2007: Peak Oil
The Electric Vehicle Imperative

Market Analysis

Technology Assessment

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Contents

1 Introduction

There has been much written about Peak Oil in the last few years.

Little has been written to analyse the range of possible solutions and to propose effective measures to this most urgent and serious challenge.

This Report fills that gap. It presents an overview of the prospects for Global Oil Production over the next 20 years. It then analyses the various Solutions which exist that can be implemented to meet this challenge.

A Global Oil Consumption Reduction Programme must then be implemented, to ensure we continue to provide the essential energy for our modern world.

There is now overwhelming evidence that a plateau in global oil production is being reached and that within a few years global oil supply will start to decline.

30% of the world's oil already comes from declining oil fields.

In November 2004, the Editor of Petroleum Review, Chris Skrebowski, wrote:

"After 2007, there is a sharp drop off in the new major oil field developments required to replace natural depletion and to meet demand growth. The new development projects required to replace declining production, let alone meet demand growth, do not exist.[1]

A seemingly unbridgeable gap will start to open up between increasing oil demand and falling oil supply."

1. Petroleum Review, Jan. 2004 and ODAC, Nov. 2004 www.odac-info.org

In June 2005, the OPEC research centre in Teheran warned that global oil production in the 4th Quarter of 2005 would fail to meet demand by 2M barrels a day.

With the price of oil at record levels of over $60 a barrel (at time of writing) in the midsummer of 2005, what will be the price by January 2006?

The price of oil can only increase further.

In response to this, the Global Automotive industry will witness a seismic shift over the next 5 - 10 years to adopt new technology vehicles.

The technologies that will win out from this will be the Plug In Hybrid Electric Vehicle and the Battery Electric Vehicle.

The PHEV20, capable of driving 20 miles on battery power before requiring the IC engine, will reduce global Light Vehicle road fuel consumption by 50%.

This vehicle technology is now under commercial development and will be launched onto the market by 2008.

2 2007: Peak Oil

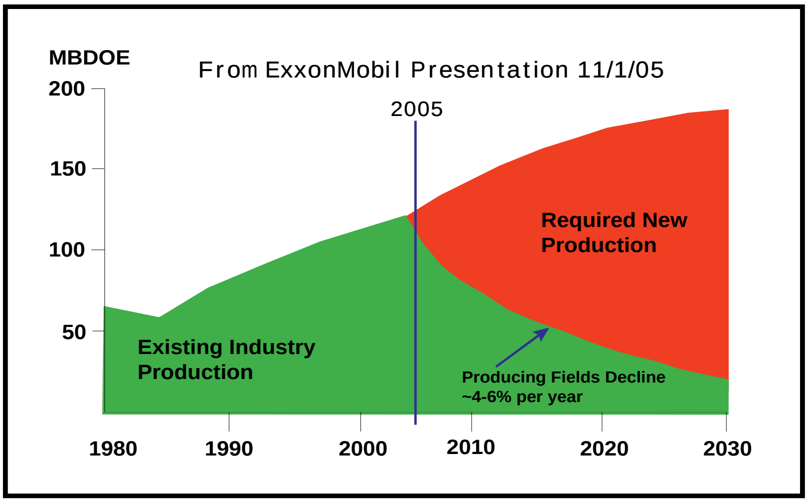
2.1 What is Peak Oil?

The Peak of Oil Production occurs when global oil production reaches an absolute maximum and then starts to decline.

It is inevitable that at some point Oil Production must start to decline, since oil is a non-renewable resource (on human timescales). Only a finite amount exists in the ground. Once a certain amount has been extracted from an oil reservoir, production starts to fall until it becomes either uneconomic or technically impossible to extract any more.

Figure 1 shows that as oil production from existing oil fields today declines by 4% - 6% per year, new oil fields or enhanced recovery methods need to be introduced to make up the shortfall - and meet growing demand.

FIGURE 1



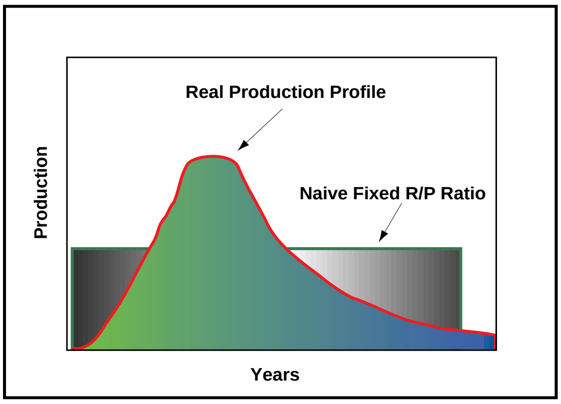
- By 2020, new oil production required is almost equivalent to replacing all of today's production.

Reserves to Production Myth

The forthcoming Peak of Global Oil Production has been widely ignored due to the fallacious belief in the ratio of “Reserves to Production”. It is naively assumed that if there are say 1 billion barrels of oil in a reservoir and it is extracted at 1M barrels a day, the reservoir will last for 1000 days. This gives a flat production profile for the life of the reservoir.

In reality, oil production from a typical field increases to a maximum where it may plateau for a few years and then once about half of the oil has been extracted, production starts to fall and then tails off over many years. It does not stay constant at a high level.

FIGURE 2 **REAL OIL PRODUCTION PROFILE vs R/P RATIO**



Therefore, while there will still be oil in the ground in 50 or 100 years time, production will continually decline as less and less can be extracted each year.

2007: The Peak of Global Oil Production

In the 1950s, oil geologist M. King Hubbard forecast that oil production in the USA would reach a maximum in or about 1970 and then start to decline. This prediction was fulfilled.

In 1980, the "Global 2000" report, commissioned by the US President, predicted that the Peak of Oil Production would be near the end of the 20th century. The biggest uncertainty lay in forecasting oil demand, not how much oil could still be discovered. Since 1980, it is demand that has not risen as quickly as forecast, pushing out the peak by a few years into the first decade of the 21st century.

Applying the same methods to global oil production indicates that Global Peak Oil will occur around 2007 - 08 at the latest. The signs are now very clear that we have entered final approach to Peak Oil. By 2008, the ever increasing demand for oil will exceed supply and oil production will enter permanent decline.

We are facing the Peak Oil Emergency.

2.2 Falling Production

Global Oil Production in 2003 was about 80M b/d. In 2030, those same oil fields will produce only 30M b/d according to the IEA and ExxonMobil.

In 2004, oil reached the record price of $57 a barrel. Shell admitted they had overstated their oil reserves by 26% and made 5 downward revisions; other oil companies also revised their reserves sharply downwards. In February 2005, Shell revised down their reserves again by another 10%. In April 2005, oil reached a new record of nearly $60 a barrel. In July 2005, it reached $61 and then $66 in August.

Yemen, Syria and Oman experienced sharp permanent drops in production in 2004.

The UK's North Sea Oil peaked in 1999; Norway's in 2001. North Sea production is falling by 9% p.a.

Argentina cut gas exports to Chile in 2004 by 15%, threatening Chilean electricity production.

The world's largest offshore oil field and the second biggest oil field in the world, Canterell in the Gulf of Mexico, is officially predicted to peak in 2006 and then decline by 14% per year.

Indonesia, one of the OPEC members, now imports more oil than it exports and will have to leave OPEC. It cannot even produce enough for its own consumption[1].

54 of the 65 largest oil producing countries are now past their peak.

One third of the world's oil is now supplied by declining oil fields.

Annual oil consumption has now exceeded new discoveries every year since the early 1980s.

Oil production has already plateaued or is in decline in 33 of the 48 major oil producing countries, including 6 of the 11 OPEC members.

The Saudi Ghawar Field

Ghawar is the single biggest oil field in the world.

In 1975, Exxon, Mobil, Texaco and Chevron estimated that Saudi Arabia's Ghawar oil field contained 60 billion barrels of oil. By 2004, 55 billion had been extracted, with production running at 1.8 billion a year. Water injection and bottle brush drilling is already widespread to maintain production, shortening the life of the field.

1. "The Oil Supply Tsunami Alert", Kjell Aleklett, Uppsala University Hydrocarbon Depletion Study Group, President of ASPO, May 2005. aleklett@tsl.uu.se

In April 2005, a Bank of Montreal analysis claimed that Ghawar has reached its peak and is in decline.

Ghawar is said in some circles to be already producing a 55% “water cut” - 55% of what is pumped out is water originally pumped in to force out the oil. When the water cut reaches 70 - 80%, the field will no longer be viable. If the original estimated reserve is correct, Ghawar will run out by September 2006.

If Ghawar runs out, 6% of world production will disappear.

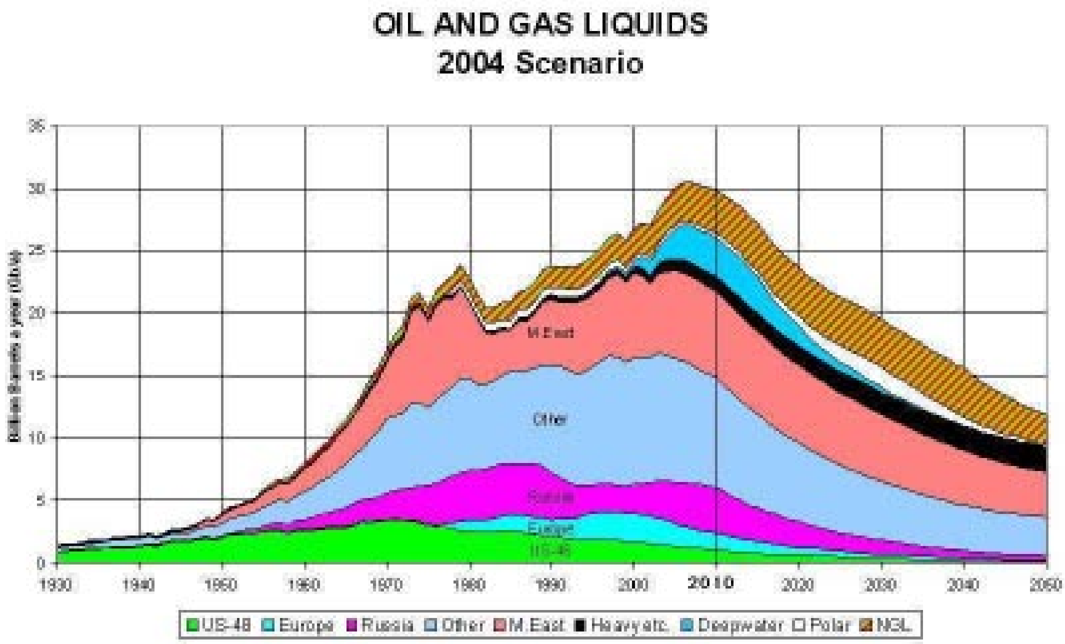
Accelerating Depletion Rate

The current depletion rate of 1M b/d per annum will accelerate to 1.3 - 1.4 Mb/d p.a. over the next two to three years as more producers enter permanent decline. By 2010, the decline in production could be up to 3 M b/d per year[1].

The graph below by the Association for the Study of Peak Oil (ASPO) and the Uppsala Hydrocarbon Depletion Study Group shows historical oil production from 1930 to the present day and forecast production up to 2050.

From the Peak of Production in 2006-07 of 85M b/d, Global Annual Oil production is forecast to drop to 33Mb/d in 2050.

FIGURE 3 **UPPSALA DEPLETION STUDY**



1. "Understanding Oil Depletion", Chris Skrebowski, ODAC News Release, 18/4/05

- Global Oil Production in 2050 will have declined to 33M b/d from 85 M b/d today.

The above graph includes non-conventional oil (tar sands, shales) and Natural Gas Liquids.

The IMF's Chief Economist Raghuram Rajan recently warned[1] that the world is about to enter a “permanent oil shock” and that non-OPEC oil production will plateau before 2010.

2.3 Accelerating Demand

Global demand for oil in 2004 grew by 2.6M b/d, the highest absolute increase since 1975. The increase was largely driven by China and India but also the USA.

OPEC is producing at close to its maximum sustainable capacity for the first time in more than 20 years.

China is now the second biggest importer of oil in the world. Chinese oil imports increased by 40% in the first 5 months of 2004 and by 16% overall. The Chinese coal stockpile fell to a 20 year low while increasing demand for coal is stretching production to the limit. China is actively sealing trade agreements with oil producing nations to secure their future supplies.

The IEA forecast is for Chinese oil consumption to grow 11% in 2005, up from 2.19Gb in 2004 to 2.44Gb this year (an average of 6.6Mb/d). Chinese oil production has now peaked and is in decline.

Indian oil consumption is growing at more than 7% per year.

US oil production peaked in the 1970s but US consumption continues to grow, despite already burning 25% of the world's oil every day.

In April 2005, demand for heating oil in the USA reached an all time high for that month, despite the warm spring.

In the same month, US demand for gasoline reached the record of 8.5M barrels a day. According to the EIA, US gasoline consumption is now (July 2005) running at 9.1M b/d.

While the IEA forecast global oil demand to increase by 1.6% per annum between 2005 and 2030, the IEA have a record of underestimating demand growth. Independent forecasts predict that oil demand will continue to grow by at least 2.5% per annum.

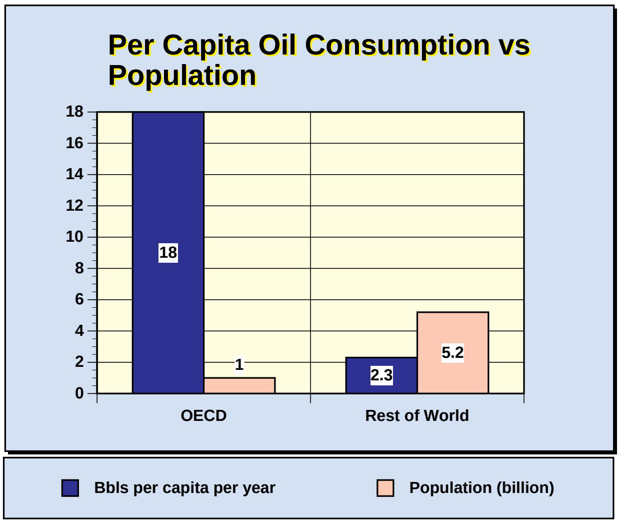
1. "IMF Warns on risk of permanent oil shock", Financial Times, April 7th 2005

Per Capita Difference

The USA consumes[1] 25 barrels of oil per capita per annum. China currently uses 1.5; India less than 1.

Figure 4 compares the relative per capita consumption and population of the OECD nations to the rest of the world.

FIGURE 4



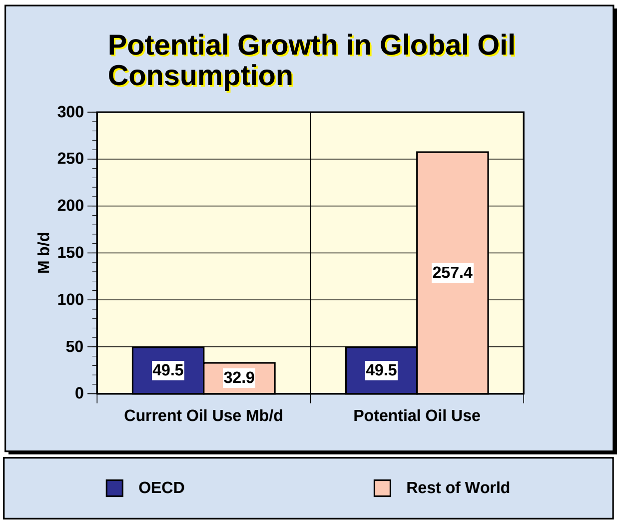
For the OECD as a whole, per capita oil consumption is 18 bbls per annum, compared to 2.3 bbls per annum for the rest of the world.

1. Simmons & Co. International

Potential Oil Demand Growth

With overall OECD oil consumption at 18 barrels per capita per year but the Rest of the World at only 2.3 barrels per capita per year, with 5 times the population, global oil consumption would have to rise from 82.4Mb/d in 2004 to 307 Mb/d for everyone to enjoy the same level of energy consumption.

FIGURE 5



- Global Oil Consumption would have to rise from 85M b/d to over 300 M b/d for the entire world to enjoy the OECD standard of living.

The IEA Reference Scenario for future growth in global oil demand assumes an average annual growth rate of 1.6%. This growth rate is considered unrealistic by most observers, who put it at 2.5% or more.

At an annual average growth rate of 2.5% instead of 1.6%, global oil demand in 2030 would be over 150 Million barrels a day instead of the IEA forecast of 121 Million barrels a day.

The main driver behind this growth in demand for oil is the industrialisation and rise in standard of living of the world's developing nations.

The USA has 700 automobiles per thousand members of the population; Europe has 500; China currently has 10. China is the fastest growing market for automobiles in the world.

Ultimately, 300 M b/d would be needed to give the whole world an OECD standard of living, even without further population growth.

Demand Inelasticity and The Price of Oil

According to CIBC World Markets the price elasticity of oil demand in relation to price is -0.15. In other words, a 10% rise in prices reduces demand by 1.5%.

Therefore, to reduce demand from 95.7 M b/d to available supply in 2010 of only 86.8 M b/d, the price of oil will have to rise to $101 a barrel according to CIBC[1].

According to the ASPO, demand in 2010 will be constrained by a supply of only 82.7 M b/d, causing even higher prices.

Goldman Sachs recently warned that we are entering a "super spike" period and predicted that the price of oil will reach $105 a barrel by 2010.

The French investment bank IXIS-CIB use a more pessimistic elasticity ratio of -0.04 - i.e. a 25% rise in prices reduces demand by only 1%.

With the even more inelastic estimates of IXIS-CIB[2], the price of oil is predicted to be $380 a barrel in 2015, even with supply at 100 M b/d. In fact, supply will only be 70M b/d.

2.4 The Supply Demand Gap

Taking the preceding factors into account, there is now a consensus, highlighted by the Association for the Study of Peak Oil (ASPO), the Oil Depletion Analysis Centre (ODAC), Simmons & Co International, PFC Energy, various investment banks and others that within 4 or 5 years an ever widening gap will emerge between demand and deliverable supply. Some experts say world oil production peaked in 2004 and is now entering decline. Others say it will peak in 2005 to 2007.

A review of oil field Mega Projects in Petroleum Review in January 2004 predicted the emergence of the gap in 2008. Insufficient new capacity is scheduled to come on stream after that date to bridge the gap. From that point on - geological rather than political oil shortages become a reality.

In November 2004, ODAC further analysed 68 mega projects with a start date between 2004 and 2010; these will add 12.5M barrels of oil production per day by 2010 (and most of this before 2008). This is insufficient to keep up with rising demand and falling production from existing fields. More than half of this new 12.5M will only replace production declines.

1. "Not Just a Spike", Jeff Rubin, Report #53, 13/4/05, CIBC World Markets
2. "The Price of Oil in 10 Years Time: $380 a Barrel", Patrick Artus, Moncef Kaabi, IXIS-CIB, 18/4/05.

Chris Skrebowski, a director of ODAC and editor of Petroleum Review, concluded:

“Even with the relatively low demand growth, our study indicates a seemingly unbridgeable supply-demand gap opening up after 2007".

The strongest indictment comes from ExxonMobil itself. On the 11th January 2004 Senior VP Stuart McGill told analysts that with demand increasing at 1.7% per year and output from existing fields falling at 4 - 6% per year:

“New production required in 2020 is nearly equivalent to replacing all of today's production”

The new oil fields required to do that do not exist.

In June 2005, Dow Jones reported that OPEC’s International Centre for Energy Studies in Teheran predicted that oil supply will fall short of rising demand by 2M b/d in the 4th Quarter of 2005.

To those who have monitored the recent changes in the oil world, it is now undeniable: at current consumption rates oil supply will be rapidly depleted.

The Cost of Increasing Production

The following graph was presented in Exxon Mobil’s “Report on Energy Trends, Greenhouse Gas Emissions & Alternative Energy” in February 2004.

FIGURE 6

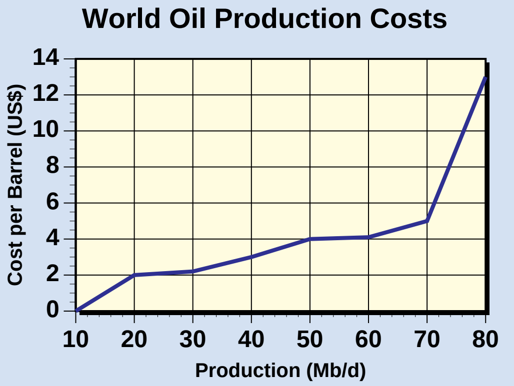
This graph illustrates the statement of the IEA in the latest World Energy Outlook 2004 that:

- "About $3 trillion will need to be invested in the oil sector from 2003 - 2030. Financing that effort will be a major challenge”.

However, studies indicate that the marginal cost of increasing global oil production over 80M b/d will start to rise exponentially.

The following graph from the 2000 EU Energy Green Paper on Security of Energy Supply illustrates this.

FIGURE 7



Source: EU Commission 2000 - Green Paper on Security of Energy Supply

According to the Bank of Montreal, Saudi Arabia claim that they require an oil price of $32 a barrel to justify investment in new production.

The required global investment of over $100 billion a year in oil infrastructure is not currently being made[1].

1. “IEA Chief warns (oil) companies will fail to meet demand”, Financial Times, 3/5/05

2.5 The Real Production Outlook

The ASPO predict that by 2010, global oil production will in fact have fallen to about 82 M b/d.

By 2020, it will have fallen further to 65 M b/d and only 33 M b/d in 2050.

Demand in 2010 is predicted to be over 95 M b/d - a gap of 15M b/d with projected ASPO production or a shortfall of 9M b/d according to CIBC World Markets' more optimistic supply forecast.

The CIBC World Markets production forecast of 86.8 M b/d in 2010 is probably too high but may be achievable as pressure bites to maintain production.

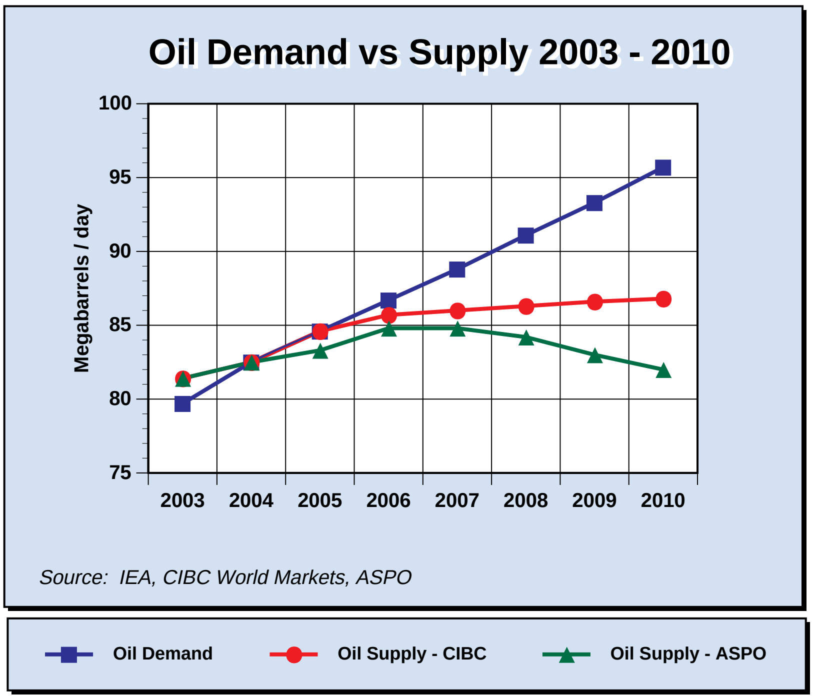
Either way, production will fail to meet demand by at least 10% in 2010.

Unless effective measures are taken to start reducing oil consumption as soon as possible, the world economy will start to experience global recession progressively leading towards depression over the next five years.

Short Term Outlook to 2010

The graph below shows projected unconstrained oil demand out to 2010 and the two supply scenarios by CIBC World Markets and the ASPO.

FIGURE 8



Even if the more optimistic CIBC supply scenario is correct, supply will fall short of demand by 9Mb/d in 2010.

Taking the more realistic ASPO assessment, supply will fall short of demand by 14 Mb/d in 2010.

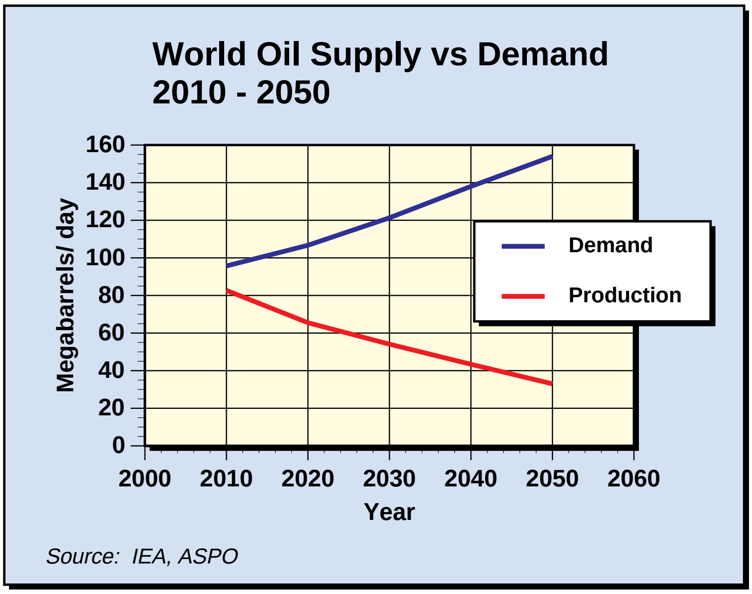
Outlook for 2010 - 2050

The Oil Depletion Analysis Centre (ODAC) project that after 2010 oil supply will start to fall even more quickly than projected by the ASPO: at up to 3Mb/d per year.

This would reduce global oil production to only 50 to 55Mb/d in 2020, not the 65Mb/d projected by ASPO.

The graph below compares the longer term projection for unconstrained oil demand (from the IEA) with the ASPO forecast supply projection.

FIGURE 9



After 2010, demand for oil will become severely constrained. While the western industrialised nations may be able to maintain their oil supplies till 2010 at the latest, at the expense of the developing nations, after 2010 oil shortages will become more and more severe every year across the globe, even assuming that the economic and geo-political disruption this causes does not affect oil production itself.

Table 1 summarises the ASPO Oil Production Forecast from 2005 - 2050.

TABLE 1

ASPO OIL PRODUCTION FORECAST

Year	M b/d
2005	83.3
2006	84.8
2007	84.8
2008	84.2
2009	83
2010	82
2020	65.5
2030	54.1
2040	43.4
2050	33

The Tar Sands and Oil Shales Will Not Save Us

It is often stated that the Tar Sands of the Orinoco Basin and Alberta contain the "equivalent" of some 4 trillion barrels of oil and the oil shales contain another 3 trillion barrels.

On the 1st January 2003, Canada's official oil reserves were increased from 5 billion to 180 billion barrels of oil. Overnight, Canada became the holder of the second largest "proven" reserves of oil after Saudi Arabia.

However, neither the Oil Sands nor the Oil Shales actually contain oil.

The Oil Sands contain Bitumen, which is a heavy tarry residue left from the exposure of old oil deposits to the weather.

To turn this bitumen into oil, the bitumen has to be hydrogenated - that is, reacted with hydrogen to add hydrogen into its structure. The word hydrocarbon means a compound comprised of hydrogen and carbon. Gasoline, petroleum etc. have the general formula C_nH_{2n+2}, so that octane in petrol for instance has the formula C_8H_{18}. Bitumen contains only 10.4% hydrogen compared to 14% for oil; therefore hydrogen is added to make it useable.

This hydrogen comes from Natural Gas.

Synthetic Crude Oil (SCO) manufactured from Tar Sands requires 400 - 1000 cubic feet of Natural Gas per barrel of oil produced. This could rise to 1700 cubic feet per barrel in future higher quality SCO projects now being developed. Natural gas production in the USA and Canada is flat or declining. Prices have tripled over the last few years. Large scale use of Natural Gas by the Canadian Tar Sands industry is unsustainable.

Oil shale actually contains keragen - a petroleum precursor. The shale (5% - 25% keragen) has first to be mined, transported and then heated to 500˙C to pyrolyse the keragen into oil. 1 to 4 barrels of water are needed per barrel of oil produced by this method. At one time, it was proposed to divert the Columbia River to provide the necessary water for large scale manufacture of oil by this process. A vast amount of dry waste (shale rock) is also produced which has to be disposed of.

Neither oil shale nor tar sands are a viable replacement source of oil. They require too much energy and resources to produce useful quantities of oil. Canadian oil sands production will certainly increase but it will literally be a drop in the bucket compared to world requirements. It cannot even compensate for the future decline in conventional Canadian and North Sea oil production combined. It certainly cannot replace Saudi Arabia.

The Canadian Natural Gas Shortfall

In 2030, the IEA say that non-conventional oil must supply 37 million barrels a day of global supply (WEO 2004).

Canada currently produces about 1M b/d of SCO from its oil sands deposits. Under the most optimistic forecast scenario, the Canadian Tar Sands are projected to produce 5 million barrels a day[1] at the most in 2030 and Venezuela 6 million barrels a day. This leaves a gap of 26 million barrels a day.

Canadian Natural Gas Production is currently about 17 billion ft^3 per day; this will have fallen to 13 billion ft^3 per day by 2030.

The Canadian Oil Sands Industry currently consumes 0.6 billion ft^3 of natural gas per day. Under the OSTRM forecast, natural gas demand would rise to 5.4 billion ft^3 per day in 2030 to produce the projected 5 million barrels a day of SCO.

If we exclude the natural gas that Canada exports to the USA (44% of production) and that Canada uses to generate electricity, under the OSTRM forecast scenario 100% of the remaining Canadian natural gas production will be consumed by the Oil Sands industry before 2025.

Even by 2013, between 25% and 40% of Canadian Natural Gas production (excluding exports, electricity production) would be consumed by projected SCO production.

Natural Gas markets in the USA are so tight that it is estimated that only a 4% reduction in Natural Gas demand over 5 years would reduce prices by 25%[2]. Therefore there seems to be little scope for Canada to

1. Oil Sands Technology Roadmap - Unlocking the Potential, Alberta Chamber of Resources, January 2004

2. Comments by the ACEEE to the Senate Energy Committee - Power Generation Resource Initiatives and Directing Standards, March 8th 2005.

reduce its exports to the USA without substantial US efforts to reduce natural gas consumption.

It is clear that Natural Gas consumption by the Canadian Tar Sands industry is unsustainable. It could only be achieved at the expense of exports to the USA. Production of SCO will not be able to rise to anything like 5 Mb/d. Even if it could, this would do little to offset conventional oil production declines elsewhere.

Conclusion

Global Oil Production is set to fall from approximately 85Mb/d today to 65Mb/d in 2020. If the ODAC turn out to be correct and oil supply falls at an even faster annual rate of 3Mb/d after 2010, global production will be down even further to 50 - 55Mb/d by 2020.

3 The IEA

3.1 2004 World Energy Outlook

The International Energy Agency was established as the world's “energy watchdog” after the oil shocks of the 1970s.

Its reports, along with those of the EIA in the United States, present the "official" version of the status of World Energy Supply and Security.

In its latest World Energy Outlook 2004, the IEA say that:

“Production of conventional oil will not peak over the projection period (2003 - 2030) if the necessary investments in the supply infrastructure are made. New capacity will be needed to offset production declines and to meet demand growth. About $3 trillion will need to be invested in the oil sector from 2003 - 2030. Financing that effort will be a major challenge”.

However, this is predicated on a USGS oil reserves estimate of 2626 Giga barrels. The IEA go on to say that if this estimate is too high, the peak could come by 2015 or earlier.

This is also the first time that the IEA have acknowledged the idea that a Peak in oil production will occur before production starts to decline.

In April 2005, the IEA also released a report entitled "Saving Oil in a Hurry" which urges nations to start demand reduction measures if global oil supply falls by as little as 1M b/d. This is a complete reversal of previous IEA policy, which has hitherto emphasised increasing oil production to meet supply shortfalls.

In May 2005, the IEA belatedly warned that insufficient investment is being made in oil production and refinery capacity to meet demand growth.

Rising Demand Forecast

A finance effort of $3 trillion over the period 2003 - 2030 is over $100 billion a year. There are no signs that this investment is forthcoming, despite the large cash stockpiles enjoyed by the oil majors.

The IEA go on to predict that demand for oil will rise to 121Mb/d in 2030 (while more realistic independent forecasts put it at 150 Mb/d). Even the IMF forecast that demand will reach 138 Mb/d in 2030.

Is this feasible?

In 2002, World Oil Production averaged 77Mb/d or 28Gb p.a. The 2030 figure of 121 Mb/d totals 44 Gb p.a. in that year.

In total, the IEA demand forecast means that between 2003 and 2030, a total of 1020 Gb of oil will be consumed.

This is more than was consumed during the entire 20th Century.

- Global Oil Consumption between 2003 - 2030 is forecast to be 1020Gb, more than was consumed during the entire 20th Century.

New Production Required

If World Demand for Oil in 2030 is 121 Million barrels a day and production from today's fields has fallen to 30 M b/d, then we need to put into new production 90M b/d of oil over the next 25 years.

The IEA World Energy Outlook 2004 states:

- “By 2030, most oil production worldwide will come from capacity that is yet to be built”.

Of this 121 M b/d, the IEA say that 25 M b/d will come from New Discoveries.

At its peak, the North Sea produced 6M b/d. The North Sea was the largest new oil province discovered since the Second World War. Therefore the IEA expect 4 new North Seas to be discovered and put into production over the next 25 years, which have evaded discovery in the last 60 years of oil exploration.

- The IEA forecast for New Oil Discoveries in the 2005 - 2030 period is equivalent to 4 North Seas or nearly 3 Saudi Arabias.

Furthermore, the IEA and the EIA require Saudi Arabian oil production to reach 22.5M b/d in 2025 to offset declining production from non OPEC nations.

Saudi "Sustainable Capacity"

In late 2004, Saudi Aramco stated that their Maximum Sustainable Capacity is only 12 M b/d until 2033, after which it would decline. Current production is 9.5 M b/d.

This leaves a 10 M b/d gap between what the Saudis say they can produce and what the IEA/EIA say they will produce.

"Sustainable Capacity" means how much oil can be produced without damaging the oil field by excessive water injection.

Sadad Al-Husseini, ex-head of Exploration and Production at Saudi Aramco has said of the EIA's production forecasts: "These are US numbers, not ours. The American production outlook is much too high".

Alternative Scenarios

In the 2004 WEO, the IEA also present a number of alternative scenarios to the main politically based scenario.

In their "Low Resource Case", the IEA advance the peak of production to 2015 and in their "High Price Scenario" the peak is advanced to close to the present day: this confirms the assessment of the ASPO.

3.2 Conclusion

There are two major shortcomings in the IEA's latest WEO:

1. Demand for oil is increasing much more rapidly than the IEA predict.
2. Recoverable reserves of oil are much lower than the IEA postulate.

The IEA have however admitted the reality of the existence of a Peak of Oil Production for the first time. Reading between the lines, the 2004 WEO supports the independent case made by many other analysts that the Peak of Global Oil Production is imminent.

4 Overstatement of Reserves

4.1 OPEC Inflation of Reserves

Between 1980 and 2002, the official “proven” reserves of the 6 largest OPEC producers doubled from 360 Gb to 720Gb of oil, despite little or no new exploration or discoveries and 22 years of production in the meantime.

In the late 1980s and through the 1990s, many OPEC nations grossly inflated their “proven” reserves figures. Production quotas were linked to the size of these reserves. Therefore inflating the reserves allowed more production.

The worst offender in percentage terms was Iraq.

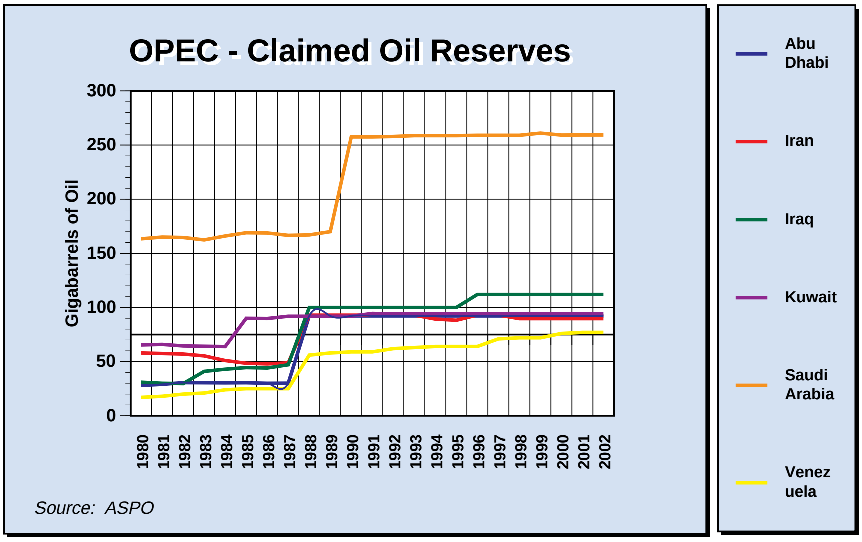
In 1982 Iraq’s reserves were 29.7 billion barrels. In 1983 they jumped to 41 billion barrels. In 1987 they rose to 47.1 billion barrels, jumping to 100 billion barrels in 1988, further rising to 112 billion barrels in 1996. 9 years later, the official reserves are still 112 billion barrels.

With production running at 2-3 million barrels a day since the 1980s, Iraq's real reserves today are probably in the order of 30 billion barrels or less, not 100 billion.

Iraq is in fact unlikely to be “floating on a sea of oil” as US Deputy Secretary of Defense James Wolfowitz termed it after the 2003 invasion.

Figure 10 shows the official levels of reserves for the 6 top OPEC producers from 1980 to the present day.

FIGURE 10



It is clear that OPEC's "proven" oil reserves are unreliable. No independent verification has ever been carried out: therefore the rest of the world has in fact no accurate data on which to base realistic estimates of OPEC's true reserves.

A safe estimate would be to take the early 1980s reserves of 360Gb (for these 6 producers) and subtract the intervening production for the last 20 years. This leaves the reserves at closer to 200 Gb, not 720 Gb.

4.2 IEA and USGS Inflation of Reserves

It was stated above that the IEA's World Energy Outlook 2004 was predicated on a new estimate of remaining recoverable oil reserves by the USGS of some 2.6 trillion barrels.

In 2000, under a new oil reserves project director, the United States Geological Survey increased its estimate of the total recoverable conventional oil resources in the Earth from 1.93 trillion barrels to 3.3 trillion barrels, an increase of 71%.

In its 2000 analysis[1], the USGS then subtracted from this 3.3 trillion barrels the 717 billion barrels produced since the mid 19th century, to leave remaining in the ground a "mean" estimate of some 2.6 trillion barrels of recoverable oil.

1. "USGS World Petroleum Assessment 2000" (www.usgs.gov)

The table below is taken from the WEO 2004. It shows how the USGS calculated their "Remaining Ultimately Recoverable Oil Reserves" of 2.6 trillion barrels.

TABLE 2

WEO 2004 - REMAINING RECOVERABLE OIL RESERVES

	Confidence Limits			
Billions of barrels	**95%**	**50%**	**5%**	**"Mean"**
Undiscovered	495	881	1589	939
Reserves Growth	229	730	1230	730
Remaining Reserves				959
Cumulative Production				717
Total Ultimately Recoverable Reserves				3345
Remaining Ultimately Recoverable Reserves				**2628**

As with any statistical estimate, there is a Confidence Limit associated with it. Normally, when a statistical estimate is presented, it is implicit that this estimate is not absolute but is subject to a certain amount of error. That error is described in terms of Confidence Limits and such estimates are always implicitly presented as having a 95% probability of being within a certain narrow limit of error from the true value.

However, in this case this estimate of 2.6 trillion barrels remaining in the ground in fact has somewhat less than 50% confidence associated with it - in other words, there is a less than 50% probability that it is correct.

One can see that so-called "Mean" values for Undiscovered oil and Reserves Growth of 939 and 730 billion barrels have been used to reach the total of 2.6 trillion barrels. In fact, these figures are not "mean" or "average" values at all - they are values which have a less than 50% probability of being close to the true estimate of the undiscovered oil and reserves growth possible.

To present them as being "mean" values is disingenuous in the extreme and is a gross misrepresentation of statistics.

In any statistical analysis or forecasting exercise, one never presents estimates that have only a 50% confidence limit associated with them. The correct procedure is to use the values with a 95% confidence limit - i.e. those estimates for which we can say there is a 95% probability they are correct.

If the 95% confidence limit estimates for remaining "undiscovered" oil of 495 Gb and "reserves growth" of 229 Gb are taken, along with already known "remaining reserves" of 959 Gb, the remaining ultimately recoverable oil resources are 1.6 trillion barrels, not 2.6 trillion.

However, this is not the end of it. The "remaining reserves" of 959 Gb are also overstated, due to the OPEC revisions of the 1980s and 1990s. This 959 Gb includes 724 Gb of OPEC reserves that should be closer to 363 Gb, less 25 years production. This means OPEC reserves are closer to 200 Gb, not 724 Gb so some 500 Gb should be taken from the "remaining reserves" of 959 Gb, leaving ~460 Gb.

If we accept the also rather dubious "Reserves Growth" figure of 229 Gb for the moment, that leaves remaining recoverable oil at 229 + 495 + 460 = 1.2 trillion barrels, which is in line with the original pre-2000 USGS estimate of 1.93 trillion less ~700 Gb of production to date.

Therefore it would appear that a more realistic assessment is that remaining recoverable oil is in the order of 1.2 trillion barrels, which is fairly close to the EIA conservative forecast for global oil consumption between 2004 and 2030 of some 1 trillion barrels.

Even more soberingly, the USGS "reserves growth" applied to global oil reserves is invalid since it is based on past practice in the USA. US oil reserves were historically understated due to stock exchange reporting rules (SEC). Therefore upwards revisions in oil reserves in the rest of the world cannot be applied. Eliminating this removes another 200 Gb of "recoverable resources", leaving only 1 trillion left to extract.

Well before that remaining 1 trillion has been extracted and consumed, production rates and flows will have plummeted.

4.3 Conclusion

A realistic estimate of Remaining Recoverable Conventional Oil Reserves is in the order of 1 to 1.2 trillion barrels.

At the conservative IEA demand growth rate of 1.6% p.a., 1 trillion barrels will need to be supplied between now and 2030.

At more realistic demand growth rates of around 2.5% p.a., this 1 trillion barrels will be consumed in less than 20 years.

Therefore, even with a naive Reserves to Production model, sufficient oil remains for only another 20 to 30 years.

In reality, it will be impossible to maintain production at current levels, let alone keep increasing production while remaining oil reserves are rapidly depleted.

5 The Hybrid Electric Vehicle

5.1 The Hybrid Electric Vehicle

In the immediate term, the best technological approach to reducing oil consumption sufficiently in line with falling oil supply will be the next logical development to the current Hybrid Electric Vehicle: the Plug In Hybrid Electric Vehicle (PHEV).

There are currently three alternative types of hybrid technology:

1. The Parallel Hybrid.
2. The Series Hybrid.
3. The Dual Hybrid

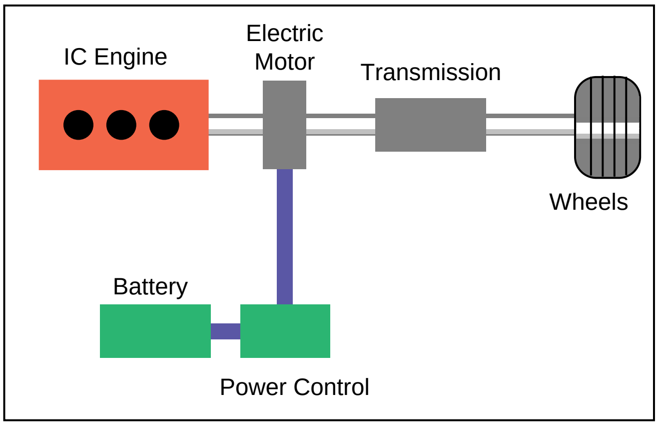
None of these conventional hybrid technologies offer sufficient fuel savings by themselves, but if enhanced with a larger battery which can be independently recharged from the domestic electricity supply, very significant fuel savings indeed will be achieved. This is discussed below.

The Parallel Hybrid

In the Parallel Hybrid system the wheels are driven by both an Internal Combustion (IC) engine and/or an electric motor. A better name for this approach is the Power Assist Hybrid, because the electric motor assists the petrol engine when needed, thus reducing fuel consumption.

This system is in effect used by Honda in their “Integrated Motor Assist” (IMA) system installed on their current range of hybrid vehicles.

FIGURE 11 **HONDA IMA HYBRID SYSTEM**



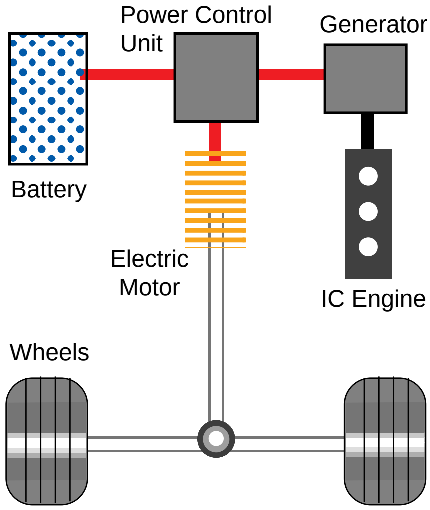
Because the IC engine is used to provide drive to the wheels, it has to be able to operate over a range of torques and speeds and therefore cannot operate at maximum fixed efficiency as it can in a Series Hybrid.

However, the current designs of Parallel Hybrid emphasise the IC engine as the primary power plant and use the electric motor as a secondary source of power. In future, especially when implemented as Plug In Parallel Hybrids, this will be reversed and greater efficiencies obtained by using the electric motor as the primary power unit and a small IC engine as the secondary.

The Series Hybrid

In the Series Hybrid system a small IC engine drives an electric generator. The generator then either charges a battery or directly powers an electric motor. The wheels are only ever driven directly by electrical power. When the drive power required exceeds that supplied by the generator, the battery supplies extra electricity; when on the other hand the drive power required is less than that supplied by the generator, the excess electricity produced is used to recharge the battery.

FIGURE 12 **SERIES HYBRID SCHEMATIC**



This Series Hybrid technology is not a recent development. The same technology is used in the Diesel Electric Train and Diesel Electric Submarine developed in the 1930s. It was first used by Ferdinand Porsche in 1899 and was generally considered for motor vehicles in the 1920s.

The advantage of this system is that the IC engine can operate at a constant speed and therefore optimum efficiency. A wide variety of IC engines and fuels can also be used to drive the generator. The designer is not limited to a conventional IC engine. However, in practice the accumulated inefficiencies of converting the fuel energy to electrical energy and then into mechanical drive at the wheels has not given the Series Hybrid any advantage over the Parallel Hybrid., except in frequent “stop - go” operations such as Public Transit or deliveries

Series Hybrids could be designed with more efficient types of thermal engines optimised for fuels other than gasoline. A small gas turbine system for instance could potentially be very efficient, since the gas turbine is most suited to constant speed operation, it is intrinsically more efficient than the piston IC engine and is a technology already widely understood for electrical power generation.

In fact, the US company Capstone Turbine Corp. manufacture small turbines for this application. In 2002, the city of Tempe, Arizona planned to test 10 series hybrid buses powered by 30kW microturbines. The fuel was Liquefied Natural Gas (LNG) to reduce NOx and particulate emissions. These cetrifugal flow turbines have only one moving part, no cooling system and require little maintenance. However, the bus manufacturer AVS went bankrupt and only a small number of buses using this technology now operate in the USA. Some buses in New Zealand are also using this turbine powered technology.

The biggest application of the Series Hybrid technology is by the New York City Transit Authority. They are operating 325 series hybrid passenger buses made by Orion Bus (owned by DaimlerChrysler). In October 2005, another 500 buses were ordered. A diesel engine drives a generator and a bank of Lead Acid batteries. The hybrid drivetrain is manufactured by BAE Systems. However, fuel efficiency is only 10% better than standard diesel buses at 2.65mpg. Another 150 of these buses have been ordered by Toronto and nearly 100 by San Francisco. This technology is currently the market leader in the North American hybrid bus market.

The entire North American bus fleet has started the process of transitioning to hybrid vehicles. Some 27,000 buses are sold in the USA annually.

In 2003, the world's top ten bus manufacturers produced 102,000 units, led by Daimler Chrysler with 28,000 units. This production will be progressively converted to hybrid propulsion over the next 5 to 10 years.

The Dual Hybrid

The dual hybrid combines parallel and series operation. It is the system used in the Toyota Prius and the ultra efficient Daihatsu UFE II.

In this dual hybrid system, the IC engine drives both the wheels and a generator. An electric motor powered by the generator and battery is also connected to the wheels. This system is designed to simplify the complexity of the transmission system.

FIGURE 13 **DAIHATSU UFE II DUAL HYBRID: 60 km/l**

This Daihatsu UFE II concept car uses a similar hybrid drivetrain to the Toyota Prius and a similar high efficiency Atkinson Cycle IC engine. The car achieves its very high fuel economy of 60km/l (140 miles per US gallon) by a combination of very low vehicle weight (570kg) and high aerodynamic efficiency.

Honda's latest IMAS hybrid concept car also has a very low weight of 700kg and high aerodynamic efficiency, giving it a fuel economy of 120 mpg.

