FORESIGHTING REPORT
Electric and Hybrid Electric Vehicles

Addressing technologies required to enhance the competitiveness of electric vehicles

For Members Only

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V1.0

EXECUTIVE SUMMARY

This paper examines the key issues affecting the market for Electric Vehicles (EVs) & Hybrid Electric Vehicles (HEVs) and the novel technologies being developed to address their current drawbacks.

Government policies to address a number of long-term issues, including local air pollution, Climate Change and energy security are creating the impetus for the introduction of both EVs and HEVs.

The global market for vehicles is truly massive (68 million light vehicles, worth over $1,500 billion, were sold in 2006) and relatively small inroads into it quickly translate into multi-million dollar opportunities.

A number of forecasters are predicting sustained and explosive market growth by these alternative vehicles over the next ten years (and beyond) once key technological barriers are removed. These primarily relate to the poor performance of existing battery designs, but generically, EVs and HEVs need to address the following challenges before their mass production can be realised:

- Range extension
- Capital cost reductions
- Operating life improvement
- Performance improvements

This report summarises the current state of development of both HEVs and EVs and identifies three key areas where opportunity exists for innovation to address these challenges, namely:

- Energy storage, management and recovery
- Motors and generators
- Power electronics

Although EVs and HEVs are a relatively new phenomenon, there are a number of well established markets for many of the electronic components used in them. These should provide an additional impetus for technological improvements and cost savings.

Until recently, EVs were expected to play a very small role in the global vehicle market, but this report suggests that once technologies for HEVs have been developed (along with supporting infrastructure) they can also be expected to show strong growth, albeit with a 10 year lag, on HEVs.

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1. MARKET POTENTIAL

1.1 Present Status

The global market for light vehicles is huge, with annual sales exceeding 68 million in 2006[1] and it is worth over $1,500 billion[2] per annum. The strong link between car ownership and economic growth means that vehicle sales are expected to continue to grow over the next ten years and beyond.

While the conventional internal combustion engine (ICE) is still undergoing significant improvements (such as the development of highly efficient direct injection engines), alternative drive-train designs, like the Hybrid Electric Vehicle (HEV) and the Electric Vehicle (EV) are also being introduced to the market.

Change is being driven by Government policies seeking to address air quality, energy security and climate change issues. These policy pressures are unlikely to reduce over the next few decades – and there are limits to what can be achieved by improvements to the ICE, particularly when it is operating in inefficient stop-start urban driving modes.

The benefits of cleaner air and less dependence on foreign oil sources are economic 'externalities', which create benefits that consumers tend to be unwilling to pay for. As a result, in the face of higher costs, Government policy and political willpower to push for 'greener' cars will be a key driver of the market for HEVs (and EVs). These policies could be set at the local, national and international level and could interact to reinforce pressures to introduce electric vehicles. Fuel taxation has typically been the primary mechanism national Governments use to drive 'green' roads policy but there are a variety of others. An example of a local policy initiative is the London Congestion Charge, which at $16 per day, equates to a significant annual charge (typically over $3,400 a year), while international emission targets – like those recently defined by the EU for CO_2 emissions – should all become factors in driving both HEV and EV market growth. The proposed 2012 EU fleet average car emission target of 120g CO_2/km (Euro 6 emission legislation) is so tight it will mean that even some HEVs will not comply with it, creating a market entry opportunity for EVs in Europe.

The following table compares CO_2 emissions of various C-segment cars.

Manufacturer and Model	Power	CO2 Emission (gms/km)		
		Combined[i]	Urban (Cold)[ii]	Urban (Extra)[iii]
Petrol Hybrid				
Honda Civic	85 kW	109	122	101
Toyota Prius	96 kW	104	118	99
Diesel				
Renault Clio dCi 106	78 kW	123	150	108
Ford Focus 1.8 Tdci	84 kW	137	177	114
BMW 318d Saloon	90 kW	123	150	108
Toyota Auris 2.0 I D	93 kW	144	184	121
Petrol				
Renault Clio 1.6 VVT	82 kW	160	212	127
Ford Focus 1.6 Zetec	84 kW	157	205	127
BMW 116i Saloon	90 kW	142	186	113
Toyota Auris 1.6	91 kW	166	212	139

Table 1: CO_2 Emissions of Various Cars
(Source: ITI Energy compilation)

Under an Urban (Extra) cycle, some of the diesel cars match petrol hybrids on their CO_2 emission levels. But on a combined cycle or Urban (Cold) cycle the petrol hybrids clearly have an edge over both their petrol and diesel counterparts.

It is worth noting that, unless the electricity is generated from renewable sources, EVs and Plug-in Hybrids displace the pollution rather than reduce it to an absolute zero.

In terms of the global HEV market, in 2005 there were only a handful of primary automotive OEMs selling HEVs worldwide. Toyota was the dominant producer, selling between 70-80% of all HEVs, while Honda sold 15% of the total. The

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[i] *The combined average of the urban (cold) and urban (extra) cycle together.*

[ii] *Test carried out in a laboratory at an ambient temperature of 20oC to 30oC and consists of a series of accelerations, steady speeds, decelerations and idling. Maximum speed is 31mph (50km/h), average speed 12mph (19km/h) and the distance covered is 2.5 miles (4km).*

[iii] *Test conducted immediately following the urban (cold) cycle and consists of roughly half steady-speed driving and the remainder accelerations, decelerations, and some idling. Maximum speed is 75mph (120km/h), average speed is 39mph (63 km/h) and the distance covered is 4.3miles (7km).*

remainder of the market was divided between several other suppliers, among which Ford had the largest share. Today, most global automakers worldwide are either introducing HEVs or have plans to do so in the near future.

The number of sales of HEVs (in 2005) represents a tiny fraction of annual sales of light vehicles of over 60million in the same year (0.1% of this sales total).

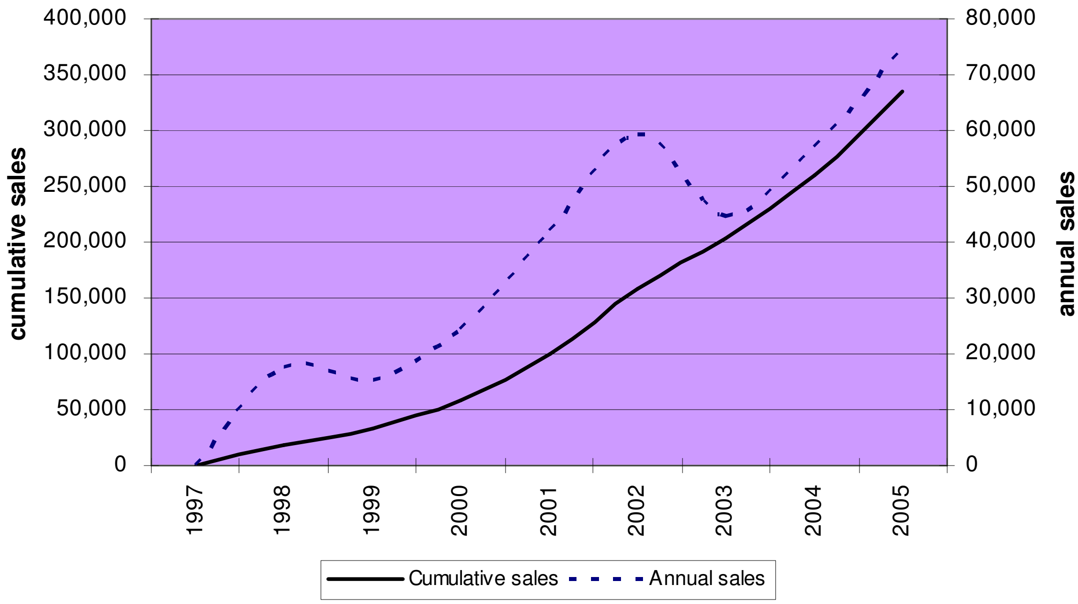

Figure 1: Historic Global Sales of HEVs (Source: US National Research Council)[3]

Political willpower does not always translate into policy results, however, as the failure of California's 'Zero Emission Vehicle' Mandate, which was created by California's Air Resources Board in 1990, shows. This required an increasing percent of Zero-Emission Vehicles to be sold in California. The target started with 2% of new car sales in 1998 and was to increase linearly to 10% in 2003. However, this policy was abandoned in 1996, partly because it appeared unfeasible and partly because of pressure from OEMs.

1.2 Market Future and Barriers to Entry

HEVs and EVs represent one of many options for improving the fuel efficiency of 'light' vehicles worldwide. Options range from using new lighter materials, vehicle downsizing, improving aerodynamic efficiency, to adopting new drive train technologies.

Work by Freedonia[4] suggests that levels and speed of market penetration by new technology in the car industry is driven by the degree of consumer demand – and by the level of political will expended to enforce regulatory requirements for it. This is because, although policy can provide the impetus for new technologies, to succeed in the longer term they must also be able to meet market needs. These ‘needs’ include the ability to act as a reasonable substitute for the dominant technology in terms of price, performance, or other benefits (including items as diverse as fuelling ease and service availability).

Thus, where a high degree of political will works in concert with strong consumer demand (for example, as occurred with the introduction of front disc brakes and airbags, on safety grounds) technologies achieved 50% market penetration in just five years. Technologies with either high market pull or regulatory pressures (like power steering and catalytic converters) took around 15 years to achieve 50% penetration. Niche technologies, like power seats and anti-theft devices, which had moderate political and/or market pressure, have taken around 20 years to achieve 20% penetration.

The table below summarises the key drivers and barriers to the uptake of alternative vehicles.

Ranked Drivers	1-2 years	3-5 years	6+ years
1 National and International Regulations Local air quality CO2 Fuel independence	High	High	High
2 Tax Incentives	High	High	High
3 Government Grants	High	Medium	Low
4 Technological Improvements	Medium	Medium	Medium
5 Suitability of Certain Niche Markets	High	Medium	Medium
6 Competitive Pressures	Low	Medium	High
7 Increasing Environmental Awareness	Medium	Medium	Medium
Ranked Barriers	1-2 years	3-5 years	6+ years
1 High Costs of Alternative Vehicles	High	High	Medium
2 Technology Readiness	High	Medium	Low
3 Conventional Fuel Prices	High	Medium	Low
4 Lower Vehicle Performance	High	Medium	Low
5 Lack of Manufacturing/Other Infrastructure	High	Medium	Low
6 Improvements in Conventional Vehicles	Medium	Medium	Medium
7 Consumer Indifference	Low	Low	Low

Table 2: Drivers and Barriers to Entry by HEVs and EVs (Source: ITI Energy compilation)

Lack of manufacturing and other infrastructure is a key barrier to market entry. The mass manufacturing of new vehicles requires significant investment in new tooling. For example, a conventional engine plant alone can cost $500 million to develop, while Lotus Engineering indicate that a battery manufacturer will typically be looking for secure orders of over 1 million to build a new manufacturing plant[5]. Similarly, buyers can be put off purchasing by a perceived lack of support for new models. These issues can create 'chicken and egg' situations.

Typically, innovative technology has entered the high end of the market (which values vehicle performance) before achieving wider market uptake. HEVs have bucked this trend because their key selling point – fuel economy – is more of a mid to low market selling point, although the high torque of electric motors at low speeds is being sold as a performance enhancer.

Market entry by EVs has, so far, been very limited. However, the strategy used appears to have been primarily focussed on fuel economy and green attributes, although several models (notably the Tesla) have entered at the high end of the market.

Annual fuel cost in the UK for an average C-segment petrol hybrid is around $2000, while the same for an equivalent full electric would be between $280 and $500[iv] depending on the electricity tariff. Although these calculations do not take into account the amortisation of the battery pack, it is clear that the electric vehicles produce less CO_2 and can be very efficient for city driving.

Added to these benefits are the savings from owning an electric car while driving in major cities like London, Milan and Stockholm, where road pricing is directly related to emissions. In London these charges could range between $16 and $50 a day, depending on the CO_2 emission levels. For a daily commuter this could cost anything between $3,400 to $12,000 a year.

1.3 Hybrid Electric Vehicles

The HEV is a technical compromise to the current lack of power/energy in batteries and the benefits of electric motors (these being highly efficient and also able to capture energy from braking, recharging the vehicle's batteries). Despite these benefits, continued reliance on ICE, issues with optimizing the performance of duplicate drive trains – and the extra weight associated with these drive trains – means HEV performance (in terms of fuel economy, CO_2 emissions etc) is often matched by diesel-engined vehicles, especially in the small car market. However, HEVs do outperform gasoline engined vehicles, particularly in urban driving modes, and offer zero-emission driving when running on their batteries. Thus market penetration by HEVs shows greatest promise in markets that do not typically use the diesel vehicle.

Based on current penetration rates by hybrid vehicles, it would appear that a 1% per annum 'niche' rate of penetration into the market is currently occurring, with forecasters suggesting HEVs will have achieved ~10% global market penetration

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[iv] *The calculations are based on total energy used over 12,000 miles. It is assumed that mileage of an average C-segment petrol hybrid is around 60mpg and a gallon of petrol costs $10.00. It is also assumed that an equivalent value for a full electric would be 0.88 MJ /mile and a unit of electricity costing between $0.10 and $0.18 depending on the tariff. .*

by 2015, roughly 10+ years after they were introduced. This rate is probably being driven by strong to moderate regulatory pressure and relatively weak customer demand. However, in the context of global market sales of nearly 80 million light vehicles in 2015[4], a 10% market penetration represents a huge absolute gain.

Many researchers predict that, to 2015, the market will see explosive absolute growth in HEVs, with a minimum of over 20% annual growth in volumes and between 3 and 6 million units being manufactured annually by 2015. The value of key HEV components (such as motors, power electronics and batteries) is being predicted at, or well over, $12bn pa by 2015.

By 2010, the global car industry is expected to produce more than 1 million HEVs per annum (from half a million now). Research work by Lotus Engineering for ITI Energy suggests mass manufacturing of HEV cost components should mean incremental costs could fall by nearly half at the 100,000 per annum production mark. Meanwhile, BCC research[6] indicates that, at the 1 million production mark, even more significant economies of scale start to occur. BCC research also indicates that the costs of key components in HEVs could be up to a third of their current levels by 2015. This would significantly enhance their 'value proposition', which is based on their fuel saving benefits (with no compromise on performance) and their higher upfront capital costs. Using the US market as an example, this could mean a change from a 3-5 to a 1-2 year payback and a drop in costs from 15-20% above conventional vehicles to only 5%, for a ~20-40% annual fuel cost saving. Clearly, any reduction in HEV component costs is likely to have a knock-on effect on components common to the EV[6].

Research into HEV technology is dominated by Japanese carmakers, which have spent hundreds of millions of pounds into this type of R&D ($200m+ pa being typical), with Toyota being quoted as being 'five years ahead of its rivals' in this area. In all, seven global car manufacturers are actively engaged in HEV development and can lever off their considerable experience developing ICE vehicles.

1.4 Electric Vehicles

HEVs have been steadily evolving – from retrofits, to existing conventional vehicles, to designs where the electric engine is providing significantly more of the power than the internal combustion engine. The electric vehicle is the ultimate extension of this concept and, from a mechanical viewpoint, is more straightforward than an HEV.

EVs are likely to enter the market after several more iterations of HEVs address the key technical and market barriers. These primarily relate to the cost and performance of the batteries, but are likely to see rapid market penetration because they will be benefiting from the development of common components used in HEVs. They will also benefit from other infrastructure that will have been developed to support HEVs.

In total, there are currently 25,000 EVs in Europe and 50,000 in the US. These small historic figures reflect concerns about EV performance. But soon to be released EVs should be able to match conventional vehicle performance, while delivering acceptable operating ranges for urban environments.

