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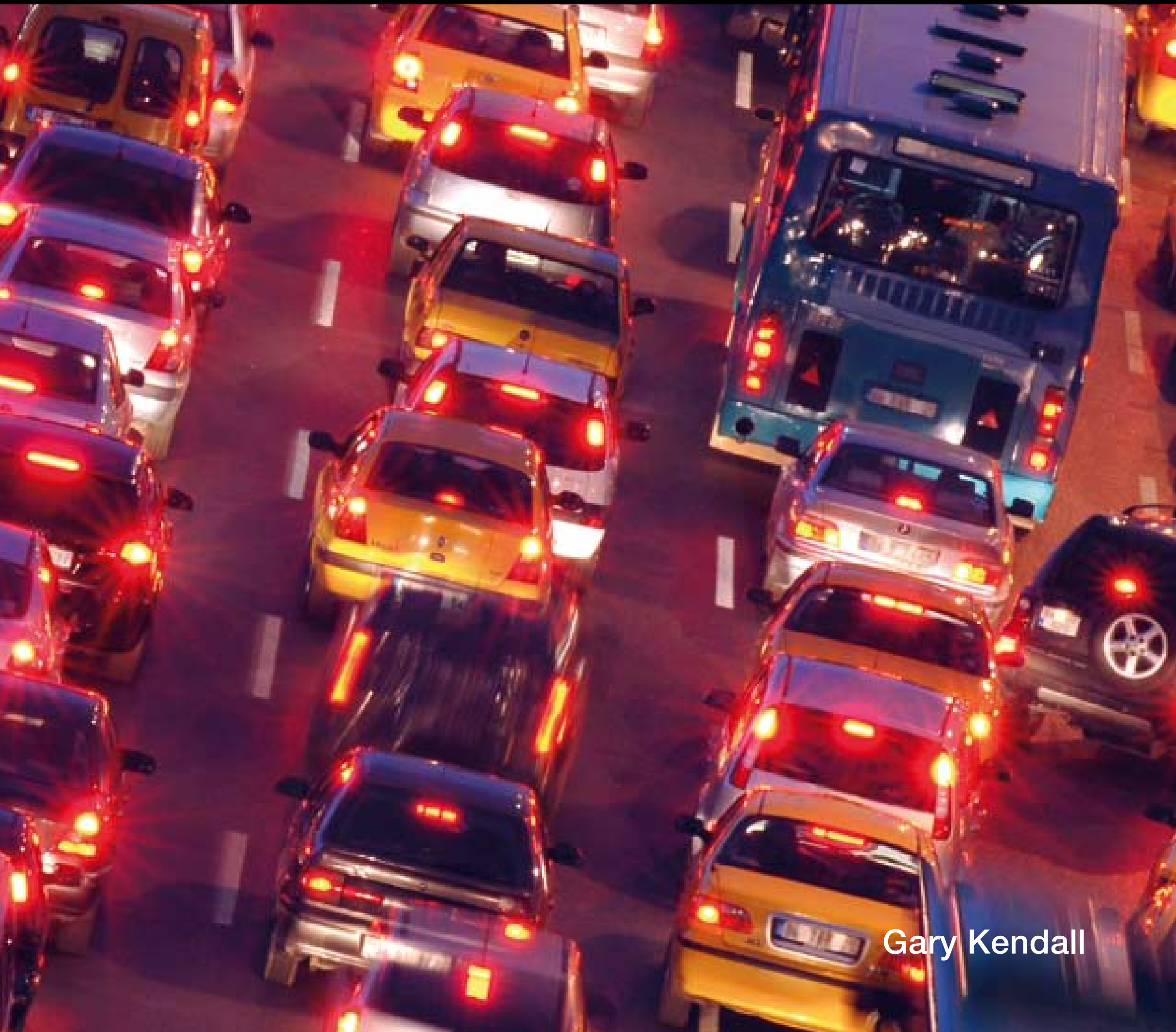
THE END OF THE OIL AGE



Gary Kendall

WWF (World Wide Fund for Nature) is one of the largest and most respected independent conservation organisations in the world. With offices in over 90 countries and almost 5 million supporters across all continents, WWF proposes solutions to stop the degradation of planet's natural environment and to build a future in which humans live in harmony with nature. Combatting climate change and reducing threats to biodiversity on land and sea are among the key priorities for WWF's work.

