ion batteries is between €670/kWh and €1,340/kWh. However there seemed to be a consensus amongst the industry sources consulted in the study that prices will fall to €170/kWh to €200/kWh once manufacture volumes rise to 100,000 battery packs per annum [11].

The UK Committee on Climate Change has also reported that there is scope for the current battery costs of €540/kWh to be significantly reduced to €130-200/kWh [5]. The Committee believes this can be achieved through a range of innovations including: technological advances in cathode materials (to be switched from a cobalt to a manganese compound); mass production of individual components and the whole battery (100,000s/year); learning effects as manufacturing processes develop and increase efficiency; and reduced impact of R&D costs in the longer term [5]. The reduction trend in battery costs can be seen in Figure 1. The incremental capital costs of medium HEVs vs conventional ICEs is given in Table 1.

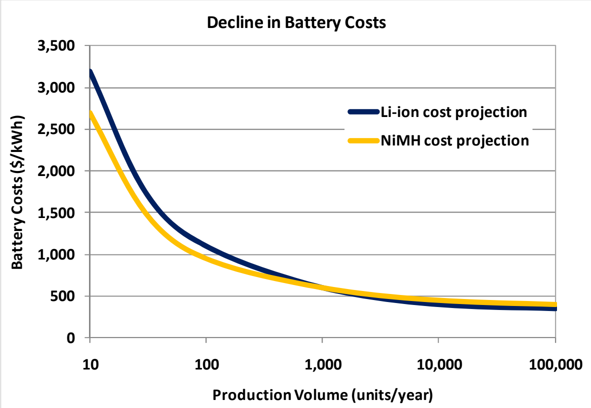

Fig. 1 - Battery cost decline vs production [12]

Table 1 - Additional capital costs of medium HEVs vs conventional ICEs (Source: [21])		
Hybrid Vehicles	Additional costs vs conventional ICEs (€)	
	Low	High
Petrol		
Stop/Start	€ 550	€ 770
Micro-hybrid	€ 990	€ 1,320
Mild Hybrid	€ 1,870	€ 1,870
Full Hybrid	€ 3,520	€ 3,520
Diesel		
Stop/Start	€ 1,100	€ 1,100
Micro-hybrid	€ 1,650	€ 1,650
Mild Hybrid	€ 2,420	€ 2,420
Full Hybrid	€ 4,290	€ 4,290

POTENTIAL & BARRIERS

■ **Major drivers for performance and costs -** There are a number of key factors driving the introduction of HEVs. The inherent benefits of the vehicles, such as lower fuel consumption, emissions and noise, are making them more attractive to consumers. Equally, producers and manufacturers are incentivised by a green image that can enhance their brand against competitors. A high uptake of HEVs may lead to important benefits such as reduced emissions and use of fossil fuels in road transport, decarbonisation of the transport sector, and the consequent reduced dependence on foreign.

■ **Role of legislation -** Various countries such as the US, Spain and Japan have set ambitious targets for the future deployment of hybrids. These targets form a major component of national and international policies for tackling climate change [13]. In particular, Europe is subject to an array of regulations that restrict the emissions of the automotive sector. A recent addition is an average 130gCO2/km limit, which will be required of all new cars between 2012 and 2015. In addition, the European Commission has suggested a tighter restriction of 95gCO_2/km for 2020. Car manufacturers

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are obliged to meet these targets and it is hoped that HEVs will benefit, as hybrid technologies that reach the 130gCO2/km target are already available [9]. The 2020 target of 95gCO_2/km is a more challenging target for HEVs and one that could be met by advanced diesel technology, which is also significantly cheaper than hybrid vehicles. Therefore, HEVs will need to compete with this technology. [9] In this sense, further regulations imposed by governments will help to improve the performance characteristics of HEVs, as they must be seen a longer term option in order to meet the emission targets of 2020. Technological developments, further refinement and advanced materials will deliver improved performance through greater efficiency and hence lower CO_2 emissions.

In the EU, the European Road Transport Research Advisory Council (ERTRAC) and the European Framework Programme are leading research into hybrids aimed at obtaining the lowest urban emission targets possible at a competitive cost for the vehicle. Over the last 5 years, the International Energy Agency (IEA) Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes has been collecting information on hybrid electric and fuel cell vehicles, and generating recommendations on how clean vehicles should be marketed in future [14].

■ **Market Potential and Prospects -** By the end of 2009, the world-wide sales of hybrid vehicles had reached around 2.7 million (some 1% of global sales), with 1.6 million in the US, 870 thousand in Japan and 237 thousand in Europe [23]. The vast majority of these sales were by Toyota/Lexus (around 2 million), although most manufacturers now have models that are scheduled for release in the next few years.

A recent study conducted by JPMorgan [25] predicts that by 2020 some 11.3 million hybrids will be sold annually (over 13% of all vehicles sold). Most of this increase is attributed to the United States, where hybrids may capture nearly 20% of the total market share according to the study. According to other studies [24], global hybrid vehicle uptake is also anticipated to increase rapidly over the next few years (from 2010-2012), with recent forecasts predicting as much as 20% annual increases in sales globally and maybe up to 23% in Europe. The future deployment and commercialisation of hybrid vehicles essentially depends upon substantial improvements and reduced prices in battery technology, but also in electric motors and power electronics [4]. Hybrid development is supported by a number of sources including national and international organisations as well as private and public entities. Various business models have been designed to encourage the uptake of hybrid and electric vehicles: **Battery leasing** – If the manufacturer retains liability for the performance of the vehicle battery, a significant element of the financial risk for consumers is removed. This also removes the question as to how the residual life of the battery should be valued at resale, when the performance of most battery technologies deteriorates with use. A monthly fee would be paid to lease the battery, and a new owner could easily take over those payments. This model also enables the manufacturer to replace batteries with new battery technology if improvements are made [13]; **Vehicle leasing** – This business model is being considered for the Mitsubishi i-MiEV electric small car, which is being released in UK (end of 2009). Vehicle leasing as an extension of battery leasing further reduces the financial risk for the consumer whilst also minimising upfront capital costs [5]; **Car-clubs** – A 'car-club' business model could enable the public to experience and test HEVs in real world conditions, without making a financial commitment or paying upfront costs. It could change the public perception of hybrid vehicles as they become integrated in road transport and become accepted. Car-clubs could effectively introduce the public to hybrid technology in the short term [13].