Given the cost and technical issues associated with EVs, it would not be unreasonable to assume a similar 'niche' market entry route for them – as seen for HEVs. Market research by IDTechEx[7] and others suggests EV market penetration is approximately 10 years behind HEVs, in terms of market penetration, and a number of credible EV developers (Renault, Think, Tesla) are expecting annual sales of several hundred thousands by 2015-20. Renault-Nissan has recently announced their plans to invest around $300 million per year to develop electric vehicle technology ready by 2012.

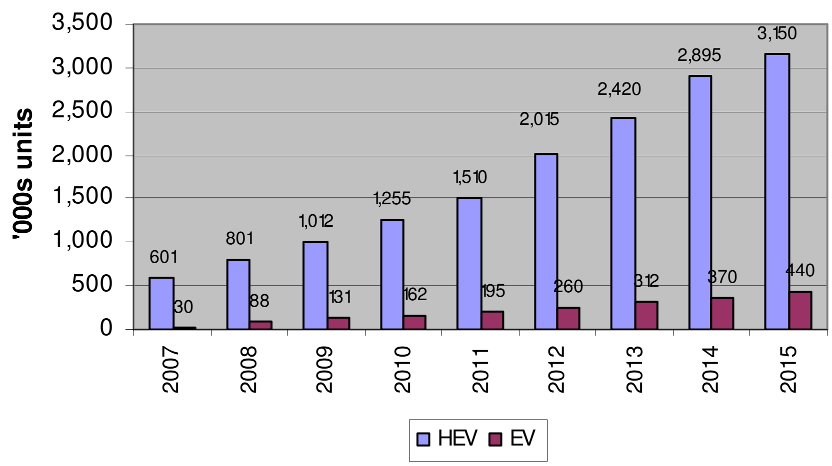

Figure 2: Forecast Annual Sales of HEVs and EVs (Data Source: IDTechEx)[8]

Some researchers suggest that initial market entry by EVs could be slower than that achieved by HEVs, but once manufacturers have 'tooled up' to produce them, entry is likely to be fast – facilitated by the development of the infrastructure (and core technology) that will have been developed to support HEVs.

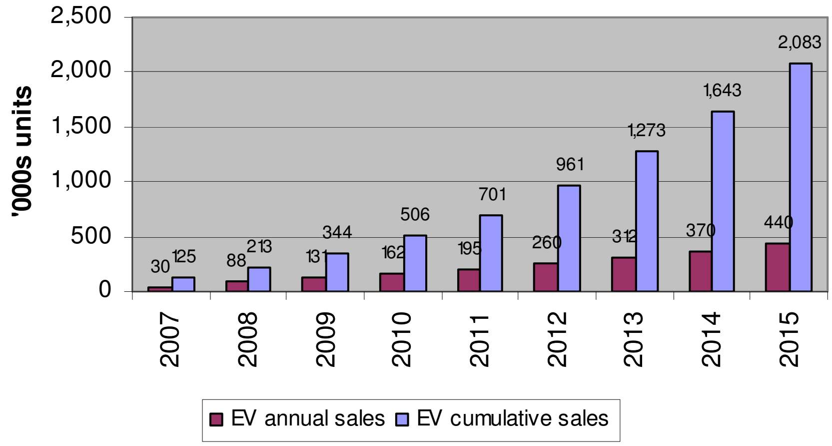

Figure 3: Forecast Annual and Cumulative Sales of EVs (Data Source: IDTechEx)[9]

EVs appear better suited to entry into the European and Japanese markets than the US. This is because of the driving behaviour in Europe and Japan (with more short commutes), their higher urban population density, steeper fuel costs and, in Europe, the stronger 'green' consumer ethos.

Whilst there are a multitude of small niche EV companies (for example Smiths, Modec and Think), far fewer mainstream carmakers are involved, with Renault and Daimler Benz being notable exceptions.

Change in this part of the car industry is moving fast, as demonstrated by announcements for the introduction of the emblematic Tesla EV in 2008. The Tesla EV offers matching performance (at approximately 2-3 times the cost) to an equivalent ICE sports car; and there is clearly room for further technological gains in key components in these vehicles. Taking batteries as an example, the Shin-Kobe electric machinery company managed to increase the power density of their main Li Ion battery design by 50% in a 10 year period, when they released their Gen2 battery in 2004[10].

The critical limiting factor of an EV remains the battery. An EV battery pack is typically sized to provide an acceptable level of power (for performance) and energy (for range). Typically, an electric vehicle will have a practical range of between 40 and 100 miles, however recent designs like the Tesla (250 miles) are approaching the benchmark ranges of conventional vehicles (350-400 miles), while offering matching performance.

Other than range, a further practical constraint in EVs is 'refuelling' time, which can be typically 6-8 hours (although in the Tesla this has been cut to 4 hours).

Provided further technological improvements deliver better vehicle performance, the removal of duplicate drive-trains and the significantly better energy conversion efficiencies of the EV, coupled with true zero-emission driving (electricity generated from nuclear/renewable sources), should make the EV a viable option for certain market segments in the longer-term.

The figure below shows Lotus' view of drive train evolution over the coming decades. This particular 'pathway' culminates in mainstream penetration of all electric vehicles, either via battery or fuel cell powered vehicles.

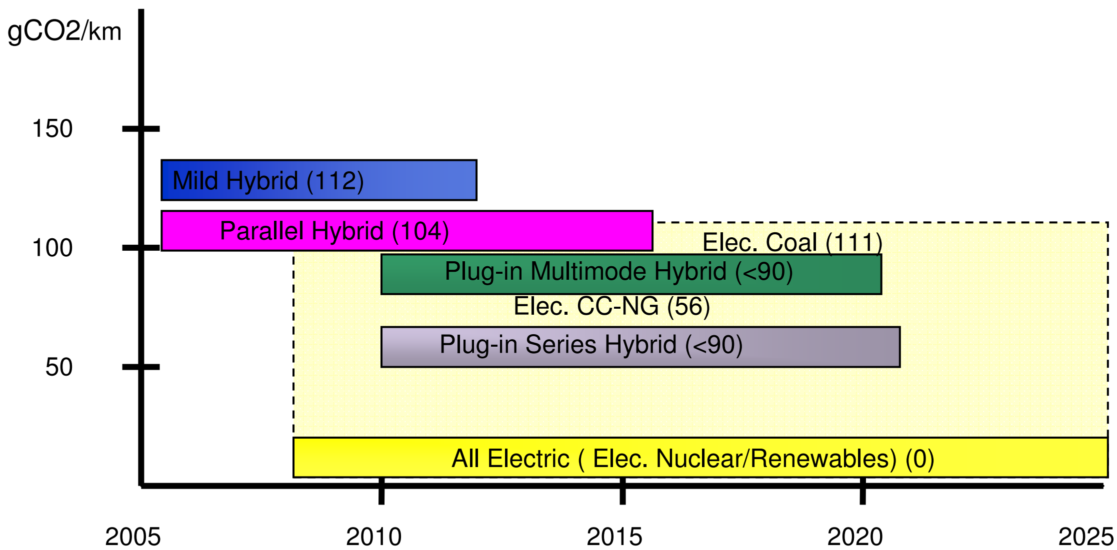

Figure 4- Drive train evolution
(Data Source: Lotus)[11]

1.5 EV and HEV Innovation Process

Typically, conservative automotive Original Equipment Manufacturers (OEM) and their system integrators (their tier 1 suppliers) seem stuck in an evolutionary mode of R&D which has and will continue to yield beneficial fuel and CO_2 reductions. An average design cycle in the automotive industry can be anything between three to seven years, which means some of the new technology could take up to seven years to make a market entry.

The car industry is characterized by a high degree of commercial secrecy, with carmakers tending to keep their R&D for their own 'stable' of vehicles. However, smaller companies and research organizations are making an impact. For example, PML Flightlink – a small unquoted UK company – created global interest in 2007 by unveiling a re-designed Mini with unique wheel mounted 120kW electric motors, which collectively produced seven times the performance of the engine they had replaced under the hood. Within this industry, regionally, the UK now has a reputation for developing 'niche' high performance vehicles and has several research and engineering firms involved in cutting edge EV and HEV work (Lotus, Ricardo, Axeon, Zytec and PML, for example).

It is clear that potential exists for step-change improvements in several areas of EV and HEV technology, which could be introduced by 2015 if the right R&D breakthroughs could be identified now. Many of these innovations could also be applied to other industries, such as aerospace, shipping and railways.

According to Freedonia, since so many resources are required for product development, these activities tend to become worldwide and often involve consortiums. Because these organisations actively participate in most major markets, new ideas tend to spread through the global industry very rapidly – if they contribute to solving problems specific to given regions or markets. As a result, the hybrid-electric technologies developed in Japan by Toyota and Honda were on sale in the US within a few years of introduction in Japan. Furthermore, the technologies themselves that Toyota employs in its hybrids are also being used by other OEMs, such as Ford and Nissan.

2. DRIVE TRAIN COSTS

2.1 Hybrid Electric Vehicle Drive Train Costs

Research work carried out by Lotus Engineering for ITI indicates that, at present, the cost of key HEV components adds around $7000 in component costs, with the largest of these costs being the battery (27%) and the next being the motor (22%).

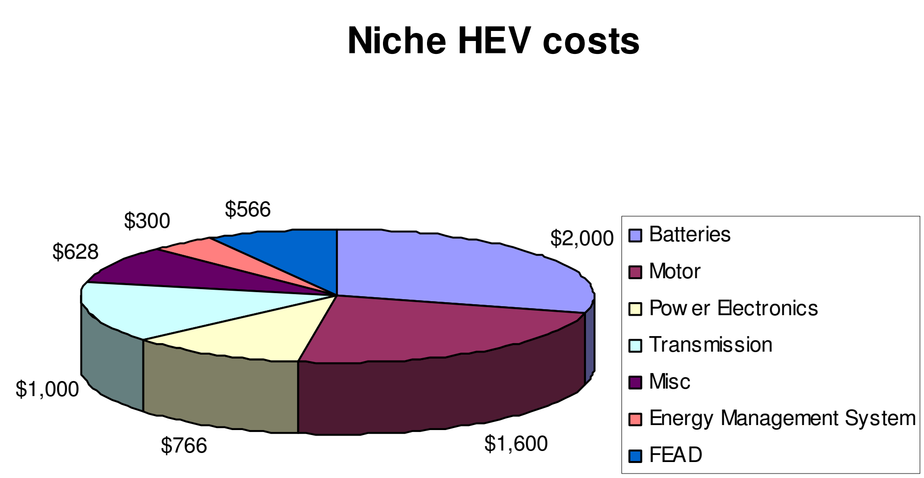

Figure 5: Drive Train Component Cost for an HEV (Data Source: Lotus)[12]

Lotus suggest that once manufacturers have started to mass manufacture more than 100,000 vehicles annually (which is what the market is approaching now), scale economies will mean these costs start to fall significantly – as shown in the diagram below. These cost reductions exclude any additional gains from improvements in battery technology.

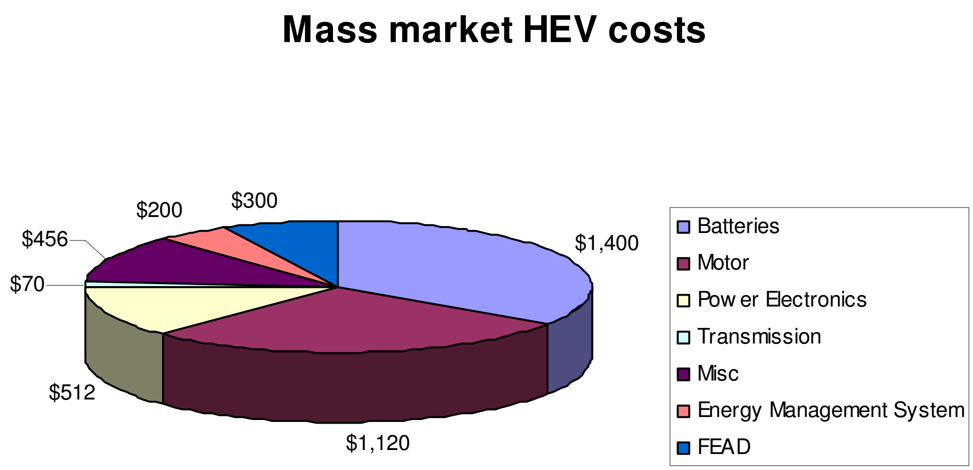

Figure 6: Drive Train Component Cost for a Mass Built HEV (Data Source: Lotus)[13]

Based on Lotus' research work, these HEV drive-train component costs should drop by 43% as a result of economies of scale; from just under $7k to just over $4k, with particularly significant cuts in the cost of the transmission.

Putting these costs in context, the cost of manufacturing a 'standard' petrol vehicle's ICE drive-train is estimated as being around $5000, so these HEVs components represent a significant add-on cost. These cost estimates are considerably larger than public statements by Toyota that HEV components represent around $2500 in on-costs for normal car drive-train production.

2.2 The Market for Hybrid Electric Vehicle Components

Using the researched component cost estimates of Lotus and several conservative market forecasts for sales of HEVs, it has been possible to estimate the likely market size for key components used in HEVs, out to the year 2020. Two market researchers, Freedonia and IDTechEx, have forecast annual sales of HEVs rising from around 300,000 in 2005 to over 3 million in 2015.

Based on these annual sales figures, the following market forecasts for HEV components have been derived. These show that all of these markets should achieve rapid and sustained growth (above 20% per annum) from the present to become multi-billion pound opportunities by 2010.

	Annual HEV sales figures by:					
US$ Million	Freedonia	IDTechEx	Freedonia	IDTechEx	Freedonia	IDTechEx
	2005		**2010**		**2015**	
Batteries	395	420	2,415	1,757	6,020	4,410
Motor	316	336	1,932	1,406	4,816	3,528
Power Electronics	144	154	883	643	2,202	1,613
Transmission	20	21	121	88	301	221
Misc	129	137	787	572	1,961	1,436
Energy Management !	56	60	345	251	860	630
FEAD*	85	90	518	377	1,290	945
Total	1,144	1,217	7,000	5,093	17,449	12,783

Table 3: Forecast Annual Market Value of HEV Components (Data Sources: Lotus, Freedonia and IDTechEx)[14]

The diagram below summarises the derived estimates of the total market size for the key components used in HEVs in 2005, 2010 and 2015.

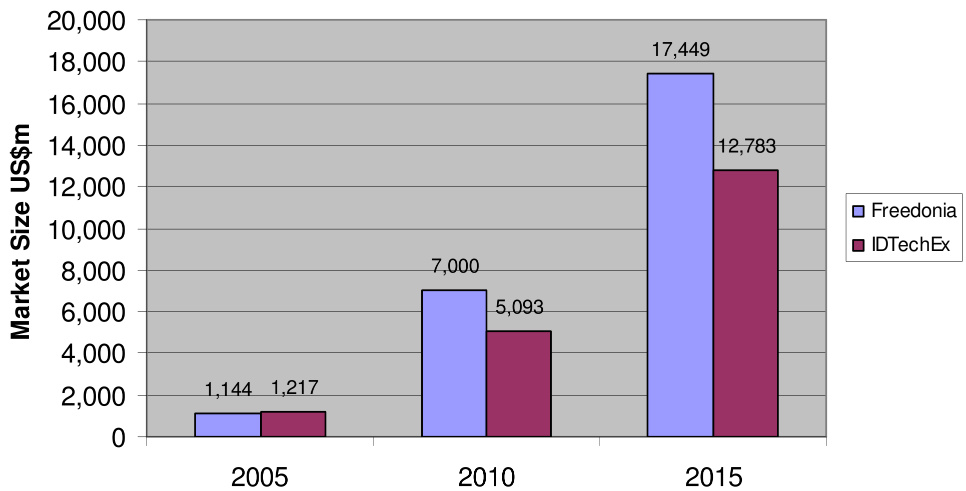

Figure 8: Total Annual Market Value for HEV Components (Data Sources: Lotus, Freedonia and IDTechEx)[15]

2.3 Electric Vehicle Drive Train Costs

Research carried out by Lotus for ITI indicates that currently key EV components cost around $27,000, with by far the largest of these (at 64%) being the battery and the next being the motor (7%). However, a full EV no longer needs an IC engine and associated components, which results in a saving of $5000, making the incremental cost of components $22,000.