Current Hybrid Developments

Most of the hybrids currently on the market cannot operate on electric power alone. The primary power unit is the petrol engine and the electric motor is only used to assist acceleration and to spin the engine up to an efficient ignition speed from rest. The motor or a separate generator also acts to recharge the battery during braking.

The Fuel Efficiency of the Toyota Prius is 60mpg at optimum speed. This is only comparable to a European diesel car and is not sufficient to meet declining oil supplies. The electrical drive system in the Prius is limited with a small battery capacity and restricted electric-only performance to make electric drive purely accessory to the petrol engine, not truly complementary.

However, in an important development a number of independent companies are improving the Prius by replacing its NiMH battery pack with higher capacity Lithium Ion batteries and enabling the feature which allows the car to drive on battery power alone. (This feature is normally disabled for the US market). The car can also be externally recharged, becoming a Plug In Hybrid (PHEV).

The US company EDrive LLC has modified a standard Prius with an externally rechargeable LiIon battery pack developed by the leading US automotive LiIon battery manufacturer, Valence Technology Inc. The car can drive the first 30 miles on battery power alone at speeds of up to 35mph. On the first 50-60 miles driving per day, the vehicle can achieve a fuel economy of between 100 and 150mpg, depending on vehicle speed. This range would cover the majority of drivers' daily requirements and the battery can then be recharged overnight. Beyond that distance, the vehicle operates as an ordinary Prius.

At $12,000, the cost of this third party conversion is prohibitive for the mass market. However, the cost would be much lower if it was incorporated during original manufacture.

While the major manufacturers are not publicly taking any steps themselves towards launch of a Plug In Hybrid car, Toyota are known to be evaluating the technology. Honda launched the latest 2006 version of their Civic model in September 2005. Unlike the previous model, the 2006 version does permit the vehicle to be driven in limited electric-only mode, which is a significant break with past Honda policy. It would not be a great step for either Honda or Toyota to launch a PHEV version of these vehicles.

5.2 The Future of Hybrids - The PHEV

It is clear that the Plug In Hybrid car is overwhelmingly the best existing solution to declining oil supplies. A PHEV60 - a plug in hybrid that can travel 60 miles on battery power alone before requiring the petrol or diesel engine - would meet the daily mileage requirements of the vast majority of drivers in the USA and Europe without any need for petrol or diesel at all. The concept is not new - Volvo and Mitsubishi both proposed PHEVs to the California Air Resources Board in 1995.

It is likely that the first Plug In Hybrid cars will be limited to 20 - 30 miles electric range. The main reason is to reduce the cost of the battery and therefore reduce the price premium of the PHEV20/30 over a conventional hybrid. As production volumes increase, battery prices will fall and the all-electric range can be increased.

In addition, 50% of US drivers travel less than 20-30 miles per day. Therefore even a PHEV20/30 would reduce overall petroleum consumption by over 50%.

The data on which this is based is shown below in Figure 14, taken from the 1990 National Personal Transportation Survey.

FIGURE 14

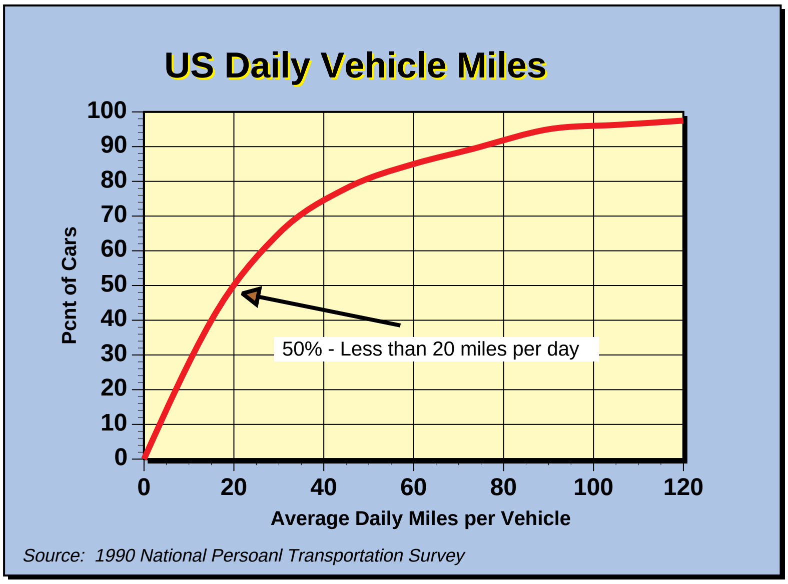


Figure 14 shows that on any given day, 50% of the Light Vehicles on the road in the USA will drive less than 20 miles.

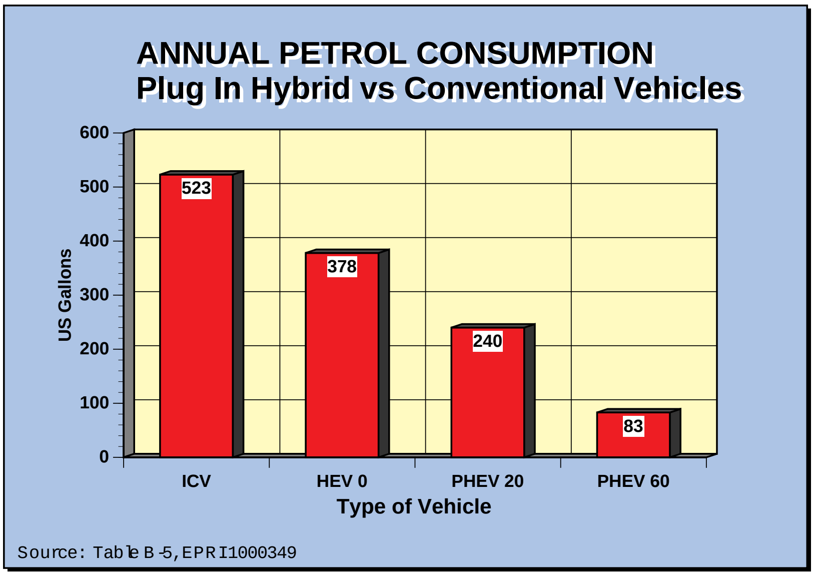
90% of the cars will drive less than 80 miles per day.

Therefore a PHEV80 could theoretically reduce US petrol or gasoline consumption to 10% of existing levels.

Figure 15 shows the predicted average annual petrol consumption for a mid-size car in the USA travelling 13,000 miles per annum[1]. The four versions of the car are:

- A conventional Internal Combustion Engine Vehicle (ICV).
- A conventional Power Assist Hybrid (HEV 0).
- A Plug In Hybrid with 20 miles electric range (PHEV 20).
- A Plug In Hybrid with 60 miles electric range (PHEV 60).

FIGURE 15



- A mid-size PHEV 20 would burn about 45% as much fuel per year as a conventional IC engined vehicle.
- A mid-size PHEV 60 would burn 16% of the fuel of a conventional IC engined vehicle.

These predictions were obtained with the ADVISOR vehicle performance modelling software developed by the Argonne National Laboratory.

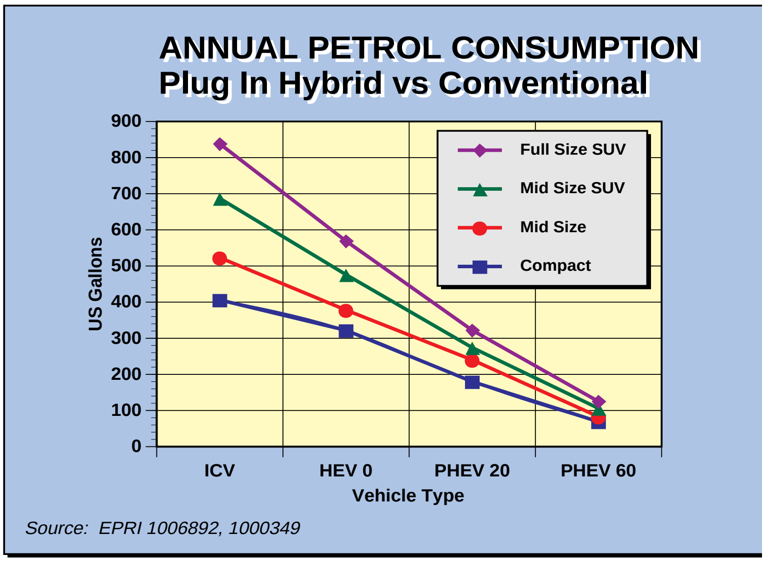
Even greater fuel saving benefits are obtained by converting “Full Size” and “Mid Size” SUVs to PHEVs. SUVs travel no more miles per year than ordinary passenger cars but are much less fuel efficient. Therefore, the base all-electric range will save proportionately more fuel in the case of an SUV than for a passenger car. Since these vehicles are larger and heavier, a larger and more costly battery will be required. However, SUVs are luxury vehicles that sell at a premium.

1. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, EPRI, Palo Alto, CA: 2001. 1000349. Page 189, Table B-5.

Figure 16 shows that a Full Size conventional SUV driving 13,000 miles per year burns twice as much fuel as a compact car - 838 USG versus 406 USG per year.

However, a PHEV 20 version of a Full Size SUV would burn 322 US gallons and a PHEV 60 would burn only 125 US gallons.

FIGURE 16



- A modest PHEV 20 capability in all vehicles could eliminate 55-60% of current fuel consumption by the US Light Vehicle Fleet.
- PHEV 60 capability would reduce the fuel consumption of the US Light Vehicle Fleet by 85%.

The Plug In Hybrid EV and the pure Battery EV can complement each other for different requirements: the PHEV for assured longer range, the Battery EV as a second car for local and urban use.

The Sprinter PHEV

The only major public PHEV test and development programme underway at the current time is a joint project between DaimlerChrysler and the Electric Power Research Institute (EPRI). A Plug In Hybrid version of the Mercedes Sprinter van with an all electric range of 20-30 miles was developed in 2004. Between 2005 and 2007, 30 of these vehicles will be tested in Germany and the USA, comparing both LiIon (SAFT) and NiMH (Varta) batteries. The NiMH batteries are capable of 3,000 deep discharge cycles; the LiIon battery is capable of 2,500 deep cycles. 30 miles of electric range in good weather will cover the majority of the miles driven per day by an urban delivery vehicle and ensure adequate range (20 miles) in cold weather.

DaimlerChrysler are developing this vehicle partly because of moves by European cities to close their city centres to motor vehicles. This is intended to reduce pollution and improve air quality, as mandated by various EU directives.

Increasingly the only possibility for commercial delivery vehicles to operate in European city centres will be by electric power. Daimler Chrysler see the Sprinter PHEV as a way to provide ZEV propulsion in the inner cities while still providing range for the vehicle to travel between its depot and the delivery area.

The City of Austin, Texas in the USA will be one of the US municipalities to test the Sprinter PHEV. The city's electric utility company is a significant user of wind turbines and sees PHEVs/ EVs as a possible load levelling solution and extra market for electricity. Austin is actively promoting the PHEV concept. Other US electric utilities are also starting to adopt EVs for similar reasons.

Air Quality

In line with EU Directives, the UK's Air Quality Strategy sets the following limits for NO_2 and PM_{10} levels to be achieved.

TABLE 3 **UK AIR QUALITY STRATEGY**

Emission Type	NO_2	PM_{10}
Deadline	2005	
Annual Mean	40µgm^{-3}	40µgm^{-3}
Hourly Mean	200µgm^{-3} Not to be exceeded > 18 times a year	-
24 Hour Mean	-	50µgm^{-3} Not to be exceeded > 35 times a year
Deadline	2010	
Annual Mean	40µgm^{-3}	20µgm^{-3}
Hourly Mean	200µgm^{-3} Not to be exceeded > 18 times a year	
24 Hour Mean		50µgm^{-3} Not to be exceeded > 7 times a year

National modelling projected that in 2005, the annual mean NO_2 concentration limit of 40µgm^{-3} would be exceeded alongside 65% of major roads in London and by 18% of major roads in the rest of England. DoT studies also showed that to meet the NO_2 emissions limits, traffic emissions will have to be reduced by between 60% and

90% at various urban locations around the UK. London is the worst affected.

These figures indicate why there is such strong interest in Low Emissions Vehicles in Europe.

Similar pressures apply in the USA. The New York City Transit Authority (NYCT) ordered their first 10 Orion series hybrid buses in 1997, at a price of $465,000 each compared to $290,000 for a conventional diesel bus. The whole program in New York and other cities has been driven by air quality considerations. The NOx emissions from diesel buses in New York have been measured at over 70 grams per mile. This would fill a box 33m high by 33m wide with $40\mu gm^{-3}$ of NO_x along the entire route of the bus.

The State of the Art - The Plug In Parallel Hybrid

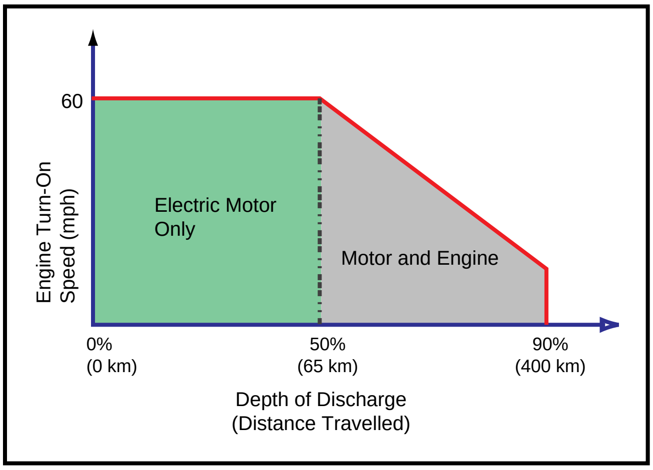
While a large number of different hybrid configurations are possible, it seems that the optimal future design will eventually be a light-weight, aerodynamically efficient Plug In Parallel Hybrid Vehicle in which 75% of the installed power is derived from an electric motor and 25% from a small 660cc engine[1]. The battery size should be about 18kWh to give a ZEV range of between 60 and 80 miles, depending on vehicle weight. An aluminium or aluminium-composite body will be used to reduce weight. Aluminium can reduce the weight by up to 50% compared to an equivalent steel body and has the same or better crashworthiness. The transmission will be a Continuously Variable Transmission (CVT) to optimise power sharing and efficiency between the electric motor and IC engine.

By using a small IC engine, the IC engine can be operated at high power and high efficiency when it is required. At low and medium speed (up to 60mph) the electric motor meets all the load while the state of charge of the battery is high. When the speed or power requirements exceed the capability of the electric motor or the battery charge drops, the IC engine cuts in with power assist and to decrease the rate of battery depletion. The battery can then be topped up or recharged overnight.

This control strategy is shown in Figure 17.

1. “A Mid Size Sedan Designed for High Fuel Economy and Low Emissions: the UC Davis FutureCar”, Dr. Andrew Frank, Dr. Andrew Burke, UC Davis, 1998

FIGURE 17 **ADVANCED PHEV CONTROL STRATEGY**



Up to 60mph and 50% battery State of Charge (SOC), the vehicle runs on electric power alone. Above that speed, the IC engine switches on to provide power assist.

Once the battery starts to deplete past 50% SOC, the threshold speed for the IC engine to switch on decreases. This slows down the rate of battery depletion until at 90% depletion, the engine turns on immediately from rest. At this point, the vehicle operates as a standard HEV0 in charge sustaining mode.

This design is therefore diametrically opposite in concept to the existing Power Assist Hybrids such as the Toyota Prius or Honda Insight. The Electric Motor is the primary powerplant and the IC engine acts to assist it and maintain range after the battery has partly discharged. The IC engine does not operate a generator to recharge the battery until 80% depletion has been reached - it reduces battery depletion by feeding its power directly to the wheels. The car is an Electric Vehicle with IC Engine Assist, rather than an ICV with electric motor assist.

In this way, this Parallel Hybrid design has the advantage of the Series Hybrid - relatively high efficiency operation for the IC engine when it is switched on - but avoids the disadvantage of energy efficiency losses in converting fuel energy to mechanical energy to electrical energy back to mechanical energy to drive the wheels.

This concept, refined at the University of California at Davis over the last 40 years, represents the state of the art in Hybrid and Plug-In Hybrid Vehicle design.

The TM4 System

A unique plug in series-parallel hybrid drivetrain has been developed by the Canadian company TM4, who are a subsidiary of Hydro Quebec. The system has been adopted by the French joint venture Societe Vehicules Electriques for their Cleanova range of plug-in hybrid vehicles.

The TM4 system allows seamless transition between series, parallel or pure EV operation for maximum efficiency depending on the speed regime of the vehicle.

SVE have a number of vehicles equipped with this drivetrain on trial with the French postal service, La Poste.

Battery and Motor Combinations

Depending on the ZEV range of a PHEV, the following electric motor/ IC engine and battery capacity combinations would be required[1].

TABLE 4

	PHEV 20		PHEV 60	
	Battery	Motor	Battery	Motor
Compact Sedan	5.1kWh		15.5kWh	
Mid Size Sedan	5.9kWh	22kW	17.9kWh	32kW
Mid Size SUV	7.7kWh		22.9kWh	
Full SUV	9.3kWh		27.7kWh	

For a PHEV20-30, using an 8kWh battery, current NiMH technology would be sufficient. The Panasonic NiMH battery used in the Honda EV+ had a specific energy of 70Wh/kg - nearly equivalent to the Valence Technology iron phosphate cathode LiIon battery.

A current generation SAFT LiIon EV battery containing 8kWh would weigh 70kg.

The ZEBRA NaNiCl battery could also be used. For a small 8kWh battery, specific energy would probably fall to around 90Wh/kg due to the fixed weight of the controller. However, the ZEBRA technology has potentially the lowest cost of all the competing EV battery technologies, notwithstanding the recent increase in the price of Nickel.

1. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, EPRI, Palo Alto, CA: 2001. 1000349.

Conclusion

The Plug In Hybrid addresses the two major limitations of the pure Battery Electric Vehicle: limited range and slow battery recharge time, while still providing its major advantage: zero petroleum usage for the short journeys which constitute the overwhelming majority of road vehicle trips.

A PHEV20 would reduce the fuel consumption of the US Light Vehicle Fleet by over 50%.

A PHEV 60 would reduce US Light Vehicle fuel consumption by up to 85%.

The University of California at Davis estimate that a PHEV80 would reduce Californian petroleum consumption to 10% of current levels (based on Figure 14). Since 10% of Californian gasoline is already comprised of ethanol, this would effectively mean that a fleet of PHEV80s could entirely displace fossil fuel and could in theory be powered by biofuel alone. (However, there are serious questions about the energy balance in producing ethanol and other biofuels).

The EDrive conversion of a standard Toyota Prius has shown what can be achieved using existing off the shelf technology. The logical next step for Toyota and Honda - or another hybrid car manufacturer - would be to launch a purpose designed Plug In Hybrid.

5.3 The Compressed Air Car

The compressed air car has received some recent attention. It can be considered to be a form of hybrid or electric vehicle. The energy source is provided by a tank of compressed air which is slowly released through a pneumatic system to provide mechanical power - much like a steam engine except the working fluid is air, not steam.

Numerous inventors have devised variants on this idea since the early 20th century. In the late 1990s, French inventor Guy Negre designed a modern version of this technology and established a company called Moteur Developpement International to market it.

This technological approach is fairly efficient. In effect, compressed air is the energy carrier for converting electricity to motive power.

As of mid-2005, MDI have built 12 prototypes but have not been able to raise the finance to start production. As with a hydrogen fuel cell vehicle, it would however be more efficient to charge a battery in an electric vehicle directly with electricity rather than use electricity to drive a compressor. On the other hand, the technology of compressed air is fairly straightforward and simple and might be cost effective compared to certain battery technologies. Refuelling is a matter of recharging the air tanks in the car from a high pressure reservoir - this could be quicker than recharging a battery overnight.

Conclusion

The compressed air car is unlikely to be successful. Competition from pure electric and plug in hybrid technologies is too strong. It is still more efficient to use electricity to charge directly batteries on board an EV than to use that electricity to compress air, which must then be converted into traction power through a relatively inefficient mechanical drivetrain. Safety issues associated with the widespread presence of compressed air cylinders in motor vehicles would be significant.

6 Battery EV Programmes

6.1 Introduction

The heart of the Electric Vehicle is its Battery. It has also been its Achilles Heel. Up to the 1990s, batteries could not hold sufficient power to provide generally acceptable range. That situation is no longer the case with the development of the Sodium Nickel Chloride battery, the NiMH battery and the Lithium Ion battery.

This section presents an overview of recent Battery EV developments, some BEV concepts and the effect that different battery technologies would have on their performance.

Historical Overview

The history of the Electric Vehicle is as old as the automobile. In the early 20th century, the number of EVs in the USA exceeded that of petrol cars. The Electric Car did not really die until the 1920s and might have been saved by Thomas Edison's Nickel - Iron battery.

The latest resurgence in the development of EVs took place in the 1990s. In September 1990, the California Air Resources Board (CARB) introduced a Zero Emissions Vehicle Mandate[1]. This required that in each year from 1998 to 2002, 2% of the vehicles offered for sale in California were to have been ZEVs, rising to 5% p.a. in 2001 and 10% p.a. in 2003. California represents 11% of the US car market; 10% of Californian car sales would therefore be over 180,000 vehicles per year.

The CARB were partly stimulated to introduce these measures by the unveiling of the GM "Impact" EV at the January 1990 Los Angeles Motor Show and GM's announcement in April 1990 of their intention to manufacture 25,000 Electric Vehicles a year from 1995. By 2010, CARB expected 70% of the vehicles in Southern California (where air pollution problems are the worst) to be EVs.

1. "ZEV Mandate in California: Misguided Policy or Example of Enlightened Leadership?", René Kemp, 13/12/02

Five other states in the North Eastern USA also intended to adopt the Californian regulations. However, after 1996 the regulations were progressively watered down and are now to all intents and purposes worthless.

The original progression of the CARB Mandate is shown below in Table 5.

TABLE 5

CARB ZEV MANDATE

Year	Pcnt ZEV Sales	No. of Vehicles
1998 - 2000	2%	35,000
2001 - 02	5%	85,000
2003 - 08	10%	180,000
2009 - 11	11%	210,000
2012 - 14	12%	225,000
2015 - 17	14%	265,000
2018 onwards	16%	300,000

It can be seen that if today in 2005, 10% of the vehicles sold in California and the North East USA were EVs, action to respond to declining global oil production would now have been much easier and faster to implement. By the end of 2005, there would have been over 800,000 EVs on California's roads if the minimum CARB mandate had been met.

The few Electric Vehicles the car manufacturers produced to meet the CARB rules used less than optimum battery technology and were very expensive. In 2004 the major car manufacturers recalled and crushed some 3000 EVs they had leased to customers to meet the CARB rulings, instead of continuing development and investing in battery upgrades. This EV crushing program was despite the overwhelming opposition of the EV drivers who wanted to keep the vehicles. This opposition has had some recent success in 2005 in keeping some EVs on the road.

There is one overriding reason why the EVs failed to achieve widespread sales in California: they cost nearly twice the price of the equivalent petrol vehicle.

The average monthly lease cost for the seven EVs on the Californian market was $478; for the equivalent petrol model it was $285. The electric Ford Ranger was $450 a month compared to $200 a month for the petrol version. The only car made available with a LiIon battery, the Nissan Altra, was priced at $600 per month. Not surprisingly, only 81 examples of this model were placed.

However, the technology and operational viability of the EV has still been proven beyond doubt in California and Norway by the GM EV1, Ford Ranger, Ford Th!nk, Toyota RAV4EV, Honda EV+ etc. All that these vehicles required to become a very attractive proposition was a high energy density battery and sensible pricing. The purpose designed “Zebra” EV battery of the same weight would double or triple their range. A Zinc Air or Lithium Ion battery of the same weight as the NiCad or NiMH batteries these vehicles used would more than triple their range.

6.2 Recent Historical Programmes

This section presents a number of Battery EVs that were developed during the 1990s, some current test concepts and a number of concept possibilities.

Th!nk City

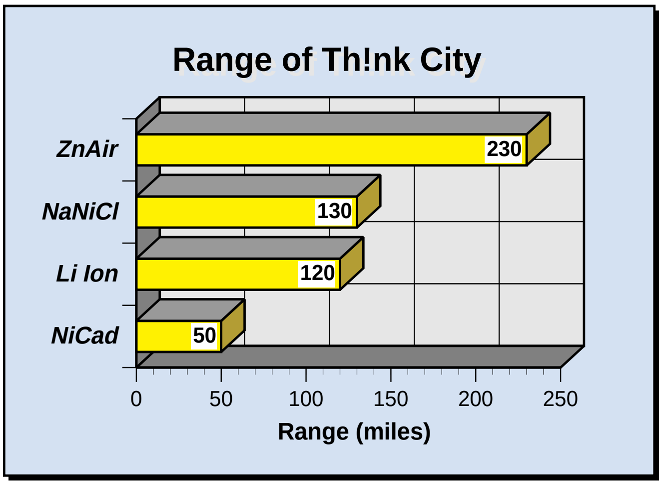
First we will consider the Ford Th!nk city car. This small electric commuter car had a range of only 50 miles with 250kg of NiCad batteries that supplied 11.5kWh of electricity. The car is still used in Oslo and saw limited use in California. Ford recalled all of the vehicles that were in use in the USA and proceeded to crush them in 2004; only the request of the Norwegian Transport Ministry to return them to Norway to meet public demand stopped this.

If the battery in the Ford Th!nk was replaced by the same weight of Li Ion cells widely available on the market today, the range would increase to 120 miles. This would be more than adequate for city and commuter use.

If it was replaced with the cheaper and very rugged “Zebra” NaNiCl EV battery, the range would increase to 130 miles.

Zinc Air metal fuel cell technology would increase the range to 230 miles.

FIGURE 18 **FORD THINK - BATTERY /RANGE COMPARISONS**

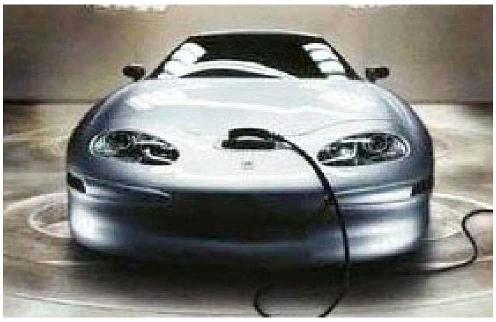


The NaNiCl Zebra battery would be the best near-term upgrade for this vehicle. One standard 22.2kWh module weighing 195kg would double the range of the car to 100 miles. In limited volume, the cost of this battery unit would be about 4000 euros. In high volume, the cost would be half that.

GM EV1

The General Motors EV1 is the most famous and most advanced Battery Electric Vehicle manufactured to date. It was launched in 1997 with minimal marketing, after (it is stated) $1 billion was spent on its development.

FIGURE 19 **GM EV1**



The first version of this car contained 18.7kWh of Lead Acid batteries weighing 1310lb (595kg). The range was only 55 - 95 miles.

The second version launched in 1999 contained 26.4kWh of NiMH batteries weighing 1147lb (521kg). The range was 75 - 130 miles. Sales improved slightly.

In 2004, GM started to crush the vehicles as they were returned from lease rental, despite the overwhelming desire of lessees to buy them.

If instead of crushing these vehicles, the battery was replaced with 3 of the commercially available Zebra battery modules, weighing 195kg each (585kg total) and providing 63.6kWh of total energy capacity, the range would increase to between 200 and 300 miles.

With 6 Electric Fuel ZnAir metal fuel cell units, weighing 528kg and providing 104.4kWh of energy, range would increase by a factor of 4 to between 300 and 520 miles.

The range that the GM EV1 would exhibit if retrofitted with different battery types is shown below.

TABLE 6

EV1 RANGE BY BATTERY TYPE

Battery	Range
PbA	55 - 95 miles
NiMH	75 - 130 miles
Sodium Nickel Chloride	180 - 300 miles
Zinc Air	300 - 520 miles
Lithium Ion	260 - 450 miles

Mercedes A Class Electric Vehicle

During the mid 1990s, Mercedes Benz developed an EV version of the small A Class city car. The car was powered by a 30kWh Zebra NaNiCl battery module weighing 370kg that was installed below the passenger compartment. The internal space and comfort of the car was therefore not affected. This battery gave the car a real world driving range of 125 miles. In 1998, the vehicle was ready to be launched but was withdrawn after the merger between Daimler and Chrysler.

FIGURE 20

MERCEDES-BENZ ELECTRIC A CLASS

This early version of the Zebra battery had an energy density of 81Wh/kg. If the battery was upgraded to the latest version of this technology, with an energy density of 120Wh/kg, the range of the Electric A Class would increase to 180 miles today.

Daimler Chrysler's latest Fuel Cell version of the A Class has a range in 2004 of only 90 miles.

Esoro E301

During the mid 1990s, the independent Swiss motor engineering firm Esoro AG developed a number of EV and Hybrid concept vehicles. The E310 battery powered commuter car was one of the most efficient EVs developed. It consumed only 9kWh of electricity per 100km or

0.144kWh per mile. The 260kg NiCad battery was similar to that in the Ford/Kamkorp Th!nk.

If the battery was replaced with a 22.2kWh Zebra battery module weighing 195kg, the range of the E301 would increase to 150 miles.

Esoro are no longer involved in EV development.

Korean Developments

During the 1990s, the Korean motor manufacturers Daewoo and Hyundai developed a number of EVs and HEVs. Hyundai obtained CARB ZEV certification for their Accent EV in 1997 (using an NiMH battery). In November 2000, Hyundai produced the Santa Fe EV, an EV version of an SUV with 160km range from an NiMH battery. This vehicle was similar to the Toyota RAV4EV.

The electronics group Samsung also produced a battery EV demonstrator at the end of 1996 called the SEV-IV.

Hyundai plan to launch two hybrids onto the US market in 2006, one a version of the Accent and the other a version of the Kia Rio. The vehicles will have a continuously variable transmission and will use NiMH batteries from Panasonic EV Energy Ltd.

The CVT and other systems for these vehicles have been on trial in a testbed called the Getz EV.

The Korean car manufacturers would clearly have the expertise to launch pure EVs and PHEVs if they chose to do so.

The CARB Vehicles

The late 1990s was the heyday of EVs (to date). For a brief period of time, a significant number of electric cars from major manufacturers were made available to the general public.

These vehicles were all hampered by the very high cost of leasing or purchasing them. No allowance was made for the fact that these were new technology vehicles and that the initial low production volume would inevitably lead to high cost.

Table 7 shows the monthly lease rates for the main EVs that were available in California in the late 1990s. The monthly lease rate for the Internal Combustion version of the vehicle (or a comparable one) is shown for comparison.

TABLE 7

EV LEASE RATES CALIFORNIA 1997 - 2000

Vehicle	Battery	Battery Supplier	EV Lease Cost ($/mth)	ICV Lease Cost
Chevrolet S10	NiMH	?	440	225
DC EPIC	NiMH	?	450	325
Ford Ranger	NiMH	Panasonic	450 (199)	200
GM EV1	NiMH	Ovonics	477 (349)	375
Honda EV+	NiMH	Panasonic	455	300
Nissan Altra	LiIon	Sony	599	275
Toyota RAV4EV	NiMH	Panasonic	457	300

It can clearly be seen why sales of EVs were low. Petrol prices were low at the time and the lower operating cost of the EV could not compensate for the much higher leasing cost or the loss in functionality - range.

(The lease price of the Ford Ranger was later reduced to $199 and that of the GM EV1 to $349).

Honda EV+

The Honda EV+ was equipped with a 26.2kWh NiMH battery weighing 840lbs (380kg). It had a range of 100 - 120 miles in ordinary driving - 140 miles could be achieved with careful use.

Nissan Altra EV

The Nissan Altra was the only EV equipped with a LiIon battery to be made available in California in the late 1990s.

The monthly lease cost was $599. Only 81 vehicles were placed.

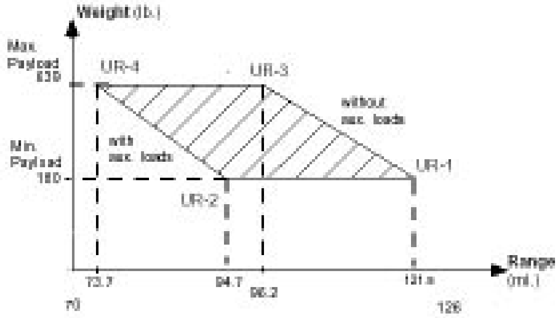
The car was an estate car weighing 1790kg unladen. Maximum Payload was 370kg.

It was equipped with a 32.4kWh Sony LiIon battery weighing 364kg, for a specific energy of 89Wh/kg. Power density was 300W/kg. The weight of the battery pack, consisting of 12 modules each containing 8 100Ah cells, was made up of 317kg for the cells and 46kg for control circuitry, packaging and the case.

FIGURE 21 **NISSAM ALTRA**

The vehicle performance was quite good. On an urban cycle, the range varied between 95 and 120 miles depending on payload, without the air conditioning. In the worst case, with maximum payload and the air-conditioning in operation, range fell to 74 miles between recharges.

FIGURE 22 **NISSAN ALTRA URBAN CYCLE PERFORMANCE**



On the freeway cycle, the vehicle achieved[1] a range of between 80 and 90 miles at an average speed of 45mph.

The current SAFT LiIon EV battery has a specific energy of 110Wh/kg per module. Assuming no capacity loss on assembling modules into the final pack, a Nissan Altra equipped with a SAFT battery of the same weight as this Sony battery would obtain a 22% range improvement, i.e. urban range of between 92 and 150 miles.

The vehicle could also be equipped with the Zebra NaNiCl battery. Two standard Zebra modules would weigh 390kg and provide 42.4kWh of energy storage. The weight increase over the original Sony battery would be marginal. Urban range could increase by 30%, i.e. to between 100 and 160 miles.

1. Performance Characterization: 1999 Nissan Altra-EV with LiIon Battery, Southern California Edison, C. Madrid, J. Argueta, J. Smith, Sept. 1999.

Volvo 3CC

The Volvo 3CC concept car was the only Battery Electric vehicle presented by any major western manufacturer at the October 2004 Michelin Bibendum Challenge in Shanghai. This event is the premier world showcase and car rally for Sustainable Mobility.

FIGURE 23 VOLVO 3CC

Designed by Volvo's design centre in California, the 3 seater is powered by 3000 off the shelf LiIon cells and uses the AC Propulsion AC150 drivetrain. AC Propulsion are a leading independent developer of Electric Vehicle technology. The Volvo 3CC has a range of 300kms (190 miles) per charge.

An optimised LiIon battery format could improve the packing density and hence the range of the vehicle. This concept vehicle is only designed to show what is possible but a range of 190 miles would cover a large percentage of most drivers' foreseeable daily requirements.

Use of these small commercial 18650 cells is impractical and unsafe for a commercial EV.

6.3 Current Test and Development Programmes

Plug In Prius Hybrid

The independent US electric vehicle company EDrive are marketing a modification of the Toyota Prius Hybrid to retrofit it with a larger LiIon battery pack. The battery is manufactured by Valence Technology and uses the much safer Iron Phosphate cathode material. The battery has 7 times the energy capacity of the factory fitted NiMH battery and can be externally recharged. This allows the vehicle to drive about 35 miles per day on battery power alone and achieve an estimated 100 to 150mpg fuel economy on the first 50 miles of driving.

Toyota have consistently made public statements that are negative towards Plug In Hybrids, even though it would be relatively straightforward for them to modify the existing Prius into a plug-in version.

However, in mid-2005, Toyota showcased a concept “house of the future” in Japan, to show what features a future house with integrated technology might display. This concept house, called “Toyota Dream House PAPI”, features a garage with a central electricity charging point for EVs and Plug In Hybrids. A Prius hybrid was present, plugged in and capable of receiving power from the house. The vehicles can also supply power back to the house. The Vehicle to Grid (V2G) concept has been promoted in the USA as an integrated EV/ electrical generation system to use the electrical power of EVs as part of the national electricity production system. Toyota also gave a presentation at the October 2005 Tokyo Motor Show that was very positive about PHEVs, in a complete turnaround from their previous public position.

Therefore, it would appear that Toyota are in fact well aware of the possibilities of PHEVs and may be in the process of developing it.

Electrovaya Maya 100

This electric vehicle is a technology testbed developed by the Canadian Lithium Ion battery manufacturer Electrovaya Inc.

The vehicle contains a 40kWh LiIon polymer battery based on standard Cobalt Oxide cathode technology. The battery has a very high claimed energy density of 225Wh/kg; the range is claimed to be 200 miles. The battery has a calendar life of 7 years and 150,000 kms. These performance claims are difficult to substantiate and cobalt oxide will not be suitable for EV use. According to other sources, a PbA battery is also used to provide high power when required.

The vehicle costs $70,000 and is therefore not yet suitable as a mass market product.

FIGURE 24 **MAYA 100**

At the 2004 Tour de Sol, a premier US event for electric vehicles, the Maya 100 won a number of awards. Large scale commercialisation of this vehicle is beyond the means or mission of a relatively small battery manufacturer such as Electrovaya but the vehicle is a demonstration of what is technically possible today with LiIon batteries.

Bolloré Blue Car

The Bolloré Blue Car is one of the latest dedicated EV designs. Unveiled at the 2005 Geneva Motor Show, the car was designed as a showcase for Lithium Metal Polymer battery technology developed by the French industrial group Bolloré.

FIGURE 25 **BOLLORÉ BLUE CAR**

The vehicle is a city car equipped with a 27kWh LiMP battery weighing “less than 200kg”. Energy density is actually 120Wh/kg. Range is claimed to be between 125 and 150 miles which seems reasonable for the weight of the vehicle and energy content of the battery.

LiMP battery technology is falling further out of favour for safety reasons.

The Blue Car was designed by the designer of the groundbreaking Renault Espace. Production will depend on the establishment of a partnership with a suitable vehicle manufacturer.

Despite the tax credits available in France for the purchase of clean vehicles, out of the 2 million new cars sold in France in 2003 only 10,000 were GPL, hybrid or electric. As in Norway, where there are even more extensive incentives, the vehicles are not available to take advantage of the tax credits.

Reva NXG

This car has been designed as a two seat city car by the Indian EV manufacturer Reva. It will replace or complement their existing low cost model. Production is not currently expected to start before 2007.

The vehicle is very similar in concept to the two seat Smart Car.

FIGURE 26 **REVA NXG**

The Zebra NaNiCl battery has been selected for the vehicle. With a 21.2kWh module, the car should have an urban range of over 100 miles. This is a much more sophisticated vehicle than the existing “Classé” model. It is probably initially aimed for export to Japan and other right-hand drive markets, capitalising on India’s low labour costs.

Th!nk City New

Between 11th November 1999 and the 22nd March 2002, Think Nordic produced 1,005 Think City EVs. The Ford designation was A306.

In the Autumn of 2002, production was due to start on the replacement vehicle (A366) but Ford pulled out of the company. In February 2003, Think was bought by the Swiss group Kamkorp and unveiled the Think Public utility vehicle in March 2004.

The new Think City (A366) is shown below.

FIGURE 27 **TH!NK CITY NEW**

The new Th!nk City was designed when Th!nk Nordic were still under Ford ownership. The vehicle would be a good urban or second car for local use. A number of prototypes have been built but Th!nk Nordic currently lack the capital resources to develop the vehicle further.

6.4 Current Electric Car Programmes

There is now another resurgence in the number of pure EV or Plug In Hybrid commercial programmes underway across the world. This section presents an overview of some of those already on the market or serious commercial programmes with a high probability of making it to market.

US Manufacturers

There are no mainstream EV or PHEV programs underway in the USA. US manufacturers are only reluctantly adopting power assist hybrid technology because of Japanese competition. In fact, as of six months ago, Ford and GM were trying to crush the remaining GM EV1 and Ford Ranger EVs in service.

A number of small independent companies offer conversions of ordinary vehicles. While these attract niche customers, they will never be able to compete economically with mass produced vehicles.

However, one program has created significant market awareness as to the future possibilities, as it has been able to capitalise on an already available hybrid platform to reduce the cost.

EDrive/Energy CS

The US company EDrive LLC has modified a standard Toyota Prius with an externally rechargeable LiIon battery pack developed by the leading US automotive LiIon battery manufacturer, Valence Technology Inc. The car can drive the first 30 miles on battery power alone at speeds of up to 35mph. On the first 50-60 miles driving per day, the vehicle can achieve a fuel economy of between 100 and 150mpg, depending on vehicle speed. This range would cover the majority of drivers' daily requirements and the battery can then be recharged overnight. Beyond that distance, the vehicle operates as an ordinary Prius.

At $12,000, the cost of this third party conversion is prohibitive for the mass market. However, the cost would be much lower if it was incorporated during original manufacture.

The conversion program will also be made available in the UK from 2006, marketed by the company Amberjac Projects Ltd. They hope to sell up to 500 conversions a year in full production. The main market will be fleet vehicle users who can cost justify the capital investment with reduced fuel costs.

European Manufacturers

Dassault/SVE Cleanova II and III

The Cleanova II is a programme to offer a conversion of the Renault Kangoo van to the French Post Office, La Poste. The Kangoo is the standard delivery van used by La Poste. In the early 2000s, Renault did offer a PHEV version of this vehicle with a NiCad battery but have now discontinued it. 250 Renault Kangoo PHEV vans were ordered by the Norwegian Post Office at the end of 2001 but quality problems caused only 50 to be delivered and the order was cancelled. These vehicles are now out of service.

La Poste operate over 50,000 delivery vans, at least half of which could be replaced with this EV/PHEV. Forthcoming European legislation to increasingly ban IC engined vehicles from city centres to improve air quality is focusing the attention of commercial operators on Electric Vehicles. Even without the pressure of oil prices, there will be a massive switchover to Plug In Hybrid and pure BEV vehicles in the European commercial and utility sector over the next 10 years.

Of the mainstream manufacturers, only Daimler Chrysler are responding to this forthcoming requirement, with their Sprinter PHEV.

Société Véhicules Éléctriques (SVE) is a joint venture between Dassault and the independent motor engineering company Heuliez. Heuliez manufactured 6,419 electric vehicles for Peugeot and Citroen between 1995 and 2003 when production stopped. Heuliez are therefore the most experienced manufacturer of mainstream commercial electric cars in the world. Their programme to convert the smaller Kangoo commercial vehicle to electric propulsion is the only other electric vehicle programme in Europe (apart from the Sprinter) with significant industrial backing.

FIGURE 28 **CLEANOVA II**

Dassault have stated that the Cleanova II and III will be commercialised in the second half of 2006.

The Cleanova II is available in two versions: a pure EV and as a PHEV. The PHEV Cleanova II will operate 140-200kms per charge and the IC engine can act as a range extender if necessary. It has a 22kWh LiIon battery supplied by SAFT, capable of 2000 deep discharge cycles. SVE state that with a sufficiently powerful charger, the battery can be 80% recharged in 30 minutes. This would probably reduce cycle life if carried out on a regular basis. Normal recharge time is 6 hours.

The pure EV version has a 30kWh SAFT LiIon battery and no range extender. Real world range would probably be in the order of 120 miles.

TABLE 8

CLEANOVA II PERFORMANCE

	Electric	Hybrid
Battery	30kWh SAFT LiIon	22kWh + 20l petrol
Urban Range	245km	485km
50km/h Range	280km	545km
Extra Urban	200km	440km
90km/h Range	175km	390km

Total European New Registrations of small vans in the Renault Kangoo class were some 670,000 units in 2004. The Kangoo is the market leader with 25% of the market, closely followed by the Citroen Berlingo with 23%.

The Cleanova III is a conversion of the Renault Scenic sub-compact car. It was first unveiled at the Geneva Motor Show in early 2005. This is not such a priority for SVE as the Cleanova II commercial vehicle but could form the basis of an EV for the private car market.

FIGURE 29

CLEANOVA III

The Cleanova II and III therefore are probably the most significant EV programmes in Europe - indeed, outside of Japan at the current time. If the announced timescale is adhered to, they will be the first mass produced EVs or PHEVs to reach the market since the demise of the CARB mandates in California.

MES-DEA

The Swiss manufacturer of the Zebra NaNiCl battery has launched a limited commercial program to convert the Renault Twingo and Smart Car to electric propulsion, equipped with the Zebra battery.

The program is really aimed at the Italian market, where the government offer a 65% subsidy to purchasers of EVs. At 18,000 euros for the Twingo, the vehicle is otherwise too expensive. This programme will also serve to obtain further test data on the battery and to validate its performance in real world conditions.

Rome and seven other northern Italian cities have already introduced pedestrian only days to reduce air pollution. Five other Italian cities are also implementing traffic reduction measures to reduce air pollution. Air quality is a major problem on the Italian peninsula and European Union limits for NO_x and SO_2 are frequently exceeded. The city of Bologna has even been threatened with EU fines for not doing enough to ensure air pollution is reduced.

All European towns and cities must now monitor air pollution levels and take measures if required to ensure certain NOx levels are not exceeded. Europe particularly suffers from air pollution due to its high use of diesel powered vehicles. Introduction of EVs and PHEVs is undoubtedly the best way to ensure these air quality targets are met, apart from reducing traffic.

In this market environment, it is surprising that European motor manufacturers are not doing more to develop Zero Emission Vehicles, which are exempt from traffic reduction measures.

Zytek

The independent UK motor engineering company Zytek have converted six Smart cars to electric propulsion. They have had an ongoing programme to launch a commercial conversion programme for two years, if a viable business case can be made. The vehicle is powered by a 12kWh Zebra battery which adds 110kg to the normal empty weight.

FIGURE 30

The vehicle would cost 30,000 euros and would be targeted at fleet customers. Recently, the OEM Smart GmbH have become actively interested in the programme, probably because of rising oil prices. They are even involving their dealers in the UK in promoting the concept. A better business case could be made for Smart to launch an EV version of their models themselves, using electric drivetrain technology from Zytek or another company. Smart now have 4 models in their product range. Two other companies in the USA (ZAP and Hybrid Technologies) are also attempting to launch EV conversions of the Smart Car. The two seat Smart Car is a popular choice for conversion programmes because it was originally designed to be an electric vehicle.

Smart GmbH

Smart is a wholly owned subsidiary of Daimler Chrysler (Mercedes Benz). The original two seat car launched in 1994 was designed as an EV. Smart have launched three new models over the last few years. Smart are now actively evaluating EVs and would be well positioned to launch EV versions of their models. They are a relatively small car manufacturer, but have produced over 400,000 vehicles and have much greater capability than any existing independent vehicle manufacturer in Europe.

Smart's largest car, the SmartforFour, is about the same size as the Mercedes A Class. It shares a common platform with the Mitsubishi Colt. This is the vehicle that Mitsubishi are currently testing as an EV. Mitsubishi have announced definite plans to launch an EV by 2008.

While Smart will not yet publicly confirm their intent, the chances are high that they will be one of the first European manufacturers to launch an EV in the future as oil prices continue to rise.

Indian Manufacturers

There are a number of EV manufacturers in India which are becoming well established. The leading manufacturer is the Reva Electric Car Company. There are a substantial number of smaller vehicle manufacturers as well, particularly those specialising in 3 wheel EVs.

The largest car manufacturer in India is Maruti, owned by Suzuki. They have 50% of the domestic car market but have not yet launched a hybrid or EV vehicle.

Battery EVs in India have the advantage that they are entering a market which has very little pre-existing use of internal combustion engined vehicles. As oil prices rise, the economics of petrol vehicles for the developing economies is becoming unsustainable and EVs or biofuel powered vehicles are rapidly becoming the only option. For people who have had no mobility, the mobility of EVs does not seem limited and people will accommodate themselves to what is available.

Reva R-Car

Reva are the prime manufacturer of city electric cars in India. The market for these vehicles is expanding rapidly in a country which has never experienced widespread vehicle ownership.

The Reva R-Car or "Classé" is a very small two seat city vehicle. Like the Think City, the body is made of ABS. It is only 2.6m long and weighs 750kg unladen.

The cost is kept down by using Lead Acid batteries providing just 9.6kWh of energy. The vehicle is also sold in other countries which use right hand drive vehicles - the UK, Malta and potentially Japan, where a US$2,600 subsidy is available per vehicle sold. In the UK, the selling price is 7,000 euros. Over 1,000 have apparently been sold in London where EVs are exempt from the inner city congestion pricing scheme and can enter the centre of London free of charge.

Reva have capacity to manufacture 8,000 vehicles per year.

Mahindra and Mahindra

This company manufacture an electric three wheeler widely used as a taxi.

In October 2005, they were in discussions with three Indian state governments to open 200 electric recharging points to service these vehicles.

Nepal has some 400 of these 3 wheeled electric vehicles called “tempos” operating as small buses. These vehicles are manufactured by Scooter India Ltd. Surplus electric milk floats from the UK are now also being used in Nepal as buses. Kathmandu suffers from some of the worst air pollution in the world.

Japanese Manufacturers

The Japanese automotive industry is the most advanced in introducing a new generation of EVs to the market. A Plug In version of the Prius hybrid is likely to also become available before 2010.

Subaru R1e

In October 2003, Fuji Heavy Industries/ Subaru unveiled a sub-compact EV concept car at the Tokyo Motor Show called the R1e. In September 2005 Subaru announced that they would start marketing the R1e before 2010. Shares in the company rose on the announcement.

The press announcement in 2003 stated that it uses LiIon batteries jointly developed with NEC. This can only mean that it uses Lithium Manganate Spinel as the cathode material. Subaru are using the same battery technology on their new range of hybrids. It was later confirmed in 2005 that the battery does use the NEC Lamilion Manganate Spinel material.