A number of national governments in Europe and both federal and state Governments in the USA have already introduced financial support packages to help stimulate the early uptake of hybrids. In the UK, congestion charge exemption from the Greater London Authority is also supporting the commercialisation of hybrid vehicles [16]. In the US, President Obama's Stimulus Bill granted €9.6 billion for hybrids [17]. In the US, where diesel vehicles are far less common, HEVs are predicted to take a larger share of medium-size cars. A promising application for hybrid powertrains is for transit buses. This is because the vehicle's duty cycle includes frequent stop-start conditions and buses are often based in urban environments and operated from a single central location. For this reason, Transport for London has 6 diesel-electric buses in operation and has pledged to make every new bus a hybrid from 2012, hoping to reduce emissions by 30% on the conventional diesel buses [18]. Other American and European cities are involved in projects using experimental fleets of hybrid transportation means to show the advantages of these technologies in terms of high efficiency and pollution reduction [27].

The global economic crisis has encouraged interest in smaller and more fuel-efficient vehicles, resulting in the proportion of hybrid vehicles in total car sales growing in many countries. The International Energy Agency expects this trend to continue, as more hybrid models are expected to join the market, government incentives such as tax reductions increase, and costs lower as the technology develops [19]. According to the IEA, the hybrid market is expected to grow and global sales figures could potentially reach 2.2 million units in 2012, yet the share of hybrids in new car sales will still remain below 10% in 2015 [19]. Several vehicle manufacturers have medium-sized passenger HEVs in mass production, with new models entering the market in the near future. However the long term potential of the

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hybrid technology is less certain, as it is often seen as a transition technology on the path to fuel cell vehicles.

■ **Barriers to Development and Deployment -** As previously mentioned, the high price of HEVs is certainly an inhibiting factor for their widespread adoption. The additional capital costs surmount to a vehicle price that is mostly prohibitive to the general population. A reduction in the costs of battery technology is essential for the HEVs to further penetrate into the market. However other factors also play a large role in the future deployment of HEVs: **External markets** – If oil prices drop, the low running costs of HEVs are not as attractive in comparison to equivalent conventional vehicles, consumers would not value the future savings from using less fuel. This is particularly true with diesel vehicles; when replacing advanced diesel technology, which has similar fuel economy, the benefits of a hybrid are reduced. For this reason, improvements in battery technology are necessary in order for hybrids to compete with advanced diesel technologies. **Poor consumer understanding** – the public have concerns about the maturity of the technology, and the availability and adequacy of after-sales service. This is mostly attributed to poor understanding of the technology status, but also due to a lack of qualified hybrid parts and components available for replacements. Business models such as 'car-clubs' could help to overcome this misconception. **Environmental impacts** – there are also some concerns over the environmental impact of the energy-intensive battery manufacture processes, and disposal of the redundant battery [6]. This potential recycling of battery parts is still being investigated and requires further research.

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Table 2 – Summary Table: Key Data and Figures for Hybrid Electric Vehicles [21, 22]

Hybrid Electric Vehicles (Gasoline)			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Gasoline		
Base Energy Consumption (l/km)	0.052	0.051	0.079
Base Energy Consumption (MJ/km)	1.71	1.69	2.58
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO_2 and other GHG emissions, g/km	120.0	118.3	181.0
Costs			
Capital Cost, overnight, Euro/unit	11,124	20,708	28,910
O&M cost (fixed and variable), Euro/km	0.031	0.044	0.054
Economic Lifetime, yrs	12	12	12
Hybrid Electric Vehicles (Diesel)			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Diesel		
Base Energy Consumption (l/km)	0.048	0.041	0.063
Base Energy Consumption (MJ/km)	1.70	1.45	2.26
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO_2 and other GHG emissions, g/km	125.8	107.2	166.8
Costs			
Capital Cost, overnight, Euro/unit	12,954	21,563	30,476
O&M cost (fixed and variable), Euro/km	0.031	0.044	0.054
Economic Lifetime, yrs	12	12	12
Baseline Gasoline Vehicles [22]			
Technical Performance	**Small Cars**	**Medium Cars**	**Large Cars**
Energy Input	Gasoline		
Base Energy Consumption (l/km)	0.062	0.072	0.111
Base Energy Consumption (MJ/km)	2.05	2.38	3.64
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO_2 and other GHG emissions, g/km	143.5	166.7	255.0
Costs			
Capital Cost, overnight, Euro/unit	10,279	16,643	25,505
O&M cost (fixed and variable), Euro/km	0.03	0.04	0.05
Economic Lifetime, yrs	12	12	12

Notes: Dataset is for current (2010) performance and costs. For medium and large cars, figures for HEVs are for full hybrid powertrains. For small cars, only micro-hybrid technology (stop-start and regeneration of braking energy – no electric motor assist) is currently applied, hence the higher energy consumption versus medium HEV cars.

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