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THE END OF THE OIL AGE

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PART IV

LIST OF ABBREVIATIONS AND ACRONYMS

AT PZEV	Alternative Technology Partial Zero Emissions Vehicle
BAU	Business As Usual
bbl	Barrel (unit of measure: volume)
BEV	Battery Electric Vehicle
boe	Barrel of oil equivalent (unit of measure: energy)
BTL	Biomass-to-Liquids
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CNOOC	China National Offshore Oil Company
CNPC	China National Petroleum Corporation
CTL	Coal-to-Liquids
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTL	Gas-to-Liquids
HEV	Hybrid Electric Vehicle
IEA	International Energy Agency
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICT	Information and Communications Technology
IOC	International Oil Company
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-hour (unit of measure: energy)
NDRC	National Development and Reform Commission
NOC	National Oil Company
OECD	Organisation for Economic Cooperation and Development
ONGC	Oil and Natural Gas Corporation
OPEC	Organisation of Petroleum Exporting Countries
PHEV	Plug-in Hybrid Electric Vehicle
toe	Tonne of oil equivalent (unit of measure: energy)
T&D	Transmission and Distribution
UNFCCC	United Nations Framework Convention on Climate Change
WWF	World Wide Fund for Nature (formerly World Wildlife Fund)
ZEV	Zero-emissions Vehicle

PREFACE

Liquid hydrocarbon fuels derived from crude oil provide ninety-five percent of the primary energy consumed in the transport sector worldwide. There is no other sector which is so utterly reliant on a single source of primary energy, and this fuel specificity represents a unique threat to both the environment and global security.

The transport sector as a whole, which includes automotive, aviation, and marine transportation modes, is responsible for roughly one-quarter of energy-related greenhouse gas emissions worldwide, the second largest sectoral contribution after power generation. Despite growing awareness of the dangers and causes of global warming, the climate change impacts of transport have, until now, played an extremely minor role in the development of alternative fuels. Economic and political considerations are frequently addressed at the expense of the environment, and the transport sector is no exception. Many of the fuel technologies which are either under consideration or in various stages of commercialisation have environmental footprints which are significantly worse than conventional crude oil. They are developed primarily in response to energy security concerns, stoked by fears of resource nationalism as remaining crude oil reserves concentrate into the hands of the few.

In order to avert the worst impacts of climate change, the global economy must as soon as possible embark on a pathway towards decarbonisation and sustainability. Within the power sector – the number one source of greenhouse gas emissions today – a broad range of sustainable low-carbon generating options exist, many of which are becoming increasingly competitive as climate change policies penalise carbon dioxide emissions worldwide. Meanwhile, the transport sector looks set to increase its carbon footprint as the oil industry and governments are forced to exploit these energy-intensive unconventional oils to satisfy a steadily growing demand for liquid fuels. Road vehicles account for three-quarters of all the primary energy consumed in transport, thus we focus the following discussion on the automotive sub-sector.

This book will argue that the very term ‘alternative fuels’, as it is applied today, may be misleading the public and policy makers, since the fuels themselves are essentially identical to what we currently derive from conventional crude oil. These physical and chemical likenesses represent the greatest advantage of today’s oil substitutes – minimal disruption to the status quo – but also describe their fundamental limitation: they sustain our dependency on the internal combustion engine powering a mechanical drivetrain, an outdated combination which is inherently inefficient in converting stored chemical energy into motive energy.

Energy efficiency is by far the cheapest and most immediate means to reduce primary energy consumption and greenhouse gas emissions, and will therefore be an important goal in all sectors and applications. In addition to energy efficiency, there is an urgent need to accelerate the development and commercialisation of low-emissions technologies. However, while the automotive transport sector remains firmly shackled to the internal combustion engine, the best we can hope for are incremental vehicle efficiency gains which will be wiped out by the charge towards high-carbon unconventional oils.

Incremental efficiency improvements will no longer suffice. The climate change imperative – to avert catastrophe, global greenhouse gas emissions must peak and decline within the next decade – demands transformational change, which only comes about through disruption to the status quo. For the main incumbent stakeholders in the world’s transport infrastructure – from oil producing nations and corporations to automotive manufacturers – perpetuating our dependence on liquid hydrocarbon fuels is the surest pathway to continued growth and profitability in the short-term. It might be argued that in the context of climate change, their focus on short-term goals is at best myopic and at worst negligent. But this view fails to appreciate that companies are encouraged to behave this way by the rules we as a society have placed upon them. In this light, we cannot depend entirely upon today’s dominant transport solution providers to drive – or even support – a shift away from the liquid hydrocarbon paradigm any time soon.