FIGURE 31 **R1e**

Subaru claim that the battery can be 90% recharged in five minutes. This is a 10C charging rate. The $LiMn_2O_4$ cathode material can support high discharge rates but a 10C charge rate might indicate that the anode is not graphite but a high rate material such as Lithium Titanate Spinel. The main US proponent of Li Titanate Spinel anodes (Altair) views Li Manganate Spinel as the ideal cathode to complement the anode. If this is indeed the combination used in the R1e, it will have lower energy density than standard LiIon but much greater safety.

Mitsubishi MIEV

In September 2005 Mitsubishi announced that they would market an EV within 3 years, i.e. by 2008. Mitsubishi have therefore brought forward their original plans by 2 years and earlier in 2005, Mitsubishi abandoned fuel cells in favour of Battery EV development.

The vehicle will be based on the existing Colt platform. It will have a range of 250km (155 miles) between recharges and will be capable of being recharged within 4 hours with the on-board charger. (This would be from a 220V supply, not a US 110V supply). The price planned for the vehicle is said to be $18,000.

The prototype was developed with the Tokyo Electric Power Company and has a range of 150km. The battery will be LiIon (type unknown).

FIGURE 32 **MITSUBISHI MIEV COLT MIEV**

Mitsubishi favour the use of individual wheel motors rather than a central electric motor and driveshaft. The Colt EV is equipped with two in-wheel motors located in the rear wheels. The actual EV to be launched may be based on a smaller platform than the Colt.

An electric version of the Mitsubishi Lancer saloon car participated in the recent annual Shinkoku EV rally. This vehicle has an in-wheel motor in all 4 wheels. The vehicle has a 355V LiIon battery of 24 modules and has a range of 155 miles. The battery therefore probably has a capacity in the order of 40kWh.

Unless another major manufacturer announces a more imminent programme, the Mitsubishi and Subaru programmes will be the first pure EVs from a major car manufacturer to reach the market since the late 1990s.

Korean Manufacturers

The independent Korean manufacturer Geo intends to start production in March 2006 of a small EV called the EV1. The empty weight of the car is 600kg and it will cost $25,000. The battery is a LiIon polymer battery capable of 500 cycles at 80% DoD. Energy density is given as 370Wh/l and the vehicle range between 150km and 250km.

Hyundai/Kia intend to launch hybrid versions of their current product range but no public announcements of definite EV or PHEV programmes have yet been made.

Chinese Manufacturers

There are currently over 20 Electric Car manufacturers in China. 11 different Chinese manufacturers or institutes demonstrated Battery EVs at the 2004 Shanghai Michelin Bibendum Challenge. This event has become the premier world showcase for Sustainable Mobility. China’s Ministry of Science and Technology (MOST) established an ambitious goal to have 70,000 EVs operating in Beijing by 2008 for the Olympic Games. This target may not be met but it has provided a boost to Chinese manufacturers developing EVs. Most of the conventional car manufacturers have a division dedicated to pure EVs. All of the Chinese manufacturers are also developing hybrids. There are close links between Chinese motor vehicle companies and battery manufacturers.

The main Chinese manufacturers include:

- Zhonghua
- Dongfeng Electric Vehicle Company Ltd.
- Geely
- BYD
- Xiangfeng Electric Vehicle Company Ltd.
- Chargebroad EV Company Ltd.
- Beijing Institute of Technology EV Co Ltd.
- Wuhan EV Demonstration Company
- Yongjiu Battery EV Co

At the end of 2001, there were 18 million motor vehicles in China, including 5 million passenger cars. By 2030, the vehicle population is projected to grow sixfold to 108 million and the passenger car fraction to have grown to 60%, i.e. 65 million.

This will only be possible with vehicles that use a fraction of the fossil oil that they do at present.

In 2000, China imported 70M tonnes of oil. On current growth projections, by 2010 China will need 300M tonnes of oil and by 2030, 360M tonnes of oil. This growth is incompatible with forthcoming oil supply constraints - Chinese oil consumption will in fact have to fall from current levels, not increase.

Between 2002 and 2003, Chinese exports of LiIon batteries increased by 127% and in the last five years, Chinese LiIon battery production has increased by over 100%.

10 large scale LiIon battery plants are now operating in China with capacity of at least 50,000 units per day each.

In February 2004, China's MOST established a National Electric Vehicle Base (China's 863 program) in the Wuhan Economic and Technical Development Zone. Dongfeng EV and Wuhan EV are the main companies based there along with third party EV component and systems suppliers. Tax incentives are given for the first three years.

The Chinese are therefore well positioned to develop and market a new generation of LiIon powered EVs.

BYD

The Chinese battery company BYD are the second largest manufacturer of LiIon mobile phone batteries in the world after Sanyo. In the course of 10 years, they have grown from nowhere to assume this position.

For several years they have been planning to enter the electric car market and have been developing versions of their batteries suitable for EV use.

In 2003, BYD bought the Chinese car manufacturer Xian Qinchuan Automotive for $32M. BYD claim to have developed an EV with a range of 250 miles per charge to be launched in 2006 and are building a plant capable of producing 200,000 vehicles a year. BYD have said they intend to export worldwide.

BYD were due to exhibit an electric taxi in 2004 but this has not yet taken place.

In 2003, BYD produced 30,000 cars and are rapidly expanding production. Their "Flyer" car, launched in 2003, is priced at $3,500. They have developed a number of other models as well.

Another Chinese manufacturer Geely sold 80,000 vehicles in 2003 and market a saloon car for $5,800 (48,000 yuan). Product quality is not yet up to western standards but this will undoubtedly change rapidly as they gain more experience and update their production processes. Geely already export to markets such as Mexico, Sudan and the Middle East.

It is not unreasonable to conjecture that a full function Chinese Electric Car could arrive on the western market in the next few years priced at under $10,000.

Dongfeng Electric Vehicle Company

Dongfeng are the largest Chinese motor vehicle manufacturer. Their EV division has recently launched a diesel hybrid bus and a hybrid version of the Nissan Bluebird, the EQ7200. The drivetrains for both vehicles were developed indigenously.

Dongfeng have recently formed a partnership with Li Sun Power for lithium ion batteries to power their future hybrids and EVs. In 2004, they demonstrated 4 different EV models at the Shanghai Bibendum Challenge.

6.5 Commercial Vehicles

Azure Dynamics

The Canadian electric drivetrain manufacturer Azure Dynamics are becoming one of the leading suppliers of drivetrains and EV technology for light and medium duty commercial vehicles. One of the biggest potential markets is the package delivery companies such as UPS and DHL. These companies already operate a small number of hybrid and alternative fuel vehicles, even a small number of pure EVs and are testing hybrid vehicles. Other potential markets include postal, urban delivery, taxi and shuttle bus applications. These are all high stop-start applications where the Series Hybrid or pure EV drivetrains would be well suited.

In 2004, Azure had 7 hybrid vans on trial with Canada Post. They have also delivered 30 pre-production hybrid delivery vans to Purolator, a major North American delivery company. This could lead to an order for 2,000 vehicles. Azure also developed the e-Mercury delivery vehicle for LTI Vehicles of the UK. LTI is the manufacturer of the famous “Black Cab”. In October 2004 the e-Mercury program was sold by LTI to an associate company Modec Vehicles Ltd. and Modec are now using Zytek drivetrain technology. Azure are instead supplying EV drivetrains to Tanfield Group for their Faraday Electric Delivery Vehicle.

However Azure are still working with LTI on development of a hybrid “Black Cab”. A third taxi was converted in mid 2005 and this could turn into a commercial product by LTI.

The number of organisations starting trials of Azure hybrid or EV vehicles is starting to grow rapidly. In mid-2005, 5 shuttle buses went on trial in New York, several pure electric Azure "Citivans" went on trial with the USPS in New York and Boston, public deliveries started with Purolator in Toronto and many more developments are in the pipeline.

Azure have also developed with another UK company, Leyland Product Development, an EV version of a Renault Master van. This is on trial at Heathrow Airport. Azure are therefore very active in the UK market where they have recently expanded their engineering facilities.

There is absolutely no doubt that the entire commercial vehicle sector in North America is now very actively evaluating fuel efficiency technologies and intends to move to hybrid, plug in hybrid and pure EV technology as much as possible. As hybrid technology brings down the cost of components, in particular the battery, this market will then adopt plug in hybrids and EVs.

Eaton Controls

The US hybrid drivetrain manufacturer Eaton Controls have had a number of hybrid vans on trial with FedEx since 2003 and with UPS since 1998. FedEx have 30 of Eaton's E700 hybrids on trial. In total, FedEx have 30,000 medium duty delivery vehicles which could be replaced by hybrids or PHEVs. Eaton are a diversified group and have not been as active as Azure Dynamics in this market. This may change if FedEx decide to expand their hybrid fleet.

US Bus Manufacturers

There are two major US bus manufacturers leading the market for Hybrid Electric buses - Orion and Allison. Orion use a series hybrid drivetrain while Allison are committed to a parallel hybrid configuration. Orion now have over 1,000 vehicles in operation or on order.

The smaller companies E-Bus and ISE offer both hybrid and pure Battery Electric buses.

Again, all of the Area Transit authorities in the USA are actively evaluating or adopting hybrid buses to reduce fuel consumption and emissions. The next ten years will witness a major shift from conventional diesel powered buses in North America to hybrids. It is only a matter of time before a bus manufacturer launches a Plug In Hybrid bus to further improve fuel economy.

Th!nk Public

The Think Public is a 4 seater utility vehicle designed for public transport in closed environments like airports, city centre, US gated communities etc.

It has a maximum speed of 50km/h, weighs 850kg unladen and is equipped with a 17.5kWh Zebra NaNiCl battery module. This gives it an operational range of 100km.

FIGURE 33

The vehicle has been ordered by one major airport authority for evaluation.

Tanfield Faraday

The oldest established EV manufacturer in the UK is Smiths Electric Vehicles (SEV). They have manufactured electric milk floats and industrial vehicles for decades. In 2004, they were bought by the Tanfield Group. In mid-2005, Tanfield Group ordered 1000 electric drivetrains from Azure Dynamics of Canada. In September 2005, Tanfield announced the launch of the Faraday, an all electric delivery vehicle for the UK market.

FIGURE 34

TANFIELD FARADAY

In early October 205, Tanfield announced an order for 800 delivery vehicles by Dairy Crest, the largest UK dairy. This includes an unspecified number of Faraday EVs. The vehicles will be used for delivering milk to customers around the country.

The vehicle has a payload of 2.5 tonnes, a top speed of 62mph and an estimated range on a single charge of 60 - 100 miles.

Modec Vehicles E-Mercury

LTI Vehicles in the UK manufacture the famous "Black Cab". In 2004, they put into trial with a UK local authority an all electric delivery vehicle called the e-Mercury. The program was then transferred to a dedicated associated company, Modec Vehicles Ltd., in October 2004. The vehicle has a payload of 2000kg, top speed of 50mph and range of 100 miles. The ABS body panels can be changed by the operator to allow the vehicle to undertake different missions.

FIGURE 35 **e-MERCURY**

The vehicle is equipped with two Zebra NaNiCl battery modules. These can be quickly removed and replaced at the depot for fast turnaround times if required.

This vehicle is planned to enter production in 2006, following the Tanfield Faraday. It is aimed at the same light delivery and utility market.

Leyland Product Development

LPD and Zebra Batteries (UK) have developed an electric version of the Renault Master van with an Azure Dynamics drivetrain. This is on trial at Heathrow Airport and LPD are attempting to develop a commercial program. However, Renault Trucks (UK) have withdrawn support so a new platform will have to be found.

LPD also developed an electric shuttle bus, the EV110, based on the same platform. Capable of carrying 16 people, the vehicle has been in use by the City of Lincoln since 2003.

The UK market is therefore very active in developing electric light commercial vehicles. Sales will probably be in the order of a few hundred units a year from 2007 but could grow exponentially thereafter.

Daimler Chrysler Sprinter PHEV

This vehicle is the most advanced commercial EV under development.

At the present time, a test and development programme is underway as a joint project between DaimlerChrysler and the Electric Power Research Institute (EPRI). A Plug In Hybrid version of the Mercedes Sprinter van with an all electric range of 20-30 miles was developed in 2004. Between 2005 and 2007, 30 of these vehicles will be tested in Germany and the USA, comparing both LiIon (SAFT) and NiMH (Varta) batteries. The NiMH batteries are capable of 3,000 deep discharge (80%) cycles; the LiIon battery is capable of 2,500 deep cycles. 30 miles of electric range in good weather will cover the majority of the miles driven per day by an urban delivery vehicle and ensure adequate range (20 miles) in cold weather.

The vehicle has been actively promoted and programme participants believe the vehicle will be definitely commercialised from 2008. The main driver in Europe is moves by European cities to ban IC vehicles from city centres to reduce pollution.

In the package delivery market, UPS have a large (over 2000) conventional Sprinter fleet in the USA and over 750 Sprinters in Europe. Most of these could be effectively replaced with a PHEV20-30 version of the Sprinter.

In 2004, some 600,000 Full - Size vans in the Sprinter class were registered in Europe. The Sprinter has about 16% of the European market in this category.

The total Western European Market for Small, Medium and Full Size Vans is 1.5M units per year, with another 0.4M of other Commercial Vehicles below 6 tonnes in weight.

6.6 Economics of BEVs

Operating Costs

Although Electric Vehicles have historically been disadvantaged by their limited range, they have one enormous advantage over all other types of motor vehicle: very low operating costs.

Electric cars consume between 0.17 to 0.3kWh of electricity per mile.

The current price of off peak domestic electricity in France is 0.054 euros per kWh. The price of peak time electricity is 0.091 euros (including VAT).

The electricity to propel an efficient design such as the Prius 400 miles is estimated to be approximately 80kWh (0.20kWh/mile).

Therefore the price of recharging the battery with 80kWh of electricity would be 4.32 euros overnight or 7.28 euros during the day.

The current price of petrol in France (July 2005) is 1.2 euros per litre.

On 40 miles per imperial gallon (of 4.55 litres), the cost of the petrol to drive 400 miles would therefore be 54.6 euros.

The Fuel Costs of the Electric Vehicle are between 6.9% and 11.6% of the Petrol Vehicle (including taxes).

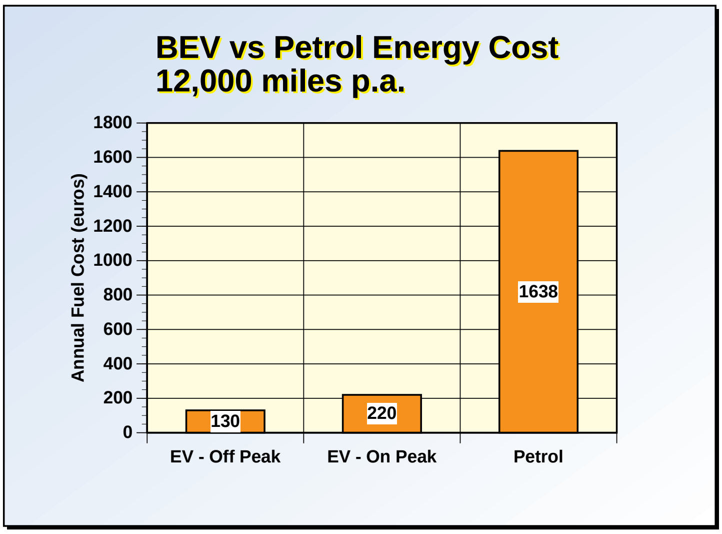
At 0.25kWh/mile, the “Fuel” Cost of the EV for a 400 mile trip would rise to 5.4 euros (off peak) or 9.1 euros (on peak).

On a utilisation of 12,000 miles per year, the EV would cost 130 euros off peak to 220 euros on peak per year in electricity (based on 0.2kWh/mile). The petrol costs would be 1638 euros.

This is illustrated below in Figure 36.

FIGURE 36

BATTERY EV vs PETROL COST



The maintenance cost of BEVs is significantly lower than petroleum vehicles. This will have a major impact on after sales service revenues and dealership structures. These factors might stimulate greater use of direct sales by the manufacturers themselves, even on-line. This is already the subject of experimentation by Ford in the USA.

Battery Cost

The main barrier to the economics of the EV is the initial cost of the battery, particularly for NiMH and LiIon technology. After 8-10 years, it may be necessary to replace the battery. However, it will be recyclable and it should be possible to obtain a credit for the new unit, as is the case with existing repairable components.

The ZnAir technology could remove this issue. Zinc is abundant and cheap; the battery construction is relatively simple. With ZnAir, the cost barrier to EV batteries could potentially be completely overcome, now that oil prices have reached levels that make ZnAir economic.

The cost of the NaNiCl Zebra battery at $220/kWh in volume is also highly attractive and it will become even more competitive as oil prices continue to rise. If a cost of $108 - $150/kWh can be achieved at a production rate of 100,000 units a year, NaNiCl technology should be the immediate battery of choice for Battery EVs.

The 2003 EPRI Study

An important life-cycle cost analysis[1] of BEVs, HEVs and PHEVs was carried out by the Electric Power Research Institute in 2003. This study showed that even using current technology NiMH batteries, electric-drive vehicles can achieve life-cycle cost parity with conventional petrol vehicles over a 10 year 150,000 mile life.

The study found that a 9kWh NiMH battery for a PHEV20 (a plug in hybrid with a 20 mile range on battery power alone) would cost $320/kWh for a mid-size car, based on production of 100,000 batteries a year. At that battery price, the Net Present Value of the life cycle costs of this PHEV20 car would be $1200 less than a petrol car over 10 years and 150,000 miles. This did not include the $1000 credit given to manufacturers for CAFE compliance in the USA.

For a small battery electric city car (BEV 40, i.e. a BEV with a 40 mile range) using the same 9kWh battery used in the PHEV 20, the Net Present value of the life cycle costs of the BEV40 are $420 less than the equivalent petrol car. This did not include the $2000 credit given to manufacturers for CAFE compliance.

The EPRI study shows that batteries for PHEVs or BEVs do not have to reach the USABC goal of $150/kWh or the BTAP 2000 figure[2] of $235/kWh to achieve cost parity with petrol vehicles. In fact, at $471/kWh for the battery, the mid-size PHEV20 car would match the cost of a petrol car over 10 years.

These results were based on a battery production of only 100,000 batteries a year and a petrol price of $1.75 per USG. The price of petrol in the USA is currently (August 2005) over $2.50 and rising.

The EPRI study makes the important point that the increasing production of pure hybrids (HEV 0s) like the existing Prius will bring down the cost of electric drivetrains, while the commercialisation of Plug In Hybrids (PHEVs) “holds the key to addressing the one remaining major barrier to PHEVs and BEVs - the cost of the “energy” battery.”

However, the Zebra NaNiCl battery manufactured by MES-DEA in Italy may cost $220/kWh in medium volume (10,000 units) today. This is less than half the PHEV20 cost parity figure of $471/kWh, which was calculated at US petrol prices which are now low and even lower by European standards. Petrol in Western Europe now costs over $6 per USG. At $108/kWh in high volume for the NaNiCl technology, the economic case in favour of the EV would be overwhelming.

1. “Advanced Batteries for Electric Drive Vehicles: A Technology and Cost Effectiveness Assessment for Battery Electric, Power Assist Hybrid Electric and Plug-In Hybrid Electric Vehicles”, EPRI, Palo Alto, CA, 2003. 10001577.

2. “Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost and Availability”, California Air Resources Board, June 2000.

6.7 Improved Electrical Energy Efficiency

The conversion of Road Transport to Electrical Power goes hand in hand with improving the general efficiency of electrical energy consumption.

Overnight recharging of the EV is also an ideal solution for load levelling of electricity demand, to level out the differences between peak and off-peak demand. Load levelling is a major efficiency strategy for electric utilities.

Studies[1] indicate that 20% of the German car fleet could be converted to EVs to soak up existing excess off-peak capacity. The petrol consumption of those cars could be replaced with already existing electricity generating capacity.

The entire UK road vehicle fleet could be powered by approximately 10-11% of the central electricity generated today[2]. Electrical energy efficiency measures at point of consumption could save at least 10% of the electricity generated today in the UK. Therefore Energy efficiency savings alone could power the majority of the UK road vehicle fleet without any requirement for additional generating capacity.

Studies estimate that at least 24% of the electricity generated in the USA could be saved by energy efficiency measures[3]. So a combination of BEVs and energy efficiency could replace much petroleum based road transport for no required increase in central electricity generating capacity - in fact, there could still be a saving in electricity consumption[4]. The EV also provides a useful load levelling solution for electric utilities.

Spare unutilised electricity generating capacity provides a ready-made buffer to allow quick introduction of the EV without environmental or economic penalty. This will gain time to then build additional renewable or CHP electricity generating capacity if necessary and introduce efficiency measures. Time is also gained for expansion in biofuels and other measures to start having an effect. The reduced oil consumption also lowers the volume of bio-fuels that have to be produced.

In short, Europe would be able to eliminate at least 20% of its automobile fuel consumption as quickly as EVs could be built and put into service for no extra electrical energy production.

1. Electric Vehicle & Electricity Supply, Makens, Boonekamp, ECN I-90-036, 1990
2. Internal calculations: UK Electricity Prodn=360TWh, Fuel Use=29Glitres
3. American Council for an Energy Efficient Economy
4. See “Effect on US Electricity Generating Capacity” on page 184.

6.8 Conclusion

There is evidently a wave of activity building in the worldwide development of EVs and PHEVs. There are now two credible PHEV programs underway in Europe - the Sprinter Van and the Cleanova II delivery van. There are also two credible pure EV delivery vehicle programmes in the UK for quite substantial vehicles. The host of new EV programmes is of course riding on the record price of oil which will not decrease without large scale reductions in oil consumption.

There is no sign that any of the major western car manufacturers will launch either an EV or a PHEV. They are still trying to catch up with the market shift towards Power Assist Hybrids.

It is indicative that the two Japanese manufacturers to have launched EV programmes, Subaru and Mitsubishi, are smaller players. Mitsubishi in particular have seen their market share decline in the USA in recent years. These companies may be taking advantage of their smaller size to establish their position in the developing EV market before the larger manufacturers can enter the scene.

It would be possible for some car manufacturers to implement large scale manufacture of Plug In Hybrid Electric Vehicles relatively quickly. The obvious manufacturers are Toyota and Honda who already have HEV0s in production. There are indications that Toyota are already planning to do so: it is the logical next step to the existing power assist hybrid.

7 Battery Technologies

7.1 Introduction

The heart of the Electric Vehicle is its Battery. It has also been its Achilles Heel. Up to the 1990s, batteries could not hold sufficient energy to provide generally acceptable range. That situation is no longer the case with the advent of the Sodium Nickel Chloride battery, the NiMH battery and the Lithium Ion battery.

7.2 Battery Requirements

This chapter gives an overview of the main battery types for EVs and their relative features. There are currently three major battery technology contenders for future BEVs:

1. Lithium Ion
2. Sodium Nickel Chloride
3. Nickel Metal Hydride

The original rechargeable battery technology of Lead Acid is also seeing some new developments and there are a number of less well known technologies which may be able to provide significant performance improvements.

The most important characteristic of a battery for EV and other mobile applications is its energy density - the number of Watt Hours of electrical energy it can store per unit weight and unit volume. This dictates the range of the vehicle.

Table 9 shows the energy density of the main battery types in a complete finished battery format - i.e. as the battery and its controller would be fitted into a car. The energy density of the individual cells which make up a battery is higher but energy density is always reduced when many cells are added together to make the complete battery.

TABLE 9

MAIN EV BATTERY TYPES

Battery Type	Specific Energy Density
Standard LiIon	100 - 120 Wh/kg
Advanced LiIon	120 - 150 Wh/kg
NaNiCl	120 Wh/kg
NiMH	40 - 80 Wh/kg
ZnAir	200 - 220 Wh/kg
NiCad	50 Wh/kg
PbA (Lead Acid)	30 Wh/kg

Other technical factors of key importance for batteries for future BEVs are:

1. Recharge Time. A drawback with Electric Vehicles is the length of time it takes to recharge a depleted battery. Overnight recharging at home is suitable for routine use but on long journeys the capability to "refuel" in the same time it takes to fill up with petrol would be desirable. If batteries could be recharged in a matter of minutes rather than hours, this would remove a significant psychological obstacle to the adoption of EVs.
2. Cycle Life. The battery needs to last for a reasonable length of time - ideally 10 years and 150,000 miles. Each time a battery is charged and discharged, it loses some of its capacity. A life of at least 1,000 cycles is ideally required for general Electric Car use. This would give two recharges a week for 10 years.
3. Low Temperature Performance. Many batteries perform poorly in cold weather. A general purpose battery for EVs must perform adequately down to at least -20˚C.
4. Cost. The NiMH and LiIon batteries currently available are too expensive for general PHEV and BEV use. The cost will fall as HEVs continue to enter the market. Pure BEVs face a particular cost challenge since they require a large battery.

The USABC Criteria for a BEV Battery

The United States Advanced Battery Consortium was formed in 1991 by Chrysler, Ford and General Motors to promote the development of advanced batteries for EVs. It provides funding for applied battery research in the USA and has set a number of performance goals which are used to guide the industry. Since 1991, it has invested over $90 million in battery research projects.

The Cost and Performance Goals established by the USABC for a pure EV battery are shown below in Table 10.

TABLE 10

USABC GOALS FOR EV BATTERIES

Parameter	Mid Term Criteria	Commercial Criteria	Long Term Criteria
Price $/kWh	<150	<150	<100
Specific Energy Wh/kg, C/3 Discharge	80	150	200
Specific Power, W/kg (at 80% DOD, 30 sec)	200	300	400
Power Density W/l	250	460	600
Cycle Life	600 at 80% DoD	1,000 at 80% DoD 1,600 at 50% DoD 2,670 at 30% DoD	1,000 at 80% DoD

Price

None of the battery technologies currently available have reached the USABC price criterion of $150/kWh, except Lead Acid which is too heavy for widespread use. The ZEBRA NaNiCl battery is the most likely technology to be able to reach a price of $150/kWh in mass production. LiIon and NiMH are likely to remain over $250/kWh.

Specific Energy

The mid term specific energy criterion is now exceeded by the LiIon and ZEBRA battery. NiMH is within reach of 80Wh/kg. The ZEBRA and LiIon batteries both approach the commercialisation criterion of 150Wh/kg, with LiIon more likely to reach it and go on to meet the Long Term criterion of 200Wh/kg.

Specific Power

All of the specific power criterion are achievable by the main EV battery types available.

Cycle Life

All of the three main EV battery technologies - NiMH, LiIon and NaNiCl - can achieve all of the cycle life criteria. Lead Acid can achieve the Mid Term criterion but may not yet be able to reach the commercialisation criteria.

EPRI Criteria for PHEV Batteries

The Electric Power Research Institute (EPRI) in Palo Alto have carried out a number of important studies into the potential for EVs, HEVs and PHEVs.

The following table[1] shows the battery performance levels required to permit a PHEV20 and PHEV60 to match the performance of a comparable conventional vehicle.

TABLE 11 **PHEV BATTERY REQUIREMENTS**

	HEV 0	PHEV 20	PHEV 60
ZEV Range	0	20	60
Battery Capacity (kWh)	<3	6	18
Cell Size (Ah)	5 - 10	15 - 30	45 - 90
Specific Energy (Wh/kg)	>30	≥50	70 - 110
Specific Power (W/kg)	1000	440 - 700	390 - 550
Cycle Life 80% DoD	n.a	≥2,500	≥1,500
Cycle Life Shallow	200,000	200,000	200,000

EPRI stress that the total lifetime energy throughput for a battery increases non-linearly as the cycle Depth of Discharge (DOD) decreases. As DoD decreases, non-linear increases in cycle life lead to a significant increase in total energy throughput. This can extend battery life in a vehicle where the state of charge (SOC) can be controlled, such as a PHEV or HEV0. For a PHEV, this results in greater capacity for all electric travel before reaching the end of the battery life.

Therefore shallower cycling, e.g from 90% to 30% SOC, increases cycle life and gives greater capacity for a PHEV to operate in all electric mode, by extending the life of the battery.

The main EV and HEV battery technologies are analysed below in relation to these and other criteria.

1. Advanced Batteries for Electric Drive Vehicles, EPRI 1009299, May 2004.

7.3 Lead Acid

Lead Acid batteries are the oldest rechargeable battery technology in use. They have the poorest specific energy density and poor cycle life but the lowest cost.

In recent years, there have been numerous improvements developed or proposed for the Lead Acid battery.

In the UK, the RHOLAB (Reliable Highly Optimised Lead Acid Battery) project is testing a cylindrical spiral wound PbA cell in a 144V battery. The battery pack was due to be tested in a Honda Insight hybrid for 50,000 miles but testing has been delayed. This battery is a form of Absorbed Glass Mat battery in which the H_2SO_4 electrolyte is held in a glass fibre electrode separator.

The Chinese company Guangdong Jiangmen Yuyang claim that their improved Lead Acid Gel battery increases specific energy from the 30-40Wh/kg of standard PbA to between 45-50Wh/kg.These are probably cell level figures. The battery is being used in electric scooters in China.

The US company Firefly Energy, an off-shoot of Caterpillar Inc., state that they have developed a porous composite material to replace the lead plates in the PbA cell. They claim this will eventually remove 70% of the lead in a Lead Acid battery and give similar specific energy, specific power and cycle life to NiMH at 20% of the cost. Electrolux are testing the technology for outdoor garden products.

Developments in Lead Acid technology are therefore still ongoing but the major battery groups are focusing on NiMH and LiIon technology.

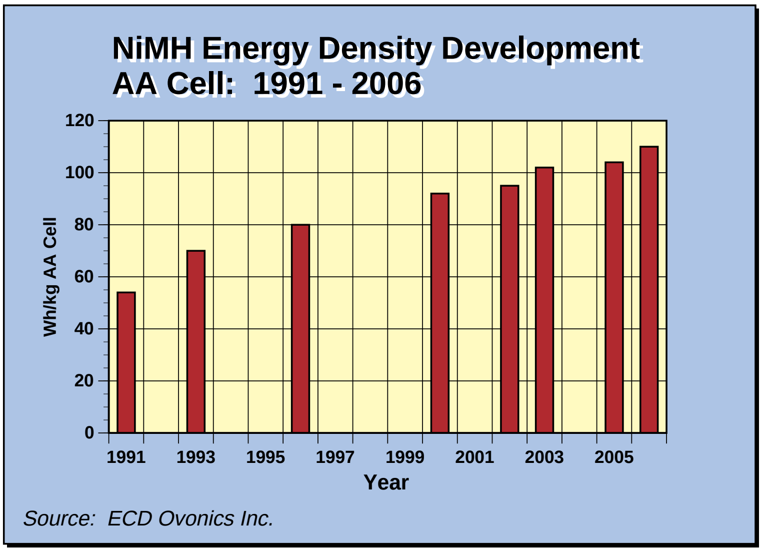
7.4 NiMH

Although the long term future of EVs may lie with other battery technologies, the NiMH battery proves that very functional EVs can already be produced today with this technology.

The Nickel Metal Hydride (NiMH) battery is currently the most commonly used EV and HEV battery. Most of the EVs marketed in California in the late 1990s to meet the CARB rules were equipped with NiMH batteries. It is now also the most commonly used rechargeable battery in the consumer market and is rapidly replacing alkaline primary cells.

In the consumer market, NiMH AA cells are now available with a capacity of 2.5Ah. This has increased steadily from 1.1Ah when these cells arrived on the market in 1991. This is equivalent to 104Wh/kg and 423Wh/l per AA cell. The US company Energy Conversion Devices Inc., (Ovonics) which has pioneered NiMH development since 1960, expects AA cells with 3000mAh capacity to arrive in 2006. This would be an energy density of 110Wh/kg and 490Wh/l.

FIGURE 37 **NiMH DEVELOPMENT**



The practical energy density of the NiMH battery for EV batteries is currently between 40 and 80Wh/kg, i.e. between one third and two thirds that of LiIon or NaNiCl. However, it has now been in EV service for over a decade and is well tested. It is a rugged technology and NiMH battery life has been found to be very good. It is still expensive and may not currently offer much cost advantage over LiIon but this could change as production increases and if demand for lithium outstrips supply.

NiMH outperforms LiIon in one very important area: safety. The aqueous electrochemistry of NiMH will automatically balance cells in series and accommodate a certain amount of overcharging, without the need for external protective circuits. They can also handle the high power rates required for regenerative braking. With the energy density per cell of NiMH at two thirds that of standard LiIon and at a higher percentage of that for safer LiIon technologies such as Iron Phosphate but without the need for control electronics, NiMH is not necessarily at a great disadvantage to LiIon.

NiMH also has better low temperature performance than LiIon and will operate sufficiently well down to -30˚C.

NiMH has the advantage over the Zebra NaNiCl of somewhat higher volumetric energy density. This is arguably as important for a practical EV, to avoid taking up excessive space in the vehicle with battery cells, even if the weight is higher (within reason).

NiMH batteries do contain cobalt, which would also become a constraint if production increased to millions of EV batteries per year. The amount of cobalt in the battery has been reduced over the years and research is ongoing to continue this.

The major manufacturers of NiMH batteries for EV applications are companies such as Panasonic EV Energy Ltd., SAFT, Sanyo, Johnson Controls (Varta) and Cobasys (a joint venture between Chevron and Ovonics). Panasonic supply the NiMH batteries for all of the current range of Toyota and Honda Power Assist Hybrids. They are therefore by far the largest manufacturer of EV NiMH batteries.

The Varta NiMH battery in the DaimlerChrysler Sprinter PHEV has a capacity of 14.4kWh and weighs 364kg. Volume is 360 litres. Energy density is therefore 40Wh/kg and 40Wh/l. However, it can undergo 5000 deep discharge cycles.

The NiMH battery is now in widespread use in the Hybrid cars entering the market. High power NiMH batteries are now available with a specific energy of 70Wh/kg and power density of 1000W/kg. The Panasonic NiMH battery in the Toyota RAV4EV has been found[1] to have no appreciable degradation after 5 years use and 100,000 miles. Cycle tests by SAFT have achieved nearly 3000 cycles and Ford have achieved over 2000 cycles. These results mean that NiMH batteries can certainly provide 130,000 - 150,000 lifetime mileage for HEV0s, BEVs and PHEV60s.

A battery for a PHEV20 would only need a capacity of 6kWh, a specific energy of 50Wh/kg and specific power of 440W/kg. A PHEV60 would need an 18kWh battery, with preferably a specific energy of 70Wh/kg and specific power of 390W/kg.

These performance levels are well within the capabilities of existing NiMH technology.

1. Advanced Batteries for Electric Drive Vehicles, EPRI, #1009299, 2003

Cost Analysis

In their report, EPRI estimated that the cost of an 18kWh NiMH battery in volume production would be $270/kWh. A 6kWh battery was estimated to cost $320/kWh. This is in the same cost range as estimates for nickelate LiIon batteries, although manganate spinel and iron phosphate based LiIon batteries could potentially be cheaper.

Johnson Controls/ Varta in fact estimate that their NiMH batteries will cost $450/kWh in full commercial production of 100,000 units per year. LiIon may have better cost reduction potential if elements other than nickel are used, although Lithium production could also become an issue.

The US company Electro Energy Inc. have developed a bipolar NiMH battery for automotive applications. They have recently signed an agreement with Calcars, the Californian PHEV advocacy group, to apply this technology to PHEVs.

In 2002, Electro Energy published[1] the following cost analysis for their NiMH battery, based on an unspecified high volume production.

TABLE 12 **ELECTRO ENERGY INC. BIPOLAR NiMH COST ANALYSIS**

	Qty kg/kWh	Cost $/kWh	Total Cost $/kWh
$Ni(OH)_2$ Active Material	3.8	9	34.20
Hydride Active Material	4.2	16	67.20
Other Cell Materials			66.00
Housing/Packaging			28.00
Total Materials Cost			**$195.40**
Selling Price at x1.5 Materials Cost			$293.10

The analysis included no manufacturing costs.

The total Material Cost is in the order of $200/kWh.

This is some 5 times the Material Cost[2] per kWh for the Zebra NaNiCl battery, which has 71% higher energy density.

1. "Bipolar NiMH Battery", MG Klein, M Eskra, R Plivelich, P Ralston, Electro Energy Inc., Danbury, CT, USA, EVS19 2002.
2. See "Cost Potential of the Zebra Battery" on page 107.

Market Developments

In a recent (11th October 2005) major market development, Johnson Controls (Varta) and SAFT signed a joint venture to merge their NiMH and LiIon battery programmes for HEVs and EVs globally. R&D will be combined and joint sales and marketing will start immediately. This follows rapidly on the announcement of the opening of a new Lithium Ion Development Laboratory by Johnson Controls in Milwaukee in September 2005. This must position the joint venture as one of the leading contenders in the upcoming HEV and EV battery market which will see exponential growth over the next ten years.

In another very significant recent market development, at the beginning of October 2005 Toyota increased its stake in Panasonic EV Energy Ltd. from 40% to 60%, making it a Toyota subsidiary. Panasonic is now preparing to build a new factory in Kosai, Shizuoka Prefecture to boost production capacity of NiMH HEV batteries.

These moves show that the major battery groups are rapidly positioning themselves to accelerate production, research and product development, first of NiMH technology and then LiIon technology. Until the safety of LiIon in large format EV applications is proven beyond doubt and it becomes cost competitive with NiMH, the NiMH battery will continue to be the market leader.

Conclusion

The NiMH batteries already in production could provide at least sufficient performance for Plug In Hybrid Vehicles. Mass production of 6kWh and 18kWh NiMH battery packs is well within existing manufacturing capacity and experience.

Therefore, manufacture of PHEVs could start in the near future with existing NiMH technology which has already been well tested in automotive service. As time progresses, the market can then transition to LiIon or other future technologies.

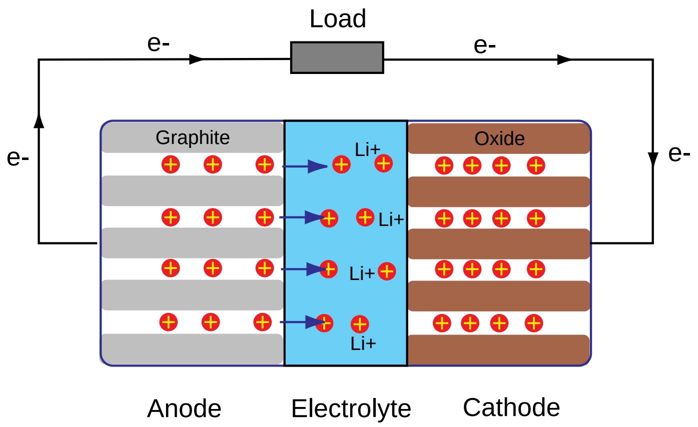
7.5 Lithium Ion

Introduction

The Lithium Ion battery is widely seen as the most exciting candidate to power future EVs and PHEVs. However, Lithium ion technology is in fact a complex and diverse area and there are some significant issues to be addressed before LiIon will achieve widespread use in large formats for Electric Vehicles.

The general structure of a LiIon battery is shown below.

FIGURE 38



There are three major components in any battery, including LiIon:

1. Anode
2. Cathode
3. Electrolyte

The Anode is usually made of graphite. Lithium ions slot or intercalate into the structure of the graphite when the battery is charged. Lithium metal is used as the anode in primary or non-rechargeable lithium batteries but is rarely used as the anode in rechargeable lithium batteries due to safety issues. Some rechargeable Lithium Metal Polymer batteries have been developed but by definition these are not Lithium Ion batteries - they are Lithium Metal batteries. This will be discussed in more detail below. Some new anode types are under development and are just starting to reach the consumer market.

The Cathode is made of Lithium Cobaltite ($LiCoO_2$). When the battery is discharged, lithium ions travel out of the graphite anode and intercalate into the cathode. While this cobaltite cathode is generally suitable for consumer devices, it is too expensive and unsafe for large format EV batteries. Many different cathode types are now available and cathode chemistry is the area of the most active research in LiIon development.

Most batteries contain an aqueous electrolyte. Since Lithium reacts with water, this is not possible in the LiIon battery. Therefore the electrolyte is an organic solvent with a lithium salt dissolved into it to provide sufficient ionic conductivity for the battery to function. The electrolyte is also an area of active research to reduce weight, improve safety and allow completely solid state batteries to be produced in future.

There are currently five major factors which have to be addressed regarding Lithium Ion battery technology and development for EVs:

1. Cost and Availability of Materials
2. Safety
3. Energy Density
4. Calendar Life
5. Low Temperature Performance

Lithium ion battery development is the subject of intensive R&D and competition across the world. Significant advances are being announced every few months in terms of improved safety, increased energy density, improved recharge time and cycle life, discharge rate, calendar life etc. This section will give an overview of the main issues and developments in LiIon technology.

Cost and Availability of Materials

In terms of cost, it is often said that the LiIon battery is too expensive for mass market automotive applications. According to the independent EV drivetrain specialist AC Propulsion Inc., in very high volume the commercially available 18650 cell LiIon batteries retail for $250 per kWh, compared to $500/kWh for EV Lead Acid batteries from Panasonic. A 40kWh LiIon battery composed of these small 18650 cells would therefore retail for $10,000 not including the necessary control electronics. The current price of an EV LiIon battery pack would therefore be well in excess of this and in any case these small commercial 18650 cells are not suitable for production EV use.

No mass automotive large format LiIon batteries have yet been marketed by any manufacturer, so manufacturing costs are far from having been optimised. Cheaper electrode materials are continuously being developed. Only time will tell how far costs can be reduced.

In 1999, the battery company SAFT stated a cost goal of $200/kWh for a high energy LiIon cell for EVs, based on a production of 100,000 complete EV batteries per year. In 2005, this projection had risen to $280 - $300/kWh at 100,000 units. This level of battery cost would still give a BEV lower life cycle costs than an equivalent petrol vehicle.

Cobalt, Nickel, Manganese

The biggest individual cost item[1] in current LiIon batteries is the metal Cobalt. The price of this strategic metal can be very volatile[2] and if EVs were to enter mass production using conventional Lithium Cobaltite cathodes, demand for Cobalt would outstrip currently available supplies.

A mass market LiIon EV battery cannot rely on Cobalt for this reason alone. Manganese and Nickel are cheaper alternatives, with Manganese particularly favoured for reasons of safety and very low cost.

The price of Nickel has also increased steadily over the last few years and is now over $7/lb. By contrast, the starting material for layered manganese dioxide LiIon batteries is Electrolytic Manganese Dioxide. This is priced at about $1/lb. Global production of manganese (11,000,000 tonnes) is about ten times higher than Nickel (1,400,000 tonnes). Cobalt is only produced in very limited quantities (47,000 tonnes per year) and would quickly become exhausted if it was used for EVs. A 32.4kWh LiIon EV battery using conventional cobalt oxide technology would contain 80kg of cobalt: global cobalt production would only allow 600,000 such EV batteries to be produced. Even though Cobalt production tripled between 1993 and 2004 and another 40,000 tonnes of capacity could become available over the next two years (to 2007) from new nickel mines, Cobalt must still be used in EV batteries in much smaller quantities than in consumer batteries or replaced.

Lithium Supply

It is possible that even Lithium supply could be constrained. World production of lithium is currently about 20,000 tonnes per year. World reserves of lithium have been identified at 13 million tonnes. The Argonne National Laboratory estimate that a 32.4kWh LiIon battery (as used in the Nissan Altra) contains 9.6kg of Lithium. Global lithium production today would therefore be sufficient for about 2 million EV batteries of that size. If they were 8kWh batteries for a PHEV20-30, 8 - 10 million such batteries could be made per year. Not all of the lithium produced would be available to do this - most of it is used in paints, glass, ceramics and aluminium manufacture.

The Lithium Metal Polymer (LiMP) battery manufactured by Avestor for telecommunications backup contains 0.66lb of Lithium metal per kWh of stored energy, which is nearly the same as the Argonne estimate for LiIon batteries. The two battery types have similar energy density of about 100Wh/kg. Therefore, even if the energy density of LiIon batteries is doubled, only 16 - 20 million PHEV20-30 batteries could be manufactured each year even by using all of the lithium produced annually. This is insufficient to meet declining oil production.

If LiIon battery production was expanded to 60 million 8kWh PHEV20 batteries per year, so that all of the light vehicles manufactured globally each year were Plug In Hybrids, the Lithium requirement would exceed 140,000 tonnes per year. Four times that amount would be required to manufacture 60 million BEVs per year equipped with 32kWh batteries.

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1. “Costs of LiIon Batteries for EVs”, L. Gaines, R. Cuenca, Argonne National Laboratory, Centre for Transportation Research 1999.
2. September 2005: Cobalt was priced at $20 - $25/lb

Most of the lithium produced is extracted in the form of the compounds lithium carbonate or lithium hydroxide. Manufacture of LiIon batteries can use lithium carbonate directly: lithium metal is not required. Lithium metal containing batteries (such as LiMP and non-rechargeable lithium batteries) contain lithium metal itself which has to be produced by electrolysis of lithium compounds. It is therefore significantly cheaper and less energy intensive to use lithium carbonate in the fabrication of LiIon cells than lithium metal.

This issue of lithium availability must be considered very carefully. It would not be possible to greatly expand LiIon battery manufacture for EVs unless Lithium production can also be greatly expanded. This is a significant factor in favour of NiMH or NaNICl technology. If the whole HEV, PHEV and EV market relies entirely on LiIon technology, battery costs may fall initially only to rise dramatically as future Lithium supply becomes constrained.

Lithium production is concentrated in a relatively few locations: Chile, Australia and China are the largest producers followed by Canada, Argentina and Zimbabwe.

Safety

Safety is the single most important issue concerning the adoption of Lithium containing batteries for EVs.

Lithium is a very reactive metal. It reacts exothermically with water and also with many organic solvents including ethanol. In 1989, 1.5 million mobile phone batteries made by the Vancouver firm Moli Energy had to be recalled after some of them caught fire. The anode in these batteries was made of Lithium metal foil. When the battery is fresh, the metal is covered with a layer of inert lithium carbonate which protects it and limits its reactivity. After the battery has been charged and discharged a few hundred times, the surface of the Lithium metal grows millions of tiny metal hairs or dendrites and takes on the appearance of moss. This breaks the protective layer and the metal might start to react with the electrolyte in the battery. The temperature inside the battery will rise: if it rises too far the electrolyte will decompose, releasing a large volume of gas and causing the battery to explode.

If the dendrites grow too long, they can reach the other electrode (the cathode) and short the battery. This can cause all of the Lithium metal to melt and react explosively with the electrolyte.

To meet these concerns, the Lithium Ion battery was developed in the early 1990s to replace Lithium metal in the design and improve safety. Instead of using a Lithium metal anode, a safer graphite anode is used. Lithium ions then slot into and out of the structure of the graphite when the battery is charged and discharged.

The most commonly used cathode (negative electrode) of the Lithium Ion battery is lithium cobalt oxide ($LiCoO_2$). This is used in most LiIon batteries in mobile phones, laptop computers etc. Other LiIon batteries commonly use nickel ($LiNiO_2$), manganese ($LiMnO_2$ or $LiMn_2O_4$) or mixtures of all three in various proportions ($LiMn_xNi_yCo_zO_2$)

While they are safer than Lithium Metal batteries, LiIon batteries are not immune from safety considerations. The main danger with LiIon batteries is a phenomenon known as thermal runaway which can occur due to *overcharging* of LiIon batteries that contain Cobalt or Nickel oxides.

The electric motors in some HEVs and EVs operate at 300 Volts or more. Since individual LiIon cells deliver 3.6V each, 90 cells or more (in different modules) may need to be connected in series to provide the required voltage. (The cost of a battery also increases with voltage).

In contrast to batteries with an aqueous electrolyte (such as NiMH), which can accept some overcharging, batteries with a non-aqueous electrolyte (such as LiIon) cannot easily accept overcharging. This is a serious problem for HEVs and EVs because if even one cell in the string is slightly weaker than the others, it will become overcharged when the battery is recharged. Overcharging of a LiIon cell is very dangerous since it overheats the cell and can lead to thermal runaway, followed by decomposition of the electrolyte. Even at voltages as low as 4.2V, the electrolyte can start to decompose and accumulate CO and CO_2 after repeated recharges. In consumer batteries, an electronic control circuit is used to regulate each individual cell to prevent overvoltage from occurring. This is expensive and complex for an EV in which the battery will have 100 times the capacity of a laptop computer battery. The Sony LiIon battery used in the Nissan Altra was comprised of 12 modules, each containing 8 100Ah cells.

FIGURE 39 **SONY NISSAN ALTRA EV LiIon MODULE**

EV Challenges

LiIon batteries therefore present some particular challenges for use in EVs. The cells in a series connected string must each be monitored and any imbalances corrected by altering the state of charge in particular cells. As the battery ages, cells may change capacity and drift apart at different rates. Regenerative braking is a particular issue, since the high incoming rush of current will cause the battery voltage to increase rapidly. Even if the overall voltage of each module appears to be within limits, some cells may be at a higher voltage than others and so could be in danger of being overcharged.

Even having different parts of the battery at different temperatures can cause problems. Warmer cells may have lower internal resistance and higher self-discharge than cooler cells, causing temporary imbalances. The battery therefore also needs to be thermally regulated to prevent this. A motor vehicle of course operates in a much more demanding environment than a consumer laptop computer or mobile phone.

In contrast, Lead Acid, NiMH and NaNiCl batteries all have inbuilt cell balancing mechanisms due to the nature of their chemistry and do not require such tight monitoring, control and regulation.