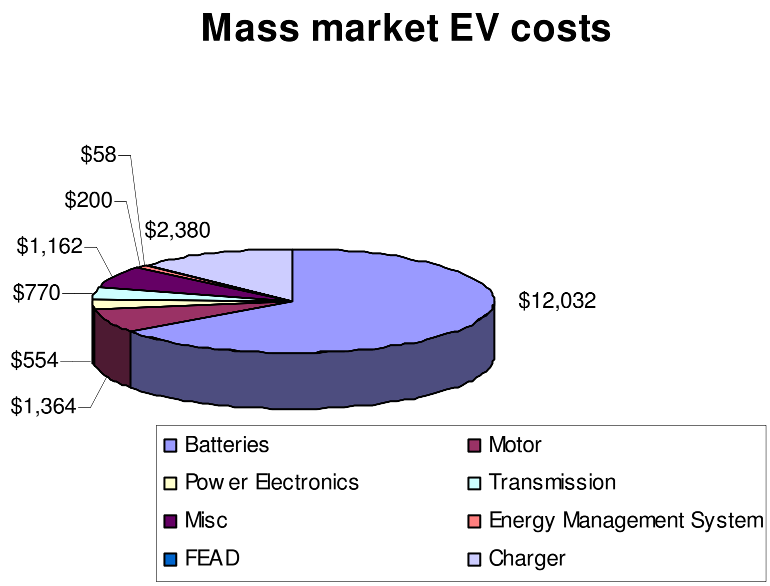

Figure 9: Drive Train Component Cost of Niche Production EV (Data Source: Lotus)[16]

These costs make an EV drive-train roughly five times more expensive to manufacture than conventional vehicles – and more than three times higher than comparable HEV drive-train costs.

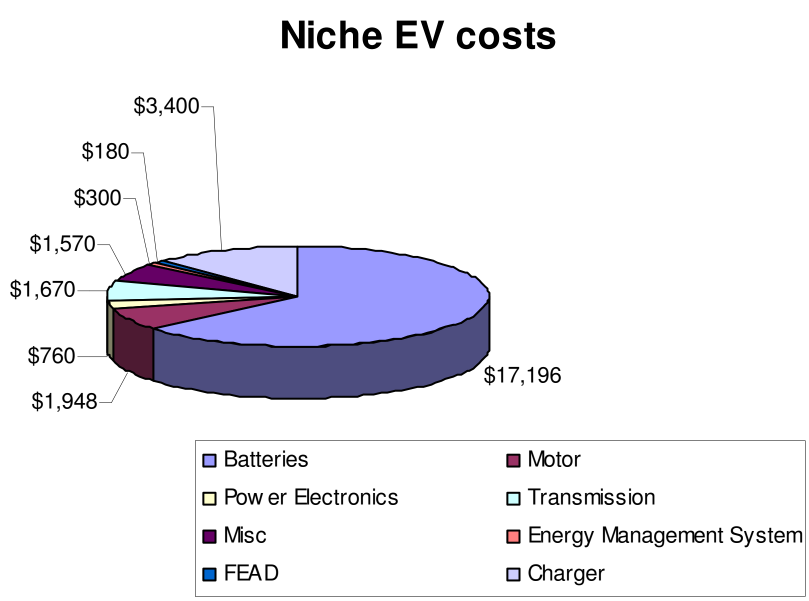

Figure 10: Drive Train Component Costs of a Mass Production EV (Data Source: Lotus)[17]

As Lotus have suggested, when manufacturers have started to manufacture more than 100,000 EV vehicles annually (which, based on available forecasts, is likely to happen around 2010), scale economies will mean EV costs will start to fall significantly, as shown above.

Based on this work, EV drive-train component costs should drop by over 30% as a result of economies of scale, from just over $27k to around $18.5k with across the board cuts in the cost of components making up this total. Putting these in context, a ‘standard’ ICE drive-train is estimated as costing around $5000 to manufacture, so a mass market EV would still present a significant premium over this. However, as with the HEV cost estimates, these cost reductions exclude any additional gains from improvements in battery technology, the key cost component of the vehicle.

2.4 The Market for Electric Vehicle Components

Using the EV component cost estimates of Lotus and a market forecast for sales of EVs, it has been possible to estimate the likely market size for components used in HEVs out to 2015.

Based on these sales figures for EVs from IDTechEx, which predict annual sales of EVs rising from around 15,000 in 2005 to 440,000 by 2015, the following forecasts of the size of markets for EV components have been derived. These show that all of the markets for components should achieve sustained growth (over 20% annually) to become multi-million pound opportunities by 2015.

Of these components, the market for batteries, should rapidly become a multi-billion dollar market by 2010, because of the significantly higher unit costs of EV batteries (which cost up to eight times more in an EV than in an HEV).

US$Million	Annual EV sales figures by: IDTechEx		
	2005	**2010**	**2015**
Batteries	258	2,786	7,566
Motor	29	316	857
Power Electronics	11	123	334
Transmission	25	271	735
Misc	24	254	691
Energy Management S	5	49	132
FEAD	3	29	79
Charger	51	551	1,496
Total	405	4,378	11,891

Table 4: Forecast Market Value of EV Components (Data Sources: Lotus and IDTechEx)[18]

The diagram below summarises the total market size of the key components used in EVs in 2005, 2010 and 2015.

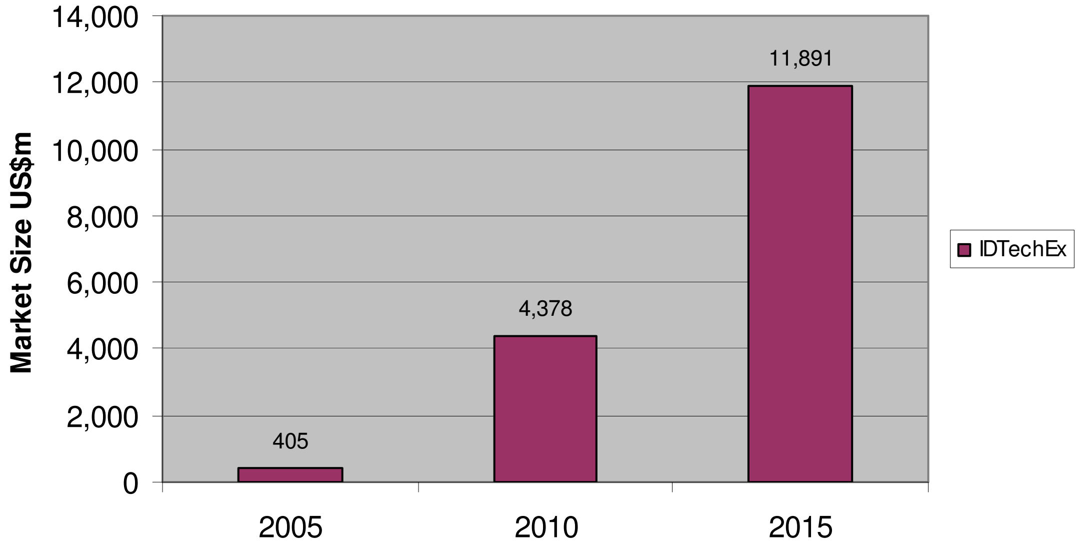

Figure 12: Total Market Value for EV Components (Data Sources: Lotus and IDTechEx)[19]

3. HEV AND EV MANUFACTURERS AND SUPPLIERS

3.1 Original Equipment Manufacturers

The HEV industry, while relatively new, is really an adjunct to the larger global auto industry. Because of this, any discussion regarding industry structure must take into account the much larger industry that builds vehicles using pure ICEs. For conventional ICE powerplants, such as spark ignition or diesel engines, the global automotive industry follows a rigid model where the automaker itself produces major value-added elements of the engine, such as the cylinder block and heads, crankshaft and other key parts. The original equipment manufacturer (OEM) then relies on its supply chain for other engine-related components, such as fuel injection systems, pistons, camshafts, exhaust systems, etc.

The OEMs also act as system designers and integrators for engines and (typically) for transmissions which, among all the components that make up a light vehicle, are believed within the industry to be imbued with true product differentiation power – especially in performance-oriented and luxury vehicles.

Hybrid differentiation extends beyond the engine itself and includes the transmission as well. In some cases, such as the joint venture between BMW, DaimlerChrysler and General Motors that produced an integrated hybrid transmission for rear-wheel-drive vehicles, the main hybrid capability is wholly contained in the transmission, giving OEMs greater flexibility in fully utilizing their ranges of engine families.

3.2 Original Equipment Manufacturer Strategies

Freedonia and other researchers suggest the next 10+ years will bring increasing uncertainty for the global automotive OEMs and their suppliers. Strategic decisions that must be made now will be significantly more complicated than those that have confronted management teams in the past, because companies face placing multi-million dollar bets on new engine technologies.

The strategy of most OEMs seems to have been to enter the hybrid market to varying degrees using modifications of existing models, while also pursuing some R&D into a variety of novel engine techologies. This is a low risk strategy that minimises the re-tooling and other reorganisation required to produce HEVs vehicles (allowing some economies scale); but enables them to gain some of the know-how required to move into electric and fuel cell vehicles.

According to research by Freedonia, only Toyota and General Motors have chosen to become very heavily involved in multiple drive train technologies and to develop these internally. Even given the average size of global auto companies, few others have the resources to follow this path (and even they have joined with each other, and with others, in certain areas to share the cost of developing so many new technologies at once). Among other companies, Honda, for example, has focussed on developing leading edge spark ignition and hybrid ICE technologies. Nissan, which recently emerged from severe financial difficulties, has adopted a fairly aggressive outsourcing policy regarding new technologies. It is purchasing hybrid-electric ICE drive train technology from Toyota, for example. Ford outsources diesel engines in the US from Navistar, and sources hybrid drive dual systems from Aisin AW (which in turn uses Toyota-based designs).

A given in the current market is that even the biggest OEMs will likely be forced to collaborate with other OEMs, and with suppliers, to remain at the leading edge regarding the multiple technologies currently under research. Given its oligopolistic nature, the auto industry has not in the past been particularly adept at fostering successful collaborative partnerships.

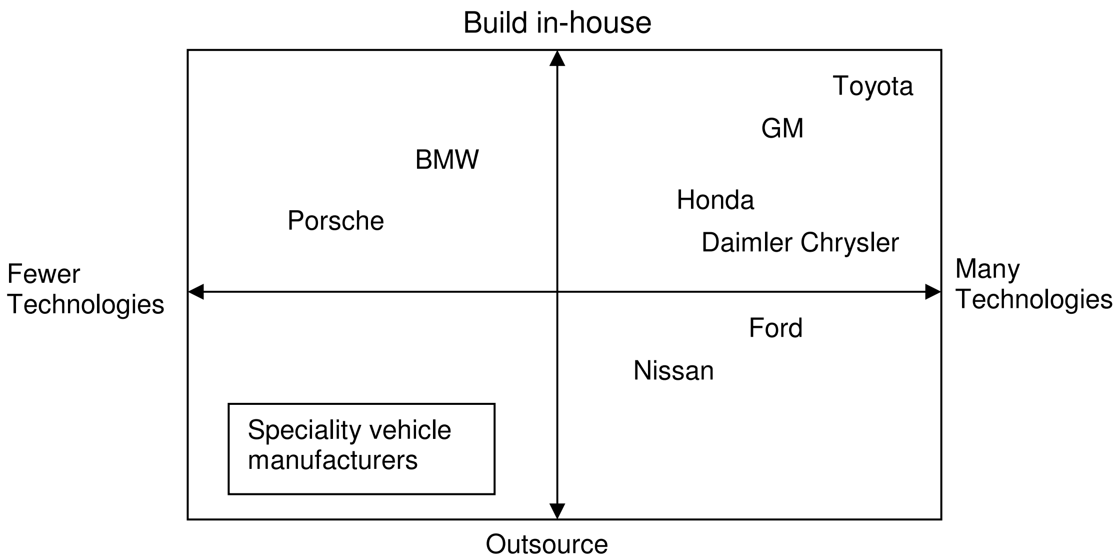

Figure 13: Market Strategy of OEMs (Data Source: Freedonia)[20]

In the EV market, beneath the global OEMs, there are numerous, small (from an car industry perspective) manufacturers that are generally focussed on producing a single vehicle model for niche applications. This is a high risk strategy and, historically, 90% of new EV firms have failed. It is highly likely that there will be consolidations and takeovers by OEMs of these firms, as EV technology progresses to the point where it is able to compete with conventional designs. The financial issues surrounding electric vehicle design, production and marketing are in a sense the same issues facing the industry itself on a broader scale, due to the high levels of asset intensity required to both design and develop advanced drive trains.

3.3 Component Supplier Strategies

As with the OEMs, suppliers must determine both where and how they are going to contribute as strategies evolve beyond supporting the spark ignition internal combustion engine. Companies can choose to focus on a few technologies, or aspire to participate in a multitude of alternatives.

Strategic choices are generally based on their core skills and resources, and on whether these could be augmented by investments in building new expertise in technologies. Suppliers must also decide at what level they wish to participate in these technologies (from being a supplier of parts to being a true system supplier). In the latter case, the supplier often provides deeper expertise and greater capabilities in design development and integration than the OEM itself could often provide.

According to research by Freedonia, the strategic positions of individual automotive suppliers, in terms of their technology and design and development capabilities, for all technologies, is highly varied. Large systems suppliers, such as Bosch, Delphi and DENSO, participate in many different technologies for many different drive train systems and types. Meanwhile, specialized suppliers such as Aisin and Panasonic are much more focused on limited technologies.

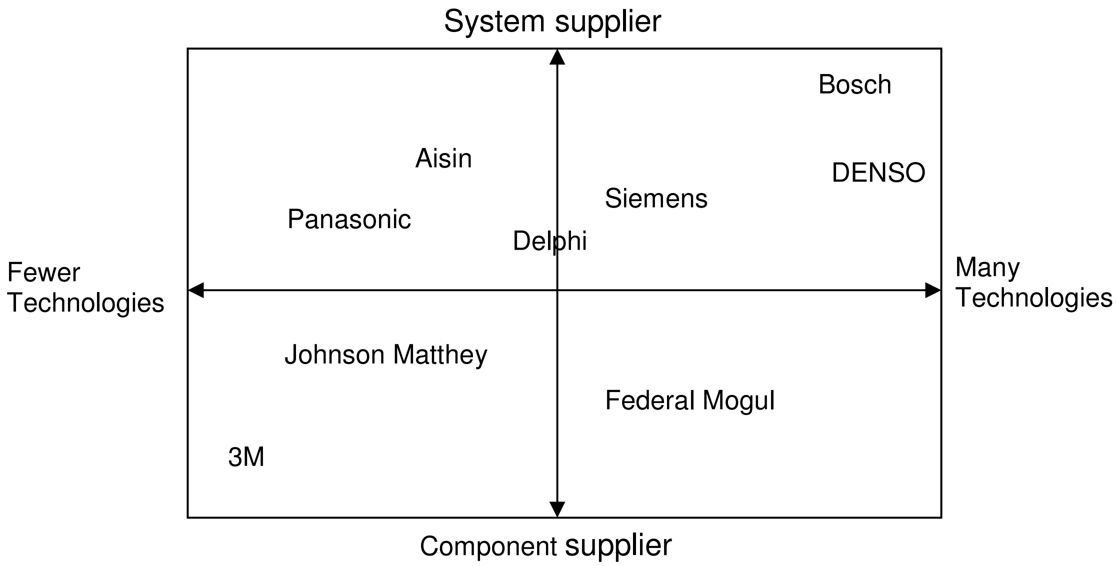

Figure 14: Market Strategy of OEM Suppliers (Data Source: Freedonia)[21]

Other supply companies, such as Federal-Mogul, provide individual parts (eg, engine seals, spark plugs) that are incorporated into many larger systems. Some specialist suppliers, such as 3M and Johnson Matthey, focus on supplying individual components that are integrated into other suppliers' systems.

4. EV AND HEV DRIVE TRAIN CONFIGURATION

There are essentially two types of HEV; the parallel and series designs. The difference between them is whether the ICE directly powers the drive train, as it does in the Parallel design.

4.1 Parallel Hybrid

A parallel hybrid has an electric motor which enables full electric drive at low speed, low load, conditions. The drive goes into hybrid mode at higher loads/speeds, with torque coming from a mixture of ICE and electric motor power. When the vehicle is stationary, through de-clutching, the system goes into regenerative power mode and charges a relatively low range, high voltage, battery pack. The system also enables a limited amount of regenerative braking when decelerating. The typical max power mix of engine/electric motor power would be a 60/40 split. This system offers improved vehicle efficiencies, relative to ICE drive trains, without any compromise in performance or range. However, the battery pack is so small that the electric-only range is severely limited.

Examples of series hybrids are the Honda Civic and the Ford Escape (with 15 kW and 70 kW electric motors, respectively)

Figure 15 below attempts to show the relative size (in kW or kWh) of key components against other types of HEV and EVs.

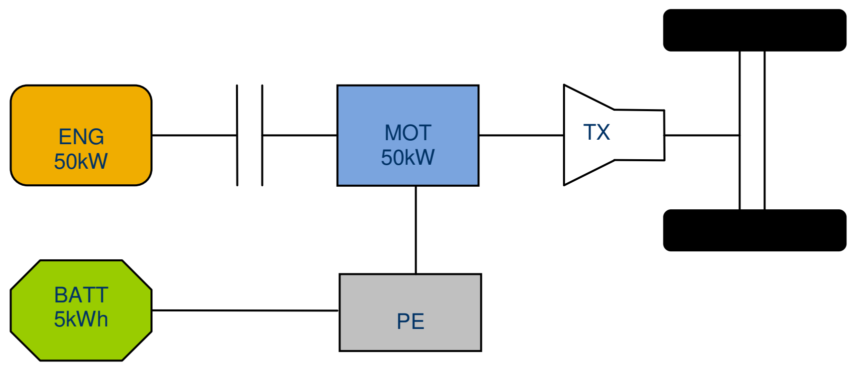

Figure 15: Parallel Hybrid Drive Train
(Data Source: ITI Energy compilation)

4.2 Series Hybrid

A series hybrid is fundamentally an EV which incorporates an engine-generator set that recharges the battery pack to extend its range. As the ICE and generator set are not constrained by mechanical connection to the wheels, they can be operated at optimal efficiency. The design also creates potential cost savings relative to the parallel design, as the transmission system can be simpler. However, the electric motor must be larger than in the parallel design and there is also the additional cost of a generator. The design does not optimally lend itself to constant energy-sustaining high speed (ie, motorway running) because of the rate of energy drawdown from the battery in these conditions. GM's Volt is an example of a series design and has 53 kW generator and a 120 kW electric motor.

Figure 16 below attempts to show the relative size (in kW or kWh) of key components against other types of HEV and EVs.

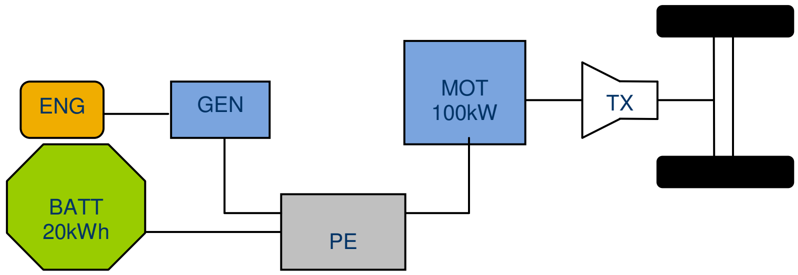

Figure 16: Series Hybrid Drive Train
(Data Source: ITI Energy compilation)

4.3 Multi Mode Hybrid

The latest (ie, circa third/fourth generation) Prius hybrid from Toyota can be described as the multi mode hybrid. It can operate either in parallel or series mode. The system features a drive train that incorporates a power split device, incorporating variable ratio planetary gear sets and two electric motor/gensets. By utilising several clutch units and the variable ratio gearbox, the system enables: zero emission running, hybrid drive enabled enhanced performance, series charging of the battery pack and efficient high speed cruising.

This architecture, as shown in figure 17, seems to offer the best hybrid compromise. The downsides seem to be a) added system complexity; and b) electric only range is limited by the size of the battery pack. Also, outside limited drive modes, efficiency gains drop off significantly. This is discussed elsewhere and is a probably a limitation of the control system efficiency. Lexus GS 400H is another example of a multimode HEV and has a 123kW motor.

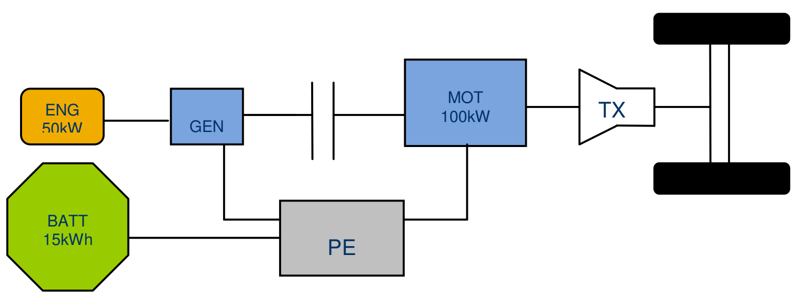

Figure 17: Multi Mode (Combined) Hybrid Drive Train
(Data Source: ITI Energy compilation)

4.4 Plug in HEV

This design is a modified series (or parallel) with a larger than normal battery pack that is used for extended electric only driving (typically to 40 miles), which is recharged daily. While the capital cost of larger battery packs can generally be justified by lower running costs, this mode of operation often shortens battery life and the cost of replacement batteries is significant. GM's Volt features this adaptation.

4.5 Electric Vehicles

In EVs, the whole mechanical drive train (engine, transmission etc) is replaced by electric drive motor(s). These are sized to provide the desired level of torque (for acceleration and gradient climbing), speed (for maximum speed requirements) and power (average and peak requirements). An energy storage system, typically a Li Ion battery pack, replaces the fuel tank to provide an energy source. The 'tank to wheel' energy efficiency of an electric vehicle is far better than any vehicle that incorporates an internal combustion engine, conventional or hybrid.

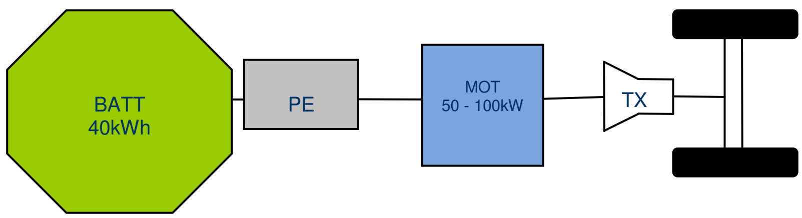

Figure 18: Full Electric Drive Train
(Data Source: ITI Energy compilation)

Two examples of EVs are: the high performance Tesla (which has a 185kW motor and a range of 250 miles); and the Think City (which has a 30kW motor and a 70 mile range). Both of these will be released in 2008.

Research by ITI indicates that, despite a multiplicity of HEV and EV designs, market requirements have meant these have tended to coalesce around two basic types – the smaller 'urban' type vehicle (with a 50kW motor) and the 'performance' vehicle (with a 120kW motor). Figure 19 below shows the market segmentation and highlights the commonality.

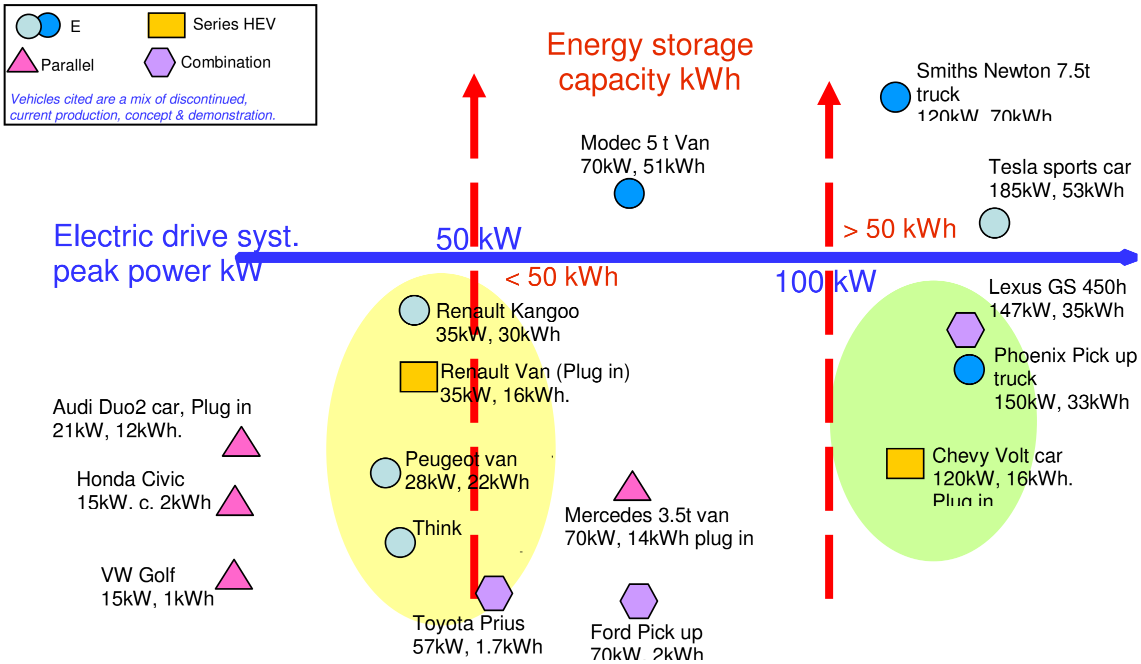

Figure 19: Market Segmentation of HEVs and EVs Showing Commonality (Data Source: ITI Energy compilation)

5. EV AND HEV COMMON COMPONENTS AND SYSTEMS

EV and HEVs consist of several key systems and components. Many of these are common to both, but with varying specifications. The following section reviews these and contrasts the needs of EV and HEV drive trains. In fact, the performance criteria required from series and plug in HEVs is very similar to that for EVs, as in all these cases the electric motor and battery are used to deliver extended electric only driving.

5.1 Battery System

In an EV, or plug in HEV, the battery pack typically cycles from 100% to under 20% state of charge daily; while an HEV pack is cycled less deeply many times daily between pre-determined limits (for instance between a 80% and 60% charge). As deeper cycling can damage batteries, a shallow cycled hybrid pack will typically last several years longer than an EV, or plug in HEV, pack.

In HEVs the energy storage capacity requirement is typically a factor of up to ten times smaller than in an EV. However, because the HEV battery pack is regularly subjected to short bursts of fast charging from the ICE, higher rate of charge is required.

Although matching the performance of conventional vehicles is seen as a critical criteria for mass market entry by EVs, energy, not power density, is a key design constraint in EVs – because of the lack of battery range extension support from the HEVs ICE.

Only introduced in the last few years to vehicles, new Li Ion battery technology represents the current state of the art in energy and power density – being 2-3 times greater than earlier NiMH batteries. Even so, power and energy density remains a fraction (under 5% by volume) of that of diesel or gasoline. This, coupled with relatively low operating lives, high costs and slow recharge times, presents key challenges for HEV and EV designers.

Battery Management System (BMS) technology is used in both EVs and HEVs. A BMS manages: battery charging and discharging, cell balancing, prevents overcharging, while providing state of charge and state of health information.

5.2 Regenerative braking systems

In most HEVs and EVs, regenerative braking systems capture a proportion of the kinetic energy dissipated during deceleration. This serves to extend the range of the vehicle. However, only a relatively small proportion of energy is actually recovered this way, because of current system design limitations. In theory, better regen systems would improve the fuel efficiency of the HEV by up to 15% (and extend the range of EVs by an even greater percentage).

Supercapacitors appear well suited to regenerative braking applications in HEVs and EVs. Their development for this application is well advanced, although various sources have indicated that the number of units required to provide suitable operating voltages for EV/HEV applications makes their effective integration and control problematic. Typically, an EV would have a larger bank of supercapacitors than an HEV because they would be used to provide a power boost to the EV motor.

5.3 Motors and Generators

Series and plug in HEVs, like EVs, need motors capable of providing power and torque without assistance from an ICE. Depending on the performance requirements of the vehicle, these motors could range in size from 50-185kW.

Generally all electric motors used in current generation EV/HEVs exhibit extremely flat torque curves, from zero rpm rotational speed. Motor speed is matched to how the motor/generator is used in a vehicle. For instance, a motor/generator packaged into a parallel hybrid will be tuned to a similar speed range to the section of the drive train into which it is integrated. For EVs and series HEVs, standard configurations of motor designs can be geared down to provide suitable rotational speed outputs to suit a conventional axle; or the motor may be matched to wheel speeds for EVs and series HEVs in the case of hub motor configurations. Generally, there is no reason a 50kW motor, for example, used in an HEV could not be used in an EV.

5.4 Power Electronics

Power electronics (PE) play a key interfacing role in the management of electrical power – and in the conversion of electrical power to mechanical motion in both HEVs and EVs.

The table below summarises some of the commonalities between an EV and HEV drive train systems.

	Specific to EVs	Commonality	Specific to HEVs
Battery Systems	• Higher energy density • Larger battery pack size • 1-2 full charge – discharge cycles/ day • Operates at 20-100% state of charge	• Can use similar chemistries – eg Li ion • BMS/EMS to manage pack and safety/thermal/ regen features	• Higher power density • 10's of charge - discharge cycles/day • Operates at c. 60-80% state of charge
Regenerative braking Systems inc Supercaps	• High regen increases range	• Regen system eg supercaps	• High regen used to increase efficiency
Motors & Generators	• Generally larger motors • No generators	• High torque/high power density/ high efficiency critical features	• Generators
Power Electronics	• More PE components required • Higher power levels to control and manage	• Need low cost, reliable and durable power electronic components	• Higher temperature environment

Table 4: Commonalities between HEV & EV Drivetrain Systems (Data Source: ITI Energy compilation)

Differences between EV and HEV drive train power electronics specifications are mainly driven by power specification of the motors and generators for a given vehicle. In some cases, an HEV represents a more challenging operating environment than an EV, because of the higher temperatures generated by the ICE. However, usually, PE for an HEV could be applied to an EV for the same applications.

6. AREAS OF OPPORTUNITY

There are a number of common components being used in HEVs and EVs. The mass production of these, for the HEV market will reduce their costs, which will have a knock on effect on EV costs.