Safety Developments

Safety features are built into LiIon cells to shut them down as a last resort in the event of a thermal runaway, although this renders the battery unusable. Other developments are using solid polymer electrolytes which are safer than liquid electrolyte LiIon types. Researchers at the Berkeley Lab. are trying to develop conducting polymer electrolytes that can protect against overcharge.

The Lithium Iron Phosphate ($LiFePO_4$) cathode material has been under development for about 10 years. It is much safer than the commonly used $LiCoO_x$ cathode material and is not subject to thermal runaway but has somewhat lower energy density than Cobalt. Its safety features, lower cost and fast recharge capability are making it one of the leading contenders for LiIon batteries for EVs at the moment.

Other cathode types using Manganese have been developed that are also much safer and cheaper than LiIon batteries that use Cobalt or Nickel. Manganese technology for LiIon batteries is an area of active research worldwide. In particular, the Lithium Manganate Spinel ($LiMn_2O_4$) material is also a leading contender for LiIon EV use.

Another issue with LiIon batteries is that in the event of a crash, the battery might short-circuit and cause a fire. Non-inflammable polymer electrolytes may be the answer to this problem.

The Dry Solid Conducting Polymer Electrolyte technology developed by MIT and licensed to Voltaflex Corp. could offer an important safety advantage. It is thermally stable up to 300˚C and is therefore very resistant to thermal runaway. However, it has low ionic conductivity at room temperature. In cold weather, its performance would be even worse and external heating would be required.

The approach by the leading Japanese LiIon company Sony to improving safety is to combine Manganese with lower amounts of Nickel and Cobalt in the oxide cathode. The objective is to reduce the amount of expensive and potentially dangerous Nickel and Cobalt as much as possible.

Panasonic have developed a nickel-manganate cathode that does not use cobalt at all.

Work is going on in the USA using the same approach as Sony. Layered manganese oxides are used with dopant levels of other metals (cobalt and nickel) included in the lattice structure. This should have improved safety characteristics.

Safety Incidents

In 2004-05, there were three fires involving shipments of Lithium Ion batteries at airports in the USA. This included one small prototype LiIon battery pack (made by AC Propulsion) for an EV. The module contained 256 18650 cells. In August 2004, 28,000 LiIon batteries manufactured by LG Chem for Apple PowerBook computers were recalled after four fires. This is a concern, given that Apple had to withdraw a range of laptop computers in 1995 after the LiIon batteries caught fire. In June 2004, 50,000 Verizon cell phones were recalled after 18 incidents including injuries. In many cases, it seems that the cause of these fires has not been able to be determined.

Previous to this, there have been seven other known fires caused by Lithium batteries in transit by air or road in the USA and incidents abroad.

The US Department of Transport (DOT) intend to regulate the transport of LiIon batteries more stringently and may subject them to the same regulations as lithium metal batteries. In April 2003, IATA and the DoT banned the carriage of any battery containing more than 8g of Lithium or having a capacity greater than 96Wh in the passenger compartment of an aircraft.

At the end of 2004, the DoT banned[1] the transportation of *all* primary lithium batteries on board passenger aircraft no matter what their size or where they are carried: primary (non-rechargeable) lithium batteries use lithium metal. Tests are being carried out by the FAA on LiIon batteries using the same methods that were used to evaluate lithium metal primary batteries. Federal Express now only accept shipments of LiIon batteries from qualified shippers and they classify them as Class 9 Hazardous Goods.

In response to these incidents, the IEEE published a new standard (IEEE P1625) in April 2004 to regulate the design and manufacture of laptop computer batteries. It does not apply to other types of portable devices.

The annual International Seminar on Primary and Secondary Batteries is an important event in the battery world. At the 22nd seminar in March

1. Interim Final Rule, Docket RSPA-04-19886 Hazardous Materials: Prohibition on the Transportation of Primary Lithium Batteries and Cells Aboard Passenger Aircraft, December 15 2004.

2005, the opening presentations concerned these airport fires and the latest DoT investigation into LiIon battery safety. Safety has become an important issue again in the LiIon battery industry.

During 2003 and 2004, the US Product Safety Commission received 83 reports of mobile phones exploding or catching fire. Some reports state that 1.6 million lithium ion batteries have been recalled in the USA between 2000 and 2004.

During 2005 alone, there have been 6 major product recalls of LiIon rechargeable batteries in the USA. These are listed in Table 13 below.

TABLE 13 **2005 LiION BATTERY RECALLS**

Company	Lithium Battery Product	Date	Qty
Hewlett Packard	LiIon notebook computer batteries	14/10/05	135,000
Battery Biz	LiIon high capacity notebook computer batteries	22/6/05	10,000
Apple Computer	LiIon notebook computer batteries	20/5/05	128,000
Belkin	Li Polymer batteries for Bluetooth GPS Units	21/6/05	10,300
Mantek Digital	LiIon Portable DVD Player	8/6/05	116,000
Thomson Inc.	LiIon Portable DVD Player	23/3/05	47,000

There have been numerous LiIon battery recalls in previous years as well, for all types of portable electronic devices. For instance, in 2003, 2,000 LiIon batteries in Mini E Bike electric bikes made by EV Global were recalled.

It appears that the recall of LiIon batteries due to overheating is still a regular occurrence, even with relatively small batteries of less than 100Wh capacity.

Lithium Metal Polymer

The alternative to the Lithium Ion battery is the Lithium Metal Polymer battery which uses a lithium metal anode.

The attraction of using lithium metal for the anode instead of graphite is higher charge density. The practical achievable charge density with lithium metal is 960mAh/g compared to 300mAh/g for LiC_6 - i.e. graphite into which Lithium ions are intercalated when they are transported over from the cathode.

The electrolyte is a solid semi-conducting polymer, which has a salt infused into it. This polymer electrolyte is designed to protect the Lithium metal anode and reduce cycling problems.

Apart from the safety concerns, excess Lithium metal has to be used in the anode to obtain sufficient cycle life, due to the poor efficiency of the stripping and plating process in an LiMP battery. This counteracts the theoretical energy density advantage of LiMP over LiIon and reduces the net benefit.

The leading proponent of LiMP technology, Avestor in Canada, withdrew from the EV market in early 2005. The company is a joint venture between Hydro Quebec and Kerr McGee and was originally established specifically to address the battery market for Electric Vehicles. They had tested their battery in a Th!nk City but it only had a cycle life of 300 cycles. Specific energy was 121Wh/kg and Energy Density was 143Wh/l, which is inferior to the NaNiCl ZEBRA battery. The polymer in the Avestor battery requires heating to maintain a temperature of between 42 and 60˚C, to ensure adequate conductivity of the electrolyte. Avestor are now concentrating their focus on the telecommunications backup market.

The French industrial group Bolloré have developed a very similar, (possibly identical) battery to the Avestor technology for EVs and have established a subsidiary Batscap to market it. The company also developed a concept car (the Blue Car) to act as a demonstrator and testbed for the battery.

The US company Delphi also developed a high power LiMP battery for Power Assist Hybrids in 2002. The company was bought by Johnson Controls in mid 2005.

However, it is beyond doubt that the use of LiMP technology for a large format multi-kilowatt hour battery, installed in a moving vehicle, is currently out of the question due to the safety issues associated with the presence of lithium metal in the battery.

Cathode Developments

This section examines the most important aspect of LiIon development for EV use: the cathode.

There are four types of materials being investigated to replace the $LiCoO_2$ material used in consumer batteries, which is too dangerous and expensive for large format applications.

1. Nickel Oxide Based Systems
2. Layered Manganese Oxides
3. Lithium Manganate Spinel
4. Lithium Iron Phosphate

Nickel Oxides (Nickelates)

The large format LiIon batteries already available for EV use are based on Nickel, with lower quantities of manganese and cobalt. The so-called 123 material uses one third of each metal in the oxide. This $LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2$ material is being found to be somewhat superior in performance to the $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ material which is the current benchmark for automotive LiIon batteries.

Other materials that are often used include $LiNi_{0.8}Co_{0.2}O_2$ or $LiNi_{0.75}Co_{0.15}Ti_{0.05}Mg_{0.05}O_2$.

A wide variety of different compositions is possible and different battery manufacturers have their own variants and preferences.

The leading commercial supplier of LiIon batteries for EVs at the moment is probably SAFT. Their cells are based on a $LiNiO_2$ material, with some cobalt and other elements incorporated. Their VL45E cell (45Ah) has an energy density of 149Wh/kg and 313Wh/l. When 6 of these are put together into a module (VLE22) of 900Wh, weighing 8kgs, energy density per module falls to 110Wh/kg and 160Wh/l. Operating temperature is quoted as -10˚C to +45˚C. Therefore low temperature performance needs to be improved.

TABLE 14 **SAFT EV LiION SPECIFICIATIONS**

	Voltage	Capacity	Weight	Volume	Wh/kg	WH/l	Dimensions
VL45E Cell	3.6V	45Ah	1.07kg	0.51l	149Wh/kg	313Wh/l	222mm Long x 54.3mm diam.
VLE22 Module	21.6V	42Ah	8 kg	5.66l	110Wh/kg	160Wh/l	24 x 19 x 12 cm

This table shows the limitation of energy density figures quoted for individual cells. When 6 of the VL45E cells are combined into a VLE22 module, weight increases by 25% and volume by 85%. When modules are added together, energy density overall will fall even further.

These nickel based systems still have safety issues due to the reactivity of nickel when the battery is charged and will be superseded by manganese based materials. In $LiNiO_2$ and $LiCoO_2$ batteries, the trivalent metal cation is oxidised during charging to the tetravalent oxidation state. Co^{4+} and Ni^{4+} are powerful oxidising agents and can react with the electrolyte.

Layered Manganese Oxide Materials

The use of layered Manganese Oxide ($LiMnO_2$) materials is one of the 3 main approaches now being pursued to replace $LiCoO_2$ in the cathode of EV LiIon batteries. A leading research establishment in this field is the Argonne National Laboratory in the USA. A variety of dopants are being tested in different quantities, including nickel, cobalt, chromium, titanium or aluminium.

The advantages of $LiMnO_2$ over the $LiCoO_2$ cobalt based oxide are:

- Lower Cost
- Improved Safety
- Unlimited material availability
- Equivalent or improved energy density.

A significant advantage over other cathode materials is that $LiMnO_2$ can be prepared from industrially available EMD (electrolytic manganese dioxide) which has a very low cost ($1/lb).

Unfortunately, $LiMnO_2$ is not stable. When the battery is charged, lithium ions in the cathode migrate to the graphite anode, thus delithiating the cathode. This causes the layered MnO_2 configuration to change to the Manganate Spinel Mn_2O_4 structure. This reduces the voltage of the cell and one ends up with a Lithium Manganate Spinel cathode (see below). The energy density falls and the Mn_2O_4 has its own deficiencies of capacity fade, if other measures are not taken.

Therefore the objective of research in this field is to find ways to stabilise the $LiMnO_2$ material so it will not undergo a phase transition to $LiMn_2O_4$ on electrochemical cycling, with accompanying loss in energy density and then capacity fade.

The approach taken by the Argonne National Laboratory and others under the US DoE FCVT research programme, is to introduce another material into the cathode to stabilise it. Argonne are using lithium transition metal oxides with a rocksalt crystal structure to do this, of general formula $Li_2M'O_3$. The M' species is a tetravalent transition metal cation, such as Mn^{4+}, Ti^{4+} or Zr^{4+}, or a number of these together. The introduced material plays no electrochemical part in the cell but is a “structural dopant” which stabilises the layered $LiMnO_2$ material.

These mixed materials have the general formula $xLiMO_2 . (1\text{-}x)Li_2M'O_3$.

Some examples of materials that Argonne[1] and FCVT have investigated include:

1. $0.2\ (Li_2MnO_3)\ .\ 0.8\ (LiNi_{0.8}Co_{0.2}O_2)$
2. $0.2\ (Li_2Mn_{(1-x)}Ti_xO_3)\ .\ 0.8\ (LiNi_{0.8}Co_{0.2}O_2)$
3. $0.15\ (Li_2TiO_3)\ .\ 0.85\ (LiMnO_2)$
4. $0.1\ (Li_2TiO_3)\ .\ 0.9\ (LiMn_{0.9}Ni_{0.1}O_2)$
5. $0.03\ (Li_2ZrO_3)\ .\ 0.97\ (LiMn_{0.5}Ni_{0.5}O_2)$

The first and second of these were found to have a sustained discharge capacity of 136mAh/g and 108mAh/g respectively. The fourth one has a theoretical discharge capacity of 252mAh/g, only 8% less than $LiCoO_2$. The fifth one had a sustained capacity of 180mAh/g at 50˚C, although

1. US Patent 6,677,082 “Lithium Metal Oxide Electrodes for Lithium Cells and Batteries”, MM Thackeray et al., University of Chicago, 2004.

Zirconium would be an expensive material to use in a commercial battery. At the 22nd International Seminar on Primary and Secondary Batteries in March 2005, a material with 250mAh/g sustained discharge capacity was presented, but only at low rate of C/20 to C/24.

In general, materials in this category are now capable of 180- 200mAh/g sustained discharge capacity at C/3, the EV standard discharge rate.

The ultimate objective is to use as little Nickel and Cobalt as possible, particularly Cobalt due to the supply constraints that would arise in high manufacturing volume. However, the power requirements may mean that some cobalt is always needed.

Sony's "Nexelion" LiIon battery launched in early 2005 is the first commercial example of this approach. The cathode is a layered manganese oxide, with some nickel and cobalt incorporated. Its composition is probably closer to the examples (3) and (4) above, with the majority of the material composed of $LiMnO_2$. It has a 30% higher energy density than standard $LiCoO_2$ LiIon cells. The anode is not graphite but a tin carbon composite. The cell can be 90% recharged in 30 minutes. One very interesting feature of this technology is its low temperature performance. It can maintain high power output down to -20˚C. Winter performance has always been a concern for widespread use of EVs and for LiIon batteries in particular. This technology will form the basis of future developments at Sony.

Sony provided the LiIon battery pack for the Nissan Altra, the only car marketed in California under the CARB ZEV programme equipped with an LiIon battery. If LiIon EV batteries are developed based on this Sony / Argonne technological approach, they promise to have better energy density than $LiCoO_2$ or $LiMn_2O_4$ but with the safety and very low cost of $LiMnO_2$. It will become the leading material for EV LiIon cathodes.

Lithium Manganate Spinel

The Lithium Manganate Spinel ($LiMn_2O_4$) cathode material is known to be very safe, have very low cost and have good rate capability but has not been widely favoured for consumer applications due to its lower energy density (than cobalt) and perceived loss of capacity on repeated cycling. Dissolution of the manganese into the electrolyte at elevated temperatures has been the main difficulty.

However, the Lithium Manganate Spinel ($LiMn_2O_4$) material is becoming a leading contender for LiIon EV use. The Canadian company Moli Energy were the first to commercialise Lithium Manganate batteries after their bankruptcy caused by the unsafe lithium metal mobile phone batteries. Manganate technology was then adopted by NEC after NEC bought Moli Energy in 1991. In 2000, NEC launched a $LiMn_2O_4$ battery for personal mobile devices with a claimed specific energy of 150Wh/kg.

In 2002, NEC formed a Joint Venture with Fuji Heavy Industries (owner of the car manufacturer Subaru) to advance the development of Lithium Ion Manganate Spinel batteries for EVs. This JV is called NEC Lamilion Energy Ltd. Subaru announced in September 2005 that they will use

LiIon Manganate Spinel batteries for their new range of Hybrid cars. It will also be used in their pure Battery EV, the R1e. An adequate battery cooling system will probably be used to keep the temperature of the battery in an EV within acceptable limits to prevent manganese dissolution if necessary. Manganate technology (from Moli Energy) is also now used in portable power tools manufactured by the market leading Milwaukee Power Tool Company.

In 2003, Sanyo also adopted Lithium Manganate Spinel by launching a consumer market hybrid battery containing a mixture of both cobaltite ($LiCoO_2$) and Manganate ($LiMn_2O_4$). Production was increased in 2004. Sanyo are providing battery packs to Ford for their range of hybrid vehicles.

Panasonic's nickel-manganate cathode material has slightly higher capacity and better rate capability than $LiCoO_2$ but is much safer, more thermally stable and would be lower cost. It is a combination of $LiNiO_2$ and $LiMn_2O_4$ (manganate spinel), similar in concept to Sanyo's combination of Manganate Spinel with Lithium Cobaltite ($LiCoO_2$).

This material may find its way into the LiIon batteries under development at Panasonic EV Energy Ltd.

Therefore Lithium Manganate Spinel currently has a head start into both the consumer market and the EV market over Lithium Iron Phosphate.

The high power IMR 26700 $LiMn_2O_4$ cell manufactured by E-One Moli Energy has an energy density of 285Wh/l, specific energy of 109Wh/kg and power density of 1500W/kg.

In 2004 the Korean manufacturer LG Chem was working on a USABC funded project to develop a $LiMn_2O_4$ spinel cathode for HEVs. Cycle life was expected to reach the FCVT[1] Program target of 300,000 cycles. The adoption of $LiMn_2O_4$ spinel technology by Subaru is also evidence that acceptable performance can be obtained.

Johnson Controls/ Varta are also evaluating the material and will probably move to it from their current nickelate system, though they would not rule out $LiFePO_4$ if its performance improves.

The manganate spinel material is very resistant to overcharge. The LG Chem material was found to exhibit no hazardous behaviour below 8V and currents up to 60A.

Doping of the Manganate Spinel material with metals such as Titanium or Aluminium may allow capacity to reach the same levels as cobalt oxide and reduce manganese dissolution. Japanese researchers claim that these dopants increase charge capacity to 168 - 177mAh/g and will reduce the price of the cathode to 20% of that of cobalt.

1. US Dept. of Energy's FreedomCAR and Vehicle Technologies Program

Extensive research has also been carried out on alternative electrolytes to reduce the manganese dissolution problem. The promising lithium oxalatoborate salt is one possibility. NEC have also patented the use of lithium sulphonylimide salts to reduce HF formation.

Lithium Iron Phosphate

The Lithium Iron Phosphate cathode material has excellent safety characteristics. It is widely seen to be the safest material currently available for LiIon batteries for EVs. Its disadvantage is that it has significantly lower energy density than layered manganese oxide materials or manganate spinel. It operates at 3.2V compared to 3.6V and has lower charge density. (Figures vary between 135mAh/g and 170mAh/g).

The lower voltage also means that more cells have to be added in series to obtain sufficient operating voltage for EV/ HEV electric motors.

There is no possibility of thermal runaway of the phosphate material, which is thermally stable to 800˚C. Unlike $LiCoO_2$, which is thermally unstable and can easily release oxygen when heated, thus catalysing a thermal runaway event, $LiFePO_4$ will not release oxygen even under severe abuse. Cells can be overcharged to 4.5V and overdischarged down to 0V with full recovery, whereas standard LiIon cells have to be kept within tightly controlled limits (2V - 4.2V). This simplifies the control system, gives greater flexibility for management of regenerative braking and greatly improves safety.

Although the raw material is potentially very inexpensive, the phosphate has to be heated under an inert atmosphere of nitrogen or argon and very high purity is required. Therefore the raw material is cheaper than layered oxide, but the processing costs are higher and the performance is lower. The cost advantage over oxide material is offset to a certain extent by the higher manufacturing costs. Its real advantage is unquestionably safety but Manganate Spinel or layered manganese oxides may be adequately safe and have higher performance.

The safety performance of the battery will also be limited by the anode and electrolyte. At 120˚C the graphite anode will start to react with the electrolyte - overall cell safety will be limited by the weakest link.

The Lithium Iron Phosphate ($LiFePO_4$) cathode material has been under development for about 10 years. Its safety features, lower cost and fast recharge capability are making it one of the leading contenders for LiIon batteries for EVs at the moment. However, a certain amount of commercial uncertainty is being caused by a patent dispute between the inventor of the technology, Texas A&M University and NTT of Japan who are accused of patent infringement. The legal dispute has lasted four years and is still ongoing. Until this is resolved, other companies will not know from whom they should license it or whether they can use it. Until very recently, Valence Technology of Austin, Texas were the only company actively commercialising batteries based on $LiFePO_4$ technology. Electrovaya of Canada are doing some more limited work with it.

Valence Technology manufacture an 18650 cell with an energy density of 207Wh/l and 118Wh/kg. Valence's larger 1.68kWh 12V modules have specific energy of 101Wh/kg (without control electronics).

The power capability of Valence's batteries is very high. Their Power cells can discharge continuously at 15C with 35C peak discharge capability. Their Energy cells will discharge at 1C continuously. The technology should therefore be suitable for both Power Assist Hybrids and PHEVs / EVs.

The Valence battery has been adopted by a number of smaller EV manufacturers and the Italian scooter manufacturer Oxygen s.p.a will be using it on their next model of electric scooter, to replace NiMH batteries. Valence Technology have recently moved their factory from Northern Ireland to China and could therefore be well positioned to take advantage of the Chinese EV market.

Research is mostly focused on adding carbon particles to $LiFePO_4$ to improve its rate and power capability. This is the approach taken by Phostech Lithium in Canada. The use of Iron Nitrate has been found to improve the structure and electrical properties of carbon.

In 2004, DoE tested samples of 1% Niobium doped $LiFePO_4$ obtained from Prof. Yet-Ming Chiang (MIT), who is a leading researcher into iron phosphate cathodes. They found that residual carbon content left in the material was responsible for the conductivity. The effect of Niobium could not be determined. Research into doping of iron phosphate to improve conductivity and energy density is on-going.

However, in a major market development, Prof. Yet-Ming Chiang's company A123 Systems announced in early November 2005 the adoption of their $LiFePO_4$ technology by Black & Decker for cordless power tools. A123 state that the batteries can be 90% recharged in 5 minutes, peak discharge rate is 100C and power density is 5 times conventional LiIon. This move by Black and Decker is intended to compete with the Milwaukee Power Tool range that uses Lithium Manganate Spinel power batteries. Both of these LiIon technologies have overcome the historical power density limitations of LiIon batteries which has prevented their widespread use for power tools. The implications for Power Assist Hybrids are clear.

A123 state that they will introduce a High Energy Density Cell in 2006 to improve the energy density of notebook computer and cellphone batteries. This would be very significant, if $LiFePO_4$ cathode technology could now exceed the energy density of $LiCoO_2$ while maintaining excellent safety characteristics and low cost.

Conclusion

The Japanese groups are currently focusing on Manganate Spinel based technology for their next LiIon EV batteries. They evidently consider it to be sufficiently safe, but cost effective and with better performance than $LiFePO_4$. It has a clear headstart into the market. Layered manganese oxides ($LiMnO_2$) have better performance than manganate spinel with equal safety and may follow or displace $LiMn_2O_4$. Phosphate technology seemed to be being held back by the patent dispute and its poorer performance, but the latest announcement from A123 could completely change the picture. It may now be a powerful competitor against manganate spinel and layered manganese oxide for HEVs, PHEVs and EVs. The pace of change with all three technologies is rapid and development is ongoing. We may see vehicles developed incorporating all three types of cathode material. Competition is intensifying and growing to develop the highest performance, lowest cost and highest safety cathode material.

Electrolytes

Apart from improvement of the cathode and anode material, extensive research is focused on improving the electrolyte in the LiIon battery. The subject is quite complex since there are a number of different variants and variations being developed. There are four main types of electrolyte technology:

1. Liquid electrolytes, which contain an organic solvent and a lithium salt.
2. Polymer gel electrolytes. An organic polymer and a lithium salt are injected into a porous polymer sponge or mechanical separator to form a semi-solid or gel electrolyte.
3. Solid Ionically Conducting Polymer Electrolytes. An organic polymer which will conduct lithium ions in its own right and does not require the addition of a salt or a mechanical separator.
4. Solid Inorganic Ionically Conducting Electrolytes. These are typically glasses or ceramics.

Liquid Electrolytes

The liquid electrolyte is the original technology used in LiIon batteries and is still used in the majority of consumer batteries today. The solvent is usually a simple organic carbonate such as propylene carbonate, ethylene carbonate or dimethyl/ diethyl carbonate. The most commonly used salt to give this electrolyte conducting properties is $LiPF_6$. This salt is thermally unstable above 60˚C and is a safety concern in the event of thermal runaway. For future LiIon batteries based on Manganese cathodes, this salt will have to be replaced since it also tends to form Hydrofluoric Acid in the cell (by reacting with trace amounts of water that cannot be removed). This in turn reacts with the manganese in the cathode and dissolves it out. Sony’s Nexelion battery which has a high manganese content cathode also has a new “hybrid” electrolyte.

Research activity on a Manganese compatible electrolyte is focused on the salt Lithium Oxalatoborate (LiBOB). The advantages of these materials are that they:

- Contain no fluorine
- May passivate the Al current collector
- Stabilise graphite in propylene carbonate electrolytes

The drawbacks are limited low-temperature performance and low solubility limits. Solutions to these drawbacks are being investigated, including the use of different solvents.

Polymer Gel Electrolytes

The polymer gel electrolytes are now used in the commercially available “Lithium Ion Polymer” battery. Although they are often called “Solid Polymer Electrolytes”, they are not composed just of polymers that are intrinsically conducting in their own right: they are doped with ionic salts and possibly other materials to improve their properties.

A widely used approach is to take a porous polypropylene film (often manufactured by the company Celgard) and inject it with a solution of a lithium salt dissolved in a mixture of the organic carbonates. Chemically, the battery is identical to a liquid electrolyte battery: the liquids are simply contained in a porous plastic sponge to form a gel. In another widely used approach, developed by Bellcore, the plastic separator sponge is made of polyvinylidene fluoride (PVDF).

Avestor use a mixture of a polyethylene oxide (PEO) and the salt LiTFSI as the electrolyte in their Lithium Metal Polymer (LiMP) battery. However, this has to be heated to at least 40˙C to operate effectively. In cold weather, the battery would cease to function without internal electrical heating.

Lithium Power Technologies have developed a composite polymer electrolyte improvement. It consists of a conducting polymer such as PEO, a non conducting inert polymer, a standard lithium salt and an inorganic single ion conducting material such as beta alumina, fumed silica or a phosphate glass. The use of the inorganic material increases thermal stability, improves conductivity and improves mechanical properties. This company claims that their polymer electrolyte has a conductivity of more than 10^{-4}S/cm at room temperature (25˙C).

Gel polymer electrolytes are also known to reduce the capacity fade of Manganate Spinel batteries.

A poly (vinylidene fluoride) (PVDF) gel polymer electrolyte developed by the Argonne National Laboratory uses PVDF as the microporous polymer layer and the Lithium ion conductor. This is similar to the Bellcore technology.

Conducting Polymer Electrolytes

A fully conducting polymer electrolyte that does not require additives or doping with a lithium salt is still the subject of worldwide research.

An important driver behind this is for overcharge protection. As the US DoE FCVT research programme puts it, “Given the susceptibility of lithium-based batteries to energetic venting or even explosion following overcharging, a reliable overcharge protection mechanism is an indispensable requirement for large cell assemblies”.

Electroactive polymers whose conductivity depends on their state of charge can provide overcharge protection by means of a reversible, self-actuating low resistance internal shunt that allows overcharge currents to pass through the cell.

In 2004, the FCVT programme demonstrated protection of $LiFePO_4$ cathodes, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ and Li123 material cathodes (q.v.) at moderate overcharge.

The Sadoway Research Group at MIT has developed a co-polymer conducting electrolyte with excellent thermal stability up to 300˚C which would greatly enhance safety. However, its conductivity is still low. They have demonstrated a prototype thin-film Lithium Ion Polymer cell (dubbed sLimcell) with a claimed energy density of 400Wh/kg. The research models use a Lithium Vanadium Oxide cathode, which has a high theoretical cathode charge density of 290mAh/g. However this material has discharge rate and stability deficiencies and is not favoured for high cycle applications.

Another advantage of the conducting polymer approach is that in theory the separate mechanical separator which plays no active part in the battery can be removed. This saves weight and volume.

In mid-2005 the Berkeley National Laboratory also announced a single-ion conducting polymer electrolyte. It claims a conductivity of 10^{-5}S/cm at room temperature (25˚C) and a transference number of 1. This would appear to be somewhat superior to the MIT material. However, improvement in conductivity to 10^{-4}S/cm is really required for robust applications.

These solid conducting polymer electrolytes are particularly suited to manufacture of batteries in a different way to conventional batteries. A new class of thin film solid-state batteries is being developed in which the electrodes and electrolyte will be laid down back to back in successive thin layers only micrometers in thickness.

However, while these conducting polymers may be becoming suitable for small format batteries, in consumer devices that operate in relatively benign conditions, their conductivity is not yet good enough for low temperature operation. Below 20˚C ambient temperature, performance would start to degrade.

For polymer electrolytes to prevent interfacial roughening and subsequent dendritic growth on the surface of a lithium metal anode, the shear modulus has to be in the gigapascal[1] range. Existing polymer research has focused on materials with shear moduli in the megapascal range. Therefore a three orders of magnitude increase is required for polymer electrolytes to be able to suppress dendrite growth effectively.

1. Progress Report for Energy Storage Research and Development, DoE FCVT Annual Progress Report, 2004,

Dendritic growth from lithium metal anodes can be prevented if polarisation of the cell is kept sufficiently low, i.e less than 20mV for 0.1mA/cm2. The imide electrolyte salts LiTFSI and LiBETI can sustain this level of current density indefinitely but are expensive. Standard electrolyte salts such as LiPF6, LiBF4, LiBOB and LiClO4 react with lithium metal during cycling.

Inorganic Ionic Conducting Electrolytes

The last approach is the inorganic glass or ceramic single ion conducting electrolyte. The conducting glass electrolyte LiPON (Lithium Phosphorous Oxynitride) has already made some headway as an electrolyte for thin film LiIon batteries for specialist applications. This technology is demonstrating high energy densities (300Wh/kg) and fast recharge times (5 to 10 minutes) for small biomedical batteries using conventional LiIon electrodes. None of the companies commercialising this LiPON technology have yet scaled up to cell phone or laptop computer sized batteries, let alone the kilowatt-hour sized batteries required for EVs. If a way can be found to scale up LiPON technology, LiIon battery performance could double.

LiPON has been found to be very difficult to work with on larger scales. For the time being, it will be restricted to microbatteries. Extensive research is therefore being carried out into alternatives. One approach being pioneered by PolyPlus/ Berkeley Laboratory is the development of a complex amorphous ionically conductive membrane. This consists of a mixture of glasses and ceramics including metal oxide glass, phosphorous glass, phosphorous-oxynitride glass and ionically conducting ceramics such as the well known beta alumina. Some of these glasses have conductivity as high as 10^{-3} S/cm. Such materials are available off the shelf from Ohara of Japan. It remains to be seen if this idea can be scaled up to allow manufacture of larger batteries - or even mobile phone and notebook computer sized batteries.

Ionically conductive glasses are already used in electrochromic displays and windows in sizes up to 1 foot square or more. However, in these windows an external voltage is applied to drive lithium ions through the glass layer: the resistance of these glasses is still too high for a battery and would simply use up the energy of the battery internally.

If this solid glass electrolyte approach can be brought to fruition, it will have major benefits in terms of safety and energy density of LiIon batteries. It may even allow a Lithium Air battery (similar to the ZnAir battery) to be developed commercially for specialist applications.

Many other research groups around the world are working on improving Lithium battery technology. Improved safety and lowered cost go hand in hand as Nickel and Cobalt is replaced with Phosphate, Manganese or combined oxide technologies. Even without the impetus that a large EV market would give to R&D, the prospects of Lithium battery technology providing safe, low weight, small volume, high energy density and quickly rechargeable EV batteries are very promising.

Anodes

Research into improved anodes is receiving less attention in LiIon battery development but is still the scene of advances. The aim is to develop an anode material with higher performance than graphite but without the safety implications of Lithium metal. Graphite can also be a safety hazard at high charge rates, which limits the rate at which LiIon batteries can be recharged.

There are 3 main approaches being pursued:

- Lithium Titanate Spinel and other metal oxides
- Tin or Silicon composites
- Intermetallics

Lithium Titanate Spinel ($Li_4Ti_{15}O_{12}$)

This material attained widespread notice in early 2005 when one of its main proponents, Altair Nanotechnologies, announced a battery using this material that could be recharged in 6 minutes. They are using Lithium Manganate Spinel for the cathode, for its high power rate capabilities.

While Lithium Titanate Spinel does allow very fast recharge times (if a sufficiently powerful charger is available), it has some drawbacks. It has a potential 1.5V lower than graphite. Battery voltage therefore falls to 2.1V with commensurate loss in energy density. Combined with the Iron Phosphate cathode material and 2,5 diterbutyl 1,4 dimethoxybenzene as the electrolyte solvent, a very safe and robust battery could be produced with probably similar energy density to NiMH.

The US/Chinese battery manufacturer Advanced Battery Technology is testing a Lithium Titanate/ Lithium Manganate battery for EV applications. In conjunction with Altair, they are testing the battery in an electric bus testbed in California. Altair project that this combination will give a battery with twice the energy density of Lead Acid, i.e. in the range of NiMH. This would appear to be reasonable.

Metal oxides such as Li_2MoO_3 and $LiVO_2$ have been researched to find an alternative to Lithium Titanate Spinel with higher capacity and a lower potential difference vs. Lithium.

Tin and Silicon

Tin and Silicon are very effective anodes that can absorb large quantities of Lithium. However they both undergo a marked volume expansion on intercalation of Lithium and therefore face engineering challenges. Nano sized (10 - 20nm) Silicon is a very promising anode material that has demonstrated a capacity of about 900mAh/g and overcomes the volume issue.

Amorphous mixtures of Tin and Silicon (and Aluminium) are also being investigated but still undergo volume change. Silicon has a theoretical charge capacity of up to 4000mAh/g. Some researchers believe the volume change should be accepted and taken into account in the design because of the high energy storage capability.

Sony have developed a tin based amorphous material containing nanometre scale particles of tin, cobalt and graphite. This greatly reduces the volume change during charge and discharge and the material is now on the market in Sony's latest "Nexelion" commercial battery. This material also allows faster recharging than graphite. Sony quote 90% recharge in 30 minutes for a small 900mAh cell.

The emphasis at the DoE FMCVT program in 2004 also switched away from intermetallics to Carbon - Tin or Carbon - Antimony composites. A Carbon - Tin composite limited to 10% Tin demonstrated a capacity of 400mAh/g up to 100 cycles with no capacity fade.

Intermetallics

Intermetallics are alloys with the crystal structure of zinc blende. Examples that have been investigated include Cu_6Sn_5, Cu_2Sb and In_2Sb.

These compounds have the drawback that upon initial lithiation, they retain a certain amount of the lithium which can cause up to 50% capacity loss.

Conclusion

It seems likely that the next generation of anodes for LiIon batteries will be based on tin or silicon composites, using a compromise approach that provides higher capacity and faster rate capability than graphite without excessive volume change on cycling.

Other Developments

The latest LiIon polymer battery prototype from Toshiba is claimed to be able to recharge 80% of its capacity in 1 minute. It can apparently withstand 1,000 charge and discharge cycles with only a 1% loss in capacity. Its cell energy density is greater than 170Wh/kg.

The CrFLi Lithium Polymer battery manufactured in China has a somewhat lower energy density than standard LiIon but lower cost. Quality control is not yet standardised.

A number of other LiIon developers are pushing cell energy density to 200Wh/kg. One of these, Fortu Power Cell GmbH, uses standard graphite and Lithium Cobaltite LiIon electrodes with electrolyte technology derived from primary Lithium Sulphur Dioxide batteries. (The electrolyte is $LiAlCl_4$ in liquid SO_2). This apparently achieves 200Wh/kg cell energy density. Fortu claim that the battery can be overcharged, that thermal runaway cannot occur and the weight, cost and complexity of a control circuit for each module is reduced. These are strong advantages for EV applications but this electrolyte technology is unlikely to find favour. Its current reliance on cobalt electrodes will also be too expensive for widespread use.

Conclusion

There is an enormous amount of research and development taking place around the world into LiIon batteries. There is no doubt that over the next ten years, they will continue to improve in all areas - cost, safety, power capability and energy density. It is perhaps envisageable that future thin film LiIon batteries in a large format could reach 300Wh/kg to 400Wh/kg over the next 10 years. They are already in effect pushing towards 200Wh/kg for individual cells.

The Lithium Metal Polymer battery which uses a lithium metal anode will be regarded with great circumspection for large format mobile applications. It will stay restricted to stationary applications such as telecommunications backup. The leading proponent of LiMP technology, Avestor in Canada, withdrew from the EV market in early 2005. The safety of LiIon itself in large format multi-kilowatt hour batteries still remains to be ascertained although manganese and phosphate based cathodes should solve many of the existing problems. Lithium metal batteries are simply too risky for EV use, when the known safer alternative of LiIon is available.

At the present time, Manganese based cathodes are the front-runners for the large format EV LiIon market. Lithium Manganate Spinel is now being adopted for HEVs by one Japanese manufacturer but the layered Manganese Oxide material may offer greater advantages and major developments are also taking place with the Iron Phosphate material.

Lithium Ion batteries may not be able to power the world's entire future BEV and PHEV fleet. Lithium production will have to be expanded by nearly an order of magnitude to achieve this.

There are therefore two significant issues with the widespread adoption of LiIon batteries for HEVs, PHEVs and BEVs:

1. Safety
2. Availability of Lithium

For these reasons, future reliance should not be placed just on LiIon or any other Lithium battery technology alone.

7.6 The Sodium Nickel Chloride "Zebra" Battery

Introduction

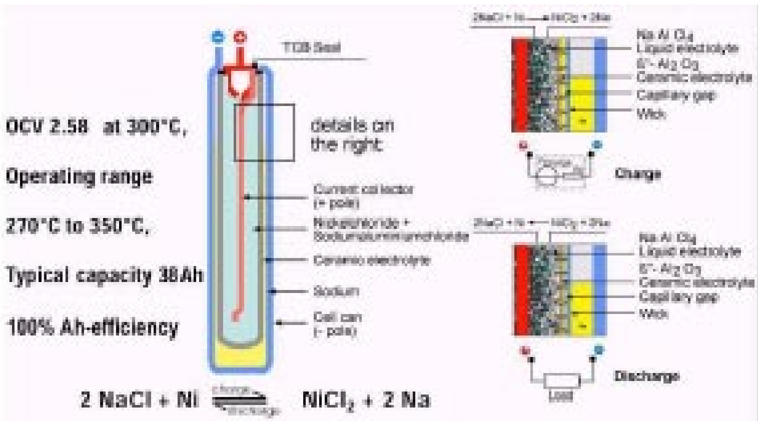
The "ZEBRA" Battery (Zero Emissions Batteries Research Activity) is a Sodium Nickel Chloride battery, manufactured in limited volume in Switzerland for EV applications. It is the only dedicated EV battery in production in the world today.

The technology was first developed in South Africa during the 1970s and 1980s. The major development then took place at AERE Harwell, who then entered joint development with AEG. AEG were later bought by Daimler Benz and then divested.

This technology is only manufactured today by the company MES-DEA GmbH, located in Stabio, Switzerland. MES-DEA bought the rights to the technology from AEG in 1999 after Daimler Benz divested itself of AEG in the late 1990s. MES-DEA built a new $66M factory in 2001 to manufacture the battery. The factory presently has an annual capacity of 30,000 units.

Figure 40 shows the functioning[1] of the Zebra cell.

FIGURE 40 **ZEBRA CELL**



The β-alumina ceramic electrolyte tube has the cross section of a clover leaf to increase the surface area available for ion transport between anode and cathode.

The finished battery package with control electronics has a specific energy density of 90 - 120Wh/kg (depending on format). Volumetric energy density is 166Wh/l. The theoretical specific energy of a cell is

1. From "ZEBRA Battery - Material Cost, Availability and Recycling", Dr. Galloway, Dr. Dustmann, MES-DEA GmbH, EVS 20, 2003.

790Wh/kg. The battery is robust, potentially inexpensive, available in a number of large EV formats and is a well tested technology. This specific energy density is about the same or better than current generation LiIon battery packs for EVs, available from SAFT or Sony. The Sony 32.4kWh LiIon battery pack in the 1999 Nissan Altra had a specific energy of 89Wh/kg. Existing SAFT LiIon EV modules have a specific energy of 110Wh/kg.

In comparison, the 9kWh LiIon battery provided by Valence Technology for retrofit into the Toyota Prius weighs 250 lbs, i.e. an effective specific energy density of only 80kWh/kg

The Zebra battery will withstand at least 1,000 100% DOD charge/discharge cycles including any type of partial charge/recharge and is also marketed by Rolls-Royce for demanding marine applications, including stand-by power in military submarines and surface vessels. It is an extremely robust and rugged battery capable of being used in demanding and harsh environments.

On rapid recharge, the Zebra battery can be 80% recharged in 75 minutes.

BMW used an earlier related technology (Sodium Sulphur) on their prototype E2 electric car in the early 1990s. Sodium Sulphur technology was developed by Ford in the 1960s and discontinued in the 1990s due to corrosion problems. Mercedes Benz announced that they would launch an electric version of the A Class in 1998 equipped with the NaNiCl battery. The Electric A Class would have had a range of 120 miles. The vehicle was not marketed. With the latest generation of Zebra battery, the range of the A Class EV would increase to 180 miles.

Efficiency Comparison

The major perceived drawback of the Sodium Nickel Chloride battery is that it is a high temperature technology. The battery has to be maintained at an internal operating temperature of between 270˚C and 350˚C for efficient operation. While the battery is being used, this causes no energy penalty since the internal resistance of the Zebra battery coverts resistive losses to heat with 100% efficiency. All batteries have internal resistance and in all batteries, this internally generated heat has to be removed by a cooling system to prevent overheating.

Therefore in the case of the Zebra battery, the heat generated during operation can be used to maintain the temperature.

However, when the vehicle is not in use, the battery will start to cool down. After about 4 hours, external heat has to be applied to maintain the temperature. The battery contains a heater which can be powered by the mains or powered by the battery itself. If the vehicle is left overnight it can be plugged in to both recharge it and to keep the battery hot. If the vehicle is left for more than 4 hours in a location without access to a source of mains power, the onboard DC heater switches on to maintain the temperature.

The key question in relation to other ambient temperature battery technologies is therefore:

- How much more life-cycle electrical energy does the ZEBRA battery use than ambient temperature batteries?

The Mendrisio Operating Trial

Between 1995 and the present, the Swiss town of Mendrisio has been operating an EV trial programme. The programme started with Peugeot 106 EVs equipped with a 14kWh NiCad battery pack, supplied by SAFT. The electric motor is a 20kW DC motor.

In 2001, a fleet of Renault Twingo electric cars powered by a 21.2kWh ZEBRA battery started operations. The motor is a 36kW AC induction motor.

The trial has been carried out under the auspices of the Swiss Federal Office of Energy and monitored independently by the local municipal authorities.

An important difference between the two vehicles is that the Peugeot 106s are equipped with a small gasoline heater for the passenger cabin, while the Renault Twingos use a 3kW electric heater powered by the main drive battery.

Operating results from this trial were presented by MES-DEA at the latest Electric Vehicle Symposium[1] in April 2005.

The table below summarises the characteristics of the two vehicles.

TABLE 15 **MENDRISIO VEHICLE COMPARISON**

	Peugeot 106	Renault Twingo
Gross Vehicle Weight	1350 kg	1230 kg
Empty Weight	1050 kg	980 kg
Range at 50 mph	50 miles	75 miles
Heater	Petrol	3kW electric
Battery	14kWh NiCad	21.2kWh
Motor	20kW DC	36kW AC
Avg. Energy Use	0.41Wh/mile	0.37Wh/mile
Fleet Sample Size	15	5

Over a two year period, the Peugeot 106 used an average of 25.8kWh of electricity from the mains per 100 km driven, or 0.41Wh/mile. Over a

1. “Mendrisio Operating Results using NiCd and ZEBRA Batteries”, EVS-21, Monaco, 2-6 April 2005

4 year period, the Renault Twingos have used an average of 23.2kWh/ 100km delivered from the mains, or 0.37Wh/mile.

These figures for the Renault Twingos equipped with the ZEBRA battery include use of the battery to heat the car in winter, not a trivial requirement in Switzerland. In fact, the winter consumption averaged 25kWh/100km versus 20kWh/100km in summer. In addition, the Twingos were equipped with winter tyres which increase rolling resistance, while the Peugeot 106s were not. There was no difference between winter and summer energy use by the Peugeot 106s for these same reasons.

With both vehicles, energy use per km decreases as the distance travelled per day increases.

The thermal energy loss of the ZEBRA battery when not in use is about 90W or 2.16kWh per day. However, in normal use the energy loss will be lower than this. Even if the vehicle was left unused with the battery plugged in for an extended period of time, the cost of this electricity to keep the battery at operating temperature would be minimal - less than 20 cents per day in Europe or the USA and would be equivalent to about 5 - 8 miles driving distance per day.

Conclusion

In normal everyday use, it does not appear that the ZEBRA Battery will use any more electricity than a NiCad system. There is so much variation in daily driving habits that the extra energy required to keep the ZEBRA battery hot does not appear to make much difference to overall energy efficiency.

The ZEBRA may in fact be superior to NiCad, since it has demonstrated slightly higher efficiency while also supplying cabin heat in winter and having higher resistance winter tyres.

Cost Potential of the Zebra Battery

MES-DEA believe that the selling price of the ZEBRA battery would be $240/kWh in low volume production (10,000 units). At 100,000 units per year it is projected that the price would fall to $109/kWh.

In 2003, MES-DEA published a cost analysis[1] to justify these forecasts. The production cost breakdown of the ZEBRA battery is shown below.

1. ZEBRA Battery - Material Cost Availability and Recycling, RC Galloway, C-H Dustmann, EVS 20, Nov. 15 - 19 2003, Long Beach, CA.

TABLE 16

ZEBRA BATTERY COST PROJECTION

	$/kWh	$/ Battery (21.2kWh)
Nickel	17.75	376.30
Other Internal Materials	10.53	223.24
Battery Case	9.37	198.65
Cell Manufacture	13.82	292.98
Case Manufacture	9.37	198.65
Controller	-	250
TOTAL		**$1540**

The total production cost is estimated at $1,540 or $73/kWh. MES-DEA assumed that the production cost would be 2/3rds of the selling price, giving an end user price of $109/kWh.

The most expensive item in the ZEBRA battery is the Nickel metal used in the cathode. MES-DEA state that the NaNiCl technology makes much more efficient use of Nickel than NiMH or NiCd: 1.53kg of Ni is used per kWh of stored electricity compared to 6.8kg/kWh for NiMH and 3.5kg/kWh for NiCd. This is partly because the potential of the NaNiCl cell is 2.58V, more than twice the 1.2V of other Nickel systems.

Argonne National Laboratory estimated[1] in 2000 that the Nickel content per kWh of a LiIon high energy EV battery (using a nickelate $LiNiO_2$ cathode) would be 2.5kg/kWh.

TABLE 17

COMPARATIVE NICKEL USE BY BATTERY

Battery	Nickel Use per kWh
NaNiCl	1.53 kg/kWh
$LiNiO_2$	2.5 kg/kWh
NiMH	6.8 kg/kWh
NiCad	3.5 kg/kWh

In practice, future Mixed Oxide cathodes using Mn, Ni and Co for LiIon EV batteries will probably use less Nickel than 2.5kg/kWh but it may still be the second metal in the cathode after Manganese, so it could be present in similar quantities to that used in ZEBRA technology.

1. “Costs of Lithium-Ion Batteries”, Linda Gaines, Roy Cuenca, Argonne National Laboratory, May 2000

The current price of Nickel is between $7 and $8 per lb ($17.6/kg), which is $6/kg more than the cost used above in Table 16 by MES-DEA in 2003. This price increase will affect all Nickel based battery technologies[1] but there is no shortage of Nickel resources for increasing production in future if required. Global Nickel production is currently about 1.2M tonnes per annum with many new mines scheduled to open over the next 5 years. Global Nickel production would currently be sufficient to manufacture 37 million 21.2kWh ZEBRA batteries per year.

At current Nickel prices, the cost of the 21.2kWh NaNiCl battery above would increase to US$1,735, i.e. an end user selling price of $123/kWh.

The other main chemicals used in the ZEBRA battery are Iron, common salt (NaCl) and the inert mineral boehmite, a form of alumina. These substances are cheap and available in unlimited quantities. The total material cost is less than $40 per kWh.

The cost of the case is quite significant, since the battery requires good thermal insulation. The case is made of a double walled stainless steel box, containing a vacuum like a Dewar flask to minimise thermal conduction. However, the cost of the case rises at a lower rate than the size of the battery, so larger capacity batteries have a proportionately lower casing cost.

The cost of the controller is also independent of battery size, adding to the economy of scale as battery size increases.

Using MES-DEA’s methodology, a ZEBRA battery with a capacity of 42.4kWh would cost about US$3,640 to produce, based on a Nickel price of $18 per kg. Taking MES-DEA’s assumption that the production cost would be 2/3rds of the selling price, the price of a 42.4kWh ZEBRA battery would therefore be $5,461 or about $130 per kWh.

Even at today’s high Nickel prices, $130/kWh would be far cheaper than any competing battery technology, with the possible exception of Lead Acid.

If Nickel availability or price became an issue, the battery will work almost equally well with Iron instead of or partially replacing the nickel. In this case, the battery becomes a Sodium Iron Chloride battery. The cell potential is slightly lower (2.35V instead of 2.58V) but the operating temperature can be reduced from 300˚C to 250˚C. The cost of the battery could be reduced even further if iron was used instead of nickel. There would of course be no material supply issues at all with a $NaFeCl_2$ battery: practically unlimited quantities of this battery could be manufactured from iron and common salt. In fact, starting in 1998, later versions of the ZEBRA battery already used a 4:1 nickel to iron mix, along with some aluminium to improve overdischarge capability.