Several beneficial areas of opportunity have been identified which relate to these common systems and components. Opportunities with significant potential are summarised below. They are fully documented in the attached Appendices.

6.1 Energy storage, management and recovery

Energy storage represents a significant part of the higher upfront costs of HEVs and EVs. Currently, battery size, weight and cost, coupled with relatively poor operating lives, low energy and power density (relative to fossil fuels) and slow time to charge, present major challenges to the market entry of EVs and HEVs. More recently, the adoption of higher energy density technology like Li-ion has brought several safety concerns. All of these issues make vehicle battery development a major area of opportunity.

The development of an Energy Management System (EMS) to enable improved condition based monitoring of drive trains (including battery cells), and to provide better management of EV and HEV sub-systems (the battery pack, supercaps etc) is also seen as a significant area of opportunity. Technological breakthroughs in this area could offer opportunities to significantly cut the whole life costs of EVs, by effectively managing and extending battery life. It could also improve the operating range by more effectively managing regenerative energy, particularly for supercapacitors. Vehicle safety would also be improved through more effective battery condition and state of health monitoring.

6.2 Motors & generators

For EV and HEVs, the key motor related issue is reducing cost per kW, while maintaining high power density, torque factors and efficiency.

A significant opportunity identified in this area was the development of alternative (or ‘synthetic’) permanent magnet materials – the global supply of rare earth material (from which to manufacture permanent magnets) is limited and finite. It is reported that 90% of known sources are controlled by China. This creates risk for future growth. It is evident that R&D to enable alternative lower cost materials with similar properties would be extremely valuable to both the automotive industry and the electronics industry in general. Equally important could be the development of a robust, reliable, low cost, high power density alternative to the permanent magnet motor. This is likely to relate to induction or switched reluctance technology.

6.3 Power electronics & control

The electrical power requirements associated with HEVs are about 25 times that of a normal car, with a full EV requiring the management of a further two to three times more power. This is creating significant PE management issues.

A significant opportunity has been identified in this area related to high temperature dielectrics/magnetic materials. The availability of materials with an ability to demonstrate: thermal stability up to 250℃; bulk manufacturing potential; electrical operating stability over a range of -40℃ through to +150℃; good electrical insulation strength; and a wide range of thermo-mechanical compatibility, are now cited as a significant barrier to cost effective design of EVs.

New materials which would enable the manufacture of capacitors or magnetic components able to operate in EV environmental conditions would command significant interest. New polymer based dielectric materials for capacitors or encapsulants for packaging are seen as a significant opportunity. For capacitor applications, the material would also have to demonstrate high dielectric permittivity. Ideally, the capacitor polymer would need to be a solid material, while the packaging material will need to be a curable liquid.

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8) Based on data from Ref 7, Table 7.12 (for HEV numbers) and Table 7.13 (for EV numbers)
9) Based on data from Ref 7, Table 7.13 (for EV numbers)
10) 'Development of Li Ion Batteries with High Power Density', presentation by Tatsuo Horiba, Shin-Kobe Electric Machinery Co at Advanced Automotive Battery Conference, San Francisco, 2004
11) Based on figure from Ref 5, Figure 2-5
12) Based on figure in Ref 5, Figure 4-1
13) Based on figure in Ref 5, Figure 4-3
14) Based on data in Ref 4, page 3 Summary Table; Ref 5, Figure 4-3; and Ref 7, Table 7.12
15) Based on data in Ref 14
16) Based on figure in Ref 5, Figure 4-2
17) Based on figure in Ref 5, Figure 4-4
18) Based on data in Ref 5, Figure 4-2; Ref 7, Table 7.13
19) Based on data in Ref 18
20) Based on figure in Ref 4, Chart X-4
21) Based on figure in Ref 4, Chart X-5

APPENDIX 1: Energy Storage, Management & Recovery

1. Current State of the Art

Batteries, whilst being a core enabling technology for electric vehicles, are often seen as their 'Achilles heel' and represent the single highest cost item in both HEVs and EVs. However, high cost is not the only significant issue associated with them and the introduction of the HEV in the late 1990s was seen as an engineering compromise to overcome their power and energy limitations. As a result of these (and other) short-comings, significant R&D effort is going into delivering superior energy storage technology. This is not limited to improving the chemistry and structure of batteries, but also encompasses developing alternative storage technologies like supercapacitors and better methods of managing and recovering (regen) energy.

The demands on storage technologies diverge between HEVs and EVs, with the presence of duplicate power trains in HEVs meaning there is a greater need for power, whereas in EVs there is a greater need for energy (while still delivering sufficient power for urban, or other, driving modes).

Currently, virtually all HEV and EV designs use batteries as their main energy storage medium and Lithium Ion offers both superior energy and power density to other battery chemistries. As a result, it is likely to become the dominant battery design in both HEVs and EVs in the medium term, once safety concerns have been addressed.

Ultra, or super capacitors which could potentially offer far superior power density and operating lives to batteries, could be used to complement, or even replace, them – if new designs can cut energy costs by an order of magnitude (at present supercapacitors cost around $3,500/kWh vs $450/kWh for Li Ion batteries).

Managing energy from a variety of systems on board HEVs and EVs presents a major challenge to designers. Consequently, energy management system technology continues to evolve to address this problem.

2. Market drivers, players and opportunities

Energy storage represents a significant part (often over 30%) of the component costs of HEV drive-trains (around $2,000 for a low volume production model). This cost rises to over 60% in EVs (around $17,000 for a low volume EV model). Thus any drop in the cost of energy storage will be a key enabler for entry by electric vehicles into the mass automotive market.

Research commissioned by ITI Energy indicates that the market for energy storage devices for electric vehicles should be around the $2Bn pa mark by 2010. This is backed up by market research by BCC[1] which indicates a similar figure and sustained growth of over 20% per annum out to 2010. As the key drivers of this market are unlikely to have reduced by then, growth beyond this point is likely to be strong.

Annual market sales $ million	**2003**	**2004**	**2005**	**2010**
Energy storage devices (batteries, supercapacitors)	136	288	675	2063

Table 1: Global market for energy storage devices in mild and full HEVs through 2010 (Data Source: BCC Inc) [2]

In addition to the electric vehicle markets, some form of energy storage system is utilized in conventional and fuel cell vehicle designs to provide electric power and to store energy generated by regenerative braking systems. There are several other well established multi-million dollar markets for lower power storage devices, ranging from military communications applications to toys. Thus the overall market for energy storage devices is very large and many of these markets will provide certainty of earnings for suppliers, enabling scale economies to be applied to the manufacturing of HEV and EV batteries.

In 2005, according to BCC, the two key suppliers of nickel-metal hydride (NiMH) batteries for electric vehicles were Panasonic EV (60% of the market) and Cobasys (29%), with the remainder covered by Sanyo (6%), UQM (3%), and others supplying the remaining 1% of the market. As yet, there is no known mass production facility for automotive specific Li Ion batteries in operation. However, the Johnson Saft Li ion automotive battery factory opened in Nersac in France in February 2008 is meant to be scaleable to accommodate increasing demand. Initial deliveries from this factory are believed to be destined for the Chinese automotive market.

It is highly likely that all the global car manufacturers currently marketing HEVs are actively engaged in energy storage R&D. In addition, there are at least as many global component suppliers, such as Sanyo, Johnson Controls, Sony, Matsushita and Siemens, involved in this area.

Panasonic EV is a JV part-owned by Toyota and reflects both Toyota's strategic decision to produce all core HEV components (the motor, the batteries and the power inverters) in-house and its dominance of this market. It is believed that Panasonic supplies all the key HEV manufacturers currently in the market with hybrid batteries.

Cobasys is a hybrid battery joint venture of Chevron and Energy Conversion Devices. In 2003 the JV completed a plant with the capacity to build over 2 million NiMH batteries annually.

A summary of the key market drivers for automotive energy storage technology includes the following:

- A high safety rating (tolerance to impacts, high temperatures etc)
- A high energy density and power density
- A low cost per kWh delivered
- Low weight and low volume
- Long useful life of hundreds of thousands of cycles
- A tolerance for a range of discharge depths
- An ability to operate in a range of temperatures, between -20 to +50 C
- A high rate of charge and discharge when required
- An ability to deliver a sustained and high level of charge
- An ability to capture energy from braking

The table below attempts to summarise the current performance of several technologies that could be used for energy storage against some of these key challenges. It is meant to illustrate relative differences between technologies, as there is considerable range in these figures depending on what source is being used.

	Batteries			Supercaps				
Evaluation criteria	Lead Acid	Nickel Metal Hydride	Lithium	Current	Advanced	Flywheel	Compressed Air	Gasoline
Energy (Wh/kg)	30	70	120	5	60	3	59	11660
Power (W/kg)	160	500	1000	3500	100000	1100	not known	not applicable
Operating life (cycles)	1k+	3k+	3k+	100k+	300k+	100k+	100k+	not applicable
Cost $/kWh	100	500	700 (450)	3570	not known	3000	100*	not applicable
Cost $/kW	9	45	41	18	not known	6000	820*	not applicable
Safety issues	robust but toxic	robust	critical failure modes (except in phosphates)	robust	robust	gyroscopic effects, physical storage medium	physical storage medium	flammable

Table 2: Technology comparisons (Source: ITI Energy compilation)

Overall, as indicated earlier, there appear clear advantages in using batteries for energy applications and supercapacitors for power applications. This issue is explored in more detail below. Within the batteries, Li Ion batteries appear superior to nickel-metal hydride (NiMh) batteries, but appear more expensive. However, to date, no mass manufactured automotive specific Li Ion batteries are being produced and consultants employed by ITI Energy are indicating that costs of $450/kWh are likely in the near future. This is considerably more than lead acid batteries, but these offer such poor energy density that they have proved unsuitable for HEVs and EVs.

Gasoline clearly stands out as a superior energy source in terms of energy density when set against the capabilities of these storage technologies, particularly if one considers that the US pump cost of gasoline is around \$1.2/kWh (based on an energy content of 9.7kWh/liter and pump price of \$1/liter). However, it would be more appropriate to compare this against the cost of electricity, which presently is about 9c/kWh for US residential customers. In addition, the conversion of gasoline (or diesel) to locomotive energy is far less efficient than in electric powered vehicles. Research commissioned by ITI Energy indicates that electric vehicles typically require a third as much energy as conventional vehicles to travel the same distance (0.6 MJ/km vs 1.5MJ/km+).

3. Technology Challenges

Battery energy and power density

In batteries, power is dependant on the area available for electron transfer and energy depends on the quantity of active material present in the electrodes. As both are characteristics of the electrode, they are difficult to separate. However, it is possible to optimise the battery for a particular functionality – ie, high surface area means more power; and more dense electrodes means more energy.

New Lithium Ion (Li Ion) battery technology shows a considerable increase in energy and power density, relative to earlier nickel-metal hydride (NiMH) batteries). Lithium has several key properties that are highly prized in battery materials; in particular light weight, high electrochemical potential and the ability to be fabricated into a variety of shapes. Lithium group batteries, (including Lithium-ion designs), have double the specific power and energy of NiMH batteries and nearly four times their cycle life.

However, disadvantages include their higher costs and greater volatility compared to other battery chemistries. Further incremental gains in this chemistry can be expected in the next ten years. A battery technology based on Lithium polymer chemistry – where a flexible polymeric material serves as the electrolyte – is expected by many observers to emerge as a good candidate for automotive use.

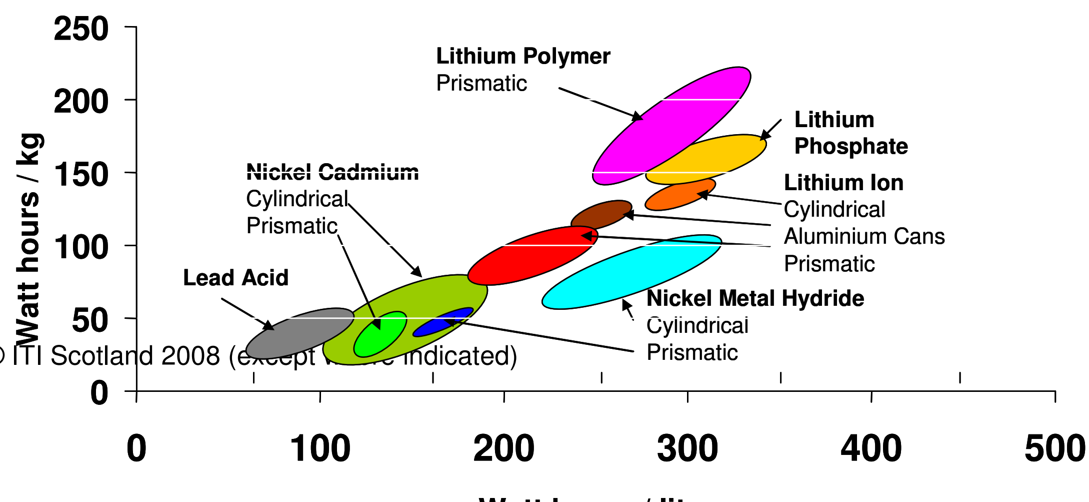

Figure 1: Battery comparison in terms of energy and volume
(Source: Axion Power) [3]

The figure above summarises the relative energy density of differing battery chemistries and shows the clear advantages of Li Ion chemistry.

On the back of Li Ion batteries, car designers like Tesla have been able to develop high performance EVs with similar acceleration and top speeds as ICE vehicles. Despite being more expensive than NiMH batteries, ever increasing demands to raise battery performance for both specific power and range, mean Li Ion batteries should become the dominant vehicle battery chemistry in the medium-term.

It is expected that current concerns about Li-Ion safety can be overcome by use of a more stable chemistry, but solving this issue may delay mass introduction of Li-Ion batteries by the conservative global auto-manufacturers by one to two generations of HEV (or approximately five+ years[4,5]).

Outside battery chemistry, improvements to the design of anodes and cathodes at 'nano' level could also deliver 'denser' energy and power from batteries by effectively increasing the area available for charging or discharging ions.

Battery size and weight

A corollary of the lower power and energy density of batteries (relative to gasoline, for example, as shown below) is that to deliver the requisite vehicle performance requires a large battery – therefore improving energy density is crucial for the HEV/EV market.

Energy density Wh/kg	As stored	After motor conversion
Gasoline	11660	2915
Electricity (Li Ion)	130	111

Table 3: Energy Density of Gasoline vs Li Ion batteries
(Source: Institute of Transportation Studies) [6]

Battery size and weight has come down as battery chemistry improves (and is likely to continue to do so). But because of the limits of battery power and energy density, they still represent a significant part of overall car weight (a 400kg battery pack in a 1200kg saloon being typical).

The limited depth of discharge (DoD) cycles most batteries can currently deliver, along with their resulting over-sizing, means a battery that could reliably deliver a required cycle life at 80-100% DoD could be made much smaller and lighter. As a device, these would cost significantly less than batteries that are currently designed for ~20-50% DoD. However, it is not clear how this could be achieved as, presently, very deep discharges do irreversible damage to batteries.

Battery life

The recent withdrawal by Toyota and Honda of high voltage battery warranties that extended to eight years and covered 100,000 miles, reflects ongoing issues with battery durability that continue to affect HEV (and EV) competitiveness. It is the number of cycles and the depth and rate of discharges (or recharges) a battery experiences that primarily affects its useful life and in this regard, their use in an EV (or HEV) proves extremely challenging. In EVs, or HEVs where more reliance is placed on the battery to supply motive power, deeper discharges mean batteries are currently lasting around 3 years, with less deeply cycled ones lasting around 5 years. Given the significant cost of replacement and the considerably longer expected life of the vehicle they are in, this has a major and adverse impact on the economics of electric vehicles.

There are several solutions being developed to limit the depth and rate of discharge. The key principle used in these is 'buffering' (to protect the battery cells from excessively deep or steep dis/recharging). In parallel HEVs, the ICE acts as a buffer for the batteries (hence their longer battery life vs EVs and Series HEVs at the moment). Another buffering solution would be supercapacitors (which could be used in both HEVs and EVs) and/or some form of sophisticated energy (rather than 'battery') management system (EMS).

Battery recharging

Some 5-10% of the energy put into a lithium battery is lost during charging and another 5-10% is lost during discharge (and this chemistry is superior to others). However, this rate can vary significantly, depending on the rate of discharge. Several methodologies are being proposed to improve these efficiencies.

At present, EVs like the Tesla take 3-4 hours to fully recharge because of constraints designed to prevent battery damage. One method to facilitate faster charging would be to rely on trickling power into the battery – eg, by using supercapacitors to buffer an initial fast charge. Another method would consist of increasing the surface area of the electrodes to facilitate faster/more efficient charging. A number of manufacturers (A123, AltairNano, Toshiba) are now claiming to have cells that can be recharged in considerably shorter times because of increases to the available surface/electron transfer area of their batteries.

Battery cell chemistries also suffer from parasitic losses – in the case of NiMH, of around 30% of its stored energy per month. Lithium Ion is more efficient in this respect and discharges around 5-10% per month. Generally, however, this would not be an issue because batteries will be recharged at daily intervals.

Regenerative energy recovery

It is apparent that, despite featuring regenerative energy recovery systems, current generations of EVs and HEVs recover a relatively small amount of kinetic energy on a typical urban drive cycle.

Modelling work recently carried by Warwick University for ITI Energy to explore regenerative braking opportunities for EVs, indicated that up to 20% range increase could be enabled on urban duty cycles, if the available kinetic energy recovery could be optimised. Key issues associated with this are:

- Maximum rate that the energy storage medium (eg batteries) can accept inputs during high braking events
- The maximum regen rate that the electric drive motor can deliver when used as a generator
- Recovery of low grade energy under low levels of acceleration and deceleration
- Potential effects associated with vehicle driveability and stability under optimized regen conditions

Achieving 100% regen recovery would require a system able to capture energy from the extremes of energy recovery conditions, namely from stop-start / low speed 'low grade' braking events and by 'high grade' energy generated from high speed braking. This technology would be common to both EVs and HEVs, but would have more impact on EVs as range performance could be significantly improved.

Current battery-based regen systems are limited by the rate at which energy can be re-charged into the battery pack, and by the practical amount of energy that can be extracted from the regenerating motor at low speeds. Most braking (in traffic etc) occurs in under 1 second timescales and batteries are currently unable to effectively capture this energy (they generally react to 1s+ recharges). Allowing overly-rapid recharging is damaging to batteries, hence is designed out of existing regen systems.

To capture all of the potential energy available from high energy braking, it would be necessary to scale up the capacity of components involved by roughly three times the capacity they would require for normal driving modes. This is because the energy ‘pulse’ produced in a braking event is often much larger than that developed during acceleration. This is not done at present because, based on existing battery based systems, this imposes an unacceptably high weight and cost penalty.

Very little effort has gone into regenerative capture from ‘low energy’ braking. This is because of the power requirements and losses associated with boosting anything captured this way onto the vehicle bus bar, plus the additional cost and weight burden of any associated power electronics.

Kinetic energy recovery is currently a ‘hot topic’ in Formula One racing. New legislation will encourage the use of KERS (kinetic energy recovery systems). It is known that several teams are currently evaluating and developing flywheel and motor/generator/battery systems. It will be interesting to see what solutions emerge and whether these enable any significant technological breakthroughs that could be carried across into consumer automotive products. However, as noted, the energy and power density of flywheels appears to fall between supercapacitors and batteries. Being kinetic may be less appropriate for electric vehicle regen applications.

Supercapacitors

Some emerging EV and HEV designs now incorporate supercapacitors for capturing energy from regenerative braking. Solid state supercapacitors can typically absorb energy many times faster than batteries. They are much better suited to cycling (because they are significantly less affected by deep or rapid discharges) and are far lighter (supercapacitors typically having a power density of 3+ kW/kg vs 1 kW/kg in batteries). They are also superior to other possible regen solutions, like flywheels or capacitors, both of which only capture energy from very short duration braking events (of under 1 second). However, the most likely duration of these in normal driving conditions is from 0.1 to 5 seconds, which can be covered by the performance envelope of supercapacitors.

For these reasons, some designers are claiming supercaps are ideal for regenerative braking systems and could capture 90% of the energy potential available in these events. It should be borne in mind this assumes that the motor provides the sole source of braking which, in the near term, is unlikely to be acceptable to the general public. Most drivers prefer the traditional friction brake as the failsafe and primary means of deceleration.

Low power (under 5 volts) carbon based supercapacitors have been in the market for 20 years. However, because of their inherent low operating voltage, they individually deliver much less power than needed in HEV or EV applications (which could require up to 300V when braking). Supercapacitor ‘banks’ – sets of supercapacitors in series and parallel – are becoming available to provide the power capability required (PML Flightlink Ltd unveiled a HEV Mini with a supercap bank in 2007). Various sources have indicated that the number of units required to provide suitable operating voltages for EV/HEV applications makes their effective integration and control problematic. Thus there may be scope for the development of an advanced Energy Management System (EMS) which would represent an evolution of ITI's BMS programme technology.

It is difficult to determine where the costs of carbon based supercapacitors sit at present. Figures of $3,500-4,000/kWh are suggested as the best achievable within the boundaries of current technologies[7]. US developers Maxwell have claimed (in 2006) that their supercap production costs are already around this mark and that these could be halved over the next four years. Maxwell presently has a $7million co-funded program with the United States Advanced Battery Consortium (USABC) to develop better supercaps. While they are projecting prices to drop to $3,500/kWh by 2010, through the advent of 3V cells, prospects to drive costs down further are reliant on the development of 4-5V cells and the electrode technology does not yet exist to deliver this.

At $3,500/kWh, a 20kJ supercap, capable of operating for five seconds, would cost around $400. If it achieved a 20% fuel saving, based on typical US fuel use and costs, this would equate to ~$150 pa fuel saving, so its payback would be over three years. This is roughly the same as best payback times for HEVs versus conventional vehicles. But in addition, by acting as a power 'buffer', supercaps would increase the life of a vehicle's battery (by buffering it from steep or deep re- or discharges) and potentially reduce battery charge / discharge losses by efficiently trickling power into it.

Maxwell Technologies and EEStor (in the US), PML Flightlink and Nesscap (Korea), have emerged as innovative supercapacitor developers. Continental ISAD Electronic Systems GMBH also recently announced that they were developing a system capable of capturing up to 90% of energy available to regen, although it is not yet clear how this is done, whether if it has been achieved, or what the costs are.

In 2005 Maxwell Technologies supplied 44% of the supercapacitor market, Nesscap 38%, Panasonic 15% and others 3%.

Researchers at MIT[8] are claiming to have developed nanostructures that increase the surface area of supercapacitor electrodes, improving their energy density to comparable levels of NiMh batteries (of around 70Wh/kg). With a power density of 100kW/kg and a 300,000 cycle life, these designs look extremely promising. EEStor, a US company, has developed an alternative method of producing an energy dense supercapacitor. This method uses barium titanate, coated with aluminum oxide and glass, to achieve a level of capacitance that has three times the energy density of NiMh batteries[9] . On the back of this technology, they have won a large order from Lockheed Martin for small military power packs and one firm, Zenn, has also ordered EEStor packs to replace batteries in their urban EV.

But supercapacitor costs must come down significantly to compete effectively on an energy basis, as at $3,500/kWh they still compare poorly with battery costs of $450/kWh. However, their costs have come down significantly, being less than 1% of what they were 15 years ago and are continuing to fall.

Energy Management Systems

Energy Management Systems (EMS) continue to evolve in response to new cell chemistries and to a need to increase overall system efficiency, functionality, and reliability. The evolution of management system technology has already resulted in extended battery life and better control of stored energy. Theoretically, an advanced energy management system could significantly improve vehicle range and battery life (by up to 50%)[10] if several key issues, discussed below, could be addressed.

Consider the energy elements in the mix for a HEV systems, ie: the IC engine, battery charging and discharging, regen capture, motor, generator, power electronics, power split and transmission devices. Typically, these individual systems are characterized and controlled separately and their relatively unsophisticated control maps/algorithms inevitably lead to compromised system performance and inefficiency. For example, HEV systems are optimized for legislative drive cycles and motorway cruising conditions, but when vehicles are operated away from these conditions efficiencies are reduced. An advanced EMS, that could effectively integrate the management of all these diverse power requirements, would offer considerably improved vehicle performance and efficiency.

In addition, vehicle EMS development programmes are extremely costly, as systems need to be re-mapped and control strategies re-formulated each time a component or application is changed. By evolving the self learning capability of EMS controllers, these expensive development phases could be significantly reduced.

There exists an ongoing challenge to better understand and manage safety in current and 'next generation' cell technologies and to develop technologies that would enable effective fault onset identification and mitigation control actions, as there is a level of (consumer and Original Equipment Manufacturer) concern about the safety risk associated with current generations of batteries.

It is also generally accepted that current generation of electric vehicles are designed to receive full charge to battery packs overnight. However, the concept of 'opportunity charging' to enable fleets to benefit from a more flexible approach to taking on energy would be advantageous.

Energy storage system thermal management

The thermal management of energy storage systems is important for optimizing the performance and reducing the life-cycle costs of hybrid electric and electric vehicles. Temperature and temperature uniformity can both significantly affect the performance and life of energy storage devices. A battery, for example, must always be kept within a limited operating temperature range so that both charge capacity and cycle life can be optimised. This could require both heating and cooling to keep it within a limited range to achieve optimal performance.

Thermal management, however, is not just about keeping the temperature within optimal limits. A battery is subject to several simultaneous internal and external thermal effects, which must be controlled and managed. One example of this could be a shorted Li-Ion cell, which could get very hot and then damage the entire battery pack. So an effective energy storage thermal management system is required for electric vehicles and there appear opportunities to more optimally do this through, for example, better utilization of advances in materials, thermodynamics and control systems.

Vehicle ancillary system energy management

At present, the power required by the ancillary electrical systems in ordinary IC engined cars can be as much as 2kW and continues to rise. Car heating and cooling is a major consumer, however, other ancillary systems, like power steering, breaking, lighting and traction control are also important. This ancillary electrical demand becomes more of an issue for electrical vehicles, which rely on electrical energy storage systems with far lower energy densities than conventional vehicles. The technical challenges for improving some of these systems are quite unique to electric vehicles.

- Power Steering: In IC engined cars it is conventional to use a hydraulic system, the hydraulic pump being powered mechanically from the engine. But in electric cars where there is electrical power source it is more efficient to use electrical powered steering.
- Heating: In IC engined cars, it is common to use the waste heat produced by the engine to heat the vehicle. But in battery powered electric cars there is little waste heat and the required heat must be supplied from the primary energy source.
- ABS/Traction Control: The technical factors that affect and influence traction control in IC-engined cars are different from those in an electric vehicle. In IC engined cars the mechanical bandwidth of the active actuation systems often limits the performance of the traction control. However, in EVs that employ drive by wire strategies these factors can be addressed easily.

Due to limited production volumes, current generation electric vehicles generally feature adapted and integrated conventional vehicle ancillaries (eg power steering, brake boost etc). However, with the advent of increased HEV volumes there is an emergence of electric ancillary systems that are available for integration into future generation vehicles. However, it is unlikely that the current piecemeal and adaptive approach to providing and managing energy to these systems is efficient and effective and it is probable that significant technological breakthroughs in this area could lead to major benefits to future generations of EV's.

4. Findings

Significant R&D funding is being invested globally in energy storage for EVs and HEVs. Nevertheless, there appear to be several areas that where new technological solutions could address unmet market needs:

- Batteries represent a significant part of the higher up-front costs of HEVs and EVs and their limited lives means their replacement undermines the economic case for electric vehicles. Any lifetime cost reduction of batteries represents a major and ongoing market opportunity.
- While being currently associated with safety concerns, Li-Ion batteries are expected to enter the market as the battery of choice in the next few years for HEVs and EVs, due to their superior energy and power density. Both of these attributes are likely to improve over the next 10+ years, as are their costs, further enhancing their competitiveness.
- Since the industry continues to focus on the issue of battery and whole energy system management, it appears that technology in this area is set to evolve further. A system that could integrate a number of functionalities, going well beyond measuring the state of charge of the battery, would be highly advantageous. Possible functionality of such a device would ideally include proactively detecting cell or battery pack faults. Functionality to initiate mitigating actions to safeguard battery life and integrity, as well as a capability for managing and optimising the interaction between different energy devices, would also be desirable.
- Supercapacitors appear well suited to regenerative braking applications in both HEVs and EVs and could raise regen effectiveness, which in turn could produce fuel savings of up to 20% in a vehicle. However, the development of supercapacitors seems well advanced and there appear few opportunities to further improve them, other than in the area of new Energy Management Systems (EMS) capable of efficiently and effectively managing a bank of supercapacitors in a vehicle.
- The development of a low cost method of creating high surface area electrodes with low electric field intensification, is now a key technology enabler for increasing the energy density of both battery and supercap technologies.

Appendix 1 References

1) ‘Components for Hybrid Electric Vehicles, Business Opportunity Report’, BCC Inc, 2006
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APPENDIX 2: MOTORS AND GENERATORS

1. Current State of the Art

The majority of electric motors are designed to convert electrical energy into rotary mechanical energy. However, the reverse process is achieved when mechanical input energy is used to spin the motor (ie, it acts as a generator) such as during a braking event. For Electric and Hybrid Electric vehicles to ensure optimum energy efficiency, electrical machines must be capable of operating in both modes.

Although this document shall focus solely on electric motors, it is acknowledged that most electrical machines being considered for EV/HEV applications operate using multiphase AC. This in turn means that they rely on power electronic variable speed drives to convert the available DC voltage to multi-phase, variable voltage, variable frequency AC. The close coupling between drives, machines and functional requirement means that there is no single ideal solution and combination or configuration of some can be more efficient than others when used for different purposes. To make a good assessment, maximum efficiencies should not be compared, but the overall efficiency over a representative speed, load and duration cycle[1].

Fundamentally, motors can be split into two major groups: AC and DC. Traditional traction motors are series-wound DC types. The primary characteristics of series-wound DC traction motors are[2]:

- Maximum torque is achieved when the motor is stationary
- Maximum power output is achieved at high rpm
- Current increases with rpm
- The motor maximum speed is limited only by friction and windage losses (which means that it is possible for an unloaded motor to run away to destruction)

DC motors are generally less efficient than AC motors; a DC has typically 80% of the efficiency of an AC motor. The losses are characterised by heating of the windings. Eddy current losses in the magnetic material also cause heating[3].

AC motors are available using a variety of technologies[3]:

- Multiphase, multi-pole
- Permanent magnet
- Induction
- Switched Reluctance

- Segmented Electro Magnetic Array (SEMA)

Most AC traction motors are of three-phase design and typically four pole. However, it is possible to construct six phase or greater; it is also possible to construct motors with more poles. More poles reduce 'cogging' ie, smoothing out rotational low speed variation effects inherent in conventional AC motors. Cogging can also be reduced by techniques such as overlapping the field windings[3].

Again, most AC traction motors are of permanent magnet design, usually using neodymium magnets for maximum efficiency, especially where higher-frequency switching is desired[3].