1. For comparison with the cost of NiMH batteries, See “Cost Analysis” on page 80.

Safety

The ZEBRA battery must maintain an internal operating temperature of between 270˚C and 350˚C. In operation, the anode consists of molten sodium. The cathode consists of nickel chloride (or a mixture of nickel chloride and ferrous chloride) combined with molten sodium tetrachloroaluminate ($NaAlCl_4$).

Safety concerns are therefore frequently raised with regard to this technology, particularly since it contains molten sodium metal.

In 1998, the National Renewable Energy Research Laboratory (NREL) published[1] an independent safety study on the Zebra battery.

The report found that "when subjected to extreme external influences simulating vehicle accidents, batteries do not appear likely to add additional significant hazards to occupants or emergency response personnel". The cells are fail-safe to overcharging or overdischarging and are fabricated without the use of metallic sodium. Failure from exposure to high temperatures results in small hazards and they can be "safely and legally shipped in the cold state".

The NREL commented that AEG Zebra (as it was then) felt that a breached cell was very unlikely to release sodium, since any trauma capable of breaching the cell would also break the ceramic electrolyte, binding all of the sodium into sodium chloride. No sodium had been released in any safety tests. However, the report did recommend that tests should be undertaken to determine if there were circumstances in which sodium could be released and what the effects would be.

The use of the battery in military and civilian submarines, including its proposal by Rolls Royce for nuclear submarines, indicates that any safety concerns have been satisfactorily resolved.

In March 2005, the UK oil well logging equipment company Sondex bought the rights to advanced Zebra battery technology under development by Beta R&D in the UK. They are using NaNiCl batteries to replace Lithium Ion in downhole equipment - a very harsh operating environment. They see Zebra batteries as being a more robust, reliable and cost effective alternative to LiIon. This also indicates that any reliability or safety issues with the technology have been resolved.

High Temperature

Being a high temperature battery, the Zebra battery uses 90W of power to maintain its operating temperature if it is not used. The battery is plugged in to the mains to power an onboard mains heater when not in use and has a small onboard DC heater for use where mains power is not available. This requirement to keep the battery hot is not a problem

1. "Current Status of Health and Safety Issues of Sodium Metal Chloride (Zebra) Batteries", D. Trickett, NREL, WW171000, November 1998.

in fleet utility or public transport operations and would not be a significant cost for private drivers. The battery heats up during operation so external heating only needs to start a few hours after shutdown.

On the other hand, the high temperature of the Zebra battery has the advantage that the poor cold weather performance of ambient temperature batteries, especially LiIon, is avoided. The Electric A Class developed by Mercedes used an oil cooled Zebra battery that could also provide instant cabin heating in winter. The Zebra Battery was found by Mercedes to perform equally well in an outside temperature range from minus 40˙C to +40˙C. Standard LiIon batteries are down to 50% capacity at -20˙C and experience a further sharp drop off in performance below that temperature.

If the battery is not required for an extended period, the heater can be switched off and the battery allowed to solidify. This freezes in the state of charge and no charge is lost while the battery is frozen. Unlike the earlier Sodium Sulphur battery, an unlimited number of freeze-thaw cycles can be performed without damage or loss of capacity. On thawing the full charge that was in the battery at time of freezing becomes available again. Therefore there is no self-discharge during idle periods, unlike NiMH. The battery takes 12 - 15 hours to heat up after it has frozen.

Recent Developments

In September 2004, MES-DEA started an active commercial programme to convert the Renault Twingo and Smart Car to electric propulsion, equipped with the Zebra battery. These vehicles can be purchased from MES-DEA for about 18,000 euros. The Italian Government provide a 65% subsidy to people who buy an EV, which makes the vehicle an attractive proposition for the Italian market.

The Zebra battery has been selected by Th!nk Nordic for their new Th!nk Public 4 seater EV. The Indian electric car manufacturer Reva have also selected it for their proposed NXG city electric car. A number of US bus manufacturers also offer it as an option for hybrid or pure electric buses. The 3 UK Commercial EV programmes have all selected the Zebra battery.

The city of Lyon in France is operating 5 electric buses (45 passengers), each equipped with 8 Zebra batteries. As of July 2005, the city of Rome in Italy has ordered 36 electric buses equipped with the Zebra battery and has tendered for 400 electric taxis also to be equipped with this battery. Italy is particularly vulnerable to oil supply shortages since 73% of its electricity comes from thermal power stations, the majority of which are oil fired - not coal or natural gas.

Conclusion

The ZEBRA battery has many advantages:

1. Energy density higher or equal to LiIon
2. Lowest Cost of any modern EV battery technology
3. Available, cheap and plentiful materials
4. Resistant to Overcharge and Overdischarge
5. Fail-safe to cell failure
6. Ruggedness
7. High calendar life
8. Undiminished low temperature performance

Its disadvantages:

1. 12 - 15 hours to thaw out after freezing
2. 90W energy loss while not in use

The battery is therefore finding particular application in public transport and utility operations where it can be put into continuous use and energy losses are minimised. However, the much lower cost of the NaNiCl technology compared to NiMH or LiIon means that for a 20kWh Zebra battery, it would take more than 50 years for the energy losses of the Zebra battery if kept permanently on stand-by to equal the extra cost of the other batteries.

7.7 The Zinc Air Fuel Cell and Battery

Principle of Operation

The ZnAir battery or Fuel Cell is an interesting technology with a number of variants. A non-rechargeable version is used in many fixed power applications, such as hearing aids. The technology has a number of attractive features.

The anode of the battery is Zinc metal. The cathode is comprised of the oxygen in the atmosphere. Thus the weight of the battery is greatly reduced since one of the electrodes is the air itself. The Zinc is oxidised to Zinc Oxide by oxygen in the atmosphere and electricity is generated in the process.

The energy density of the Zinc Air battery is excellent. Small non-rechargeable versions are available with a specific energy of 440Wh/kg and a volumetric density of 1670Wh/l, more than three times that of LiIon.

Two non-rechargeable ZnAir technologies have been developed for Electric Buses or vehicle fleet operators that have an energy density of 200-220Wh/kg. This exceeds most LiIon batteries available today.

A major attraction of ZnAir is that Zinc is very inexpensive and therefore ZnAir batteries are potentially much cheaper than LiIon or any other secondary battery type to manufacture. The price of Zinc is currently about $0.60/lb. Some 9.1M tonnes of Zinc were mined in 2004 and identified global reserves are about 1.9 billion tonnes. Zinc is a widely used industrial metal and there would be little difficulty in expanding production to meet demand for millions of ZnAir EV batteries.

A hydraulic recharging system has been developed for some ZnAir battery types which allows them to be recharged like a conventional petrol vehicle. When the battery is depleted, a new charge of liquid electrolyte and Zinc pellets can be pumped in to recharge it instantly. While this does not recharge it to the same degree as electrical recharging, it would allow operability in the same way as petrol vehicles. One variant of this idea was developed and tested by Lawrence Livermore National Laboratory in the mid 1990s. The battery had an energy density of 140Wh/kg. In 1995, Lawrence Livermore estimated that the cost of a 60kWh battery or metal fuel cell using this approach would be only $2000. The company Metallic Power Inc. tried to commercialise the concept between 1995 and 2001 without success, mainly due to the difficulty and cost of establishing a “refuelling” infrastructure.

A similar ZnAir technology developed[1] at Berkeley allows both hydraulic or conventional electrical recharging. Hydraulic recharging would allow quick refuelling at a service station, while electrical recharging could be carried out at home overnight. However the battery requires a pump for its operation and the number of charge/discharge cycles that the Zinc pellets could undergo is unknown.

Electric Fuel Ltd.

One US/Israeli company, Electric Fuel Inc., has developed large format ZnAir fuel cell modules for EV applications. Each unit weighs 88kg, provides 17.4kWh of energy (i.e. 200Wh/kg) and takes up less than $0.08m^3$ of space. These have been trialled in a number of cities in the US and Europe in city buses and utility applications. For these applications, the entire units are swapped in and out at the depots within 10 minutes and the Zinc is regenerated at a central regeneration facility. They are not user rechargeable.

4 of these Electric Fuel units could fit inside a 4 seater EV car, giving it 70kWh of energy capacity and between 300 and 350 miles range.

Electric Fuel have been trying to commercialise the technology since the early 1990s. Electric Fuel state that the technology requires a fleet of about 5000 commercial delivery sized vehicles to cost justify the central Zinc regeneration plant required for processing of used battery units. They have recently developed a variant which allows ordinary Zinc to be used instead of special dendritic Zinc in the anode. This would reduce the cost and simplify regeneration of the anodes.

However, the Electric Fuel technology has so far been hampered by its high operational cost.

The battery uses only 1.3kg of Zinc per kWh of energy stored. The cost of the battery components is very low and the Metallic Power estimate of $2000 for a 60kWh battery does not seem unreasonable.However, because the batteries are not electrically rechargeable, the cost of the regeneration plants has so far rendered the technology uncompetitive.

Cost Analysis

In 1998, Bechtel prepared an analysis[2] for EPRI on the cost of the Electric Fuel system.

Bechtel estimated that the cost of constructing a regeneration plant with a capacity of 11,250kg of Zinc per hour would be about US$100 million. This size of plant would regenerate enough modules for about 240 million vehicle miles to be driven each year by passenger cars or light

1. US 5,441,820 Electrically Recharged Battery Employing a Packed/ Spouted Bed Metal Particle Electrode, 1995.

2. “Evaluation of EFL Zinc-Air Battery System Recharging”, EPRI TR-100000 WO 8837-01, Bechtel National Inc., WJ Stolte, PW Krag.

vehicles in the USA, based on an electricity consumption of 0.33kWh/ mile.

The cost of operating the plant in the USA was estimated to be US$31.7M per year, of which the cost of electricity for the electrowinning process, which converts Zinc Oxide back into dendritic Zinc, would be US$8.6M.

This did not include the cost of battery swapping stations or infrastructure. This could be installed at existing petrol service stations but there would still be installation costs.

Bechtel estimated that the plant would regenerate 76GWh of battery discharge capacity per year, which at 3 vehicle miles per kWh is in the same order as our estimate of 240M vehicle miles.

Therefore the US$31.7M annual operating cost translates into 41.7¢ per kWh of net energy discharged by the battery or between 10¢ and 14¢ per vehicle mile.

The cost of electricity was taken to be the US national average industrial sector rate of 4.6¢ per kWh.

Bechtel further estimated that if a very large plant was used (30,000kg of Zn per hour) based in a US location with low electricity costs (2.3¢/ kWh), the regeneration cost could fall to 30¢ per kWh of battery discharge energy.

To this cost of between 30¢ and 41.7¢ per kWh needs to be added the capital costs and profit margin of the operator.

In comparison, US domestic off-peak electricity rates are in the order of 5¢ per kWh. Therefore a rechargeable battery would cost 10% of the cost of an Electric Fuel ZnAir battery to recharge.

On the other hand, the initial manufacturing cost of the ZnAir battery module is very low and would not increase the price of an electric car compared to an IC car. With projected costs of $300 - $400/kWh for LiIon and NiMH technology, a 30kWh EV battery has a very significant cost in the order of $10,000 which is a major barrier to the development of EVs. This compares to about $2,000 for the installed cost of an IC engine. ZnAir battery costs would be comparable to the cost of an IC engine.

At 41.7¢ per kWh of net battery energy and assuming an overall average EV performance of 3 miles per kWh, the cost of regeneration is 14¢/mile.

This is about the same cost as the current average mileage cost of petrol in the USA, where gasoline is now $3/USG and the average fuel economy of the US Light Vehicle Fleet is 20.68 mile per USG.

If the cost of regeneration can be reduced somewhat further, to allow an adequate profit margin, the Electric Fuel ZnAir system is just becoming economic for mass market Light Vehicle use at current US petrol prices. It would probably already be economically justifiable in Europe where petrol prices are much higher. The alternative Zinc anode technology which uses ordinary industrial Zinc instead of dendritic Zinc could remove the need for a special battery regeneration plant and therefore greatly reduce regeneration costs.

Conclusion

Overall, the non-rechargeable ZnAir battery would now have similar life-cycle costs to an IC engined vehicle at current petrol prices: ZnAir would offer a low initial battery "powerplant" cost with relatively high operating costs, while a rechargeable battery has high initial capital costs and low operating costs. As petrol prices continue to increase, ZnAir will become even more competitive.

A rechargeable Zn Air battery that could effectively carry out the "electrowinning" process internally and would only require electricity would be by far the cheapest and most capable EV battery technology of all.

Powerzinc Electric

The Chinese company Powerzinc Electric Inc. are using a non-dendritic Zinc technology (which they obtained from Electric Fuel) on buses and electric scooters in China, in which spent Zinc anode cartridges in each battery are removed and replaced when necessary. This takes 5 minutes on a scooter; 30 minutes for a bus. Powerzinc call their technology the "Dynamic Quick Refuel Cell" and have four module sizes available. They are testing a 57kWh unit weighing 280kg in a car for potential use as an Electric Taxi.

Chinese cities are in the process of banning petrol scooters to improve air quality. Powerzinc have established a partnership with a Chinese scooter manufacturer to develop a dedicated ZnAir model to replace Lead Acid batteries in electric bicycles. Lead Acid batteries have become an environmental problem in China because of their short life. They tend to be discarded rather than returned for recycling, causing environmental damage and leading to proposed restrictions from 2006 on the use of these electric bicycles. The ZnAir battery would answer these concerns, since the bicycle owner must return to a recharge point to replace the anodes and the used anodes are collected for recycling. Zinc is also a much less polluting substance than lead.

Consumption of Zinc for all industrial uses is growing rapidly in China and regeneration of spent anodes would ideally be incorporated into the operations of a general purpose Zinc production plant. This would greatly reduce the cost of regenerating the anodes and avoid the need for construction of dedicated plant. PowerZinc have been in discussions with Zinc refiners and recycling companies. Use of an ordinary Zinc which can be produced in a standard large scale Zinc refinery will probably be the only way to make the ZnAir technology commercially viable in the short to medium term.

Electrically Rechargeable ZnAir

An electrically rechargeable ZnAir battery has not yet been commercialised successfully. The main problem is poor cycle life. Repeated cycling causes the Zn electrode to change shape leading to loss of capacity. In the late 1990s, the US company AER marketed a rechargeable ZnAir battery for laptop computers designed to power them all day. They were too bulky and recharge time was too long.

The Norwegian start-up Revolt Technology claims to have solved the rechargeability and cycle life problem and has recently received funding to develop a range of rechargeable ZnAir batteries for laptop computers and other mobile applications. The specific energy is claimed to be 400-500Wh/kg and 1400Wh/l volumetric. If the cycle life can be proven up to 500 cycles or more, this will be the most powerful enabling technology developed so far for EVs. Revolt say that it can be recharged at the 2C rate which in simplified terms means that it can be fully recharged in 30 minutes. This would be very useful for EVs, although the recharge efficiency is unknown.

Several major battery manufacturers worked on the related technology of Nickel Zinc batteries during the 1990s, but these have lower energy density (70Wh/kg) because of the extra weight of the nickel electrode and development seems to be inactive. Cycle life was about 500 cycles but at high temperature this deteriorated. If the cycle performance of the Zinc anode could be applied to the Zn Air technology, this would be a major step forward.

In 1995, the University of California at Berkeley patented an improvement in the alkali electrolyte to Zinc electrode batteries which allowed about 350 - 400 cycles to be reached before capacity fell to 80%. The electrolyte was a combination of potassium hydroxide, carbonate and fluoride. In our view, it did not seem to be much of an improvement over a KOH/K_2CO_3 electrolyte but 500 cycles for a Zinc electrode may now be achievable.

Conclusion

The cost of a ZnAir battery is potentially so low that even if a cycle life of only 350 cycles could be achieved, it could be commercially viable. This would allow 2 recharges a week for 3 or more years. At the end of that time, the modules could be swapped for a regenerated one against a trade-in price for the old unit. Drivers would trade lower battery life for lower cost.

Zinc Air therefore has two major potential advantages:

1. Low cost
2. High energy density

It has the disadvantage of non-rechargeability, which up to now has made the technology economically unattractive. This is changing as the price of oil increases and the ZnAir technology switches to ordinary industrial zinc, which can be regenerated in a standard zinc refinery.

For large fleet operators, such as national Post Offices or Utilities, city transit authorities etc., the Zinc Air technology could now be adopted as an effective and economic means of motive power.

7.8 Lithium Sulphur

There has been interest in the Lithium Sulphur battery since the 1960s because of its potentially high energy density. Rechargeable Lithium Sulphur (LiS) batteries have only started to become a commercial possibility since the late 1980s, although like most battery technologies the basic electrochemical theory has been known for decades and LiS primary batteries have been available since the 1970s. The LiS secondary battery is related to the well known Lithium Thionyl Chloride or Lithium Sulphur Dioxide primary battery. These non-rechargeable batteries have a specific energy density of 400-600 Wh/kg. The LiS rechargeable battery has demonstrated 400 Wh/kg at the cell level. LiS currently has the highest specific energy density of all the rechargeable batteries on the market.

The leading company in this area is Sion Power Corp. of the USA. The small UK company Intellikraft Ltd., now Oxis Energy, are also working actively on the technology. US Nanocorp was undertaking development work on a solid electrolyte for LiS batteries but this work has stopped. Another company, Polyplus Battery Corp. is a spin off from Berkeley University. It was very active in LiS development from 1990 to 2004 and holds over 20 patents in this field but switched its focus to a different secondary battery technology in 2004. Samsung, Ness and LG Chem of Korea were also working recently on the LiS technology. Some research is also being conducted in Japan, particularly into glass ionic conducting electrolytes for the LiS system.

Lithium Sulphur Development and Chemistry

The Lithium Sulphur battery has been researched since the 1960s but did not find use as a primary battery until the 1990s. In 1977, a rechargeable Li-S battery was reported with 120 cycles but only 5% utilisation of the sulphur in the cathode. The theoretical charge density of Sulphur is 1675mAh/g, so this was only 85mAh/g of the sulphur present. In 1989, another group reported 50 cycles but only obtained 25% sulphur utilisation. Since that time, steady research has led to significant performance improvements.

The Lithium Sulphur battery is comprised of an electrochemical couple between Lithium and Sulphur. The Sulphur can take the form of elemental sulphur, organo-sulphur, an inorganic sulphide or an organic polysulphide compound.

When the battery is charged, Lithium Sulphide and Lithium Polysulphide species in the cathode are oxidised and Lithium ions are released into the electrolyte. The Li^+ ions migrate back to the Lithium metal anode where they combine with the charging electrons to redeposit Li metal.

These Lithium Sulphide species are of the form Li_2S_x where $x \geq 1$. Over time, the charging process produces polysulphide species with longer and longer sulphur chains. In a normal charging reaction, x can reach

12 or more and some of the polysulphides in the cathode will even be oxidised into elemental sulphur.

On discharge, the sulphur atoms in the cathode pull electrons towards themselves through the load and Li+ ions migrate to the cathode through the electrolyte, to reform lithium sulphide and short chain polysulphides. Long chain polysulphides in the cathode are reduced to shorter chain polysulphides and lithium sulphide itself.

High molecular weight polysulphides (with more S atoms) are more highly soluble than low molecular weight (MW) polysulphides. During discharge, some of the high MW polysulphides therefore dissolve into the electrolyte and some of them move to the Lithium anode. Here they react with the lithium to form a thin beneficial protective layer of Lithium Sulphide on the Lithium metal anode. This helps to stabilise the anode and improve cycle life. However, if excess Lithium Sulphide is formed, it may precipitate out of solution and will serve no beneficial purpose at all. In fact, this precipitated Li_2S represents Lithium and Sulphur that is no longer electrochemically available and the capacity of the battery will fall.

Some of the Polysulphides may also precipitate if the local solution concentration exceeds the solubility limit for that polysulphide. This can happen if the local current density in the cathode is too high on discharge: polysulphides may be formed faster than they can diffuse away and will therefore precipitate out of solution. Therefore the higher the discharge rate - the higher the capacity loss.

Performance can be improved by use of an electrolyte that helps to keep Li_2S and relatively low MW polysulphides in solution and therefore available for further electrochemical reactions.

However, by using electrolytes that dissolve the sulphide discharge products, “self discharge” becomes an issue. Because the cathode discharge products (lithium polysulphides) are now quite soluble in the enhanced solubility electrolyte, they will automatically dissolve from the cathode into the electrolyte and migrate to the lithium metal anode, discharging the cell but giving no useful current. Here, they are reduced to lower MW polysulphides and relatively insoluble Li_2S - again, insoluble products can be formed which reduce the amount of electrochemically available lithium and sulphur and the capacity of the cell falls. The initial protective layer of Lithium (poly)Sulphide on the anode helps to reduce this but is not sufficient by itself to prevent further polysulphide attack on the anode and corrosion of the Lithium metal.

One way to reduce this self discharge and polysulphide attack is to therefore coat the anode with a more effective protective layer that will stop these dissolved polysulphides from reaching the anode, but will permit Lithium ions to pass. Substances that will do this include LiPON, single ion conducting glasses and ionically conducting polymers. This kinetic-molecular approach has been the main method used to date.

The other way to reduce the corrosion of the anode is to balance the thermodynamics of these two competing processes - dissolution and precipitation of polysulphides. This has not been straightforward to achieve but significant improvements are now also being made with this approach.

On repeated cycling, the Lithium metal anode will also grow dendrites or become “mossy” or spongy. The LiTFSI electrolyte used in LiS batteries helps to reduce this. Protective layers can help to reduce this as well, such as LiPON. In one patent, PolyPlus recommended the use of poly (1-trimethylsilyl-1-propyne) (PTMSP) but abandoned this for LiPON. Polymers are probably too soft to resist the growth of metallic dendrites from the surface of the lithium. (Shear modulus in the gigapascal region is required to resist dendritic growth).

There are therefore some significant issues due to the inherent electrochemistry of the Lithium - Sulphur cell.

An effective, highly ionic conducting protective material which can be laid down over a sufficiently large surface area in mass production would be highly attractive. This would solve the problem of both the dendritic growth and polysulphide attack and potentially open the way for high cycle life high energy density LiS batteries to be developed successfully.

US Developments

In 2004, Sion Power stated[1] that their high specific energy density 330Wh/kg LiS cell had a cycle life of 100 cycles. In the same paper, they showed a 270Wh/kg cell obtaining 200 cycles to 80% final capacity. Their lower energy 150-160Wh/kg cells had a cycle life of about 400 cycles.

Sion have recently stated that they have improved to over 400 cycles with a 100% DoD for a 250 - 300Wh/kg cell. This would be a major improvement.

Sion’s US Patent 6,210,831 shows[2] a high energy density cell starting with a sulphur utilisation of 900mAh/g. At 100 cycles, this has fallen to 700mAh/g.

In another patent[3], Sion achieved 120 cycles to 80% of initial capacity with a Lithium Sulphur cell. The cathode active material is comprised of 70% elemental sulphur, 10% graphite, 15% conducting carbon, and 5% of organic polymers. The cathode material is coated in a layer 2 microns

1. “Lithium Sulphur Rechargeable Batteries: Characteristics, State of Development and Applicability to Powering Portable Electronics”, Tudron, Akridge, Puglisi, Sion Power Corp., PowerSources 2004.
2. US 6,230,831
3. US 6,566,006

thick onto an 18 micron current collector. The anode is 50 micron thick Lithium metal film. The electrolyte is lithium trifluoro methyl sulphonylimide (LiTFSI) dissolved in a mixture of 1.3 dioxolane / dimethoxyethane incorporated into a 16 micron thick polyolefin separator. Total cell thickness is therefore about 90 microns.

The initial charge density of the complete cathode active material (70% sulphur) was about 800mAh/g, falling to 640mAh/g (80%) after 120 cycles and down to 500mAh/g (62%) after 180 cycles.

These are significant improvements over previous achievements for high specific energy LiS cells. This should certainly enable their use in weight critical high performance niche applications.

LiTFSI is also used in Avestor's LiMP battery, incorporated into a PEO gel. Imide salts have relatively high price but the lithium bis oxalatoborate (LiBOB) electrolyte undergoing widespread research forms a very stable SEI film on lithium metal anodes and might be a good replacement, as long as the LiS electrochemistry is not disturbed.

The Polyplus and Sion technologies are very similar. Both companies use lithium metal anodes, elemental sulphur in a polymer/ conducting carbon binder as the cathode, with the electrolyte comprised of LiTFSI dissolved in an organic solvent infused into a microporous separator.

Polyplus (in US patent 6,358,643) achieved 600 cycles with no noticeable degradation in output voltage for an LiS cell but this was with a sulphur utilisation of only 11% or 180mAh/g of sulphur. Since elemental sulphur only comprised 50% of the material in the cathode, the effective cathode charge density was only 90mAh/g, well below the 160mAh/g of $LiCoO_2$ in LiIon batteries. Polyplus did not show what change had taken place in the Ah capacity of the cell.

At 40% sulphur utilisation (670mAh/g of sulphur) cycle life was down to 70 cycles and at 60% utilisation (1000mAh/g), down to 35 cycles.

Sion's achievement of 120 cycles for an initial 800mAh/g of cathode material (70% of which is elemental sulphur, therefore a charge density of 1140mAh/g of sulphur) is therefore a significant improvement over the Polyplus performance.

Sion Power demonstrated their battery with a notebook computer at the WinHEC computer exhibition in 2004. Sion's LiS battery technology is now in use for military UAV (Unmanned Aerial Vehicle) applications, where the low weight is critical and the limited cycle life is not a disadvantage. The UK defence research agency QinetiQ is testing Sion's LiS batteries in UAVs.

If Sion's latest cycle life of over 400 cycles to 100% DoD for a 250 - 300Wh/kg cell can be scaled up to a large format battery comprised of 45 - 100Ah cells, the technology could become a powerful future contender for EVs. The cathode material of the LiS cell is very low cost and Lithium Sulphur batteries should be significantly cheaper (30-40%

less) than current LiIon batteries. The control circuits are also simpler and cheaper. With a cycle life of 400 - 500 cycles, the battery could be replaced after 5 years during scheduled maintenance. The commercial viability of this would of course depend on the cost of replacement. Battery leasing or other such options have been proposed to make this transparent to the end user.

Sion Power will start large scale manufacture of LiS batteries in 2007. They will become one of the largest volume producers of lithium secondary batteries in North America. This is a very positive step and is a strong indicator of the maturity now being reached by LiS technology.

UK Developments

The small UK company Oxis Energy (formerly Intellikraft) have developed what they call a “Lithium Sulphide” development of the Lithium Sulphur battery technology. Details have not yet been published on the anode and electrolyte technology used, but it appears that the anode is not composed purely of metallic lithium. A combination of lithium, lithium sulphide and an intercalation matrix seems to be the general approach, along with an electrolyte that promotes formation of a more stable SEI film. This would be an improvement to safety. Oxis claim their technology provides between 300 and 500 deep discharge cycles. Energy density is put at 300Wh/kg at the cell level or 240Wh/kg at the battery level.

Oxis say their chemistry improves the passivation of the Lithium anode, leading to improved cycle life, safety and discharge rate. Oxis also state that the cell capacity is rated at the C/2 discharge rate. Substantive details have not yet been published.

Oxis Energy have a close relationship with Manganese Bronze Holdings, the manufacturer of the famous London Black Taxi. Manganese Bronze are actively developing hybrid versions of the “Black Cab” with the Canadian electric drivetrain specialist Azure Dynamics.

Oxis have filed US and UK patents on their technology.

Safety

The metallic lithium anode in the LiS battery could be perceived to be a significant safety barrier to the automotive large format application. While Lithium metal anodes may be acceptable for very small batteries, in the present safety environment it may have difficulty in being accepted in the high absolute quantities required for a large format multi-kilowatt hour battery. (See “Safety Incidents” on page 88.)

However, the Lithium Sulphur electrochemistry is significantly different to Lithium Ion or Lithium Metal Polymer chemistry. The active material in the cathode is sulphur which is not a strong oxidising agent and will not catalyse thermal runaway. When exposed to the electrolyte, lithium metal will react with the polysulphides to form an inert surface layer, preventing further reactions. Dendritic growth is not as significant a problem, since the dendrites will tend to turn into lithium sulphide, reducing the danger of a short circuit.

The LiS chemistry is inherently resistant to overcharge for the same reason. The same mechanism that causes self discharge - dissolution of high MW polysulphides from the cathode into the electrolyte and then migration to the anode - also prevents overcharging. Cells can be discharged to 100% DOD, so overdischarge is not an issue either.

The LiTFSI imide salt used in the LiS battery also has higher thermal stability than the $LiPF_6$ used in LiIon cells.

The Lithium Sulphur/ Sulphide battery is therefore significantly safer than Lithium Metal Polymer and $LiCoO_2$ LiIon batteries.

General Issues

Research has been carried out to replace the Lithium metal anode with a graphite intercalation anode, to create a Lithium Ion Sulphur cell. Some researchers believe that this would reduce the voltage of the 2.1V LiS cell too far. The voltage loss would in fact not be very great. More significant is the fact that the polysulphides in solution will still attack the Lithium ions in the graphite structure. It is far more difficult to put a thin lithium ion conducting protective layer on a rough particulate surface such as graphite than onto a smooth metal surface. Single ion conducting polymer electrolytes are not sufficiently developed to replace salt containing liquid or gel electrolytes. New electrolytes that form more stable SEI films on both graphite and lithium metal anodes (such as LiBOB) may solve this problem, if they are compatible with Lithium Sulphide solubility. Other anode materials under development (silicon/ tin composites, intermetallics) may also provide a solution.

Attempts to use organic polysulphide polymers instead of elemental sulphur to anchor the sulphur into the cathode have apparently not been successful. Sulphur mobility is required and without that mobility, the rate of battery charge and discharge diminishes unacceptably.

The volumetric energy density of LiS is similar to that of LiIon. Therefore a LiS battery of the same energy as a LiIon battery currently takes up about the same volume for half the weight. LiS is therefore particularly suited to weight critical applications such as aerospace at the moment, but volumetric energy density can still be improved.

Conclusion

Before any car manufacturer adopted LiS technology, they would of course subject it to several years of exhaustive real-world testing. Any completely new battery technology will also have to compete against the existing technologies which have already seen extensive testing in road vehicles for over 10 years and on which development is ongoing. Therefore it would be unrealistic to expect to see Lithium Sulphur/ Sulphide powered vehicles on the road in the immediate future.

Over the next few years, the prospects of Lithium Sulphur technology becoming sufficiently mature for HEV, EV or PHEV use are promising. Sion Power and Oxis Energy appear to be making significant strides in improving the performance of LiS chemistry. LiS batteries may appear first in military vehicle applications where performance is the primary factor. This would allow production volume to be built up and costs to be reduced for the civilian market. Tests of LiS batteries for EV applications may commence in 2008.

The combination of improved safety compared to LiMP, very high energy density, overcharge resistance and simplified battery management and control systems could make Lithium Sulphur/ Sulphide a powerful competitor against LiIon and other battery technologies in the EV market.

Lithium Sulphur also represents a very significant improvement for the rapidly growing Unmanned Aerial Vehicle (UAV) market, where aircraft utilisation is low compared to a surface road vehicle. For the UAV application, a cell energy density of 350Wh/kg is twice that available from LiIon. This weight reduction translates directly into increased payload or increased mission duration. For weight critical high-performance applications, LiS is now sufficiently mature to compete with primary Lithium Sulphur Dioxide and Lithium Thionyl Chloride batteries.

The power capability of LiS is also very good and the technology could be used in power tools.

One key to further improving the Lithium Sulphur battery is more effective protection of the Lithium metal anode with a material that has high single ion conductivity. This is an area of intensive research and will be of benefit in many areas of technology. Large surface areas of lithium ion conducting glass (or polymer) are now being manufactured for electrochromic windows. Lithium Niobium Oxynitride is one material in use, with a conductivity of 10^{-5} S/cm at room temperature. This is too low for a battery but the fabrication and manufacturing techniques may be able to be adopted for higher conductivity glasses for batteries.

7.9 Lithium Air

In 2004, the US company Polyplus Battery Corp. abandoned LiS technology in favour of the Lithium Air or Lithium Water battery. This operates on the same principle as the ZnAir and AlAir battery but uses Lithium metal instead of Zinc.

Polyplus have achieved an energy density of over 1000Wh/kg in a small test cell. The theoretical energy density is 11 times that, so there is room for further improvement. Their technology may also allow electrical recharging of the battery. Otherwise, like the ZnAir fuel cell, the spent Lithium anode will be replaced and regenerated for subsequent reuse.

At 1000Wh/kg, a 100kWh battery that would give a car a range of 500 miles would weigh only 100kgs and take up only 100 litres of space (0.1m^3). However, again it is very unlikely that a large format Lithium-Air fuel cell would ever be allowed in a motor vehicle for safety reasons. The technology is already being evaluated by the US military and is likely to be restricted for use in specialist military or other niche applications.

7.10 The Aluminium (Air) Battery

Aluminium is the third most abundant element after oxygen and silicon in the Earth's crust. There would therefore be no shortage of raw material for large scale manufacture of an Aluminium based battery.

The history of Aluminium Air batteries is similar to that of Zinc Air. The principle of operation is identical. Instead of Zinc, Aluminium metal is oxidised by oxygen in the atmosphere and electricity is generated in the process.

During the 1960s, a non-rechargeable AlAir metal fuel cell was developed by Philco in the USA with an energy density of 500Wh/kg. During the 1990s, at least 10 organisations were researching this technology for EV applications. The company that achieved the most was Aluminum Power Inc. or Alupower, originally set up by Alcan in Canada. They developed a seawater version with Marconi to power submersibles. In 2000 Alupower demonstrated an 800Wh/kg primary cell for mobile phones. Like the Powerzinc technology, the battery was not electrically rechargeable but used a replaceable slot in cartridge to replace the spent Aluminium anode. An 80kWh EV battery could potentially weigh as little as 100kg and could use a rack of slot in cartridges for refuelling. However, Alupower have now abandoned this technology.

Latest Research

The latest development is from Finland. The start-up company Ab Europositron OY have filed patents on an electrically rechargeable aluminium battery technology that claims a specific energy density of

1330Wh/kg, volumetric density of 2100Wh/l and a cycle life of over 3000 cycles. If this can be scaled up to a large format EV battery, an 80kWh battery would weigh only 60kg and occupy only 38 litres. However, this technology is currently only at the laboratory testing stage and hard data is not available.

The major drawback of the Aluminium Air battery is the large amount of electrical energy required to reduce aluminium oxide back to aluminium. This is why AlAir has high energy density in the first place (the high electronegativity of Aluminium) but the efficiency of conversion in a commercial aluminium refinery is an issue. In the Hall-Héroult cell, 15kWh of electricity are required to manufacture 1kg of aluminium. Aluminium refineries are located near cheap plentiful sources of electricity such as hydroelectric powerplants.

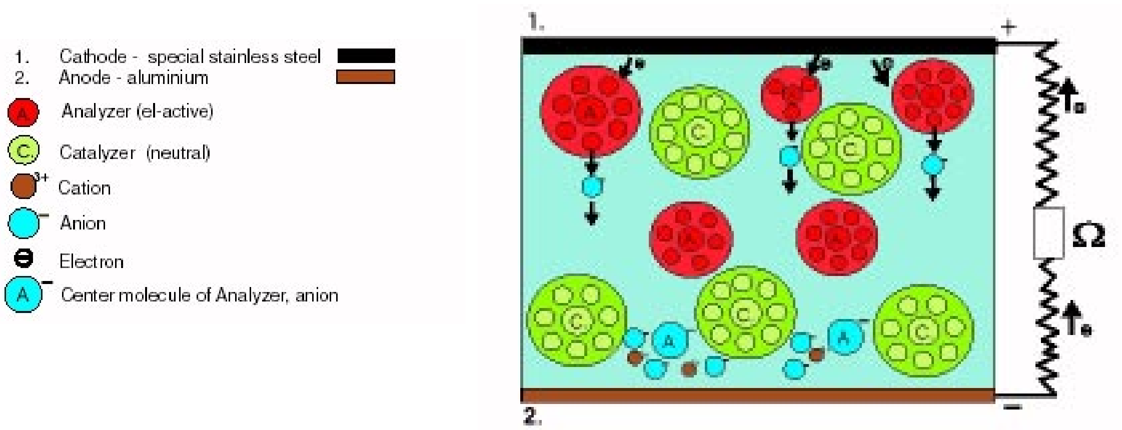
There is therefore a major energy imbalance. 15kWh of electricity are required to produce 1kg of aluminium. In all AlAir mechanically rechargeable batteries to date, at best only 0.8kWh of electricity can be obtained per kilogram of entire battery weight, let alone from 1kg of aluminium in the battery. The efficiency of recharging an AlAir battery is therefore well below 5% and the AlAir concept is completely unworkable in practice for any type of mass market application.

Europositron claim that they have found a way to overcome this barrier. If true, this would have major implications as well for aluminium manufacture, which they recognise.

The Europositron battery is not an Aluminium Air technology. The anode is aluminium and the cathode is made of a stainless steel (probably doped in an undisclosed way). The mode of operation put forward by the inventor, Rainer Partanen, is described below.

The electrolyte contains a catalyst and another electroactive component which Partanen calls an “analyser” (as opposed to the catalyser).

FIGURE 41 **AB EUROPOSITRON OY - BATTERY DISCHARGE**



On discharge, Al^{3+} cations enter solution and electrons travel from the anode to the cathode. At the cathode, electrons are accepted by molecules of the analyser in solution and anions associated with the "analyser" are released into solution. The analyser's anions and the Al^{3+} cations combine to form an aluminium complex in solution. The process is catalysed by the catalyst.

On recharge, the reverse process takes place: Aluminium is deposited on the anode and the analyser regains the anions it lost on discharge.

The central "analyser" atom is not affected by the reaction but acts as a source of anions. The analyser is evidently a Lewis Acid that accepts electrons from the cathode: an aluminium chloride or a metal tetrachloro aluminate complex is a possibility.

The key to the validity of this concept lies in the catalyst, on which no information has been disclosed.

Conclusion

The Aluminium Air battery is impossible to use for mass market applications - either consumer electronics or EVs. The energy imbalance is far too great.

The only possibility would lie in a catalysed process that reduces the energy required to reduce aluminium ions back to aluminium metal.

If the Partanen invention has achieved this, then it represents a major breakthrough in inorganic chemistry.

7.11 Conclusion

Today, the only purpose designed EV battery available off the shelf is the Sodium Nickel Chloride "Zebra" battery. This battery has good performance and a low cost of $220/kWh in medium volume that could potentially fall to $100 - 150/kWhh. Practical, reliable and cost effective EVs could be put into production today using this technology, certainly for urban use. The 1998 Mercedes Electric A Class with a range of 120 miles would be a good model. Today, a 180 mile version of this vehicle could be produced with the latest Zebra technology.

Lithium Ion has the advantage of a major manufacturing industry and major R&D effort behind it. For cost and safety reasons, only manganese or iron phosphate based LiIon technology will be suitable for EV applications. Fast recharge times could make LiIon psychologically attractive if it becomes feasible to recharge an EV in a matter of minutes, not hours. It appears that this may become possible and is a point in favour of LiIon technology, though doing this is less efficient than slow charging and an infrastructure of special high power recharging points would need to be established. (Special high power recharging infrastructure would be needed for fast recharge of any battery technology, not just LiIon). Energy density of LiIon is increasing all the time and vehicles with a range of over 200 miles could now be produced with this technology. However, cost, safety and the need to greatly increase lithium production are significant issues. Valence Technology say their “low cost” phosphate system would cost $450/kWh in volume which is still too high. SAFT are aiming for $300/kWh. At that price, LiIon battery powered EVs would have life cycle costs lower than IC vehicles. For PHEV application however, fast recharge is not necessary, nor is the energy density of LiIon required.

NiMH is the best established automotive battery technology. It has already demonstrated that it can reach a lifetime mileage of 130,000 - 150,000 miles. Therefore only one battery pack will be needed for the life of a vehicle rather than two as originally envisaged. It would be very straightforward for the manufacturers of existing HEV0 battery packs to modify their production to higher energy versions and larger capacity sizes to enable PHEV20 - 60 vehicles in the near future. The required increase in nickel production to meet future demand for NiMH and NaNiCl batteries would be a fraction of existing nickel production - whereas lithium production will have to be expanded by a factor of 10. The main drawback at the moment is cost but the rapid penetration of NiMH into the consumer battery market will help to reduce this.

Zinc Air technology is potentially an interesting option. It has two strong features - very high energy density and very low cost. It is also environmentally very benign and safe. If large format electrically rechargeable versions can be produced it could make electric cars very affordable with the same range as petrol cars. Operators of Heavy Vehicle Fleets could in any case increasingly cost justify conversion to the existing mechanically rechargeable ZnAir Fuel Cell technology.

Lithium Sulphur now appears to be making promising developments. It has greater safety and lower cost than LiMP and much better energy density than any other secondary battery available at the moment. It will be interesting to see the results of real-world vehicle tests, which could commence in 2008.

The conventional Aluminium Air technology is totally unsuitable for EV use. It remains to be seen whether the claims that an efficient electrically rechargeable technology has been developed can be proven. Even if they are, it will take some years for the technology to reach the market.

TABLE 18 **MAIN EV BATTERY CHOICES - SUMMARY**

Battery Type	Specific Energy	Cost	Maturity	Ruggedness Safety	Ease of Use
Zebra	120Wh'kg	V. Good	Good	Good	Fair
Zinc Air	220Wh/kg	Fair	Ongoing	Good	Non rechargeable
LiIon	110Wh/kg	Expensive	Ongoing	Fair	Good
NiMH	60-80Wh/kg	Expensive	Good	Good	Good

This overview of Battery Technology has shown that the technologies exist to permit the immediate production of practical Battery EVs and PHEVs that can provide Sustainable Mobility in a world where oil is becoming scarcer and is too valuable to waste as fuel.

There is no need for the automotive industry to settle on one technology before introducing EVs and PHEVs. Indeed, given the need to convert as much road transport to electric propulsion as possible and the rapid pace of battery development, it makes more sense to introduce several of these battery technologies - certainly NiMH and NaNiCl, along with ZnAir for heavy vehicle fleets and LiIon when its safety has been proven. If certain resources (e.g. nickel or lithium) become constrained, then production of other battery types can be prioritised. We do not want to put all our eggs in one basket as has been done with oil.

It would also be possible at some point to design motor vehicles with a “Universal Connector” to allow the upgrading of the battery as technology develops. This would be a programmable voltage/current power converter to allow different battery types to be used in the vehicle. As improved batteries are developed or if a driver wishes to change battery types for some reasons, quick change universal electrical connectors can be used to allow the battery to be swapped. This will also allow flexibility and competition in battery markets: it would be possible to offer new vehicles for sale with different battery sizes or types and the driver could upgrade later as desired.

8 Fuel Cell Electric Vehicles

8.1 Introduction

The FCV is an Electric Vehicle powered by a fuel cell instead of a battery or IC genset. The Fuel Cell converts hydrogen into electricity, which in turn drives an electric motor to propel the vehicle.

This chapter discusses the technical and economic features of both Hydrogen as a potential fuel and the Fuel Cell as a means of converting it to motive power.

The technology currently has serious drawbacks in practically all areas.

8.2 Hydrogen

There are a number of major issues with the widespread adoption of hydrogen as a fuel - either in fuel cells or as a combustion fuel in a modified Internal Combustion engine.

The main ones are:

- Energy Density and Storage Volume
- Safety
- Energy Efficiency and Cost of Production
- Distribution

Energy Density

At room temperature and pressure, hydrogen occupies 3000 times the volume of petrol containing the equivalent amount of energy.

To store sufficient hydrogen in a vehicle, it will either have to be stored as Liquid Hydrogen or Compressed Gas Hydrogen.

The energy required to liquefy hydrogen is enormous. Because the boiling point is so low, some 40% of the energy content of H_2 is required to liquefy it. This renders it impractical as a mass market fuel.

The energy required to compress hydrogen sufficiently is about 10% of its energy content. Compressed gas hydrogen is used in all of the prototype hydrogen FCVs today. It is stored at 5,000 psi or even 10,000 psi, about 700 times atmospheric pressure. Even at 10,000 psi, the tank would take up 4 times the volume of a comparable petrol tank to give the vehicle equivalent range.

Safety

The safety issues involved with millions of road vehicles containing tanks of hydrogen pressurised to 10,000 psi, in either an FCV or hydrogen ICV, are insurmountable. The risks of a catastrophic explosion and fireball in a crash are self evident.

The hydrogen economy is a complete non-starter for this reason alone.

When one considers the strict safety regulations that are imposed for the transport of hazardous materials by road today and in particular inflammable substances and pressurised containers, it is a wonder that the idea of the “hydrogen economy” has ever received such attention.

Hydrogen has an ignition energy 20 times lower than petrol. It will also cause many metals to become brittle, including the steel used for storage tanks.

22% of accidents involving hydrogen are caused by undetected leaks, despite the special procedures, training and equipment used in the highly regulated hydrogen industry. As has been noted[1], “with this track record it is difficult to imagine how hydrogen risks can be managed acceptably by the general public when wide scale deployment of the safety precautions would be costly and public compliance impossible to ensure”.

Energy Efficiency and Cost of Production

Hydrogen can be produced in three ways:

- By steam reformation of methane.
- As a by-product of the catalytic cracking of long chain hydrocarbons in an oil refinery.
- By electrolysis of water. Only this option is a long term renewable solution.

Methane

Large scale production of hydrogen from natural gas (methane) will not be viable. US consumption of Natural Gas is currently about 23 trillion cubic feet (tcf) per year. Supply is so tight that prices are at record

1. Testimony of Dr. Joseph Romm, Former Acting Assistant Secretary of Energy to the House Science Committee Hearing “Reviewing the Hydrogen Fuel and FreedomCAR Initiatives”, March 3rd, 2004.

levels. To replace 40% of US ground transportation fuel with hydrogen would require an additional 10 tcf of methane to produce the hydrogen.

This will not be possible.

Electrolysis

Depending on the design and efficiency of the electrolyser, it takes 55kWh to 72kWh of electricity to produce one kilogram of hydrogen gas by electrolysis of water.

Assuming that 1kg of hydrogen was put directly into a Fuel Cell Vehicle, it would give the car a range of about 60 miles.

The same amount of electricity, put into the battery of a BEV, would give the car a range of over 160 miles at least.

From the perspective of CO_2 emissions, the electricity required to electrolyse sufficient water to produce 1kg of hydrogen will release 70lbs of CO_2. Burning of 1 gallon of petrol (the energy equivalent) releases 20lbs.

Therefore, only electricity from renewable non-CO_2 emitting sources makes sense for production of hydrogen. But as shown above and will be shown in more detail below, it is far more efficient to use the electricity to power Battery or Plug In Hybrid vehicles than to use it to produce hydrogen.

Distribution

According to British Petroleum, "if hydrogen is going to make it in the mass market as a transportation fuel, it has to be available in 30% to 50% of the retail network from the day the first mass manufactured cars hit the showrooms".

Argonne National Laboratory estimate that the hydrogen delivery infrastructure to serve 40% of the US Light Vehicle Fleet would cost over $500 billion. This investment would be required before the vehicles were marketed.

To transport the hydrogen, either a pipeline infrastructure will have to be built or tanker deliveries made to refuelling stations.

In the USA, pipeline costs are estimated to be $1 million per mile. The locations and technologies that will be used to generate the hydrogen are currently unknown. Only renewable electricity sources make any sense. For this to work, a complete government plan would be required to build renewable electricity power stations near water sources and install the parallel distribution infrastructure. Market forces clearly cannot plan or undertake such uncertain projects equivalent to the complete transformation of a continent's energy infrastructure, either in Europe, the USA or any other industrialised nation.

Transportation of liquid hydrogen by tanker is impractical for reasons already discussed.

Transportation of compressed hydrogen gas by tanker is expensive due to the low energy density of hydrogen. A 40 ton truck might deliver only 400kg of hydrogen to a vehicle refuelling station. A study by ABB in 2003 found that for a delivery distance of 300 miles, the delivery energy approaches 40% of the useable energy in the hydrogen delivered.

In Europe, the losses in delivery would be much lower but are still significant: 10% for tanker delivery of gaseous hydrogen.

Production of H_2 locally at the refuelling stations, to avoid these distribution problems, is also problematic. The energy required to do it by electrolysis of water is still excessive and even less efficient than in large central facilities. Reformation of methane is the current approach: this is not renewable and natural gas supply and demand is already stretched. There is little spare natural gas available to replace petrol.

The investment required in the USA alone to set up hydrogen reformation plants at refuelling stations would be in the order of $600 billion, with no certainty that future competing technologies will not render the investment obsolete.

8.3 The Fuel Cell Vehicle (FCV)

There are two types of FCV:

- Stored Hydrogen FCVs
- Hydrocarbon Fuel Powered FCVs

The problem of insufficient hydrogen storage and therefore poor vehicle range has not been solved despite decades of research. The hydrogen must be stored on-board the vehicle in either liquid or compressed gas form. Hydride storage has been mooted for decades but is heavy and cannot exceed the density of liquid hydrogen. None of these methods can store enough hydrogen in a small enough volume to give the vehicle a range equivalent to a petrol car. Liquid hydrogen is particularly problematic and has effectively been abandoned.

Hydrogen today is produced from Natural Gas by steam reformation of methane or as a by-product of the catalytic cracking of oil in a refinery. The Fuel Cell Vehicle trials underway at various places around the world do not address this factor: the source of the hydrogen they use is not renewable but from fossil fuel.

The only renewable source of hydrogen is from electrolysis of water. Using electricity to electrolyse water is very energy intensive.

The other solution is to use a hydrocarbon fuel and convert it on-board into hydrogen. Overall, this is less energy efficient and more costly and still does not address the issue of future hydrocarbon fuel availability.

Onboard reformation of methanol as an alternative to petrol is often proposed but where will the methanol come from? Methanol today is produced from oil; bio-methanol production on the scale required is impractical.

World methanol production in 1995 would fuel 31 million FCV cars using methanol, out of the 500 million cars worldwide at the time.

While a petrol powered FCV, which reforms petrol into hydrogen, would be a more fuel efficient use of petrol than the ICE, it would still achieve only about 60mpg. This is inadequate. The Plug In Hybrid (PHEV) can attain more than double this fuel efficiency and is a much cheaper, simpler and lighter technology.

Due to the initial time it takes for the fuel cell to warm up, manufacturers are even considering FCV Hybrids with a battery to operate the car initially. This will add to the cost, weight and complexity.

Efficiency

The range of FCVs is considerably less than that of pure BEVs of the same weight. The 2005 model Honda FCX achieves 62 mpkg (miles per kilogram) of Hydrogen in city driving and 51mpkg on the highway. The vehicle has a maximum range of 200 miles. 1mpkg is equivalent to 1 mpg of petrol.

Methanol or petrol FCVs are less efficient than Hydrogen powered FCVs. They require an onboard reformer to manufacture Hydrogen from the methanol or petrol feedstock - these vehicles are therefore even heavier and less efficient than the pure stored hydrogen FCVs.

The only sustainable source of hydrogen is from water. This consumes electricity for the initial electrolysis of the water, energy to compress or liquify the hydrogen and then energy to transport it to the filling stations.

In the stored hydrogen FCV, the hydrogen has to be stored in either compressed gas or liquid form. 10% - 30% of the energy in the hydrogen is used to do this.

In a completely Renewable Future Scenario, where the electricity to electrolyse water to produce hydrogen is supplied by Wind Farms, a Well to Wheels Analysis shows that the entire process is between 22% and 30% efficient in the case of the FCV.

If instead, electricity generated by Wind Turbines is directly used to recharge the batteries of Battery Electric vehicles, the Wind Farm to Wheels efficiency would be between 66% and 76%.

Table 19 shows the breakdown of the Well to Wheels efficiency calculation, using gaseous hydrogen produced by electrolysis of water as the fuel for an FCV powered vehicle.

TABLE 19 **POWERPLANT TO WHEELS FCV EFFICIENCY**

Process	Loss/ Gain	Cumulative Efficiency
Electrolysis of Water	30%	0.70
Compression of H2	10%	0.63
Distribution of H2 Gas	10%	0.57
Hydrogen Transfer to Vehicle	3%	0.55
Fuel Cell Efficiency	50%	0.28
Parasitic Loss	10%	0.25
Drive Train Loss	10%	0.22
	Total Efficiency: 22%	

Table 20 shows the breakdown of the Well to Wheels efficiency calculation for a Battery Electric Vehicle.

TABLE 20 **POWERPLANT TO WHEELS EV EFFICIENCY**

Process	Loss/ Gain	Cumulative Efficiency
Powerplant to Home Transmission Loss	10%	0.90
Battery Charger Loss	8%	0.83
Internal Battery Losses	20%	0.66
Drive Train Loss	10%	0.60
Regenerative Braking Gain	(10)%	0.66
	Total Efficiency: 66%	

The Battery Electric vehicle is three times as energy efficient as the Hydrogen Fuel Cell Vehicle.

Electricity Requirement

Depending on the design and efficiency of the electrolyser, it takes 55kWh to 72kWh of electricity to produce one kilogram of hydrogen gas.

This then needs to be compressed for transportation and storage. Liquid hydrogen has now been all but completely discounted, due to the extra energy required to liquefy it and the issues of storing and manipulating a cryogenic liquid.

1kg of hydrogen will then be processed at, at best, 50% efficiency by the on board fuel cell, producing at best 16.6 kWh of electricity.

Fuel Cell vehicles cannot use regenerative braking to recover energy - therefore batteries or ultracapacitors have to be added to do this.

Therefore an initial 55 - 72kWh of electricity from the grid produces say 17kWh of electricity in the vehicle. The process is therefore only 24 - 30% efficient. This does not include the energy required to compress the hydrogen and transport it to the filling station or store it at each filling station in high pressure tanks, with their associated safety and cost implications.

By contrast, high speed recharging infrastructure for EVs is relatively simple and low cost. There is no need to transport anything - electricity is already there. High power rechargers have already been developed and can be installed under existing well known tried and tested electrical safety regulations. The technology is mature, well known and simple. Recharging at home overnight minimises the need for a specialised high power charging infrastructure, which can develop over time if required.

The company that developed the battery control system for the EV1, Aerovironment, have developed a 120kW recharger for EVs. A 40kWh battery in a medium sized EV could therefore be theoretically recharged in 20 minutes at the 3C rate.

Weight

Fuel Cell Vehicles (FCVs) are very heavy (e.g. the GM Hy-wire weighs over 4,000 lbs). Other figures estimate that FCVs are on average some 800kg (1760lbs) heavier than an ordinary petrol car. This weight reduces their efficiency: on average, FCVs are only 1.8 times as fuel efficient as the equivalent petrol vehicle.

Methanol and petrol FCVs are even heavier than stored hydrogen types due to the extra weight of the reformer.

Cost

According to Dr. Joseph Romm, the most promising fuel cell for transportation is still the Proton Exchange Membrane (PEM) technology, first developed in the 1960s. The price goal for the Fuel Cell in a car is $30/kW, to bring it in line with the internal combustion engine. The cost of the PEM Fuel Cell is currently 100 times that level.

Toyota have stated that only with much effort will FCVs be brought down to 2 or 3 times the cost of conventional ICE vehicles. The existing Honda FCX prototypes on trial in Tokyo cost 1 million dollars each (direct costs). Honda say that in large production volume, the FCX will sell for $100,000 each.

In March 2005, Mitsubishi Motors abandoned Fuel Cell development and decided to refocus on Battery EVs.

In July 2005, Honda staged a PR exercise to lease its FCX to the first private family in California. The vehicle was leased to them for $500 per month compared to the normal rate of $7300 per month.

In June 2005, Honda’s Fuel Cell Project Director Mr. Yozo Kami said:

‘The fuel cell technology may never be used if no one is able to cut production costs by 2020. It may take another 10 years from now to get the cost of such vehicles to 10 million Yen ($92,000)”.

The world leader in fuel cell technology, Ballard Power Systems, recently published their latest Technology Roadmap in which they hope to finally achieve commercial viability of the Fuel Cell technology by 2010. The aim (in line with the US DOE targets) is to achieve a cost of $45 per kW for the system. This would make the 100kW unit in a typical car cost approximately $4500. This would still be about twice the cost of a typical IC engine (to the car manufacturer).

It is noteworthy that the CEO of Ballard Power Systems, the leading developer of Fuel Cell technology, resigned in October 2005. The CEO was recruited to commercialise the technology, not to oversee R&D. They have also sold their German subsidiary. Ballard admitted they are still not ready to commercialise Fuel Cell technology and are continuing R&D. Ballard’s share price has declined steeply from C$192 in March 2000 to C$5.73 in October 2005.

8.4 Analysis - Prius BEV Concept vs Ford Focus FCV

We looked earlier at an AC Propulsion concept for a Battery Electric version of the Toyota Prius. Removal of the petrol drive system components and replacement of the small NiMH battery with a 34kWh LiIon battery pack, would create a 200 mile range vehicle with a cost and weight comparable to the standard Prius hybrid.

The Ford Focus FCV is a comparable size of vehicle to the Prius. It has the same range of 200 miles as this Prius BEV concept, but weighs 700lbs more and uses 6 times as much electricity to refuel, if its 4kg of hydrogen was produced by electrolysis.

Table 21 compares the two vehicles.

TABLE 21 **ACPROPULSION - FOCUS FCV vs PRIUS BEV**

	Focus FCV	Prius LiIon EV Concept
Range	200 miles	200 miles
Energy Storage	4kg H_2	34kWh LiIon
Kerb Weight	3528 lb	2800 lb
Electrical Energy to Refuel	240kWh	40kWh

8.5 Conclusion

The FCV approach is impractical, uneconomic, unsafe and uncompetitive with either BEV or Hybrid technology.

While a Ford Focus or Honda FCX Fuel Cell vehicle has a range of only 200 miles and costs 3 to 5 times the cost of today's cars, a LiIon pure BEV version of the Toyota Prius with only enough batteries to give it the same 200 mile range would cost about the same as today's Toyota Prius Hybrid. With the Zebra battery in volume it would cost even less. The latest (2005) Mercedes Benz B Class FCV vehicle (equipped with the "F Cell") has a maximum range of only 250 miles.

FCVs use three times as much energy as a BEV, the propulsion system weighs 43% more, takes up 3 times as much volume for the same power output as a BEV and costs 46% more (conservative optimistic assumption) than a BEV propulsion system. Refuelling cost is 3 times as great without including the cost of hundreds of billions of dollars to build a hydrogen infrastructure: the refuelling infrastructure has already been built for EVs[1].

There are certain technologies which claim that on-board resonant pulse electrolysis of water can produce hydrogen much more efficiently than conventional electrolysis. Even if this is the case, this will be a later technology requiring R&D; it will not be suitable for near-term implementation.

1. "Fuel Cell Vehicles: Solution or Shell Game?", S. Eaves and J. Eaves, University of California at Davis, 7th April 2003.

9 Bio Fuels

9.1 Introduction

One way to reduce fossil fuel consumption is to substitute it with biofuel. Rapid global expansion in biofuel production (ethanol, vegetable oil, biodiesel) is an obvious course of action. This approach should certainly be expanded as much as possible.

However, while this may be a good solution in countries like Brazil which are already large users of ethanol, it brings with it its own set of problems for Western industrialised nations - massive use of agricultural land, monocultures, asthma and atmospheric pollution from excessive canola production. The investment in new biofuel production facilities will also be substantial and will take time to implement.

Germany is the world's biggest user of biodiesel, with nearly 400 million litres sold in 2004. This is about 1% of Germany's diesel consumption and requires about 300,000 hectares of canola cultivation. This is 2.5% of Germany's arable land. In 2005, Germany will have to start importing rapeseed oil to meet its biodiesel production targets. European countries do not have enough land to expand biodiesel production beyond 10% of fuel consumption at the utmost. However, the EU Directive which specifies that 5.75% of fuel should be biofuel by 2010 will not be sufficient to offset the forthcoming decline in fossil fuel supplies.

Therefore a better option might be to grow higher yielding oil seed crops such as Jatropha or Palm Oil in the tropics. Jatropha can produce twice as much biodiesel per hectare as canola if well managed and will still produce useful yields on arid, marginal land not suited for food crops. Africa, India and other tropical countries could in future become important biodiesel and liquid fuel suppliers to the rest of the world.

The logistics involved in setting up an entirely new fuel industry on the scale required to make a significant dent in road fuel consumption would be enormous - biofuel cannot achieve this within the next five years though it will play an important role in future for fuelling hybrids or those vehicles which are not converted to or replaced with pure electric power.

Mass conversion of road traffic to biofuels in a crash programme is impractical. However biofuels will make an increasing contribution as time progresses, especially if combined with fuel efficiency augmentation systems. If simultaneously the fuel efficiency of vehicles could be tripled or quadrupled, which can be achieved with Plug In Hybrids, the combination of PHEVs and biofuels would be effective and carbon neutral in the medium term to reduce oil dependence.

9.2 Canola and Soy Biodiesel

Canola (rapeseed) and soya are the preferred feedstocks for biodiesel production in Europe and North America. Yields do not appear to be high enough to be sustainable. If the volume of biofuel required in future is to be produced, much higher yielding plants must be used. Europe in particular does not have the agricultural land area available to greatly expand biodiesel production, both for production of the vegetable oil and production of ethanol for transesterification.

The yield of biodiesel from canola or oil seed rape in Germany is about 1300 litres per hectare. US soybean yields are in the order of 522 litres of soybean oil per hectare. Even though soy does not need nitrogen fertiliser, several studies[1] indicate that biodiesel from soy produces 20-30% less energy than that required to produce it.

This year, Germany will start to import rapeseed oil to meet its biodiesel production targets, while production is still very low in comparison to total fossil fuel consumption. This reduces sustainability and the energy balance, due to the extra energy required to import the vegetable oil.

If the USA was to expand biodiesel production to meet its fuel needs, based on the same yields as in Germany, 39 million hectares of land would have to be planted to supply 10% of US light vehicle petroleum consumption. Out of the ~178M hectares of arable land in the USA, this represents 22%. Such massive use of agricultural land is impractical. The ratio is very similar to Germany, where 1% of Germany's diesel consumption is supplied by 2.5% of the country's arable land.

1. Ethanol Production Using Corn, Switchgrass and Wood: Biodiesel Production Using Soybean and Sunflower. D. pimentel, TW Patzek, Natural Resources Research, Vol. 14, No. 1, March 2005: also references "An Overview of biodiesel and petroleum diesel life cycles", Sheehan J., Camobreco V., Duffield J., Graboski M., Shapouri H., NREL, 1998.

9.3 Jatropha and Palm Oil Biodiesel

Tropical Plant Comparisons

Tropical energy crops generate much higher yields of biofuel than plants cultivated in temperate climates, although cellulosic ethanol might change this.

The table below compares[1] the liquid yield and energetic yield of different tropical biofuel crops.

TABLE 22 **COMPARISON OF TROPICAL BIOFUEL PLANTS**

Botanical Name	Common Name	Metric T/ha	l/ha	kWh/ha
Elaeis guineensis	Oil Palm	18 - 20	3,600 - 4,000	33,900 - 37,700
Jatropha curcas	Jatropha	6 - 8	2,100 - 2,800	19,800 - 26,400
Aleurites fordii	Tung Oil	4 - 6	1,800 - 2,700	17,000 - 25,500
Saccharum officinarum	Sugar Cane	100	6,000	39,000
Ricinus communis	Castor Bean	3 - 5	1,200 - 2,500	11,300 - 24,000
Manihot aculenta	Cassava	29	5,000	32,000

This 1982 estimate for Jatropha yield of 2,100 - 2,800 litres of bio-oil per hectare is in line with current estimates. This would be for a well managed plantation with adequate fertiliser inputs etc. On marginal, arid or waste land, the yield would be 1000 litres at the most.

Palm Oil is potentially even more prolific than Jatropha. Its only drawback is that it takes much longer for the trees to grow to maturity and to produce significant quantities of oil. At 4,000 litres per hectare yield is equal to 25 barrels of vegetable oil.

Sugar cane grown for ethanol can potentially produce the most fuel energy of all the tropical crops.

1. Adapted from Gaydou AM, Menet L, Ravelojaona G and Geneste P, 1982 “Vegetable Energy Sources in Madagascar: ethyl alcohol and oil seeds”, Oleagineux 37(3): 135-141.

Palm Oil and Sugar Cane are therefore the highest yielding tropical biofuel plants. In some cases, palm oil plantations can produce as much as 25 -38 metric tonnes (MT) of palm nut per hectare, with the yield of oil being between 15% and 22%. 20% is the normally used figure, so 1MT of palm nut will produce 200kg (or 200 litres) of palm oil.

In the best case, from plantations in South East Asia, as much as 7,600 litres of palm oil can be produced per hectare. In the worst case, from estates in Africa, as little as 800 litres might be produced.

The palm nut and palm oil industry has been well established since the 19th century and therefore a good foundation already exists on which to expand production for biofuels.

Tung Oil was used in China during the Second World War to replace petrol. It was also successfully blended with petrol. The tree is common in China and is also grown in Florida and the southern USA.

The Castor Bean plant is also a potentially viable energy pant. Yields of the bean range from 900-1000kg/ha under irrigation to 300-400kg/ha if there is insufficient irrigation. Some improved varieties have produced 1300kg/ha and even up to 5000kg/ha. The oil content is 35-55%, so the final yield of oil can be anything between 200 and 2750 litres per ha. The average yield in India is 560kg/ha, which would only produce 300 litres of oil per ha.

Jatropha

The tropical energy plant receiving the most attention is Jatropha. This is because Jatropha is a fairly fast growing, non-food plant that will grow on marginal or arid terrain not suitable for food producing crops. The UK company D1 Oils plc have options to plant 9 million hectares with Jatropha in the tropics.

The likely yield of Jatropha oil from marginal or reclaimed land will be much lower than the 3,000 litres per ha claimed by D1 Oils. For instance, India has some 130Mha of waste land of which 33Mha have been identified as suitable for Jatropha. 20-30% of this 33Mha or 10Mha have now been allocated for planting with Jatropha over the next 10 years.

It is estimated that on this poor quality land, cultivated by small farmers lacking in capital resources, the yield will actually be about 750 - 1000 litres per ha. This is in line with the forecast that 10M tonnes of Jatropha will be produced per year when this 10Mha of land is in production - i.e. 10Gl in total or 1000l/ha. This is equivalent to about 175,000 B/d.

Like other vegetable oils, Jatropha oil can be used directly as a fuel either by itself or blended with conventional diesel, which avoids the need for transesterification and a supply of ethanol.

Other Tropical Plants

There are many other tropical energy crops that have been known for a long time for their bio-fuel potential.

Two of the most interesting of these are:

- *Copaifera langsdorfii* (Diesel Tree)
- *Pittosporum resineferum* (Petroleum Nut)

Diesel Tree

The Diesel Tree is a native of South America. It produces an oleoresin called copaiba which can be tapped like rubber. The resin is rich in hydrocarbons and forms in a network of capillaries underneath the bark. Yield can apparently reach between 30 and 50 litres of oil per tree per annum. At a planting density of 100 trees per acre, yield per hectare would be in the order of 10,000 litres per hectare or 60 barrels of oil.

The tree grows to a height of 30 metres and these yields would be from a mature plantation.

The ability to directly tap the tree for liquid fuel, rather than have to crush seeds, would be a processing and cost advantage.

Petroleum Nut

Petroleum Nut is a native of the Philippines, where it is known as hanga. It is called petroleum nut because of the odour of the fruit's oil.

Estimates of oil yield are difficult to ascertain. Duke's Handbook of Energy Crops quotes one source at 60 litres of oil per tree. Similar or somewhat higher yields to Diesel Tree could be achieved if that is correct. D1 Oils are apparently planting a mixed 10,000 hectare plantation of jatropha, petroleum nut and other oil producing plants in the Philippines.

Conclusion

The yields of vegetable oils from tropical energy crops are potentially substantially higher than from temperate crops. As importantly, developing countries have the land area available to produce these crops and would benefit economically from doing so.

The UNEP estimate that some 2,000 Million hectares of land has been degraded by human activity, 300Mha of it beyond repair. Plants such as Jatropha which will grown on poor quality or marginal land can therefore contribute to both fuel production and land restoration.

However, irrigation issues and the real yield that jatropha will give in arid land with little rainfall remain to be determined. Studies are underway in South Africa to measure Jatropha's water usage and suitability as a fuel crop. While it is undoubtedly good at stabilising soil erosion, it only grows during warm wet weather. The widely varying yields of castor bean quoted above will be indicative of what to expect with Jatropha.

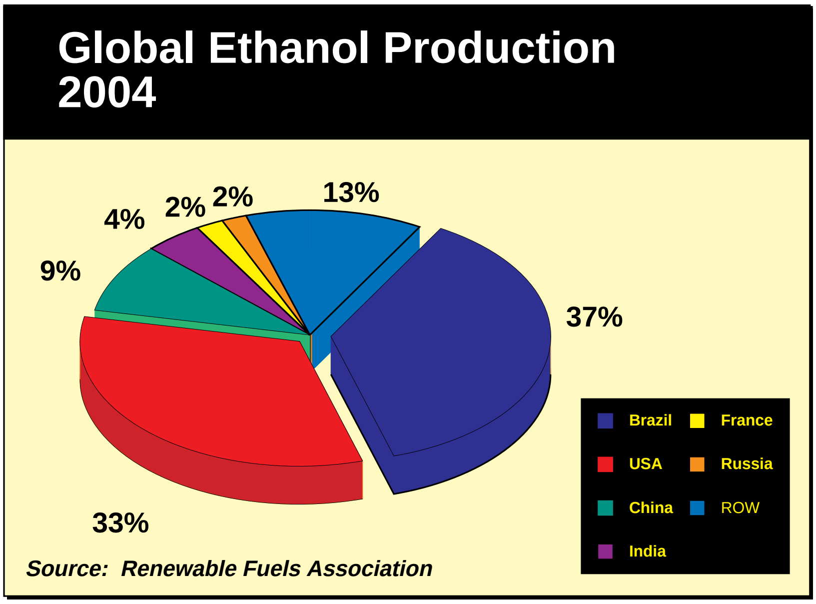
9.4 Ethanol

Global Production

Ethanol is the leading biofuel in production today. Some 10 billion USG of ethanol are now produced each year, compared to about 500M USG of biodiesel. Ethanol is now receiving political support in the USA as a means to reduce dependence on oil imports. The USA is the second largest ethanol producer in the world after Brazil, producing 3,535 million USG in 2004.

Production of ethanol across the globe has increased dramatically since the late 1990s - it has more than doubled from 5,000M USG in 1999 to over 10,000M USG last year.

FIGURE 42



- Global Ethanol production in 2004 was 10,770 million USG.
- Brazil is the largest producer with nearly 4,000 million USG followed by the USA with 3,535 million USG.
- Ethanol capacity in the USA now stands at 4,000 million USG with another 1,100 million USG of capacity under construction.
- 5,000M USG per annum of ethanol is equivalent to 220,000 b/d of gasoline - 2.4% of US Light Vehicle gasoline consumption.

Although ethanol only has two thirds of the energy content of petrol or gasoline, it can be blended directly with petrol and used in unmodified car engines. All new cars in the USA will operate on E85 - a blend of 85% ethanol and 15% petrol. Ethanol production is continuing to expand rapidly across the world. Numerous countries in South America are following Brazil’s lead and intend to make 10% ethanol blended fuel mandatory from 2006 - 2010.

Canada intends to raise ethanol production from 61 million USG to 350 Million USG to allow 35% of fuel to be E10 blended. China has the largest individual ethanol distillery in the world, producing 240M USG per year. E5 (petrol with a 5% ethanol blend) is mandatory in 9 Indian states and 20 new ethanol plants are planned. The largest sugar refinery in India recently announced plans to double its ethanol production. Thailand has mandated an E10 mix from 2007, which will increase production to 400 million USG.

South Africa is planning 8 new ethanol plants, to triple production from 110M to 320M USG.

Europe is currently more focused on biodiesel, due to the high market penetration of diesel vehicles. However, ethanol production in France increased from 23M USG in 2003 to 220M USG in 2004. Another 100M USG will be added by 2008.

Energy Balance

90% of US ethanol is produced from maize or corn. The energy balance of this is generally acknowledged to be marginal. Some estimates calculate that only 1.2 times more energy is obtained from corn produced ethanol in the USA than is consumed in producing it. Other estimates calculate that only 59% of the energy required to produce a gallon of bio-ethanol from corn is returned by the ethanol.

A more recent paper[1] by researchers from Cornell and Berkeley Universities showed that 29% more fossil energy is consumed in producing ethanol from corn than is provided by the ethanol. The paper quotes two panel studies by the USDOE reviewed by 26 scientists which also showed a negative energy return in producing ethanol from corn.

Ethanol production in the USA is currently subsidised by more than 79¢/litre. Pimentel and Patzek estimate that the true cost of producing an equivalent amount of ethanol (1.6 litres) to equal the energy output of a litre of gasoline is $1.88 or $7.12 per USG of gasoline.

Corn production uses more herbicide, pesticide and nitrogen fertiliser than any other crop produced in the USA.

There is therefore growing interest in so-called Cellulosic Ethanol. This process can produce ethanol from woody fibrous bio-material such as straw or wood, rather than the starch in corn or sugar in sugar cane.

1. Ethanol Production Using Corn, Switchgrass and Wood: Biodiesel Production Using Soybean and Sunflower. D. Pimentel, TW Patzek, Natural Resources Research, Vol. 14, No. 1, March 2005.

Cellulosic Ethanol

Cellulose is the main constituent of wood and other fibrous plant matter. Cellulose is made of many glucose molecules in a chain. Glucose can be easily fermented into ethanol but the glucose molecules in cellulose have first to be liberated by a process called hydrolysis. This is carried out by treatment of the cellulose with sulphuric acid. The glucose which is liberated can then be fermented and the ethanol distilled.

This is quite an expensive process. The EIA estimate the cost of producing ethanol from cellulose is $1.15 - $1.43 per USG in 1998 dollars. At the time, this was not competitive as a replacement for gasoline but it probably would be now.

Ethanol has about two thirds the energy density of petrol so 1.5 times as much ethanol is required to deliver the same mileage as petrol, with current inefficient internal combustion engine technology.

A more recent sulphuric acid process called the Countercurrent Hydrolysis process was estimated by the NREL to reduce the cost of production by 33¢/USG and to increase yields.

In recent years, expectations have shifted to Enzymatic Hydrolysis of cellulose as the long term best process. Genetically engineered enzymes are used to break the cellulose down into sugars but glucose is not produced. This process can take place at ambient temperature without expensive chemicals and therefore results in major energy and cost savings. Until recently, the yeasts used to then convert the sugars into ethanol only resulted in low yields and it was not known whether the yeasts would be hardy enough on a commercial basis.

The Canadian biotechnology company Iogen Corp. has pioneered the development of enzymatic hydrolysis and has had a test plant in operation since late 2002. They are now building their first commercial plant. Shell now own 22.5% of Iogen.

Switchgrass

To produce enough cellulose feedstock, cultivation of switchgrass is being proposed as an energy crop. Switchgrass is fast growing and can be harvested in the same year it is planted or the year after; alternatives such as hybrid willow or hybrid poplar take longer. Willow takes 4 years to first harvest and can then be harvested every 3 years. Poplar takes 6 to 10 years to first harvest, depending on location. In the UK, miscanthus has been proposed for the role.

Yield

No large scale production plant for producing cellulosic ethanol has yet been built.

The USDA estimate[1] that switchgrass in the USA will yield about 4,500 litres of ethanol per hectare. Other estimates are slightly lower at 4,000 l/ha. In comparison, corn produces about 2,600 - 3,200l/ha.

In the UK, Iogen estimate[1] that a plant processing 700,000 tonnes of biomass per year would produce some 200 million litres of ethanol. Miscanthus grass has a very high yield of 20 tonnes of biomass per hectare, so 35,000 ha of land would be required to feed this, for a yield of 6,000 litres of ethanol per hectare. This would be energetically equivalent to 25 barrels of petrol.

At 4,000 litres of ethanol per hectare, the petrol equivalent[2] is 15.8 barrels.

To replace 10% of current US petrol consumption (9.1Mb/d), some 20 million ha of switchgrass would have to be planted.

The USA has 178M ha of arable and permanent crop land. In 1988, 35M ha was classified as idle.

If 35Mha of arable land is idle in the USA, there may be enough land available for switchgrass cultivation to make a significant contribution to fuel supply. In theory, a PHEV 80 would only use 10% of the petrol of a conventional car. If all of the light vehicles in the USA were converted to PHEV80s, then perhaps ~1Mb/d of ethanol would provide enough liquid fuel to power all US long distance journeys, with somewhat more frequent refuelling stops due to the lower energy density of alcohol. On the other hand, more fuel efficient IC engines could make an alcohol powered engine as productive as a conventional petrol fuelled engine.

Clearly, significant time and investment will be required to convert the US Light Vehicle fleet to PHEVs and to plant 20 million hectares or more of switchgrass.

Energy Balance

Pimentel and Patzek's paper[3] makes disturbing reading when it comes to switchgrass.

The energy input to grow switchgrass is about 2.7 million kcal per hectare, from which 10 tonnes of switchgrass can be produced. If pelletised for use in fuel stoves, the energy return is about 14:1. This is clearly very energy efficient. A number of Canadian companies are promoting switchgrass pellets as a cost effective and low emissions fuel for domestic space heating.

However, if the switchgrass is converted into ethanol, the energy balance becomes negative. They estimate that ethanol produced from switchgrass will consume 50% more fossil energy than produced by the

1. www.usda.prosser.wsu.edu/commodities/biofuel.htm Accessed 24/10/05

1. Iogen Submission to UK Parliamentary Select Committee on Environment, Food and Rural Affairs, 4th April 2003.

2. Ethanol - Calorific Value per USG: 76,000 BTU. Gasoline - Calorific Value per USG: 120,000 BTU.

3. Ethanol Production Using Corn, Switchgrass and Wood: Biodiesel Production Using Soybean and Sunflower. D. Pimentel etc.

ethanol fuel. The major inputs are for steam and electricity, although this is for acid hydrolysis at elevated temperature. Iogen's Enzymatic Hydrolysis process takes place at ambient temperature, but steam treatment of the switchgrass (or waste straw) is still required before treatment with the hydrolysing enzymes to break open the stalks. This will require significant energy.

TABLE 23 **INPUTS FOR 1000 LITRES OF 99.5% ETHANOL FROM U.S. SWITCHGRASS[a]**

	Qty.	kcal x 10^3	Cost ($)
Switchgrass Cultivation	2,500kg	694	250
Switchgrass Transport	2,500kg	300	15
Water	125,000kg	70	20
Stainless Steel	3kg	45	11
Steel	4kg	46	11
Cement	8kg	15	11
Grind Switchgrass	2,500kg	100	8
Sulphuric Acid	118kg	0	83
Steam	8.1 tonnes	4,404	36
Electricity	660 kWh	1,703	46
92% to 99.5% Ethanol	9kcal/l	9	40
Sewage Treatment	20 kg (BOD)	69	6
Total		**7,455**	**$537**

a. Table 4, "Ethanol Production Using Corn, Switchgrass.", Pimentel and Patzek, 2005

1000 litres of ethanol have a calorific value of 5,130 kcal. The energy input in the above analysis to produce this (at the plant, without the energy cost to tanker it to the petrol blending refineries) is 7,455 kcal.

The above table shows that the energy inputs for steam and electricity are the major requirements. Removal of the incidental energy inputs for the construction and maintenance of the plant and sewage treatment make little difference. No energy input has been shown for the Sulphuric Acid but of course energy is required to manufacture and transport this to the ethanol plant.

Enzymatic hydrolysis may not be much more energy efficient. Sulphuric Acid is replaced with enzymes, but steam treatment replaces grinding and the 8% ethanol broth produced after fermentation still requires the same fractional distillation and removal of 92% residual water. Pure ethanol cannot be distilled from water solution: a final chemical treatment is required to convert 92% ethanol to 99.5% suitable for use as motor fuel or production of biodiesel.

Sugar Cane and Cassava

Sugar cane and cassava are the two main ethanol crops in Brazil.

Cassava will still produce appreciable quantities of starch under moderate drought and is the staple diet in many parts of the world.

In good conditions, Cassava will normally produce 5000l/ha of ethanol. Sugar cane can produce 6000 - 7000 litres of ethanol per hectare. Exceptional yields as high as 14,000 litres per hectare have been achieved with sugar cane in Australia, with appropriate fertilisation and other inputs. Sugar cane is actually the world's largest crop.

Ethanol production in Brazil has remained more or less static since the beginning of the 1990s: in some years it has reached 4 billion USG but in 2000 it fell below 3 billion USG and was only just above that in 2001. In 2004 it had increased back up to 4 billion USG.

Ethanol production is subsidised in Brazil. How yields would be affected if oil derived fertilisers and agri-chemicals were not available or too expensive is not known. Cassava may be a better option because of its drought resistance and ability to serve as a food crop.

It makes more sense to expand ethanol production in the tropics where it can make a valuable contribution to the economies of developing nations and where yields are better, than to use valuable agricultural land in Europe or to a lesser extent, the USA. However, husbandry techniques that do not rely on fossil oil derived chemicals will have to be prioritised in future.

9.5 Conclusion

The yields that can be obtained from tropical biofuel crops - sugar cane, cassava, jatropha, palm oil - are so much higher than can be produced in temperate climates, that biofuel production should be prioritised for those countries which can grow these tropical plants.

The industrialised nations will not be able to grow enough biofuel producing crops to fulfil even a fraction of their energy needs and there are significant questions to be answered concerning the energy balance and viability of doing so.

To produce enough biofuel to make a significant contribution to global fuel requirements, millions of hectares of land will be needed. That land is only available in the developing nations.

The establishment of a major bio-fuel industry in the Third World will facilitate the incorporation of these countries into an integrated global economy and help to improve their standard of living, as long as industrial farming is not allowed to displace independent producers. Sustainable agriculture and the importance of maintaining fuel supply will aid the stability of these countries and give them a more important role in the global economy. A widely distributed fuel supply industry that depends on political and economic stability across these nations will also be less subject to geopolitical events, than with highly concentrated fossil oil production facilities that involve only a relatively small proportion of the population.

There are however some major questions to be answered about the energy balance of producing biofuels. Relatively little research has been carried out to test and analyse the wide variety of energy plants that exist. Even less has been carried out on selective breeding or improvement to increase yields, improve drought tolerance etc.

Ethanol production certainly requires large energy inputs to distil and extract the ethanol after fermentation at the very least.

Yields from tropical oil seed plants will not be high without sufficient irrigation. Plants that produce oil directly without the need to transport and crush seeds may be more advantageous in the long run. The whole field is practically virgin territory waiting to be explored by agronomic science.

These issues with biofuels give added weight to the strategy of prioritising Electric Propulsion and improving Electricity Consumption Energy Efficiency, where the benefits are clear cut.

10 Global Vehicle Markets and Fuel Use

10.1 Introduction

This chapter examines the likely development of the Motor Vehicle Market in the major regions of the world over the next 10 years.

Nearly 50% of global motor vehicle production comes from 3 countries: the USA (20%), Japan (19%) and Germany (12%). Total Global Light Vehicle production in 2004 was 60M units.

In 2003, there were approximately 834 million cars and commercial vehicles on the roads worldwide. According to the 2003 Transportation Energy Data Book, this number was expected to grow by 6% per annum. Vehicle demand was expected to reach 100M units per year by 2020 by which time there were expected to be 1.1 billion light vehicles on the road. This would be a 48% increase over the 754M on the road in 2000. 80M vehicles will be scrapped each year. Cumulative vehicle sales between 2001 and 2020 were expected to be 1.6 billion units.

In 1998, the geographical location of the global automobile fleet was as follows:

North America - 33%; Europe - 30%; Asia - 21.5%; ROW - 15.5%

In 2020, the breakdown will be as follows:

Asia - 27%; North America - 26%; ROW - 47%.

These forecasts are now certain to be modified greatly by rising oil prices. Increasingly, the only vehicles that will be sold will be those that offer the best fuel economy. Sales of existing conventional models will fall dramatically from next year. Until much more efficient vehicles become available en masse - more efficient than the existing Toyota Prius - vehicle sales will stagnate.

If the US and European manufacturers do not rapidly adopt HEV, PHEV and EV technology, they will find themselves at a severe competitive disadvantage to the new Chinese and Japanese EVs which are about to be launched.

In recognition of this, practically every car manufacturer in the world is now actively developing and launching Power Assist Hybrid Vehicles. However, this will not be sufficient to reduce oil consumption to the required levels.

According to the latest report from the Freedonia Group, worldwide demand for Power Assist Hybrids will reach 4.5 million units in 2013 and will account for more than 6% of Light Vehicle demand at that time.

This does not take into account declining oil production and much greater market penetration of even more fuel efficient vehicles must be achieved far earlier. Freedonia's forecast is certainly an underestimate. Toyota's recent announcement stating their intention to sell 1M hybrids worldwide by 2010 (of which 600,000 in the USA) is only a repeat of a 2003 statement and now also appears to be an underestimate. Over the next five years, motor vehicle manufacturers must in fact improve fuel economy to an average of 100mpg to respond adequately to oil constraints.

In 2001, the number of vehicles per 1000 persons in each region of the world was as follows:

TABLE 24 **VEHICLES PER 1000, 2001**

Region	Vehicles per 1000
Africa	20.8
South America	111.5
Asia, Far East	40.4
Asia, Middle East	82.7
China	12.0
Eastern Europe	214.7
Western Europe	485
Pacific	478.9
Canada	579.7
USA	815

This table shows the potential for growth in vehicle ownership. It will now only be realised by environmentally neutral vehicles that are not dependent on fossil fuel.

10.2 Oil Consumption and Production

Table 25 shows the current oil production and consumption of major countries and oil production projections to 2020.

TABLE 25 **MAJOR OIL PRODUCERS AND CONSUMERS[a] (Mb/d)**

Country	Oil Consumpn 2003	Oil Production 2003	Oil Production 2010	Oil Production 2020	Electricity Prodn
Europe					
Germany	2.6	-	-	-	548.3TWh
France	2.04	0.023	.02	.02	529Twh
UK	1.9	2.08	1.31	0.72	360Twh
Norway	0.2	3.1	1.8	0.9	
Sweden	0.33				
Finland	0.21				
Denmark	0.22	0.393	0.226	0.106	60TWh
Italy	1.94	0.147	0.08	0.06	262TWh
Spain/Portugal	1.89	-	-	-	247.3TWh
Greece	0.41	-	-	-	
Switzerland	0.29	-	-	-	
Netherlands	0.89				
Belgium	0.595	-	-	-	
Total	**13.52**	**5.74**	**3.44**	**1.8**	
East Europe					
Russia	2.59	9.27	9.34	4.85	915 Twh
Ukraine	0.415	0.087	0.08	0.08	177TWh
SE Europe	0.396	0.115	0.085	0.062	100.6TWh
Visegrad Grp	0.828	.086	0.08	0.06	270 TWh
Baltic States	0.214	0.02	0.02	0.01	23.5Twh
Turkey	0.685	0.04	0.033	0.021	133.6TWh
Total	**5.13**	**9.62**	**9.64**	**5.1**	
North America					
USA	20.4	7.4	4.6	3.4	3,921TWh
Canada	2.3	3.1	4.0	4.0	549TWh
Total	**22.7**	**10.5**	**8.6**	**7.4**	
Asia					
China	6.05	3.5	2.6	1.7	1,575TWh
Japan	5.57	-	-	-	1,044TWh
India	2.2	0.82	0.52	0.33	547TWh
Indonesia	1.065	1.2	0.83	0.56	-
S. Korea	2.1	-	-	-	
Australia	0.88	0.63	0.45	0.29	210TWh
New Zealand	0.13	-	-	-	

TABLE 25 **MAJOR OIL PRODUCERS AND CONSUMERS[a] (Mb/d)**

Country	Oil Consumpn 2003	Oil Production 2003	Oil Production 2010	Oil Production 2020	Electricity Prodn
Malaysia	0.52	0.855	0.58	0.29	
Brunei	0.013	0.19	0.14	0.09	
Singapore	0.75	-	-	-	32.2TWh
Taiwan	0.876	-	-	-	159TWh
Total	**20.15**	**7.2**	**5.12**	**3.26**	
ME Africa					
Saudi Arabia	1.34	9.0	9.69	8.78	-
Iran	1.1	3.5	4.7	3.6	-
Iraq	0.4	2.0	3.0	4.5	-
Kuwait	0.23	1.85	2.6	2.5	-
Oman	0.054	0.82	0.62	0.41	-
Abu Dhabi	0.2	1.9	1.9	1.9	-
Qatar	0.03	0.78	0.53	0.27	-
Azerbaijan		0.3	0.8	0.7	-
Kazakstan		0.98	1.4	1.4	-
Israel	0.26	-	-	-	
Syria	0.24	0.52	0.261	0.123	-
Algeria	0.17	1.0	1.2	0.85	-
Libya	0.15	1.3	1.4	1.2	-
Angola	0.038	0.7	1.0	1.8	-
Nigeria	?	3.0	3.0	2.5	-
South Africa	0.469	0.2	0.2	0.2	202.6TWh
Egypt	0.564	0.698	0.17	0.09	81.3TWh
E. Africa	0.091	-	-	-	9.1TWh
Total	**5.34**	**28.55**	**32.47**	**30.82**	
South America					
Brazil	2.12	1.88	2.1	1.8	339TWh
Argentina	0.397	0.693	0.43	0.2	81.4TWh
Chile	0.235	0.019	0.01	0.01	43TWh
Mexico	2.02	3.8	2.0	1.2	199TWh
Venezuela	0.35	2.6	2.1	1.8	87.0TWh
Peru	0.161	0.094	0.072	0.055	21.7TWh
Colombia	0.261	0.53	0.39	0.24	44.9TWh
Total	**5.54**	**9.61**	**7.1**	**5.3**	
TOTAL	**72.38**	**71.22**	**66.37**	**53.68**	

a. Source: ASPO and EIA compilation

The Oil Production estimates for 2010 and 2020 are from the ASPO.

The industrialised nations most vulnerable to oil supply constraints in the near future are therefore much of Europe, the USA, Japan, South Korea, China, Taiwan and Singapore.

South America is potentially very secure if it controls demand growth. Russia is in the strongest position of the major nations.

The Middle East will continue to supply the lion's share of the world's oil.

The above table only lists the major producers and consumers but overall one can say that global oil consumption must be reduced by 1Mb/d per year between now and 2010 and then by 2Mb/d per year between 2010 and 2020 (including demand from smaller consumers not shown here).

10.3 Global Transportation Energy Use

The 2004 Transportation Energy Data Book[1] analyses the amount of oil and other energy used by global transport. In 1995, Light Vehicles accounted for 49% of total world transportation energy use. Trucks accounted for another 30%. Therefore Marine, Rail and Air account for only 21% of transportation energy use.

TABLE 26 **TRANSPORTATION ENERGY USE BY MODE - MTOE**

MTOE	Light Duty Vehicles	Air	Trucking	Rail	Maritime	Total
1995	934	151	584	120	129	1918
2020	1314	387	978	129	189	2997
1995	49%	8%	30%	6%	7%	100%
2020	44%	13%	33%	4%	6%	100%

1 tonne of oil is equivalent to 7.35 barrels.

- Therefore World Total Road Transport Oil Consumption in 1995 was about 11Gb or 31Mb/d of oil equivalent (31MBDOE).

In 1995, total global oil consumption was 70Mb/d. Road fuel therefore accounted for 44% of global oil demand.

1. Oak Ridge National Laboratory

The following table shows Regional Road Transport Oil Use in 1995.

TABLE 27 **ROAD TRANSPORT ENERGY USE 1995**

	Light Duty Vehicles	Trucking	Light Duty Vehicles	# LDVs	Fuel Consumption	Trucking
	MTOE		Mb/d	Millions	USG/LDV	Mb/d
Western Europe	197	71	4Mb/d	194	314	1.45Mb/d
North America	464	138	9.5Mb/d	217	660	2.8Mb/d
OECD Pacific	85	37	1.7Mb/d	79	332	0.74Mb/d
Former Soviet Union	30	33	0.6	31	299	0.67
Eastern Europe	21	13	0.43	22	295	0.27
Middle East/ North Africa	8	55	0.16	7	353	1.1
Sub Saharan Africa	17	12	0.35	12	438	0.25
South Asia	9	48	0.19	8	347	0.98
China	14	51	0.28	10	432	1.0
Other Pacific Asia	27	40	0.55	26	321	0.82
Latin America	62	86	1.3	46	416	1.8
Total			**19.06**	**652M**		**11.88**

In 1995, there were estimated to be 652M Light Duty Vehicles in the world. The WEC predicted that this will grow to 1,134M LDVs in 2020, a growth of 19.2M vehicles per year. This year in 2005, the world is on target for that growth: some 840M Light Duty Vehicles are now in service.

On a pro-rata basis, LDV oil consumption will have risen by nearly 30% to 24.7Mb/d in 2005.

It is important to note that in the less developed parts of the world, trucks use far more fuel than light vehicles. This difference was predicted to become less marked as personal car ownership grows.

However, the above predictions for oil consumption growth to 2020 are now invalid. What is required is conversion of as much of the existing vehicle parc and all new vehicle production as possible to non fossil fuel propulsion.

Major oil savings can also be effected by shifting of freight transport from trucks to rail and marine transport.

10.4 USA

In 1995, from Table 27, US LDVs consumed 660 USG per year each. This is mostly due to the poor average fuel efficiency of US vehicles of only 20.68mpg.

The USA currently burns 9.1Mb/d of petrol (gasoline) and 2.5Mb/d of diesel fuel each year.

Comparison with the fuel efficiency of vehicles in other parts of the world shows that there is ample scope for the USA to reduce its road fuel consumption. If fuel usage per vehicle was halved from 660USG to 330USG per year, a level more in line with most of the rest of the world, oil consumption would fall by 4.75Mb/d.

Some 17M Light Vehicles are sold in the USA each year. The USA manufactures about 15M light vehicles per year. Until very recently, the only hybrids in this number were those produced by Toyota and Honda at their North American plants. US manufacturers have been inexcusably slow to adopt the hybrid and to see the warning signs of forthcoming oil supply shortages. Japanese manufacturers were openly talking about “Peak Oil” in 2001.

In the 1990s, the USA also lead the world in the development and adoption of EVs. The perverse opposition by the US automotive manufacturers to the CARB ZEV mandates has destroyed that lead and now the Japanese manufacturers will probably lead the way in 21st century EV development.

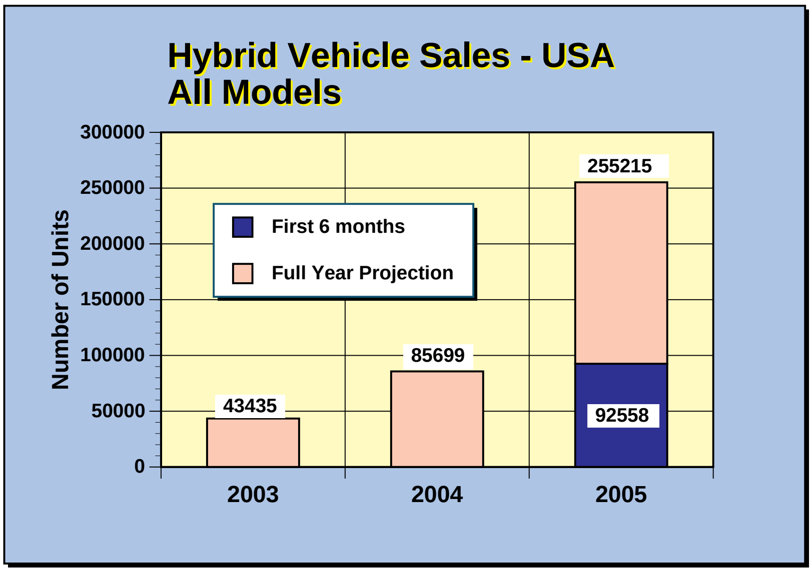
The poor fuel efficiency of US vehicles and the uncushioned feed through of higher oil market prices to the petrol pump, which is not diluted by the high excise taxes paid in Europe, will mean that the US will continue to be an excellent market for more fuel efficient vehicles. In this market environment, fuel economy gains can have the biggest impact on the amount of dollars drivers have to put in their petrol tank.

There has been recent commentary on the fact that the fuel savings gained by the hybrid (HEV0) cannot compensate for the higher capital cost of the vehicles. This does not take into account consumer psychology.

Consumers overwhelmingly base their decision to buy a particular motor vehicle on intangible emotional factors, tied up with psychological criteria of self image and self worth. The actual price of the vehicle is definitely not the most important factor: if operating cost and cost of ownership was the most important factor in buying a motor car, the industry as we know it would not exist. Therefore even though the Toyota Prius is more expensive than other comparable vehicles, because of the extra cost of the electrical drivetrain and battery, people still buy it because it meets their emotional criteria. After a vehicle has been bought, few people derive self worth or satisfaction from spending money on petrol. This seems like a waste of money, whereas the capital cost of the vehicle is an investment which generates a return every day in personal self image and self worth. As good marketeers, Toyota understand this very well. People are now buying the car in increasing numbers because it is a sensible, practical thing to do to minimise the unpleasantness of wasting money on petrol - and the vehicle itself delivers the required personal self image return. Therefore the Prius delivers a doubly positive emotional return.

Sales of Power Assist Hybrids were set to triple in the USA in 2005 before the accelerated escalation in petrol prices occurred in September. Sales could easily triple again in 2006 if production can keep up. The 1M hybrids a year mark will therefore be reached in 2007.

FIGURE 43



When Plug In Hybrids arrive, that offer all of the emotional attributes of existing vehicles coupled with extremely good fuel economy, supply will not be able to keep up with demand.

US Market Potential for the Plug In Hybrid

In 2001, Standard & Poors' Applied Decision Analysis group carried out an extensive market study[1] for Ford, EPRI and the Hybrid Electric Vehicle Working Group (HEVWG) into the Market Potential for the HEV and PHEV. The factors that had the most influence on consumer preference for the PHEV compared to a conventional vehicle were:

- Price Differential of PHEV vs. Conventional Vehicle
- Price of Fuel
- Requirement for Battery Replacement during life of vehicle

1. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, EPRI, Palo Alto, CA: 2001. 1000349.

Among drivers of mid-size cars with a short daily commuting distance, the study found that 35% of drivers would prefer a PHEV20, based on a vehicle price of about $24,700 and a petrol price of $1.65/USG. This is compared to a base Conventional Vehicle Price of $19,000 and a base HEV0 price of $23,000. At current petrol prices of US$3.00/USG, the percentage that would prefer a PHEV20 would rise to nearly 50%, assuming no increase in the cost of the vehicle.

Across all vehicle types (including SUVs), 22% of consumers were found to prefer a PHEV20, at the now low gasoline price of $1.65.