Switched Reluctance machines tend to be more expensive than permanent magnet designs. However, they offer a number of advantages, including[3]:

- Low sensitivity to temperature
- Flat torque/speed curve to zero rpm
- Rapid dynamic response owing to the lightweight rotor design
- High reliability

Figure 1 below shows technology assessment of various motor technologies:

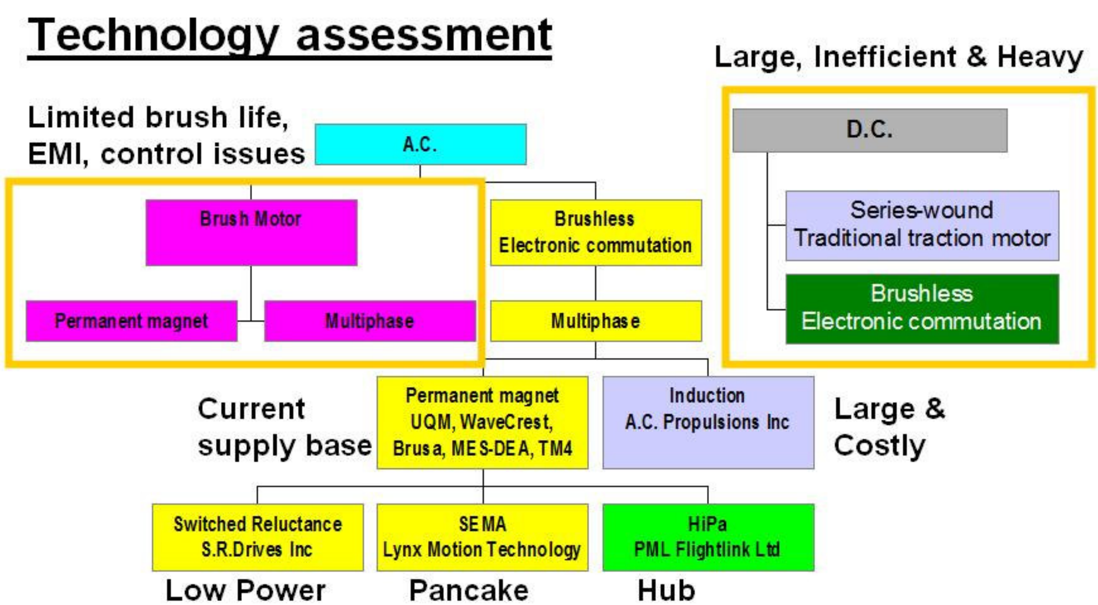

Figure 1: Technology Assessment of Electric Motor Technology (Source: Lotus) [4]

Switched Reluctance machines have technical disadvantages, the most important of which is the complex drive circuitry needed to commutate them. They are usually three-phase, but each winding needs to be separate and driven independently. This means that more discriminating position sensing is necessary to obtain good phase control than is the case with other three-phase designs[3].

Most AC electric motors achieve over 90% energy conversion efficiency over the full range of speeds and power output. They can be precisely controlled to provide the high torque required by vehicles, eliminating the need for big gearboxes and torque converters. The Tesla Roadster has only two forward gears and has a motor efficiency between 85% to 95% using an induction motor.

Table 1, below, summarises the above and compares different types of motors used in hybrid vehicles, showing the advantages and disadvantages of various AC motor types when used in electric vehicles.

	Motor Type				
Motor Parameters	Asynchron -ous	Permanent Magnet	Switched Reluctance	Direct Current	Synchron -ous
Motor size mass	0	+	0	-	0
High speed	+	+	+	-	-
Endurance maintenance	+	0	+	-	-
Efficiency	0	+	0	-	0
Controller size mass	0	0	0	+	0
Controllability	+	+	-	+	0
Number of power devices	0	0	+	+	0
Reliability	0	0	0	0	0
Total	+++	++++	++	-	- -

Table 1: Comparison of Different Motor Types used for Hybrid Electric Vehicles (Source: BCC Inc) [5]

The high price of the magnets and more complex motor construction means permanent magnet motors are currently at least twice as expensive as asynchronous motors. However, their superior power to weight ratio means they are the dominant motor design.

An alternative to permanent magnet design is an induction motor, which has no magnets. Instead, they employ both field windings and armature windings to produce the field. This has the advantage of reducing weight, at the expense of increased size for a given output. Induction motors are very robust and rather more tolerant of heat than designs using permanent magnets. Standard

Neodymium magnets can suffer permanent damage if exposed to temperatures above 80ºC (though high temperature magnets are available allowing use up to 150 - 180ºC)[3].

2. Market Players/ Opportunity

Motors have only been commercially deployed in vehicles for about 10 years and, in the academic sector, EV/ HEV research in electrical engineering is rapidly becoming the dominant research topic for machine/ electric drive groups.

The majority of EV motor suppliers cater for either low-power applications such as cycles and motorcycles, or for heavy vehicle applications such as delivery vans and light trucks. Few can offer motors sized for passenger car use. A consequence of this is that motors powerful enough to offer the performance required of a small dynamic EV are often too heavy and/or bulky to be practical[3].

Due to the secretive nature of the industry, it is very difficult to precisely determine the motor technology used in commercial vehicles. The following case study of motors and generators in some of the top selling Hybrid Vehicles, and in the new Tesla Roadster full EV, is designed to summarise the current State of the Art.

All the models described use the motors for regenerative braking to recover energy. From this list it is evident that permanent magnet AC synchronous motors currently dominate the market, due to their superior power density and torque generation – and despite their significantly higher cost. It is also apparent that many manufacturers are developing standard drive train designs that are used for several models.

To date, there appears to be no standardization of hybrid components. Major hybrid vehicle manufacturers, such as Toyota and Honda, design and manufacture their own electric motors. As these two companies dominate the hybrid market it has been difficult for tier 1 companies to secure entry, but this situation is expected to change as electric motor manufacturers become increasingly attuned to the potential of this market. Vehicle manufacturers (other than Toyota and Honda) are more likely to look to outside suppliers, since motor manufacturing is not their core business[1]. Some of the leading global electric motor manufacturers are Aisin, Hitachi, Robert Bosch, Valeo, ZF, Wavecrest and Siemens VDO.

Model	Type	Bus voltage	Power (kW)	No. of motors	RPM	Motor type
Toyota Prius	HEV	500	50	1	1,500	Permanent Magnet Synchronous AC
Honda Insight	HEV	144	10	1	3,000	Permanent Magnet Synchronous AC
Honda Civic	HEV	158 DC	15	1	3,000	Permanent Magnet Synchronous AC
Honda Accord	HEV	144	12	1	840	Permanent Magnet Synchronous AC
Ford Escape	HEV	330 DC	70	1	5,000	Permanent Magnet Synchronous AC
Toyota Highlander⊗	HEV	650 AC	123 (front) 50 (rear)	2	4,500	Permanent Magnet Synchronous AC
Tesla Roadster	EV	375 DC	185	1	13,000	3 phase 4 pole induction

Table 2: Different Motor and Generator Ratings in Hybrid Electric Vehicles (Source: ITI Energy compilation)

After batteries, motors are the most expensive component in HEV/EVs – costing in the region of $12-20 per kW for asynchronous versions and $25-50 per kW for permanent magnet versions. The high cost and security of supply of permanent magnets is a continuing concern for the automotive industry. It follows that credible alternatives to this technology are likely to attract attention. For example, US start-up venture Raser Technologies Inc (http://www.rasertech.com) has patented an alternative design of an asynchronous induction motor which, it is claimed, can deliver high torque without the need for permanent magnets. They have recently signed up with an automotive OEM to deploy this in a plug-in hybrid vehicle.

The market for HEV/EVs is likely to see sustained and rapid growth (over 20% pa) for at least the next ten years. This demand will be driven by government policies in the developed world seeking to address air quality, climate change and energy security issues. Based on a current market of around $300m pa, the global market for electric motors for HEV/EV applications is expected to reach $2bn by 2015 (see also table 3).

⊗ *Lexus RX-400h, Harrier and Kluger hybrids use essentially the same drive train.*

Annual market sales $ million	2003	2004	2005	2010
Motors, Generators and Intelligent Power Units	63	135	314	901

Table 3: Global market for Motors and Generators used in mild and Full HEVs through 2010 (Source: BCC Inc) [6]

Although cost is a prime driver for the automotive sector, reliability (especially the cost of recalls) means that fundamentally the industry is conservative to radical changes in technology. Consequently, any alternative motor technology will have to address the barrier of proving itself in the robust environment encountered by vehicles – therefore testing could become a major cost issue for small developers.

Considering the development cycles associated with EV/HEVs, vehicle manufacturers will continue to pursue iterative strategies where OEMs will continue to chip away at the presently non-competitive cost EVs and HEVs for over a decade to come.

3. Technology Challenges

Presently, over 50% of the world's generated electricity is converted back into mechanical motion – usually rotational. In nearly all cases, this is in fixed installations and (relatively) controlled environments where size and weight are not major considerations. For EV/ HEV the key driver is to reduce the cost per kW of motors, while maintaining high power density and torque factors. The key technology challenges to achieving this are:

a. High efficiency, low mass materials for stator and rotor
b. Mechanically and environmentally robust drives
c. Improvements to regenerative energy recovery
d. Design for drive train integration
e. High temperature machine operation
f. Thermal management in extreme environments
g. Integration of electromagnetic, mechanical and electrical drive systems (Packaging)
h. Fault tolerance (eg, multiphase motors that would allow 'limp home' in the event of a phase failure)
i. Higher energy density (eg, multiphase motors that offered higher energy power output per rotor revolution)

The choice of motor and its subsequent design may end up being significantly different, depending on the technology selected to transfer energy to the wheels, as illustrated below.

For parallel HEV designs it is highly likely that the electric motor will be required to operate at same rotational speed as the ICE (ie, up to 7,500 rpm). However, for series HEV and EV designs where direct to wheel drive techniques are employed, motor speeds may be significantly less (< 1500 rpm).

Several companies have developed technologies to make wheel hub motors feasible. PML Flightlink Ltd have developed a wheel motor called the Hi-Pa drive which provides low speed – high torque in a lightweight flat package. Utilizing permanent magnet technology, it delivers 120kW peak power at around 98% efficiency. Several other global manufacturers, small and large (eg Siemens), are involved in wheel hub motor technology development. Whilst there are obvious advantages (such as parts count and cost reductions) for series hybrid and electric vehicles, it is unclear whether these units will predominate in the future. Alternatively, the Toyota type systems (ie, combination hybrid with pancake / compact motors being integrated in transmission cases) may prevail. Unit cost will probably drive trends in mainstream applications and efficiency / packaging flexibility will predominate niche vehicle applications.

Of the motors highlighted in table 1, only three are likely to be serious contenders for EV/ HEV application:

i. 3 phase, multipole asynchronous induction motor: these are the most common form of motor in static applications. They are cheap to produce, but their disadvantages are that they suffer from relatively low torque, low power density and liability for torque slip. Control of these machines is relatively straightforward using variable-speed drive power electronics.

ii. Permanent magnet synchronous motor: this is presently the motor of choice for EV/ HEV applications, due to its high power density and torque. Their disadvantage is that they are not good at low speeds (struggling to generate initial inertial torque) and are sensitive to voltage variation – which is particularly relevant to islanded electrical systems, such as an EV where bus voltage regulation will be a significant issue.

iii. Switched reluctance motor: this motor is probably the cheapest to produce and can deliver high power density. However, they do have the disadvantages of more complex drive electronics and high torque ripple at low speed. Noise may also be an issue, along with problems ensuring the tight clearance gap between rotor and stator over the temperature operating range.

In all cases, these motors require control electronics that convert the DC from the battery supply to multi-phase variable voltage AC. Since motors are normally located in mechanically robust housings, the challenge is to more closely integrate the control electronics with the motor in the same housing. This has the advantage of minimising wiring and optimising thermal management strategies.

Another important feature of the electric motor is to enable capture of kinetic energy and convert it to electricity, under deceleration. This is achieved by reversing the function of the electric motor, using it as a generator. Although this is a key feature of EVs and HEVs, a relatively small amount of energy is captured in this way with the latter. The opportunity criticality for electric vehicles is much greater. Every unit of energy captured and re-used in the drive of an electric vehicle increases not only the energy efficiency, but also increases the range of an EV. This is one of the most important limiting factors considering cost, size and weight of battery packs,

4. Findings

The electric motor has been in use for over 120 years. However, the challenges presented by the automotive industry mean that there is now a demand to re-address what has been long considered to be a mature established technology. The study has highlighted a number of development opportunities, including:

- Alternative (or 'synthetic') permanent magnet materials – although permanent magnet motor technology comes out on top, it is apparent that global supply of rare earth material (for the manufacture of permanent magnets) is finite. It is reported that 90% of known sources are controlled by China, which creates significant risk for future growth. It is evident that R&D to enable alternative lower cost materials with similar properties would be extremely valuable – for both the automotive and electronics industries in general

- Alternative (fundamental) materials for future manufacture of motors – it is apparent that development of motors / generators continues at a pace, with a lot of 'evolutionary' activity from tier 1's, 2's and research establishments. However, it is possible that adequately challenging objectives (cost down, weight, efficiency etc) could yield lucrative IP for products targeted at a 2015 time frame. This IP would probably get the attention of key tier 1's and 2's

- Increased efficiency multiphase asynchronous motor technologies – these may be induction or switched reluctance. Developing a robust, reliable, low cost, high power density alternative to the permanent magnet motor is likely to be of significant interest to the automotive industry – and would address security of material supply issues. Ability to be fault-tolerant and less sensitive to voltage fluctuations in the supply would also be desirable characteristics.

However, it should be noted that the leading OEMs like Toyota, Honda and their tier 1 suppliers, all consider motor technology to a be core area and prefer to develop in-house technology, making market entry for niche players a challenge.

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3) 'Future Automotive Systems – Foresighting Study', Lotus Engineering, 2008
4) Based on Ref 3, Figure 5-1
5) Based on Ref 1, Table 12
6) Based on Ref 1, Summary Table p xxv

APPENDIX 3 POWER ELECTRONICS

1. Current State of the Art

Power electronics are systems products integrating semiconductor devices, electronic components (eg, capacitors, inductors, resistors), circuit boards and other mounting hardware and software. Power electronics play a key interfacing role in the management of electrical power and the conversion of electrical power to mechanical motion. They are the means by which the control instructions issued by the vehicle management software are implemented. Power electronics systems are themselves intelligent, utilising local embedded control software (managed by dedicated digital signal processors) to ensure that instructions received are translated into safe operational actions.

Power electronics are already widely used in conventional automotives, for applications such as windscreen wiper control and electronic ignition. However, for a hybrid vehicle the electrical power requirements are typically in the range of 30kWe to 50kWe – about 25 times that of a normal car[1] with a full EV requiring the management of a further two to three times more power than this.

The term 'power electronics' relates to a number of individual building blocks that will be needed to implement a hybrid or electric vehicle, as illustrated in figure 1. Each of these blocks represents different control functionality and power levels being managed, hence there is no single generic design or configuration that can be applied universally to a car. In essence, there are three types of power electronic application:

- DC-DC converters/ controllers: these regulate the flow of electricity between two DC components. All designs of this nature are able to buck or boost the DC output voltage to achieve power flow across the controller. The level of buck/boost required greatly influences the application design

- DC-AC drives/converters: these convert DC to polyphase AC – usually to regulate the speed of the motor by varying the frequency of the AC. At present, most hybrids use one machine drive/electric motor to augment the main drive train, however EVs may directly couple motor/drives to each wheel. These systems are also usually capable of being back-fed to allow a limited amount of regenerative recovery (ie, they can convert AC back to DC).