The PHEV60 had a fairly low market preference (18%) due to its high price of $29,000, required by the larger 17.9kWh battery. As one would expect though, drivers with longer commuting distances have a higher preference for this type of vehicle.

Battery Replacement

EPRI estimate that if the battery is replaced when its capacity has fallen to 80%, based on NiMH technology the cost to the consumer of replacing a PHEV20 battery for a mid-size vehicle would be $3,100 - assuming a $100/kWh trade in value. The cost of the 5.9kWh battery module to the repair shop would be about $320/kWh. (The difference in price to the end user is made up of mark up and labour costs). For a PHEV60, the battery replacement end-user cost would be about $7,000.

The study found that a requirement to replace the battery would have a strongly negative effect. This is partly driven by the inconvenience and perceived limitation of having to replace the battery; partly driven by the cost of replacing the battery. At a replacement cost of $3,147, preference for the PHEV20 would fall to only 15%. Drivers would rather have limited all-electric driving to extend battery life, rather than to have unlimited electric capability (within battery size limits) and be required to replace the battery. A control strategy would be implemented to prevent excessive discharge of the battery to extend its calendar life. EPRI estimate that the lifetime all-electric range of a limited PHEV20 would be 30,000 miles compared to 40,000 miles for an unlimited PHEV20.

The study also found that a majority of respondents would prefer recharging a vehicle with plug-in capability at home to refuelling at a petrol station.

Table 28 summarises the key findings of the study and sensitivities to the three most influential factors - vehicle price, fuel price and battery replacement cost.

(The sensitivities are independent of each other and apply individually to the Base Case. In combination, a high petrol price, low price premium for the PHEV and low battery replacement cost will greatly increase market preference - and vice versa).

TABLE 28

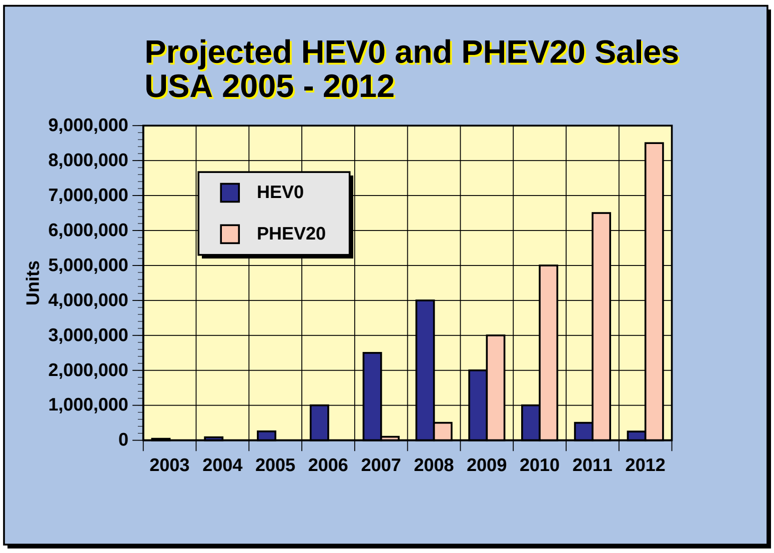
PHEV MARKET PREFERENCE SENSTIVITIES

	CV	PHEV20	PHEV60
Base Case			
Total Price over 3 Years	$18,984	$24,966	$29,053
Battery Size	-	5.9kWh	17.9kWh
Battery Replacement Cost	-	$0	$0
Fuel Price	$1.65	$1.65	$1.65
Market Preference	-	35%	18%
Sensitivities			
Battery Replacement Cost	-	$3,147	$6,679
Market Preference		15%	8%
Fuel Price		$3.00	$3.00
Market Preference		49%	28%
Vehicle Price		$21,975	$24,019
Market Preference		54%	52%

Market Forecast

Our forecast scenario for future hybrid sales in the USA, based on current hybrid vehicles and assuming that a correctly priced PHEV 20 became available in 2007 is shown below. This assumes gasoline remains at $3.00/USG in 2006 and increases towards $5.00/USG in 2007.

FIGURE 44



When Plug In Hybrids are introduced, production of HEV0s will be switched over to PHEVs. This will assist the growth in PHEV numbers and will cause a fall in HEV0 production.

It is predicted that by 2011 - 2012, 50% of the vehicles sold in the USA could be Plug In Hybrids as gasoline prices continue their inexorable rise.

Senator Joseph Liebermann is currently introducing a bill for the second time to mandate that 10% of new car sales in the USA should be HEV0s from 2007. If this is successful, hybrid sales will increase even more rapidly. Even without this bill, oil supply constraints and rising oil prices will continue to accelerate demand for more fuel efficient vehicles.

Commercial Vehicles

As in Europe, the Commercial Vehicle sector in the USA faces the most pressure to improve fuel economy, both to reduce pollution emissions and to reduce fuel costs.

As detailed in Chapters 5 and 6, the Public Transit sector is undergoing a wholesale transition to hybrid vehicles. Some 27,000 passenger buses are sold in the USA each year. These will all shift to hybrid and then plug in hybrid propulsion over the next 5 to 10 years.

The situation regarding Light Commercial Vehicles is somewhat clouded by the fact that unlike Europe, private drivers buy these vehicles for personal use. 9,144,831 Light Trucks were registered in the USA in 2004 out of 17M Light Vehicles in total.

Of these 9.1M Light Trucks, 1.2M were Fleet Sales and can be considered to be for commercial, business or government use. Another 107,000 were registered in the next weight category: 10-14,000lbs or “Class 3”. This 1.3M vehicles is more or less equivalent to the European sub 6 tonne category, in which 1.9M vehicles were registered in 2004.

A large proportion of these 1.3M vehicles present a near term market opportunity for hybrid and plug in hybrid propulsion.

In the Medium and Heavy Duty truck sector, above 14,000lbs in weight, 467,000 vehicles were registered in 2004. These are used exclusively by commercial operators and fuel efficiency improvements are a high priority. The first hybrid or plug in hybrid vehicle in this category which offers significant life time cost savings will experience high demand.

The entire existing US Commercial Vehicle market of 1.8M vehicles therefore offers a major immediate market potential for conversion to hybrid and plug-in hybrid propulsion.

10.5 Europe

In 1995, from Table 27, European LDVs consumed 314 USG per year each.

Passenger Car production in Western Europe has remained fairly static at around 15M units a year since 1998. Production of Light Commercial Vehicles (up to 3.5 tonnes) has maintained about 1.7M units a year over the same timescale.

The market for new cars is nearly as big as the US market. In 2003, 16.3M new motor vehicles were registered in Western Europe of which 14.2M were passenger cars. 1.7M Light Commercial Vehicles were registered (the same as production). Commercial Vehicle registrations (heavier than 3.5 tonnes) were 346,000 units. The total number of motor vehicles in circulation is 214M of which 187M are passenger cars.

TABLE 29 **WESTERN EUROPEAN MOTOR VEHICLE PRODUCTION**

	Passenger Cars	LCVs	Trucks	Buses
1998	14.5	1.67	.38	.035
1999	14.9	1.6	.39	.034
2000	14.8	1.9	.40	.035
2001	14.9	1.76	.48	.034
2002	14.8	1.64	.45	.032
2003	14.7	1.69	.46	.038
	Units: Millions			

Western Europe currently consumes about 3.2Mb/d of gasoline and 3.2Mb/d of diesel fuel.

The Power Assist Hybrid has so far failed to make any impact in Europe because its fuel economy is not superior to a European diesel car.

The latest Opel Astra diesel hybrid may be more successful in Europe than the Prius, if it can deliver a significant fuel economy improvement.

Europe has been slow to respond to the impact of rising oil prices on motoring costs. The high excise taxes in Europe mask increases in market oil prices to a certain extent. However, Europe is much further ahead of the USA in terms of indigenous EV and PHEV development. As oil prices continue to rise, Europe will be the next industrialised region to follow Japan and announce significant mass market EV programs for private vehicles.

There are now five active Electric Vehicle programmes in Europe to develop Light Commercial Vehicles - two in the UK, one in Germany, one in France and one in Norway. A number of other less well financed programs are trying to get off the ground.

Commercial vehicles make the most initial sense for EV development since commercial operators are the hardest hit by rising fuel prices and can cost justify the extra cost of an EV by the fuel savings. In addition, forthcoming clean air legislation in European cities will progressively prevent Internal Combustion Engined vehicles from entering city centres at all. Only PHEVs or EVs will be able to operate. This is giving a major impetus to the development of clean commercial vehicles in Europe.

The first market to develop for Electric and PHEV vehicles in Europe will therefore be Light Commercial Vehicles. We estimate that at least 10% of the current production of 1.7M units a year will become EV or PHEV versions by 2010. In 2008, Mercedes plan to launch the PHEV Sprinter onto the market. Three other EV/PHEV LCV programs will start commercialisation in 2006. The constraint on production is likely to be manufacturing capacity, not market demand.

Sales of HEV0 cars in Europe will remain weak. However, when a PHEV20 is launched, probably in 2007 or 2008, demand will be very strong. The Market Potential would be as high as in the USA - 50% or more. This would translate into a Market Potential for at least 7 Million PHEV20s a year. This will be supplied by imports from Japan if European manufacturers do not see beyond the current Diesel - HEV0 equilibrium. They need to develop even more fuel efficient diesel power assist hybrids, on which they can then build a Plug In Diesel Hybrid as soon as possible. This will then give them a competitive advantage over Toyota and Honda, instead of being at a disadvantage as they are currently.

In the Commercial Sector, 1.9M commercial vehicles below 6 tonnes were registered in 2004.

Some 315,000 HGVs (Medium and Heavy Duty Trucks) were registered and 33,000 buses were sold.

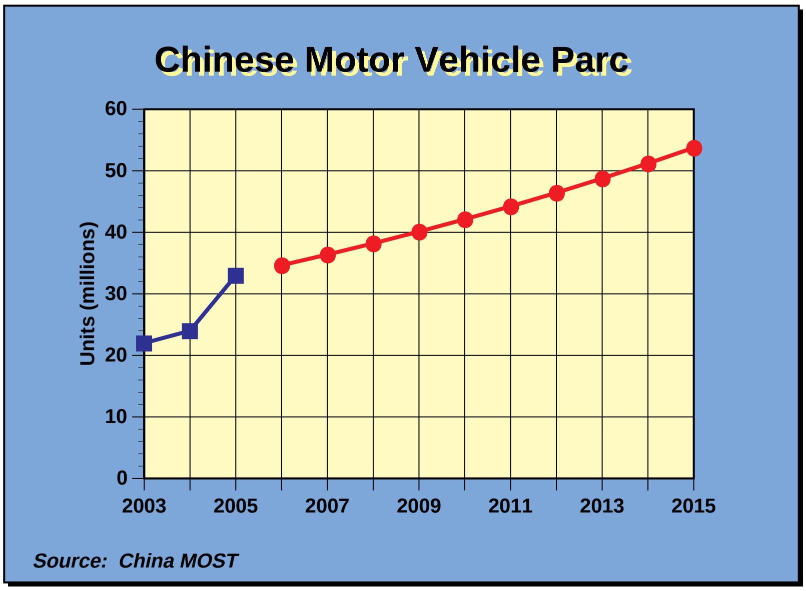
The European Commercial Vehicle Market Potential for hybrid and plug in hybrid vehicles is therefore over 2M units per year.

10.6 China

60% of Chinese oil consumption is used by the transportation sector.

According to China's MOST (Ministry of Science and Technology), at the end of 2001, there were 18 million motor vehicles in China, including 5M passenger cars. By the end of 2004, this had risen to 24 million. This is projected to rise to 33 million by the end of 2005, an increase of 38%. By 2030, it was projected to have further risen to 108M, of which 60% would be passenger cars or 64.8M. This implies a CGR of 5% p.a. Judging by historical growth rates, this seems a rather pessimistic forecast but if it is achieved, it will now be with EVs or PHEVs.

FIGURE 45



Why does China's MOST see such a sharp decrease in future demand growth for motor vehicles, from 2006 onwards? This may reflect increased oil prices.

Road vehicle fuel use was 65.6M tonnes (1.3Mb/d) in 2000 (33% of demand). This was projected to rise to 138M tonnes (2.8Mb/d) in 2010 (43% of oil demand) and 256M tonnes (5.2Mb/d) in 2020 (57% of demand). Again, these projections will not be met. Oil imports will no longer be able to increase and after 2006, will in fact start to fall.

These rapid growth rates in demand for cars have recently made China the fastest growing car market in the world. In 2003, Volkswagen sold more cars in China than in Germany. Volkswagen recently announced plans to commence production of hybrid cars in China in collaboration with a Chinese manufacturer.

These official projections will not be able to be met with conventional Internal Combustion Engine vehicles. Chinese motor vehicle growth is only possible through use of EVs, Plug In Hybrids and biofuel powered vehicles.

In 2003, China manufactured 4.45 Million cars. This is already nearly double the level of South America. MOST's growth projection from 2005 to 2030 is equivalent to 3M vehicles per year added to the Chinese vehicle parc, while production also has to make up for scrapping. At the rate production is currently growing, the implications for export growth are clear.

China already has a very active electric vehicle industry. There are over 10 significant manufacturers of EVs in the country.

Air pollution has become a major issue in China. Many cities are banning petrol scooters to improve air quality. SO_2 and NO_x levels are an order of magnitude higher than WHO limits in some cities. Traffic congestion is also a major problem and cities like Shanghai have already introduced traffic limitation measures such as banning odd/even number plates on alternate days. These measures are giving an extra impetus to EV developments.

China's MOST announced ambitious plans to have 70,000 EVs on the road for the Beijing 2008 Olympics. This goal will probably not be reached, but no other country or region has ever set comparable targets, except California.

What can be predicted is that China will soon adopt exclusively HEVs, PHEVs and EVs. If the motor vehicle population indeed grows from 33M today to 108M in 2030, an increase of 3M vehicles a year, this will be a major market for electric vehicle technology. Chinese vehicle production is already at 25% of North American production but the Chinese sell cars for as little as $5,000.

The Chinese manufacturers Dongfeng and FAW are now the second and third largest manufacturers in the world of Heavy Commercial Vehicles, after Daimler Chrysler. Their combined output in 2003 of 291,000 units exceeds that of Daimler Chrysler (229,000). Total Chinese output of Heavy and Medium Trucks in 2003 was 384,000 units. This compares with US HGV (>14,000 lbs) registrations in 2004 of 467,000 units.

10.7 India

Nearly all of Indian oil consumption is used by transportation, i.e. 114M tonnes (2.3Mb/d) of oil per year.

Maruti are the main Indian domestic motor vehicle manufacturer and they enjoy 50% of the domestic car market. They are owned by Suzuki. Sales in the third quarter of 2004 rose 17.08% to 136,000 units.

The car market is still quite small compared to China but catching up fast.

India also has an active electric vehicle industry. The main EV manufacturer in India being Reva in Bangalore

Nepal has nearly 400 electric 3 wheeled micro buses operating in Kathmandu. The vehicles are called “tempos” and are manufactured by Scooter India Ltd.

Passenger car sales in India were about 570,000 units in 2000 and 2001. Sales should reach 1 Million in 2005.

Table 30 shows an earlier projection for the growth in annual demand for motor vehicles in India.

TABLE 30 **INDIAN MOTOR VEHICLE MARKET GROWTH**

Thousands	2002 - 03	2011 - 12
Passenger cars	613	1,227
Motor Cycles	3,270	10,669
Scooters	876	1,124
MUVs	130	2,82

Passenger car sales were projected to grow by 8.0% p.a. between 2002 and 2012. By 2012, demand was projected to reach 1.2M vehicles a year, a doubling from 2002’s 600,000 passenger cars per year. In fact, growth has been much higher and the 1M unit mark has already been reached.

Motor cycle numbers are expected to grow more rapidly by 14.0% per year. Demand will therefore be over 10 million motor cycles a year by 2012.

The Scooter population will grow by 2.8% per year.

The MUV population will grow by 9% per year.

The biggest factor promoting the growth of vehicle ownership in India is the wider availability of finance.

Like China, India is an interesting developing market in that motor cycle sales are far more important than passenger cars. These vehicles could be manufactured as EVs instead or as biofuel vehicles.

In the Commercial Vehicle sector, sales of vehicles reached over 27,000 units in 2004.

India is in a similar position to China. To develop a modern mobility based economy, it will now only be able to do so if it can reduce its oil consumption at the same time. Mobility will therefore have to be based on alternative sources of motive power - electricity and biofuels. India is launching a nationwide effort to expand biofuel production and promote EVs. These actions will continue to gather pace and will accelerate over the next few years. India is in fact fortunate that it has not yet become too dependent on fossil oil for transportation and can shift to more sustainable forms of energy earlier in its development.

10.8 Japan

Of the major industrialised nations, Japan is particularly dependent on imported oil. It is the third largest consumer of oil and the second largest manufacturer of motor vehicles but has no indigenous oil production.

However, Japan is in a favourable position to transition to EVs. The country has a high proportion of nuclear power generating capacity (28%) and is a small highly urbanised country. The distances that are travelled by car are generally short and pubic transport infrastructure is well developed.

Japan is already leading world development of EVs. Japanese manufacturers will be the first to launch a serious Battery EV commercial effort and to launch PHEVs. From 2008 onwards, the Japanese motor vehicle manufacturing landscape will change dramatically as it shifts wholesale towards ultra fuel efficient models.

10.9 Conclusion

It is not possible at this time to make definitive forecasts in regard to future production and demand for HEVs, PHEVs and EVs. The motor manufacturers, with the exception of Toyota and Honda, seem to have been caught unawares by the forthcoming decline in global oil production and slow to respond. A response limited to Power Assist Hybrids is insufficient.

Behind the scenes, there is no doubt that “Sustainable Mobility” has become the major product development driver for motor vehicle manufacturers. However, the response of the non-Japanese major manufacturers, at least in terms of what is publicly stated, is too little.

At this point in time, only one technology can really create a sufficiently large reduction in global fuel consumption in the timescale required - the PHEV. Only a handful of companies, including Toyota and Honda, are positioned to produce these vehicles and the other manufacturers seem to be ignoring this requirement.

What we can say is that the dependence of the motor vehicle on fossil oil must be reduced as much as possible as quickly a s possible. Biofuel production will not be feasible on its own to achieve this. Electric propulsion - either pure electric or plug in hybrid electric - is the only viable solution. Therefore the market potential for suppliers to the electric vehicle industry can be said to be in the order of 60 million vehicles a year for the next 20 years, plus retrofit and conversion of the existing vehicle parc of 840 million light vehicles. To this can be added conversion and replacement of trucks and heavy goods vehicles.

As soon as the first EVs and PHEVs arrive on the market, from 2007 onwards, consumer demand will exceed supply. Those manufacturers who try to resist this seismic shift in motor vehicle technology that is about to occur will be at a severe and irreparable competitive disadvantage to the new wave of cost effective advanced technology vehicles coming out of China and Japan. If western manufacturers wish to survive, they must embrace PHEV and EV technology immediately.

11 Petroleum Consumption Reduction Strategies

11.1 Introduction

How much oil could particular Oil Consumption Reduction measures save? Will they be sufficient to respond to declining supply? How many vehicles of what type must be introduced and how quickly to keep oil demand within falling oil supply?

We will examine a number of scenarios and their potential impact.

11.2 US Oil Consumption

We will first examine the impact certain oil efficiency measures would have on the largest consumer of oil, the USA.

Table 31 shows the size, oil consumption, productivity and fuel efficiency of the different US transportation modes in 2004.

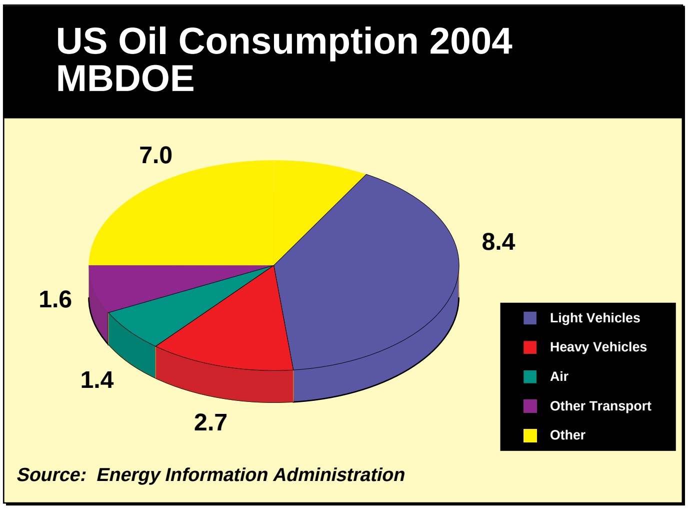
TABLE 31 **US TRANSPORTATION OIL USE 2004**[a]

	Units (million)	MBDOE	Fleet Miles Travelled p.a. ($x10^9$)	mpg (miles per USG)	Miles per Vehicle
Cars and Light Trucks	222.7	8.4	2627	20.68	11,833
Medium Trucks	5.67	.32	67	13.85	11,823
Freight Trucks	2.25	2.23	225	6.7	100,219
Buses	.78	.12	-	-	-
Air, Shipping, Rail, Other Transport	-	2.94	-	-	-
		14.01			

a. Source: EIA

The total amount of oil consumed by the US transportation sector in 2004 was some 14M b/d Oil Equivalent (MBDOE). 67% of US oil consumption is used by the transport sector, leaving another 7 M b/d for other uses and giving a total of 21M b/d of oil consumption.

FIGURE 46



We can see from Table 31 that cars and light trucks in the USA are the single largest consumers of oil. These vehicles have an average fuel efficiency of 20.68 miles per USG Oil Equivalent and travel on average about 11,800 miles per year. Overall Light Vehicle utilisation has therefore only increased slightly from 11,400 miles per vehicle per year in 1994 and for passenger cars alone it has not increased at all since the 1980s, so we will not assume any more utilisation increases over the next 10 years in our analysis.

At the current time, some 17 million new passenger cars and light trucks are sold in the USA each year.

At the same mean utilisation and fuel efficiency as the existing fleet, these 17 million vehicles will consume 0.64 MBDOE per annum.

In reality, it is known that new vehicles drive the most miles per year and that utilisation decreases with vehicle age. When they are new, light vehicles in the USA average 14,300 miles per year falling off to less than 10,000 miles per year for vehicles over 11 years old. Therefore, new fuel efficient vehicles have a greater oil saving effect than old ones.

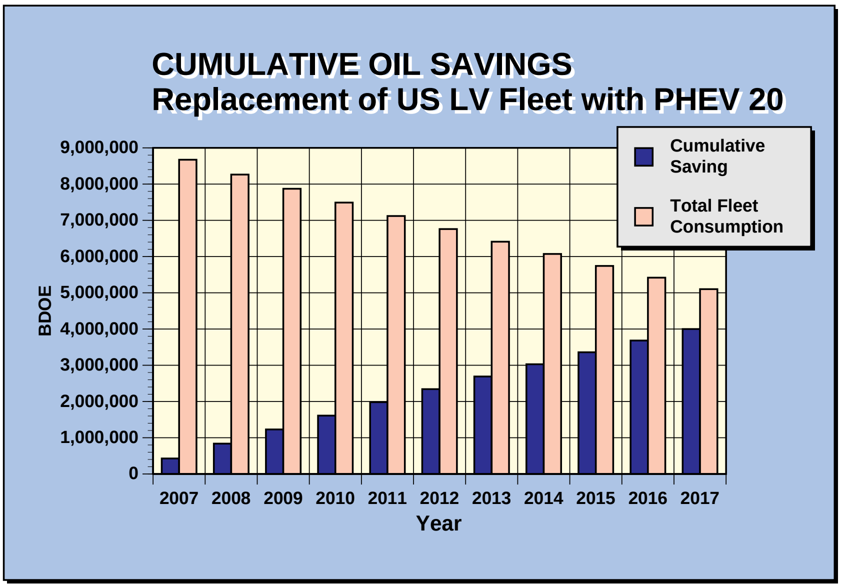
11.3 Scenario 1 - PHEV 20

We will now use the above information to estimate the effect of replacing the Internal Combustion Engine in all new Light Vehicles sold in the USA with a PHEV 20 Hybrid Electric Drivetrain - i.e. a vehicle that can drive the first 20 miles on electricity alone.

We have already seen that a PHEV20 would reduce petrol consumption in the USA by 55% on average. For a Light Vehicle that drives 11,833 miles per year at 20.68mpg, this would reduce annual petrol consumption from 570 US gallons to 260 US gallons.

If the 17 million Light Vehicles sold in the USA each year were all PHEV20s, the fuel savings effected over 10 years at a constant replacement rate of 17 million vehicles per year are shown below in Figure 47.

FIGURE 47



- By 2017, petrol consumption by the US Light Vehicle fleet would have fallen by 45% from 9.1Mb/d to 5.1Mb/d.

Global Extrapolation

If the petrol savings from the 17M US Light Vehicles sold each year as PHEV20s are extrapolated onto the 60M Light Vehicles currently sold worldwide, total oil savings would reach 18.3Mb/d by 2020. By 2020, Global Oil Production will have fallen from 85Mb/d currently to 65Mb/d. Introduction of Light Vehicle PHEV20s alone would therefore not reduce demand sufficiently - there would be a shortfall of 1.7Mb/d. Oil demand in 2007 is also projected to be 88.8Mb/d, which would increase the shortfall to 5.5Mb/d. However, in conjunction with fuel saving measures for heavy vehicles, the fuel economy of the PHEV20 is the minimum required to maintain road fuel security and mobility.

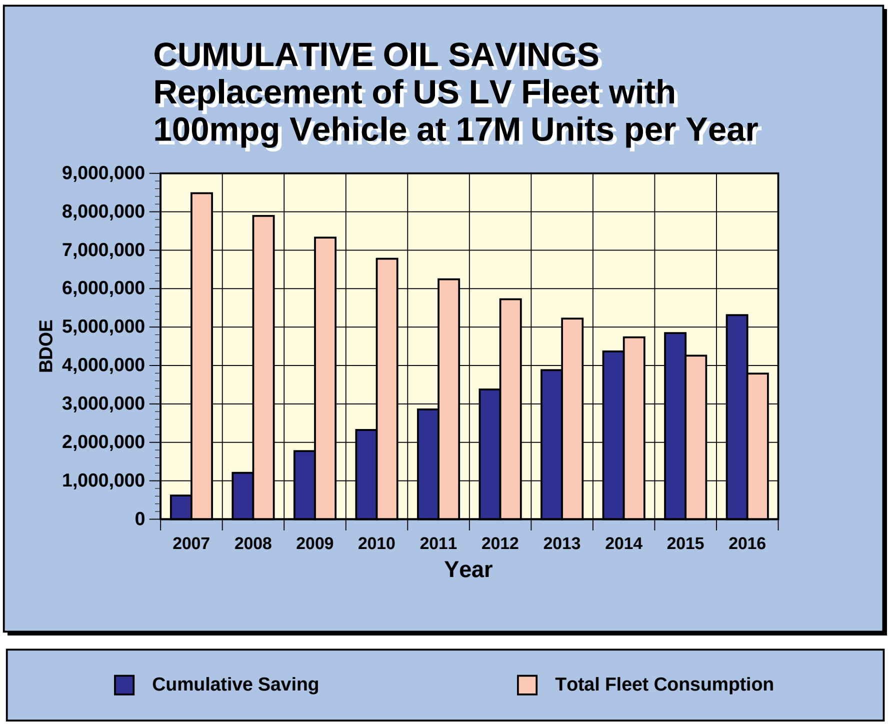
11.4 Scenario 2 - Introduction of 100mpg Hybrids

100mpg Hybrid Light Vehicle

We will now estimate the effect of replacing the Internal Combustion Engine in all new Light Vehicles sold in the USA with a 100mpg Hybrid Electric Drivetrain, i.e. a drivetrain with approximately 5 times the fuel economy as the average US Light vehicle today.

If the 17 million Light Vehicles currently sold in the USA each year were mandated to have a fuel efficiency of at least 100 miles per gallon or 42 km/l, the fuel savings effected over 10 years at a constant replacement rate of 17 million vehicles per year are shown below in Figure 48.

FIGURE 48



If Light Vehicle sales in the USA continued at the existing level of 17 million vehicles per year (and did not rise despite their replacement with a superior 100mpg drivetrain), then in 10 years time the annual saving in oil consumption would have reached 5.3Mb/d. Gasoline consumption by the Light Vehicle sector would have fallen from 9.1Mb/d in 2005 - 06 to 3.8Mb/d in 2016. This also assumes zero growth in the number of vehicles in circulation.

Of course, if this replacement rate was accelerated and the average fuel efficiency of Light Vehicles exceeded 100 mpg (both of which possibilities are achievable), oil consumption would fall even further.

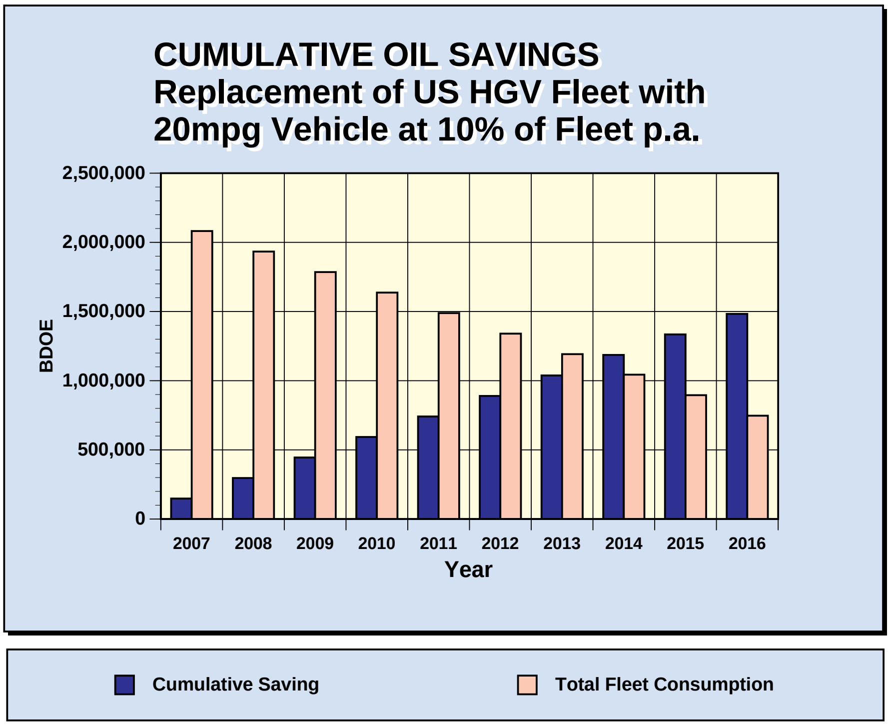
We have factored a decreasing utilisation rate with age into this analysis, which may underestimate the fuel saving achieved by older hybrids, since the utilisation of a Hybrid may in fact not decrease with age as much as an Internal Combustion Engine vehicle. This would be due to the higher reliability and lesser maintenance requirements of the electric drivetrain and the fact that the small ICE in the hybrid could operate at a constant fixed speed.

20mpg Hybrid Heavy Freight Truck

The average fuel efficiency of Heavy Goods Vehicles (HGVs) in the USA is 6.7 mpg. There is scope for achieving significant fuel savings by converting this fleet to plug-in hybrid or pure battery electric power.

If 10% of the US HGV fleet was upgraded each year to a fuel efficiency of only 20mpg, 1.5M b/d of oil consumption would be eliminated over 10 years. (In 2004, some 202,000 heavy trucks weighing over 33,000lbs and 83,000 trucks in the 26-33,000lb class were sold in the USA: i.e. annual sales were 13% of the total US Freight Truck fleet).

FIGURE 49



- Replacement of 10% of the US HGV Fleet per annum with a 20mpg Drivetrain would reduce Oil Consumption by the HGV Fleet from 2.23 MBDOE today to 0.75 MBDOE within 10 years.

By combining these two conservative measures for Light Vehicles and HGVs, current US road diesel and gasoline consumption would be reduced from 11.5Mb/d to around 4.5Mb/d in 10 years time.

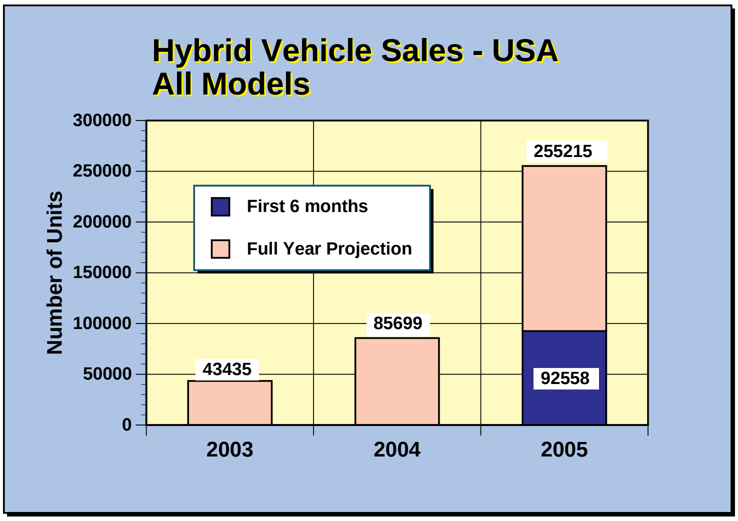
This saving of nearly 7Mb/d is equivalent to one third of current US Oil Consumption.

Current Hybrid Sales

Sales in the USA of the current range of Hybrid Vehicles are undergoing exponential growth at the moment. This is being driven by the ever increasing price of petrol, a phenomenon to which US drivers are not accustomed. In July 2005, petrol retails for approximately $2.50 per USG and numerous commentators have started to call for an active oil consumption reduction programme as a matter of National Security.

Figure 50 shows the historical sales of hybrid cars in the USA in 2003 and 2004 and our forecast for 2005.

FIGURE 50



Sales of hybrid cars in the first six months of 2005 of 92,558 units have already exceeded sales for the whole of 2004 and the monthly trend is steadily upwards. At time of writing, there are 7 main models of hybrid car available on the US market with many more planned for introduction.

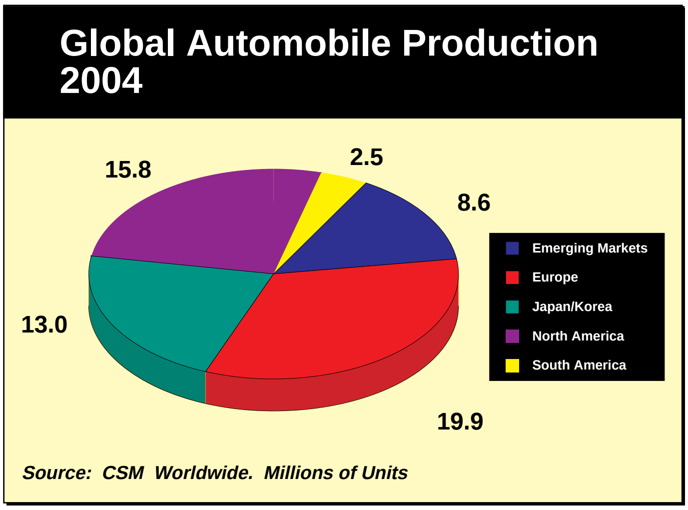
In June 2005, Toyota announced the intention to double output of the Prius. Toyota are actively developing hybrid versions of many of their other models with production due to start in 2005 - 06. Toyota's recent announcement intending to sell 1M hybrids worldwide by 2010 (of which 600,000 in the USA) is only a repeat of a 2003 statement but appears very achievable.

Therefore the US market is becoming rapidly educated and accustomed to the concept of the hybrid car as sales take off. Introduction of improved efficiency Plug-In Parallel Hybrids with more battery capacity will therefore be much easier over the next few years as market awareness of the technology develops even further.

11.5 Scenario 3 - Global 100mpg Hybrid

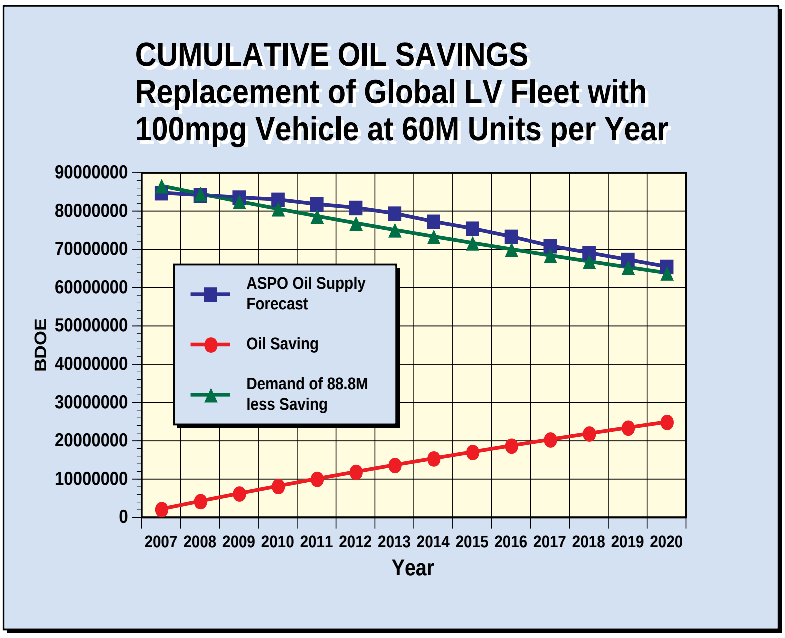
In 2004, Global Automobile Production totalled some 60 million units[1], not including trucks and buses.

FIGURE 51



If we extrapolate the US model for fuel efficient vehicles onto the rest of the world, by assuming that from 2007 these 60 million vehicles have a fuel efficiency of at least 100mpg, the following scenario would result:

FIGURE 52



1. Source: CSM Worldwide Production Barometer

- The size of the Global Light Motor Vehicle Parc in 2000 was 754M units. By 2007 it is projected to have risen to 860M units.
- By improving the Fuel Efficiency of the 60M Light Vehicles sold each year to 100mpg, Global Oil Consumption would be reduced to 63.9M b/d in 2020, some 1.6M b/d below projected supply.
- By 2020, replacement of 840 Million ICE Light Vehicles with a 100mpg vehicle would save 25 Million Barrels a Day of Oil.
- As Global Oil Production declines from 83Mb/d in 2007 to 65Mb/d in 2020, improved fuel efficiency of 100mpg in all new Light Vehicles would be sufficient to maintain security of oil supply after 2009.

In this scenario, if all Global Light Vehicle production is switched to High Efficiency types with a fuel efficiency of no less than 100 mpg from 2007, this one measure would save enough oil per annum out to 2020 to keep Global Oil Consumption just within the declining Available Supply (assuming no other additions to fossil road fuel demand).

However, this one action alone would not provide much of a buffer against unexpected supply disruptions and security of oil supply would remain of serious concern but it illustrates the feasibility of maintaining the security of the existing level of activity in the global transport infrastructure, without the need for draconian or restrictive measures that would spell an end to normal societal and economic activity.

If oil supply falls more quickly than projected, further oil savings would be needed (although we have not included potential savings from the HGV sector in this scenario).

We stress again that a fuel efficiency of 100mpg is conservative and easily achievable. The Daihatsu UFE II prototype has demonstrated 160 mpg. A PHEV version of this vehicle could achieve over 200mpg.

With the introduction of even more fuel efficient vehicles between now and 2015, even greater fuel savings and breaking of global oil dependence will be achievable.

Production could be increased over 60M units per year to accelerate fuel savings. Improvement in global HGV fuel efficiency would also increase the fuel savings.

This scenario does not take into account Pure Battery EVs, which could replace significant proportions (20% - 50%) of US and European road fuel consumption with no need for extra electricity generation, by using night time off-peak electricity that is currently unutilised.

11.6 Scenario 4 - Optimised Battery Electric: Hybrid Mix

It is well known that the average car journey length in most countries is very short. In the USA, the average car trip length is 9.8 miles. In the UK, it is 8.7 miles. On average, each car in the USA travels only 23 miles per day.

This fact has often been cited by proponents of the pure Battery Electric Vehicle (BEV) as a major factor in its favour: there is a huge practical market for the BEV, for which this type of vehicle's perceived limited range is more than adequate and also greatly compensated for by its low operating cost.

In 2001, the Total Vehicle Miles travelled by Light Vehicles in the USA were 2.3 trillion miles. Of this, 760 billion miles were driven on Long Distance Trips[1] of over 50 miles in length. This leaves 1538 billion vehicle miles or 66.9% of the total driven on short trips less than 50 miles in length.

This 1538 billion vehicle miles could potentially be replaced by a pure BEV with no loss in operational performance or flexibility. Overnight recharging would be carried out if necessary. A BEV with a range of 200 miles between recharges would more than adequately address this segment of personal travel requirements.

At the average current Light Vehicle Fuel Efficiency of 20.68 mpg, this 1538 billion vehicle miles consumed 4.9M b/d of fuel. If we extrapolate this 2001 Short Distance Fuel Consumption onto the total 2004 distance travelled of 2627 billion vehicle miles, we can estimate that 5.62 Mb/d of fuel was burned by Light Vehicles on Short Distance Trips in 2004 out of a total of 8.4M b/d.

Therefore 67% of US Light Vehicle Fuel Consumption could be theoretically eliminated and replaced with electrical power.

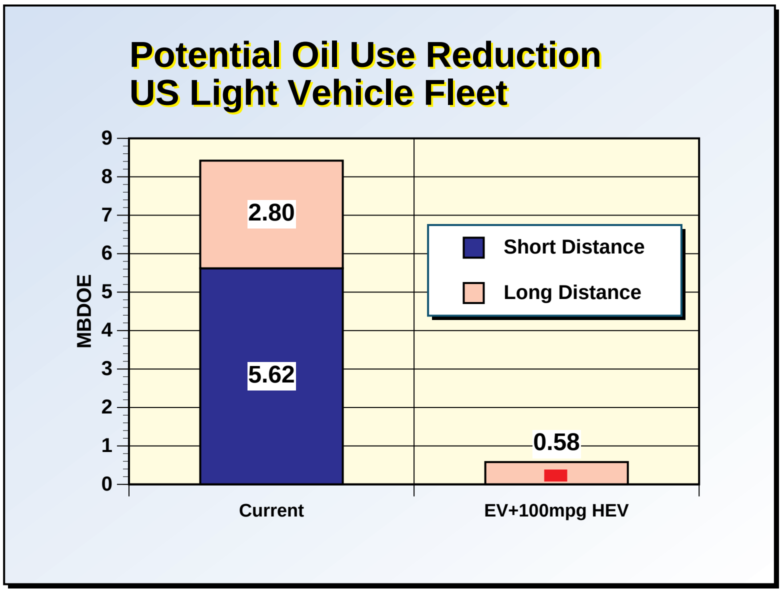
This measure alone would reduce US transportation fuel consumption from 14.01 MBDOE in 2004 to 8.4 MBDOE and total US Oil Consumption from 21 to 15.4 MBDOE.

If the rest of the Light Vehicle fleet was replaced with 100mpg hybrids for the other 869 billion of long Distance Vehicle Miles in 2004 (extrapolated), this would reduce the fuel burned on Long Distance trips from 2.8 M b/d to 0.58 M b/d.

Figure 53 shows the Total Potential Fuel Consumption Reduction from the US Light Vehicle Fleet. Oil Consumption would be reduced from 8.42Mb/d to 0.58Mb/d.

1. National Household Travel Survey 2001, Bureau of Transportation Statistics

FIGURE 53



Total US Oil Consumption would therefore fall to 13.2 M b/d.

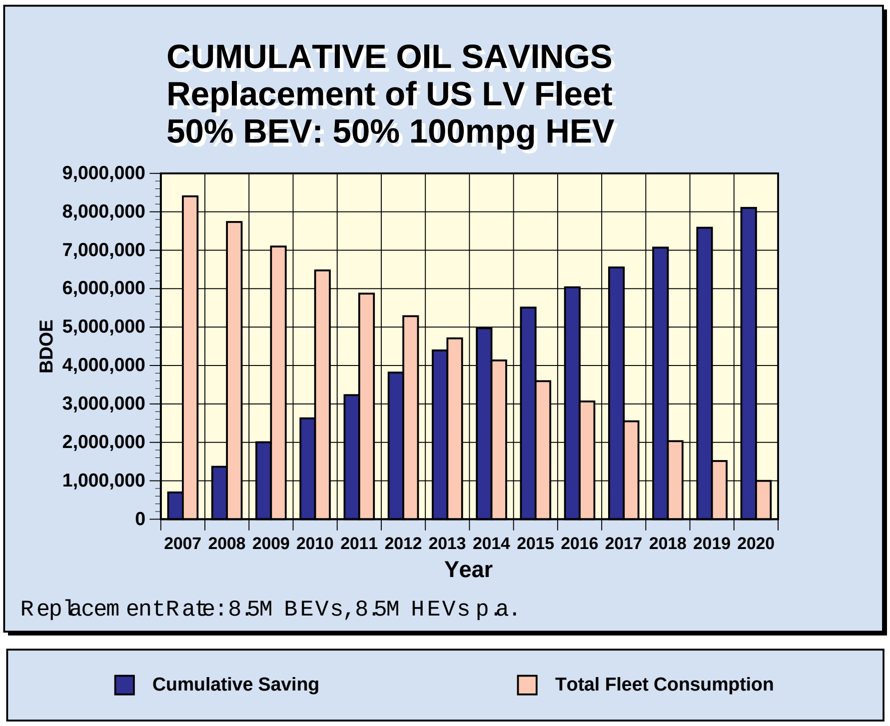
This scenario would be achievable in a single vehicle type: a Plug In Hybrid with a 100 mile range on battery power. The IC engine "genset" would act as an onboard range extender.

11.7 Scenario 5 - 50:50 Split Between Battery EV and 100mpg HEV

If the 17 million Light Vehicles sold in the USA each year were split 50% between 100mpg Plug In Hybrids (which could drive 50 miles or more on battery power alone) and 50% BEVs (with a range of 100 - 200 miles), this would provide the US automobile driver the possibility of completely replacing petrol for short journeys with electric power while retaining the range of the petrol hybrid for longer journeys over 100 miles.

If we assume the same 17 million units per year replacement pattern as before, this time with 50% BEV and 50% Hybrid operating at 100 mpg (which is very conservative and gives no credit for the pure battery mode on short trips), the following oil consumption reduction scenario would result.

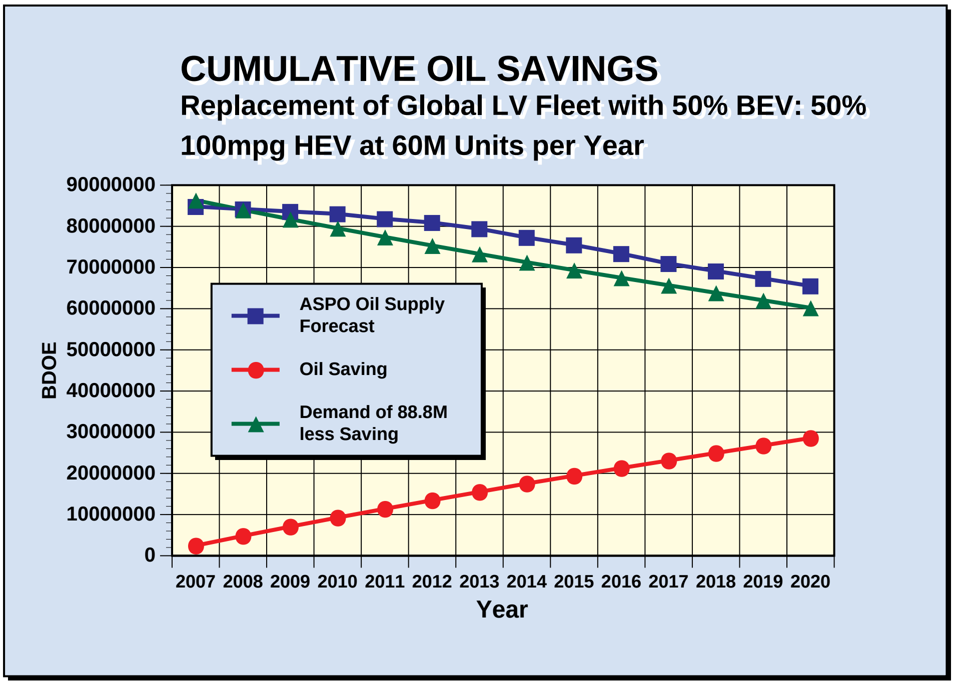
FIGURE 54



- By 2020, oil consumption by the US Light Vehicle sector will have fallen from 9.1Mb/d to 1Mb/d.

Extrapolated onto the Global Basis, the following scenario would result:

FIGURE 55



- In this scenario, Global Oil Consumption would be reduced to 60 Mb/d in 2020, some 5 Mb/d below projected supply.