- AC-DC converters: these are primarily used in HEVs to tap power from the prime mover (usually an ICE) through a conventional rotating generator. At its simplest the converter may be a controlled rectifier. However, if engine speeds vary the circuit may also be capable of applying a buck/ boost conversion to the DC output. The other area where AC-DC conversion is used is to control external mains charging of the battery supply.

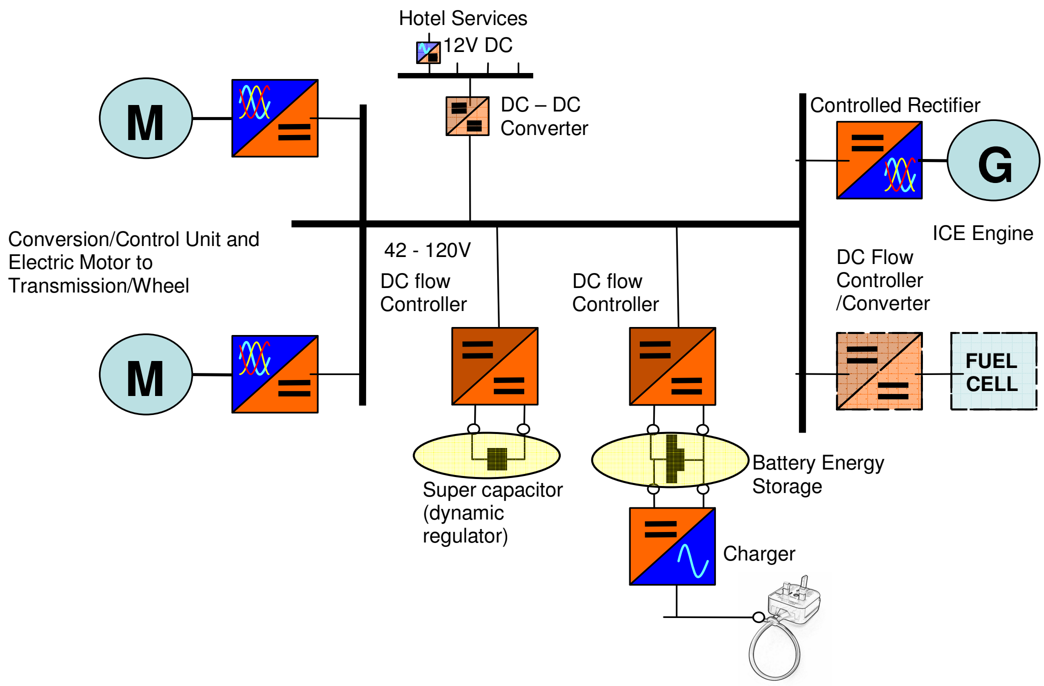

Figure 1: Basic electrical schematic of an EV/ HEV vehicle with power electronic building blocks shown (Source: ITI Energy compilation)

At present, hybrid cars usually pack the various power electronic building blocks into a single package. This will either have a secondary cooling system, or use the existing engine cooling system. While this is an approach that works for HEVs, the increase in building blocks is not going to be practical due to the weight penalty and costs associated with the additional electrical wiring needed to distribute the modified electricity around the car. Therefore, the major challenge is the distribution and embedding of these building blocks at the point of need.

For Electric or Hybrid Electric Vehicles, power electronics can be considered at four levels[2]:

- **Systems**

The systems level is predominantly addressed by the vehicle manufacturers and tier 1 suppliers. This tends to be dominated by standards and communications protocols (for control & monitoring data) which are driven by the car manufacturers working with suppliers who have a mutual interest in ensuring a level competitive playing field.

- **Applications**

The application level is a tier 1 / tier 2 issue where there is scope for novelty in applications design. A major issue with present HEVs/ EVs is that much of the control electronics is contained in a single box. However, it is widely recognised that integration of PE with electro-mechanical components is a key to driving down component cost. The embedded control software also has scope for novelty for framework software that allows rapid customisation of a largely generic control system to a specific application.

- **Components**

At the components level PE technology is restricted by the limitations of the incumbent silicon technology. For most applications the IGBT is the predominant device in use, although MOSFETs are used at lower voltages (<100V). Silicon is not ideal for automotive applications, primarily because it ceases to be a semiconductor when the junction temperature gets much above 125℃. Although there are signs that higher temperatures are being achieved using silicon-on-oxide technology, its high power applications are limited because the devices utilise the surface (rather than bulk of the semiconductor material) to operate, and hence cannot sustain high currents.

A number of companies are looking at Silicon Carbide MOSFET devices (eg, CREE, Infineon, ST). However, these are not yet stable enough for commercial production and their cost remains prohibitive. At present, the state of the art consists of encapsulated packages containing multiple semiconductor devices in preconfigured arrangements with their gate drivers (the circuitry that interfaces and buffers the control instruction from the DSP to the actual device) integrated into the same package. Externally, these packages look no different from those used in industrial applications.

Semiconductor devices represent less than 15% of the application cost. The rest is made up of the passive components (capacitors, inductors and resistors) that comprise the actual electronic circuits. For example, capacitors account for a major fraction of the weight, volume and cost of a motor drive – whereas, at present, electrolytic aluminium capacitors are used for applications below 450V. The higher voltages and temperatures encountered in EV/ HEVs mean that there is scope for development to improve or supersede them. In addition, there is a desire to achieve closer integration with semiconductor devices and further integration with the electro-mechanical device under control (mechatronics).

- **Materials**

Much of the improvement to components is likely to come at the materials level. For example, there is a recognised need for materials for passive components (eg, high temperature polymer dielectrics for capacitors, higher permeability magnetic materials); new materials for semiconductor packaging that encourage more effective heat transfer; and high temperature soldering materials.

2. Market Players/ Opportunity

At present the responsibility for PE development and supply is mainly with tier 1 suppliers, such as: Delphi; Robert Bosch; Mitsubishi Electric; Denso Corporation; Continental Automotive Systems; and Visteon[3] – all of which have experience in meeting the requirements of the automotive industry. However, much of the expertise for the general applications design of many of the functional blocks required by EV/HEVs lies with manufacturers who support the industrial machine control sector, such as: Emerson; Siemens; and Control Techniques.

PE for automotives, to the extent described here, is still in its infancy and is expected to offer significant growth potential in the years to come. In 2006, the market was estimated by BCC as likely to grow rapidly from around $160m in 2005 to be worth more than $450 million by 2010[4].

Annual market sales $ million	**2003**	**2004**	**2005**	**2010**
Power Electronics	32	68	160	455

Table 1: Global market for Motors and Generators used in mild and Full HEVs through 2010 (Source: BCC Inc)[5]

Overall, the power electronics market has a value in excess of $200B+ and is accelerating in growth due to markets such as EV/HEV and greater awareness of the energy saving potential this technology offers. The semiconductor content within any power electronics application is usually less than 20% of the cost. Delving further, the silicon content typically represents one-third of the device cost, with the remainder being accounted for by the packaging (housings and encapsulants). Hence, significant markets exist for materials and components that enable this technology and which exceed that of the raw silicon device in value.

3. Technology Challenges/Market Drivers

As a technology, power electronics is well established with industrial designs that deliver much of the functionality required in figure 1. However, there are a number of key differentiators between fixed applications and the requirements of electric vehicles:

- Cost: applications for EV/HEV requires a cost lower than $10 /kWe, compared to $50-350 /kWe for power conversion devices for industrial applications

- Intermittent use, an EV/ HEV running some 400 - 800 hours/year compared to 4000 to 8000 hours/year for industrial devices
- Operational stress, both thermal and mechanical, with potential contamination issues (water, exhaust gas)
- Weight constraints

As a result, there is a number of issues, challenges and opportunities for deploying power electronics in the EV/HEV market.

Power Electronics Issues and Challenges

Current silicon-based PE devices can only operate up to 115^{o}C before failure, as opposed to up to 200^{o}C, for motors/engines. PE components are also more susceptible to failure from excessive thermal cycling than are motors/engines. Common wisdom is that PE and motors/engines need to be mechatronically integrated for greatest power-to-weight benefit and efficiency. Thus, the management of the thermal loads of PE currently represents the primary challenge in this technology area.
PE devices come with a thermal resistance rating. This is a measure of how effectively heat is removed from the semiconductor junction to the surrounding packaging – and subsequently removed from the system. The more effectively the heat is removed, the closer devices can be pushed to their nameplate ratings. Dissipating heat effectively means these devices can be made smaller and lighter.

To illustrate this point, a 100kW EV weighing 1200kg EV could have 200kg of power electronics in it. However, the PE components are generally overrated by a factor of 2 to allow for the effect of heat stresses. Thus, potentially, up to 100kg of weight could be removed from the system.

At full power, the above EV would probably dissipate 10 kW of heat in its power electronics systems and another 15 kW in the motor(s). Each requires a cooling system operating at 60-70 deg C, as power electronics units are typically still remotely mounted from motors/generators. Integrating PE would eliminate the need for separate cooling, as the motor/generator cooling system could be integrated. For an HEV, this system is additional to the engine cooling system operating at 90-100 deg C.

As radiators (the final heat sinks for these cooling systems) weigh 6-10kg, the requirement for dual system creates efficiency/cost/reliability issues. A major challenge is to either combine these systems into one, or to simplify them by using passive components etc to increase their reliability.

Heat management is a major area of activity associated with power electronics. A number of electronics suppliers are developing evolutionary technologies in this area. Current developments are associated with alternative chip architectures, as well as new materials and heat transfer technologies. It is clear that evolution will continue and perhaps there is space for step-change breakthroughs

Improved Design and Materials for Chips and PE Devices

A barrier to developing next-generation power electronics is cooling at high heat fluxes (up to 100 Watts/cm^2) at high temperatures (>125°C) in compact (low-volume), lightweight power electronics packages (www.nrel.gov). Advanced heat transfer techniques must be used to overcome such barriers and challenges in next-generation power electronics cooling.

The problem for any designer of device packages is that heat removal is only part of the equation. Electrical insulation, mechanical clamping (to negate force effects caused by high electrical currents) and differential thermal expansion must also be taken into account.

Figure 3: Thermal Image of a 10kW Silicon IGBT (Source: ITI Energy compilation)

Heat is taken away from where it is generated (at PE junctions) by spreading it into the surrounding packaging materials and then by dissipating it out of the package itself. PE devices are attached to a base plate which is used to transfer the heat away from the device itself. The primary mechanism for thermal management at this component level is simply the transfer of heat out of these materials.

At the moment, heat is transferred through the silicon carbide that makes up the bulk of PE devices, through associated plastic or ceramic packaging and into a base plate, which is generally made of aluminium which is used to transfer heat away from the PE. The base plate's surface area is designed to be maximised through use of pin fins, for example. Better thermal conductivity of these materials would facilitate faster removal of this heat, although materials need to be matched to ensure thermal compatibility.

For lower power/heat components natural thermal convection will dissipate heat, although this requires air gaps into which the heat can escape. If this is insufficient, forced air flow is used – requiring fans and air filtering. For high power/high temperature components, liquid cooling systems are used. Generally, the high power density and high ambient temperatures in vehicles means PE devices require water cooling. These are very costly to engineer, requiring custom-built heat sinks, coolant pumping systems and heat exchangers. As some utilities have discovered, internal corrosion of heat sinks in FACTS and HVDC applications has meant that the biggest problems encountered with these technologies is not with the electrical aspect of the design, but with the ancillary electro mechanical components.

Most emerging wide band-gap semiconductor materials have notably superior thermal conductivity characteristics over Silicon. It is possible that higher power densities within packages may be achieved by increasing the die size, so that the active device is centered within a piece of larger non-active substrate. Indeed, this approach may fall out as a consequence of needing to increase surface creepage distances to accommodate higher voltage operation. Unless the former approach can be coupled with the latter, it is not likely to appeal – since it would almost invariably impact on the number of devices that manufacturers might produce from a single wafer. These new materials are currently expensive – costing up to 20x silicon carbide for example. This is a major barrier to entry in automotive applications.

Advanced Heat Transfer Technologies

Heat pipes are highly effective for removing heat and have no moving parts. Their effectiveness is mainly due to the evaporation and condensation of the working fluid, which requires/releases much more energy than simple temperature change. Almost all of that energy is rapidly transferred to the 'cold' end when the fluid condenses there, making a very effective heat transfer system with no moving parts. There is some disagreement over the cost vs benefits of heat pipes in HEV/EVs.

At the package level, the only real prospect is to more effectively spread the heat away from the working part of the device. For microelectronics applications, technologies such as heat spreaders have been considered for increasing the emitting area of the working device. A heat spreader is a highly thermally-conductive substrate, bonded to the device die to increase the heat transfer process.

Materials such as AlSiC and polycrystalline diamond have been explored for this application (eg, SP3 Inc, USA). However, these are only practical for devices where all electrical activity takes place on one side of the substrate. For power applications the energy flow tends to be through the whole wafer, rending heat spreaders impractical. In addition, the cost of incorporating such materials into the package construction is high.

4. Findings

Potential opportunities to develop innovative technology in power electronics for EV/HEV appear to occur predominantly at the components and material level, with some scope at the applications level. Opportunities identified are as follows:

- DC-DC Converters (application): at present most DC-DC converters are only around 80% efficient. There would be significant interest in any new approach that would increase this efficiency towards the 95-95% achieved by drives.

- Drive/ motor integration (applications): this, in turn, has three opportunity areas: embedded electronic design into the motor housing; robust packaging of circuits; and thermal management of resulting additional heat load.

- Wide band-gap semiconductors (components): primarily this would mean looking at MOSFET or bipolar devices able to operate at up 250℃. Main candidates for this would be Silicon Carbide or Gallium Nitride. Both suffer from the fact that devices made from these materials cost 10-20x more than their silicon equivalent. GaN potentially may lead to lower cost devices, however for power applications it is hampered by the fact that the material is grown on an insulating substrate and therefore does not presently lend itself to bulk devices.

- Low mass/ low cost EMI filter (components): filters are vital to damp the harmonics generated by the power electronics on-board a vehicle. Ways of producing low cost designs could be attractive

- High temperature capacitors and/or resistors (components/ materials): having components that can both operate and survive at the elevated temperatures in a vehicle is a key enabler. Part of the problem is that the ratings of the components need to be kept stable over an extended temperature range as well (this may be partially addressable through intelligent embedded software design). An enabling technology here is new dielectric or resistive films on which the components would be based.

- High temperature dielectrics/magnetic materials: the availability of effective materials able to demonstrate: thermal stability up to 250℃; bulk manufacturing potential; electrical operating stability over a range of -40℃

through to +150℃; good electrical insulation strength; and thermo-mechanical compatibility over the full range – are now cited as a barrier to cost effective design of EVs. New materials, which would enable the manufacture of capacitors or magnetic components able to operate in EV environmental conditions, would command significant interest.

- High temperature, thermally conductive, electrically insulating encapsulation materials: as in the bullet above, availability of effective packaging materials, for use in semiconductor and encapsulated converter packages that meet the same basic specification, would also attract a lot of attention, potentially from multiple adoption partners.

However, most of these areas are too crowded for generating valuable IP and a lot of R&D activity is underway in the academic world, funded by major organisations.

Appendix 3 References

1) 'Components for Hybrid Electric Vehicles, Business Opportunity Report', BCC Inc, 2006
2) 'Power Electronics foresighting report', ITI Energy, 2006
3) 'Future Automotive Systems Foresighting Study', Lotus Engineering, 2008
4) See Ref 1
5) Based on Ref 1, Summary Table p xxv

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