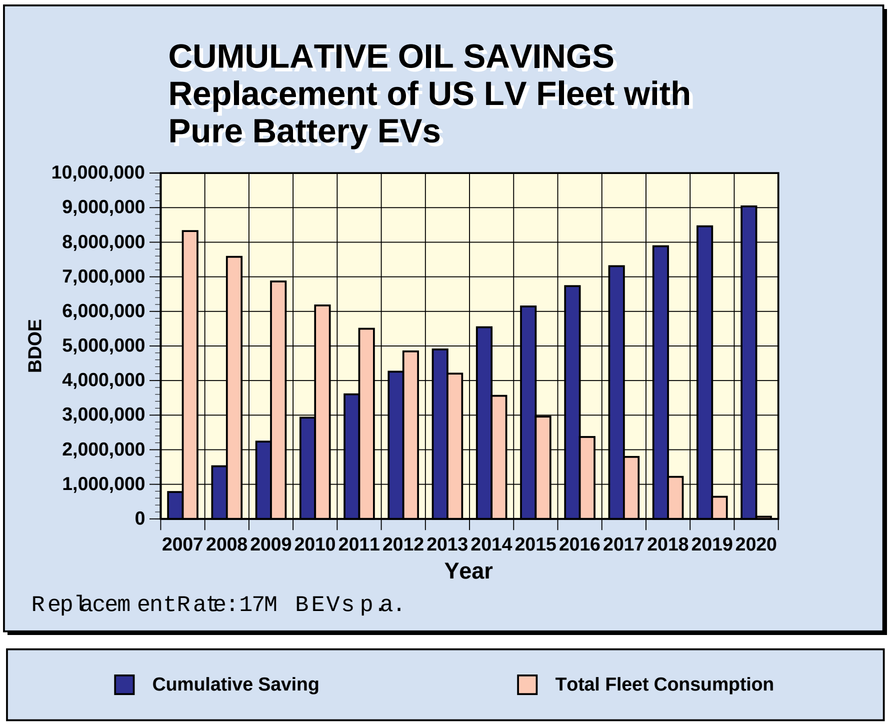
An oil consumption reduction effort of this order would certainly be preferable to maintain a reasonable buffer between falling supply and demand, particularly if the ODAC projection of a 3Mb/d decline in oil supply p.a. after 2010 turns out to be correct.

11.8 Scenario 6 - Pure Battery Electric Vehicle

In this scenario, we examine the maximum savings potential of all - complete replacement of petroleum with Electric Vehicles. In this scenario, it is assumed that EVs have sufficient range to be viable on Long Distance trips and infrastructure or battery technology is implemented to allow rapid recharging or battery swapping in a timescale comparable to refuelling a petrol vehicle at a filling station.

Figure 56 shows the effect on US Light Vehicle Petroleum Consumption if all 17 million new vehicles sold in the USA each year from 2007 were mandated to be Battery Electric Vehicles.

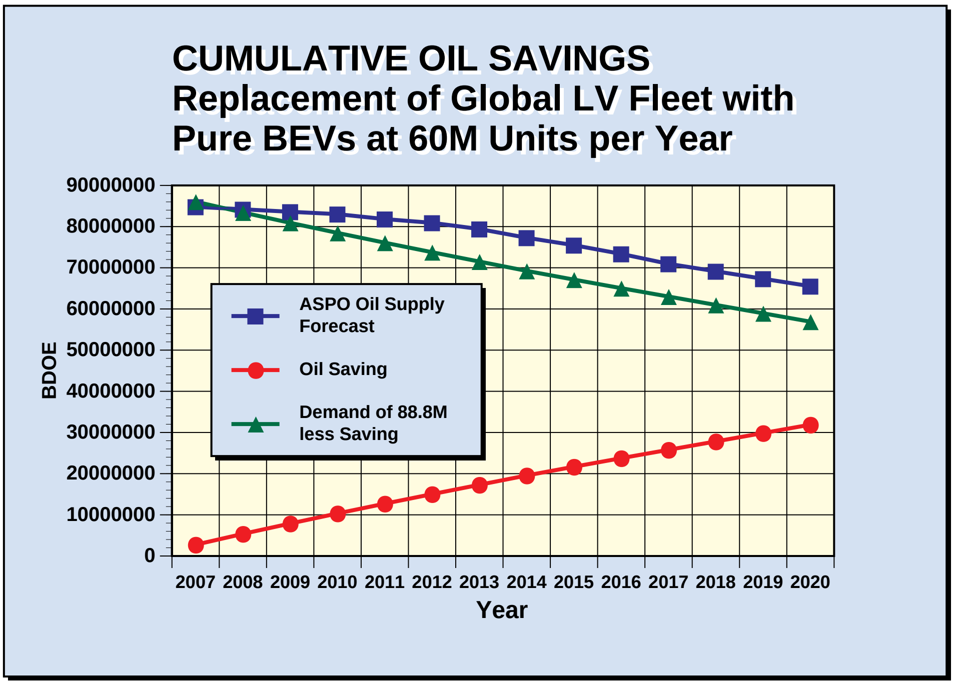
FIGURE 56



- If petroleum powered Light Vehicles in the USA were replaced by pure Battery Electric Vehicles at the current sales rate of 17 Million units per year starting in 2007, petroleum consumption by the US Light Vehicle sector would be eliminated by 2020 at the latest.

Figure 57 shows the effect of this strategy extrapolated across the globe, to all 60M Light Vehicles manufactured each year.

FIGURE 57



- Total replacement of all 60 million vehicles manufactured each year with Battery Electric vehicles would save 32Mb/d and reduce Global Oil Consumption to 56.9Mb/d in 2020. Projected Oil Supply in 2020 is 65 M b/d.

This measure - not counting conversion of HGVs or shipping - would more than adequately maintain security of transport and security of oil supply with a sizeable safety margin between oil supply and demand.

With oil supply projected to fall further to 54 Mb/d in 2030, it can be seen that a strategy of replacing petroleum powered vehicles with Electric Vehicles would be sufficient to maintain security of transport and personal mobility. As the Electric Vehicle fleet grows, renewable electricity generating capacity can be added if necessary along with electricity efficiency measures to match the growing electricity demand.

Table 32 presents the data from Figure 57.

TABLE 32 **EFFECT ON OIL DEMAND OF GLOBAL BEV FLEET GROWTH**

Year	Oil Supply (Mb/d)	Cumulative BEV Oil Saving (Mb/d)	Oil Demand (Mb/d)
2007	84.8	2.7	86.1
2008	84.2	5.4	83.4
2009	83.6	7.9	80.9
2010	83.0	10.3	78.5
2011	81.8	12.7	76.1
2012	80.9	15.0	73.8
2013	79.4	17.3	71.5
2014	77.3	19.6	69.2
2015	75.5	21.7	67.1
2016	73.4	23.8	65.0
2017	71.0	25.8	63.0
2018	69.1	27.8	61.0
2019	67.3	29.9	58.9
2020	65.5	31.9	56.9

It is preferable to save as much oil as possible as quickly as possible for another very important reason: to conserve stocks of oil for use in the future as the petrochemical feedstock.

It is easy to overlook the fact that not only is our energy and motive power dependent on oil, so is the very fabric of modern civilisation. Without petrochemicals derived from oil - e.g. plastics, pharmaceuticals, fertiliser, clothing, materials, paint to name a few - modern civilisation would cease to exist. Plastic is ubiquitous and irreplaceable. We must conserve our oil supplies as much as possible to gain time for bio alternatives to be developed from natural oils and other sources.

11.9 Effect on US Electricity Generating Capacity

This switch over from petrol as the source of automobile motive power to electricity, for short trips at least, has implications of course for electricity demand. Could the extra electricity demand be accommodated? Will this not in fact make impossible demands on the electricity generating industry as well as simply displace environmental emissions from the vehicles to the power stations?

If all 1538 billion vehicle miles driven on short trips in the USA in 2001 were powered by electricity, then using a pessimistic EV electricity consumption of 0.25 kWh per mile, some 385 billion kWh of electricity would have to be delivered by the batteries in those vehicles each year.

The efficiency of the battery chargers used to recharge the EV batteries is about 90% and we have already factored the electric drivetrain efficiency between battery and wheels and the efficiency of the batteries into our “fuel” efficiency of 0.25 kWh/mile; therefore the total electrical power that would be drawn by the consumer would be about 427 billion kWh. In practice, BEVs would use regenerative braking to recover some of the energy they use, but we will not take that into account.

The Total Electricity Consumption in the USA in 2002 was 3651 billion kWh.

Therefore, replacement of all short distance car trips in the USA would consume 11.7% of US electricity demand.

Energy Efficiency Contribution

Energy Efficiency measures alone in electricity consumption can make all the energy contribution required and more to completely switch automobile power from petroleum to electricity.

It is not proposed that vehicle trips fuelled by petroleum should simply be switched over to electric power without any other measures, although that alone would be a far more efficient way to use primary energy than the consumption of 5.6Mb/d of oil.

Energy efficiency measures in electrical power consumption will more than make up for the increased demand for electricity created by the switch to BEVs.

Historical Energy Efficiency Gains

Between 1973 and 2001, energy use per unit GDP in the USA fell by 43%. Energy consumption per capita in the USA is the same in 2002 as it was in 1973 while GDP has increased by 74%.

As an example, Federal standards for refrigerators and other appliances introduced in 1987, 1988 and 1992 saved 2.5% of US electricity consumption by 2000.

In 2001, the US Government put off introduction of a new SEER13 efficiency standard for air conditioners that would reduce US peak electricity demand by 13,000MW by 2020 - the equivalent to 43 power stations (300MW each). This is equivalent to 1.1×10^{11} KWh, enough to drive a fleet of Electric Vehicles for over 400 billion vehicle miles or 15% of annual US Light Vehicle Miles.

California 2001

An exceptional example of what can be achieved in Electricity Energy Efficiency is the experience of California in 2000 - 2001.[1]

During late 2000, California declared over 70 days of System Emergencies and experienced several instances of rolling blackouts due to increased electricity demand and insufficient supply. By February 2001, a potential shortfall during the coming Summer of over 5,000 MW was predicted, when high demand for air conditioning pushes electricity demand to peak levels.

The Governor of California Gray Davis allocated $1.3 billion to a massive demand reduction initiative including $900 million on energy efficiency programmes, more than in the rest of the USA put together. During that year, adjusted for weather, California reduced its overall electricity consumption by 6.7%. For the summer months as a whole, California achieved a 10% reduction on average and a 14% reduction in electricity consumption for the month of June.

We are faced with a similar scale of emergency on a global level. The experience of California shows what can be achieved when necessary - significant energy savings can be made very quickly.

EERS

A number of US states, the UK and Italy have introduced Energy Efficiency Resource Standards (EERS) that require electrical utilities to achieve annual increases in electricity consumption efficiency.

The American Council for an Energy-Efficient Economy (ACEEE) estimate that if their proposed EERS mandating an annual 0.25% cumulative increase in electrical energy efficiency was adopted nationwide, it would save 6.75% of US electricity use in 10 years.

It is not necessarily the case that switching over to alternative forms of energy from oil will result in economic hardship. Increased energy efficiency and awareness offers an opportunity for lowered costs and improved quality of life.

Electricity Saving Potential

Analyses that are carried out to estimate potential energy savings use three types of estimate: the Technical, the Economic and the Achievable savings potential. All three are conservative estimates and exact definitions vary. However, the Achievable potential is very conservative; the Economic potential takes into account extra measures that are definitely economically justifiable in terms of a short payback time ROI; the Technical potential takes into account measures that may be economically justifiable on a longer timescale. Even the Technical

1. ‘Examining California’s Energy Efficiency Policy Response to the 2000 - 2001 Electricity Crisis”, ACEEE, March 2003, Report #U033.

Potential falls far short of what could be achieved if energy saving became a necessity and priority.

From an analysis[1] carried out by the ACEEE, it is conservatively estimated that 24% of current US electricity consumption could be saved, at a 1.2% saving per year.

(This is the median Achievable Conservation Potential and the median annual savings rate).

The analysis estimates the median Technical Conservation Potential at 33% of current US electricity consumption. This is an estimate that would become more economic and achievable and less technical as energy prices increase.

If the USA was to indeed save 24% of its current electricity consumption, that would amount to 876 billion kWh per year (on 2002 electricity consumption). We estimated the total electricity requirement to power the total short distance trips driven of 1538 billion vehicle miles would be 427 billion kWh.

- A 24% saving in electricity consumption would therefore power double the total short distance mileage driven in the USA each year.

This potential electricity saving of 876 billion kWh would in fact power the entire US Light Vehicle fleet for 3155 billion vehicle miles - or 1.33 times the total vehicle miles driven in 2001 of 2367 billion miles.

Conclusion

US drivers could switch to pure BEVs, drive 33% more miles per year than they do at present, stop burning 9M b/d of oil and need generate no more electricity than they do at present - just by switching to BEVs and adopting conservatively achievable electrical energy efficiency measures.

11.10 Scenario 7 - Converting Electrical Energy Efficiency Gains to Power BEVs

The ACEEE meta-analysis of a number of recent studies indicates that at least 24% of US electricity consumption could be saved, at a median rate of 1.2% per year.

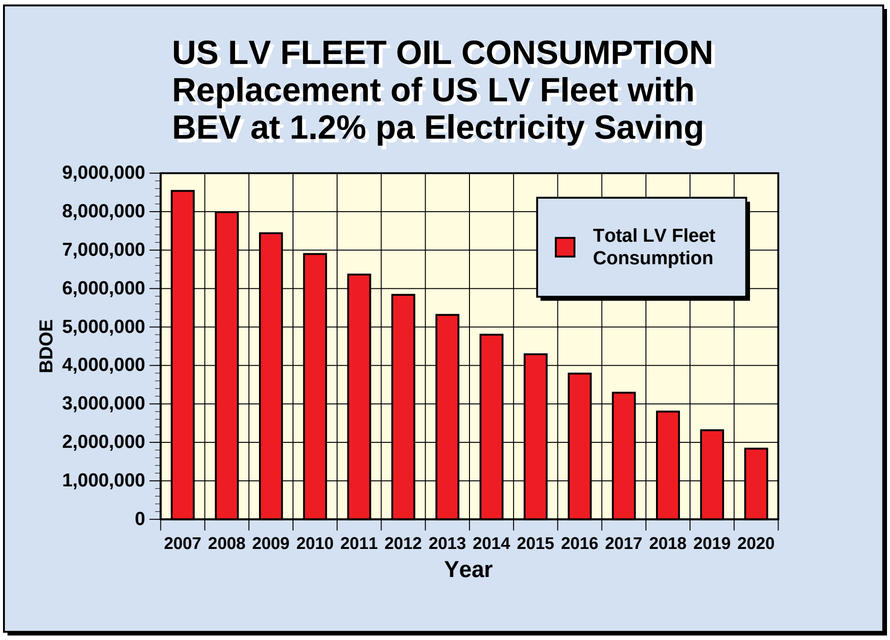
In this next scenario, we apply a constant 1.2% annual reduction in electricity consumption to the 2002 base year of 3651 billion kWh of

1. “The Technical, Economic and Achievable Potential for Energy Efficiency in the USA: A Meta Analysis of Recent Studies”, American Council for an Energy Efficient Economy, 2004, S. Nadel, A Shipley, R Elliott

electricity consumption in the USA. We assume that due to future energy supply constraints, no growth is allowed in future electricity production or consumption - instead, energy efficiency allows the same or more work to be achieved with less energy.

If the 1.2% of electricity saved each year was converted to power BEVs, the remaining petroleum consumption required each year from Year 1 to 15 is shown below in Figure 58.

FIGURE 58



- If a 1.2% annual reduction in US electricity consumption was used to power a growing fleet of Battery Electric Vehicles, and this was the only road transport oil saving measure introduced, US oil consumption by the Light Vehicle Fleet would fall from 9.1 M b/d in 2005 - 06 to 1.8M b/d in 2020.

US electricity savings transferred over this timescale to power EVs would be only 14.5% of current consumption.

By 2020, there would be 190 million EVs on the road and oil consumption (assuming no improvement in fuel efficiency of the remaining petrol cars, which continue at 20.68mpg) would have fallen to 1.8Mb/d. At 100mpg, this remaining oil consumption would have also fallen to 0.37Mb/d.

Clearly, greater savings can be made more quickly in electricity consumption in order to accelerate the introduction of EVs or to make net electricity savings while still switching over the petroleum powered automobile fleet to Battery Electric Power.

11.11 Conclusion

The means for reducing oil consumption quickly and dramatically to maintain the supply of energy which drives our modern world are straightforward.

The preceding analyses show that a number of technologically achievable measures would be more than sufficient to meet the challenge of Peak Oil and Declining Oil Supply over the next 25 years.

Rather than a crisis of energy, we seem to have a crisis of inertia and a crisis of will. In particular, we have a crisis of ignorance and unconsciousness which is inexcusable.

It can be clearly seen that our current utilisation of energy is criminally profligate and irresponsible. Oil is far too valuable as a chemical feedstock to waste as a fuel.

The basic technology of the Plug-In Hybrid car would fit seamlessly into the existing global refuelling infrastructure and reduce fuel consumption by a factor of at least 4.

Road fuel consumption could be cut to 20% of current levels as quickly as manufacture of vehicles was switched to the Hybrid Car with a mandatory minimum fuel economy of 100mpg. These vehicles should be Plug In Hybrids with the ability to drive for at least 50 miles on battery power alone.

The Challenge of Peak Oil can be overcome with this one simple and direct strategy.

Indeed, aftermarket PHEV modifications of the Toyota Prius can already achieve up to 150mpg, such as the testbed demonstrated by EnergyCS and EDrive in mid-2005.

National Governments must act unilaterally to mandate that no new vehicle will be allowed onto the road after 1st January 2007 that does not meet this basic criterion - 100mpg. This gives the car manufacturers something over one year to dedicate their design and manufacturing resources into producing these vehicles. This is not beyond the bounds of achievability: most car manufacturers are already developing conventional Power Assist Hybrids. They simply need to bring forward the development of the next logical step - the Plug In Hybrid.

At the same time, incentives should be put in place to encourage sales and development of pure Battery EVs with a progressive switch over to Battery EVs and a recharging infrastructure programmed between 2010 and 2020.

To those who believe that the whole matter should be left to market forces, it is worth quoting from the EIA's 2005 Annual Energy Outlook, when commenting on advanced technology motor vehicles:

"About 80% of advanced technology sales are as a result of Federal, and State mandates for fuel economy standards, emissions programmes or other energy regulation.

In the AEO2005, the majority of projected hybrid, fuel cell and electric vehicle sales result from compliance with low emission vehicle programmes in California, New York, Maine, Vermont and Massachusetts".

In conjunction with this strategy, national mandatory energy efficiency standards must be implemented across the board in 2006 to require significant savings in electricity consumption. National Programmes similar to the UK's very successful national "Save It!" campaign of the 1970s must be implemented forthwith. National and International targets for Reducing Oil Consumption must be set in accordance with falling oil supply: a 10% per year saving is possible and should be implemented.

Implementation of this strategy must be a global priority.

It goes without saying that real priority must also be given to developing significant renewable electricity generating capacity to replace Oil and Natural Gas in the electricity generating sector. Existing nuclear power and coal fired power stations can be progressively replaced with a mixture of renewable power and if necessary the safer nuclear technology of Accelerator Driven Fission.

The current proposals by Senator Joseph Liebermann to mandate 10% of car sales as Hybrid Vehicles from 2007 is a step in the right direction. It would be more effective to specify minimum fuel economy standards for all vehicle types.

12 Fuel for The World Airline Industry

12.1 Introduction

The world economy is now dependent on the smooth functioning of Global Air Transport. Air Transport is the glue which binds the world together. Global commerce flows along the arteries and veins of the airways. The aircraft are the corpuscles which transport the necessary articles of commerce from place to place.

However, the World Airline Industry is particularly sensitive to rising fuel prices, due to the tight margins on which it operates and intense competition. Jet Fuel prices are already at unsustainable levels.

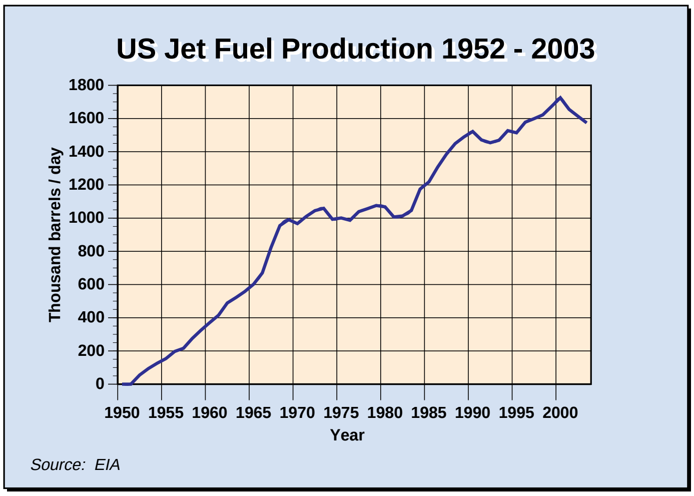
Therefore the threat that rising oil prices and reduced fuel availability poses for the Air Transport Industry is of the utmost seriousness.

There is no viable short term alternative to oil as the energy source for civil aviation. For that reason it is doubly important that Oil Consumption Reduction measures are implemented in road transport to release and safeguard fuel supplies for essential air transport services, particularly freight, cargo and logistics.

12.2 Historical Jet Fuel Demand

Growth in demand for Jet Fuel since the early 1950s has only ever slowed down or fallen due to war or a major geo-political event, as can be seen from Figure 59 below.

FIGURE 59



US Demand for Jet Fuel grew at an annual average rate of 2.3% between 1993 and 2000, the latest period of growth free of artificial economic or geo-political shocks.

In 2000, US production of jet fuel reached 1.73M barrels a day. If the future was to follow the past, we could expect to see growth resume at between 2% and 3% per annum barring renewed global uncertainty.

12.3 Future Fuel Availability

World Jet Fuel Consumption in 2000 was 160 million tonnes or 60 billion USG. The US airlines account for 18 billion USG or 30% of this.

World Jet Fuel consumption is therefore equivalent to 3.97Mb/d or 4.9% of global oil production.

In their latest Global Market Forecast, Airbus predict that 16,600 new passenger aircraft will enter service between 2004 and 2023.

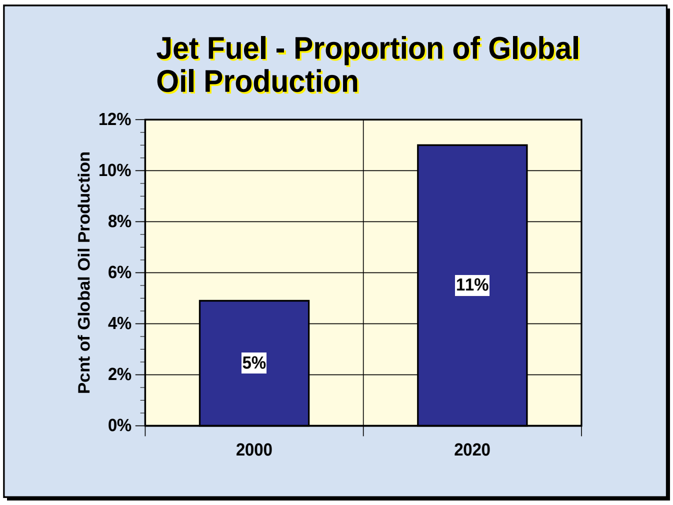
Airbus forecast that Air Passenger Traffic (RPKs) will triple and that flight departure frequencies will double in this period.

Even allowing for fuel efficiency gains and a shift to larger aircraft, unconstrained Global Demand for Jet Fuel will rise by at least two thirds as frequencies double between now and 2023 to over 260M tonnes or 100 billion USG. This will be over 6.6M b/d.

In the same period, Global Oil Production will decline by over 20%, from 85M b/d to 60M b/d.

Therefore, fuelling the world's airlines in 2023 will consume 11% of Global Oil Production at that time, compared to 5% today.

FIGURE 60



- In 2020, Jet Fuel will consume twice as high a proportion of global oil production as it does today, assuming unconstrained growth of the World's Airlines.

Needless to say, this situation is very unlikely to be realised (unless road fuel consumption is reduced to compensate). In fact, the jet fuel situation will be even more constrained for reasons discussed below.

Accelerated Decline in Jet Fuel Availability

Jet Fuel supply is doubly hit by declining oil production and increasing dependence on Middle Eastern crude.

25% of a barrel of North Sea crude oil is made up of Jet Fuel fractions.

Only 8% - 10% of a barrel of Saudi crude will produce Jet Fuel. This will be exacerbated as Middle Eastern production shifts to even heavier, sulphur containing crude oil.

Therefore, not only will oil production decline - the fraction of that oil that can produce Jet Fuel will also decline.

In 2020, the Forecast Demand for Jet Fuel will exceed Supply by a factor of 2 even without this fall in the quality of oil.

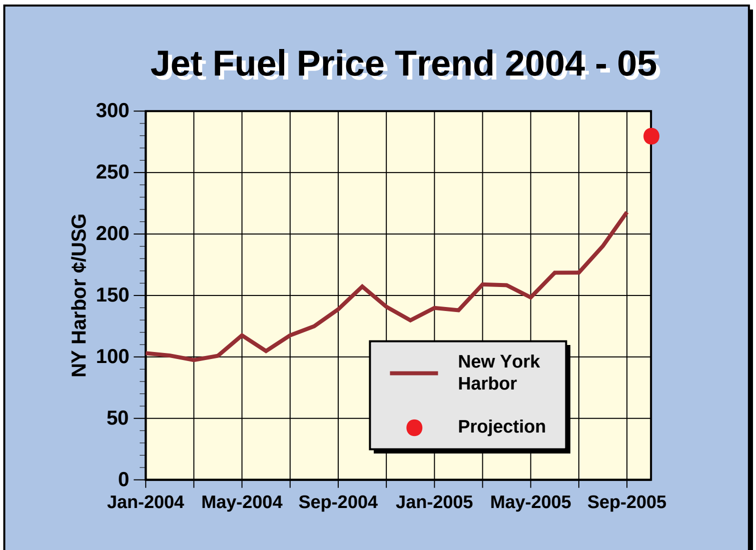
The growth in airline traffic currently predicted by the industry is unlikely to materialise, unless radical innovation is introduced to reduce fuel consumption and increase the fuel efficiency of aircraft.

12.4 Future Fuel Costs

According to the ATA, fuel is the second largest direct operating expense for the airlines after labour. It ranges between 10% and 25% of costs. Even for business jet operators, fuel can account for up to 40% of Direct Operating Cost (DOC). The average spot price of jet fuel is currently over $2.00 per USG, close to 4 times the level of the late 1990s. (Update October 2005: Jet Fuel touched $120/barrel or $2.80/USG).

Figure 61 shows the progression in spot Jet Fuel prices between January 2004 and September 2005.

FIGURE 61



Source: EIA, ATA

Since the beginning of 2004, the spot price of Jet Fuel has risen from $1.00/USG to well over $2.00/USG and at one point approached $3.00/USG in late September 2005.

Since mid-2003, the price of Jet Fuel had tripled from 77¢ to $2.20 in September 2005.

Even before the twin hurricanes of September 2005, the price of Jet Fuel had accelerated to $1.90 in August.

IATA warned in April 2005 that the world's airlines would lose $5.5 billion this year if oil averaged $43 a barrel in 2005. The price of oil has not been below $50 and has been over $60/USG since late June.

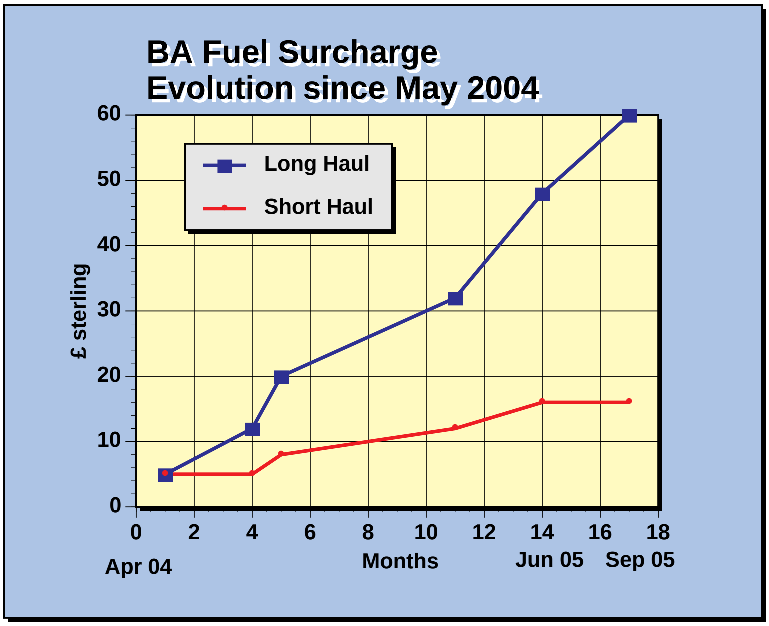
John Heimlich, Chief Economist of the ATA stated in November 2004 that for the US airlines to break even, oil has to be below $31 a barrel.

Both CIBC World Markets and Goldman Sachs predict that oil will cost over $100 a barrel by 2010. This seems conservative given it is already over $60.

Therefore it is apparent that as oil prices continue to rise into 2006 and beyond, we are on the verge of witnessing the greatest upheaval and restructuring of the airline industry imaginable.

Since introducing a Fuel Surcharge in May 2004, British Airways have increased it 5 times. A long-haul return flight now has a £60 ($100) fuel surcharge; a short haul return flight, £16 ($30).

FIGURE 62 **BRITISH AIRWAYS FUEL SURCHARGES**



In July 2005, Alitalia increased its single leg European fuel surcharge from 5 euros to 30 euros.

Airline Financial Implications

Each 1¢ increase in the cost of fuel adds $190 million in costs to the US airlines (based on latest ATA projected jet fuel consumption of 19 billion USG in 2005).

Between January and July 2005, month on month US airline fuel expenditure[1] had risen on average by 44% compared to 2004, while fuel consumption itself had risen by only 5.1%. But even by the end of 2004, fuel had risen to account for 20% of operating costs for the 6 largest US carriers. Therefore, with the increases of 2005, fuel may now be accounting for over 30% of operating expenses.

1. ATA Monthly Jet Fuel Report, www.airlines.org

The price of Jet fuel has risen from $1.30 in January 2005 by more or less $1 per USG. 19 billion USG of consumption at an extra $1/USG leads to an extra $19 billion in annual operating costs. This is equivalent to the entire operating expenses of American Airlines in 2004. The majority of the US carriers are fairly lightly hedged against fuel price increases: only Southwest has significant hedging and Continental have none at all. Smaller airlines have no opportunity to hedge themselves.

If the price of JetA had remained at $1.30 during 2005, we estimate (based on ATA figures) that fuel expenditure by the US major, national and regional airlines would have been in the order of $25.7 billion. If we assume that JetA stays at $2.00 per USG between October and the end of 2005, total fuel expenditure will in fact be about $31.1 billion - an increase of $5.4 billion. If Jet A increases to $2.50 by the end of the year, total fuel expenditure will reach $32.4 billion.

The financial results in 2002, 2003 and 2004 of the top 7 US carriers are shown below.

TABLE 33 **US MAJOR AIRLINES FINANCIAL RESULTS 2002 - 04**

Figures in 000s	Operating Revenue 04	Operating Expense 04	Net Income - 2004	Net Income - 2003	Net Income - 2002
AMR	18,645,000	18,789,000	(761,000)	(1,228,000)	(3,511,000)
Continental	9,744,000	9,973,000	(363,000)	38,000	(451,000)
Delta	15,002,000	18,310,000	(5,217,000)	(790,000)	(1,295,000)
Northwest	11,279,000	11,784,000	(878,000)	236,000	(798,000)
Southwest	6,530,000	5,980,000	313,000	442,000	240,969
UAL	16,391,000	17,168,000	(1,144,000)	(2,808,000)	(3,212,000)
US Airways	7,117,000	7,495,000	(611,000)	1,451,000	(1,646,000)
TOTAL	**84,708,000**	**89,499,000**	**(8,661,000)**	**(2,659,000)**	**(10,672,000)**

In 2004, these 7 carriers accounted for 77% of the Revenue Passenger Kilometres (RPKs) carried by all US airlines. Therefore of the minimum $5.4 billion in extra fuel costs expected in 2005, $4.1 billion (at an approximation) will fall on these 7 carriers. In fact, it will fall on the top 6 excluding Southwest, who are 85% hedged.

Conclusion

If action is not taken to reduce fuel consumption in other transport sectors, thus freeing up oil supplies for Jet Fuel production, the World's Airline Industry will be the first to suffer from oil supply constraints and will be the most severely affected. As of early October 2005, signs of strain were starting to appear. Northwest and Delta airlines both filed for bankruptcy and American Airlines announced the cancelling of flights due to fuel prices.

12.5 Airframe Design Solutions

If measures are taken without delay to start introducing significant fuel saving technologies for entry into service in 2010, some of the effects of declining fuel availability could be mitigated.

The next generation of aircraft planned for the next decade must prioritise Fuel Efficiency or propulsion technologies that minimise the use of oil.

Blended Wing Body

The McDonnell Douglas Blended Wing Body programme, which was under active development in 1997, was projected to be 27% more fuel efficient than the equivalent sized conventional design.

FIGURE 63 **BWB**

The project was cancelled when Boeing took over McDonnell Douglas.

The Boeing 754

The Boeing 754 Lifting Fuselage design (based on the original Vincent Burnelli Lifting Fuselage designs) was intended to be Boeing's first medium widebody twin engined aircraft. After orders were placed by Cargolux for the cargo version the project was cancelled in favour of the 767.

On payload-range basis, the Boeing 754 would have been twice as fuel efficient as the 767.

The following illustration appeared on the front cover of the 1975 Cargolux Annual Report after the airline became a launch customer for the B754.

FIGURE 64 **PROPOSED BOEING 754**

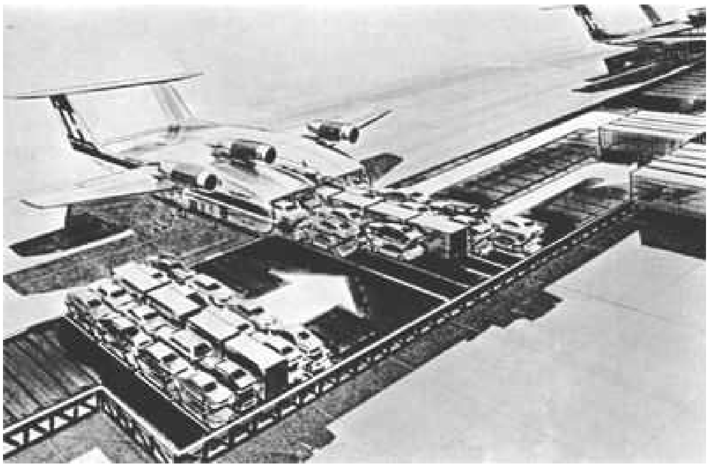


TABLE 34 **LIFTING FUSELAGE 754 vs 767**

	OEW (lbs)	Max Payload (lbs)	Max ZFW (lbs)	Max Fuel (lbs)	MTOW (lbs)	Container Vol (ft3)
B754	159,600	160,600	320,200	143,375	363,900	19,656
B767	179,580	72,770	253,000	112,725	335,000	-

In the words of the Burnelli Company:

"The twin engine Burnelli type B-754 had a maximum containerized payload of 160,000 lbs., while the B-767 could only carry less than half, 72,770 lbs., non containerized. In short, the Burnelli type could carry more than double the payload and fly it 1,200 nautical miles further than the B-767".

It has been demonstrated many times that the apparently low aspect ratio of the lifting fuselage design does not lead to high induced drag: the important factor is wetted aspect ratio, not aspect ratio per se.

12.6 Ultra Efficient Engine Technologies

The Ducted Fan

The P&W Advanced Ducted Propulsor was initially chosen by Airbus as the sole powerplant offering on the A340-500/-600. GE also proposed an Ultra High Bypass ratio (UHBR) turbofan as an alternative engine choice.

Ducted Fans have achieved thrust increase of 35% over a conventional unducted propellor for the same fuel consumption. Use of Coanda profiles within the duct itself could further increase efficiency. Active Noise Control systems are being developed to reduce the noise of this propulsion technology below Stage III.

MTU's Contra Rotating Integrated Shrouded Propfan (CRISP) would achieve 20% lower Specific Fuel Consumption (SFC) than a conventional 5:1 bypass ratio turbofan (and a 20% NOx reduction). Bypass ratios of over 15:1 would be used in practice.

Semi Constant Volume Combustion

An effective way to improve fuel efficiency in jet engines is to use the constant volume Atkinson Cycle rather than the constant pressure Brayton cycle. This could improve SFC by 40%.

Regeneration and Recuperation

Many tests have been carried out over the years on use of heat exchangers to recover waste heat from the turbine exhaust to pre-heat the air entering the combustor. Significant fuel efficiency gains can be made and modern light weight heat exchangers have been tested on turboprop testbeds.

Semi Closed Cycle Turbine Engines

The SCTE recirculates a proportion of the gas leaving the high pressure turbine into the inlet air.

The specific power of current engines could be doubled for the same SFC with this approach.

Closed Cycle Engines

The most efficient turbine engine would use a closed cycle. The working fluid would be a volatile low boiling point liquid (such as a refrigerator fluid). Due to the volatility and low specific heat capacity of the working fluid, greatly reduced thermal energy input is required to drive a turbine in comparison with air. The turbine could then be used to drive a propulsion fan in the normal way.

Bladeless Turbines

The parallel flat disk bladeless turbine is an overlooked technology that can offer a much higher power to weight ratio than conventional bladed turbines. The turbine is driven by the viscosity and adhesion of the working fluid to a set of closely spaced parallel rotatable disks. The principle is used in artificial hearts for pumping blood, where turbulence must be minimised. Lack of turbulence indicates high efficiency.

Hydrogen and Fuel Cell Technology

Although Boeing are developing a Solid Oxide Fuel Cell APU which would be potentially more fuel efficient than a conventional APU, this will do little to reduce overall fuel consumption.

The main drawback of fuel cell technology is its expense - and for aircraft applications, its high weight.

The application of fuel cells to primary aircraft propulsion will not be feasible for many years. A completely new technology of electrically driven turbine engines would also have to be developed to operate from the electricity generated by the fuel cells. Research in this direction is being undertaken at the NASA Glenn Research Centre.

Hydrogen

The use of hydrogen as a fuel for conventional jet engines is in our view unrealistic. The first issue is the source of the hydrogen. Most hydrogen today is produced by steam reformation of methane - natural gas. It is also produced as a by-product of catalytic cracking of hydrocarbons in an oil refinery. In both cases, the source is fossil fuel. The second problem is the energy balance. Only electrolysis of water can provide a viable renewable source of hydrogen, but the energy required to electrolyse water (with current approaches) and then compress and transport the hydrogen is prohibitive.

Resonant Pulse Electrolysis (RPE) of water is perhaps a much more efficient way to produce hydrogen that could be used to produce hydrogen on board a vehicle as needed from water. This technology has never been commercialised, although a Canadian company Xogen Power were attempting to do so.

Instead of electrolysis with Direct Current, a pulsed current is used with a Pulse Repetition Rate at a harmonic of the Hydrogen - Oxygen bond longitudinal frequency. This resonates the bond and breaks it for less energy than required in DC electrolysis.

Other researchers who have developed non-commercialised RPE systems include Puharich, Horvarth, Meyer, Mittelstadt, Pacheco, Inoue-Japax and Hayakawa.

12.7 Bio Jet Fuel

Biodiesel has not been used in commercial aircraft up to now due to its high freezing point. Jet fuel must remain free flowing at the low temperatures experienced by commercial aircraft in flight, i.e. down to minus 40˚C.

Bio Jet Fuel can be produced as a blend that contains 40% biodiesel and 60% fossil JetA. By extracting and using only the low freezing point esters from biodiesel, the bio jet fuel blend can meet the required operating temperature constraints. However, the efficiency of extracting only these low freezing point esters has been too low to make this worthwhile.

In a recent development[1], researchers at Purdue University have developed a process that greatly improves the efficiency of this extraction process. The high freezing point esters left over can be used for road fuel, so nothing is wasted.

However, the area of land required in the developed world to grow sufficient soya or canola to replace Jet Fuel supply would be impracticably large.

Germany produces about 400 million litres of biodiesel a year from 300,000 hectares of canola: in other words, 1% of German diesel consumption is supplied by 2.5% of Germany’s arable land.

Assuming the same yield of 350 USG or 8.4 barrels per hectare, 51 million hectares of land would be needed to supply US jet fuel demand and over 170 million hectares to supply current world jet fuel demand. This area is equivalent to the entire arable land of the USA.

Jatropha

Other oil producing plants grown in the tropics such as Jatropha may promise higher yields. The UK company D1 Oils plc claim[2] that 125,000 hectares of Jatropha would supply Germany’s 376M litres of biodiesel, i.e. it produces 2.4 times as much oil per hectare as canola or about 3000 litres of biodiesel per hectare. On this basis, 70 million hectares of Jatropha plantation would be needed to supply current world jet fuel demand. To this would need to be added sugar cane plantations to produce sufficient ethanol to produce biodiesel from the Jatropha vegetable oil.

Jatropha is a non-food plant that grows on marginal or arid terrain not suitable for food producing crops. The company D1 Oils plc have options to plant 9 million hectares with Jatropha in the tropics. One can

1. “Soya Powered Airplanes Promise Greener Air Travel”, New Scientist 26/3/04
2. “Out of Africa: Could Jatropha Vegetable Oil be Europe’s Biodiesel Feedstock?”, Phillip Wood, D1 Oils plc, Refocus, July - Aug. 2005, P40

envisage in the future that South America, Africa and South East Asia could feasibly grow enough Jatropha to supply a significant fraction of the World's Jet Fuel.

The likely yield of Jatropha oil from marginal or reclaimed land will be much lower than the 3000 litres per ha claimed by D1 Oils. For instance, India has some 130Mha of waste land of which 33Mha have been identified as suitable for Jatropha. 20-30% of this 33Mha or 10Mha have been allocated for planting with Jatropha over the next 10 years.

It is estimated that on this poor quality land, cultivated by small farmers lacking in capital resources, the yield will actually be about 1000 litres per ha. This is in line with the forecast that 10M tonnes of Jatropha will be produced per year when this 10Mha of land is in production - i.e. 10Gl in total or 1000l/ha. This is equivalent to about 175,000 B/d.

Much of this oil will be used for road transport. Like other vegetable oils, Jatropha oil can be used directly as a fuel either by itself or blended with conventional diesel, which avoids the need for transesterification and a supply of ethanol. For use as bio-jet fuel, it would need to be trans-esterified with ethanol.

If 40% of current global Jet Fuel consumption of 60 billion USG was to be replaced with bio jet fuel, the required production would be 24 billion USG. At 1000 litres per ha, 91.2M ha of land planted with Jatropha would be required. But if yields could be increased to 2000l/ha, this would fall to 45.6M ha and if the optimistic D1 Oils figure of 3000l/ha could be achieved for a developed mature industry, then only 30.4M ha would be required - equivalent to the amount of waste land already identified as suitable for Jatropha in India alone.

It will however only just be feasible for India, with an enormous amount of waste land (130Mha, equivalent to 75% of total US arable land), to plant 10Mha with Jatropha over the next 10 years. It will therefore take some years for global biodiesel production to make a truly significant contribution to road transport. If the very optimistic figure of 3000 litres per ha is used, total production of Jatropha biodiesel from this 10Mha would eventually be 525,000 B/d or 7.9 billion USG per year, compared to current Indian oil consumption of over 2.2Mb/d. However, that 7.9 billion USG would be 13% of global Jet Fuel consumption - a very significant contribution.

It would therefore make more sense to prioritise use of biodiesel for Air Transport and convert Road Transport to the available alternative of electrical power.

Table 35 shows the variation in the quantity of biodiesel that could be produced as yield and the area of land under cultivation increases.

TABLE 35

JATROPHA - POTENTIAL BIODIESEL PRODUCTION

Yield	Area of Land Under Cultivation				
	10M ha	20M ha	30M ha	40M ha	50M ha
1000l/ha	2.6G USG	5.2G USG	7.8G USG	10.4G USG	13G USG
2000l/ha	5.2G USG	10.4G USG	15.6G USG	20.8G USG	26G USG
3000l/ha	7.8G USG	15.6G USG	23.4G USG	31.2G USG	39G USG

Using an average yield of 2000l/ha, 30Mha of Jatropha would allow 25% of world jet fuel consumption to be replaced with biofuel.

Conclusion

In the near term, security of fuel supply for the air transport industry can best be maintained by reducing fuel consumption in the road transport sector. Road transport has the technological means and manufacturing capability to achieve very significant fuel reductions quickly by switching to electrical propulsion.

Air transport will however remain completely dependent on liquid hydrocarbon fuel for at least the next 20 years. As global oil production continues to fall, large scale expansion of biodiesel production in the tropics could make a very significant contribution to Jet Fuel supply and could in principle completely replace fossil Jet Fuel. At a yield of 1000l/ha, 228Mha of biodiesel producing plants could theoretically supply all current Jet Fuel demand of 60 billion USG. (The yield of low freezing point esters would in fact be lower). This is a very large amount of land but less than twice the already known waste land in India alone. It will take many years to do it, but a policy of prioritising biodiesel production for Air Transport, which only uses 5% of world oil supply but has no alternative to liquid hydrocarbons, makes more sense than trying to use biodiesel to replace road fuel which consumes 50% of oil production.

The UNEP estimate that some 2000 million ha of land has now been degraded by human activity, 300Mha of it beyond repair. Plants such as Jatropha which will grow on marginal poor quality lands can therefore make a double contribution: the supply of fuel and the restoration or repair of damaged land. The world certainly has no shortage of land available to produce biofuel. It will shift the supply of fuel from a few concentrated geographic regions to a delocalised infrastructure throughout the developing world.

12.8 The Advanced Aerospace Propulsion Solution - Electrokinetics

Electrokinetics is a subject that many are aware of but few in the aerospace industry are prepared to speak of due to its military associations.

However, the best medium term solution to maintaining and developing Air Transport in the 21st Century is Electrokinetic Propulsion. Indeed, the Oil Situation requires it.

The basic technology has already been developed and demonstrated by pioneers such as TT Brown, Major de Seversky, Marcel Pagés and in classified US Air Force programmes.

In 2001-02, NASA were awarded US Patents 6,317,310 and 6,411,493 for an electrokinetic thruster, identical to the work of TT Brown with no reference to his prior art.

Current work into magnetohydrodynamics is in essence identical to electrokinetics.

The weekly French aerospace trade magazine Air & Cosmos published a review of Electrokinetic developments in their edition 1837 of 5th April 2002.

FIGURE 65

A detailed analysis of this technology will not be presented here. However, the Civil Air Transport industry has reached a turning point. It can only truly continue to develop and advance if it takes account of electrokinetics and electroaerodynamics.

12.9 Conclusion

The World Airline Industry must take concerted action to ensure the security of its future fuel supply. Air Transport will remain dependent on liquid hydrocarbon fuel for many years, since the jet turbine engine will remain in service for decades even if an advanced electrokinetic technology became commercially available.

To ensure this security of fuel supply, the following actions should be taken:

1. Pressure should be brought to bear by the Air Transport Industry on the Motor Vehicle Manufacturing Industry to replace current motor vehicles with far more efficient technologies, primarily the Plug In Hybrid and the Electric Vehicle.
2. Development of large scale biodiesel production in the developing world, where land is available on the scale required to produce significant quantities of fuel.

This dual strategy has the potential to ensure that as oil production declines over the next 30 years, road fuel is progressively replaced with electric power and Jet Fuel is progressively replaced by increased biofuel production.

Some growth in air transport may then be achieved by introduction of much more fuel efficient technologies. The aircraft on the drawing board now, being designed for entry into service 5 years hence, must prioritise fuel efficiency above all else.

13 Conclusion

This analysis has shown that the only effective way to respond to the exigencies of declining oil production and rising oil prices is the Electric Vehicle.

The technology of the Plug-In Hybrid Vehicle would fit seamlessly into the existing global refuelling and electricity infrastructure. The PHEV20 would reduce road fuel consumption by 50% and a PHEV80 would reduce fuel consumption by 90%.

This vehicle technology is a natural progression from the existing Power Assist Hybrid and is already on the way to commercialisation.

Over the next five years, the global automotive market will witness the following major shifts:

1. The Light Commercial Vehicle Sector will be the first to see a shift to Pure Electric and Plug In Hybrids. The sector will see exponential growth in the USA and Europe. The Market Potential is some 1.9M LCVs (up to 6 tonnes) p.a. in Europe and 1.3M Units (Commercial Class 1-3) p.a. in the USA.
2. The US Public Transit Bus Fleet will see a complete shift to the Series and Parallel Hybrid technologies, progressively enhanced with Plug In capability. The Market Potential is some 27,000 units per year.
3. The Power Assist Hybrid will become the base global Motor Car Platform but will rapidly metamorphose into the Plug In Hybrid. The first PHEVs will reach the market by 2008. The eventual Market Potential for the PHEV20 is 50% of the global LV market, i.e. 30M units p.a. in 2005 reaching 50M units p.a. by 2020.
4. Pure Battery EV product launches will multiply for household second cars in Japan, Europe and the USA, as battery prices fall with the growth in Hybrid production. By 2010, 5% - 10% of global LV production will be Battery EVs, i.e. 3M to 6M units per year.
5. A mass entry of Chinese vehicle exports into the world market will take place and the Chinese automotive manufacturers will experience the fastest growth rates of all manufacturers with new HEV, PHEV and EV products.

Biofuels as a general solution will take a long time to develop, will require too much land to supply more than a fraction of road fuel requirements and have serious questions regarding their energy balance. Biofuel use will not become significant (over 10% of global fuel consumption) until after 2010.

Fuel Cell Vehicles are too expensive, inefficient, unsafe and would require hundreds of billions of dollars in upfront hydrogen infrastructure investment. This also applies to hydrogen powered internal combustion vehicles. Hydrogen technology will be bypassed by the Plug In Hybrid and EV.

There is no doubt that the Global Automotive Industry is about to undergo a “revolution” which in hindsight will be seen to have been well overdue.