Fortunately, there is a way out of the oil trap. Vehicles which are capable of receiving electricity from the grid will directly benefit from future emissions reductions and diversification of primary energy sources in the power sector. Thus, over time, grid-connected solutions such as battery-electric vehicles and plug-in hybrid electric vehicles – supplemented by sustainable biofuels for longer journeys – will grow successively cleaner while the energy system as a whole becomes more secure. Moreover, the electric powertrain is inherently energy efficient, up to four times more efficient than its mechanical counterpart. And, surprising as it may sound, we need not await the coming renewable energy revolution before expediting electric vehicles. Even based on today's relatively carbon-intensive energy mix, the electrification of automotive transport can deliver an immediate reduction of greenhouse gases, an improvement in urban air quality and noise levels, and significantly lower operating costs.

Coupled with concerted efforts to drive modal shift, optimise urban planning practices, and encourage behavioural change, the widespread adoption of electric powertrain technology will transform automotive mobility by helping to reduce the world's dependency on liquid hydrocarbon transportation fuels. It will create an explicit link between the traditionally separate power generation and transport sectors, thereby dramatically broadening the range of sustainable renewable energy options which can propel the world's motor vehicles. Establishing and accelerating this sectoral convergence will directly address many of the world's environmental challenges far beyond climate change mitigation, not least by relieving the mounting pressure on fragile ecosystems from relentless exploration, production, distribution, processing, and combustion of the Earth's limited hydrocarbon resources. Furthermore, the electrification of automotive transport will enhance global security by substantially reducing the sector's ninety-five percent dependency on crude oil, which has such a highly destabilising impact on the world today.

It should be self-evident that the scale of the task is enormous, but the resulting benefits will be even greater, and that is surely the very definition of transformational change. Oil companies must hasten the decarbonisation of their energy portfolios, assisted by the financial sector eliminating the incentives which reinforce existing unsustainable business models. Policy makers have an important role to play in order to remove the market barriers to electric vehicles which are cemented by our lock-in to the liquid hydrocarbon paradigm. Utilities, technology companies, and renewable energy suppliers stand to profit from accelerating the electrification of automotive transport, and should therefore be eager to establish new business models and public/private sector partnerships.

Geographically, a few key markets will be keen to adopt grid-connected vehicles: North America, the EU, Japan, and the rapidly emerging economies of China and India. The US is the world's largest automotive market, number one consumer of crude oil, and currently seeks to reduce import dependence by exploiting energy-intensive unconventional hydrocarbons. Europe is also a huge automotive market, while the EU positions itself as a leader on environmental protection – climate change in particular – and therefore represents an important focal point in terms of legislation and the setting of vehicle operating standards. Like the US, the EU also seeks ways to urgently address crude oil import dependency.

Japan imports one hundred percent of its crude oil supplies, and currently leads the world in hybrid vehicle technology, seen by many as an important step towards grid connectivity. Meanwhile, China, the "world's factory" has a relatively small automotive fleet and consequently does not suffer the same degree of lock-in as OECD nations. However, with sales of private cars growing at around twenty-two percent year on year, China recently became the second largest automotive market in the world. Its vehicle population could eclipse the US within two decades, an outlook which drives the country towards unconventional hydrocarbon resources such as coal-to-liquids. India faces many of the same challenges as its Asian neighbour, yet currently boasts the world's best selling battery-electric vehicle. Thus, initiating a paradigm shift in the Chinese and Indian markets will have a major impact both domestically and in terms of vehicle exports.

An environmentally sustainable transport sector will not be achieved through electrification alone. Additional measures to reduce overall demand through smarter urban planning, encouraging modal shift to mass transit, from road to rail, increased use of telecommunications technologies, and car sharing will make necessary and significant contributions. However, with around eight hundred million motor vehicles in the world today and that number growing inexorably, road-based transport will continue to play a vital role in the delivery of essential mobility services which underpin economic and social development. This book aims to demonstrate how automotive electrification can ease the necessary transition towards *a transport paradigm which is both highly efficient and compatible with a sustainable renewable energy future.*

“No power on Earth can stop an idea whose time has come”

Victor Hugo

PART I
CONTEXT

Sometime during the year 2008, humanity will probably pass the point at which it collectively consumes one thousand barrels of crude oil *every second of every day*.[1] More than half of it – and the share continues to rise – is dedicated to the movement of goods, services, and people. Oil-based transportation enables economic activity to take place, provides access to a range of welfare services and, for many, affords lifestyle choices which were unimaginable 150 years ago.

Despite the pivotal role which oil is playing during the early years of the 21st Century we are, without a doubt, entering the twilight of the Oil Age. Energy analysts generally agree on the five key factors which will fundamentally alter the energy landscape in the coming years: rising demand; dwindling supply; greater concentration of resources in the hands of a few; limited spare capacity; and the environmental impacts of energy use.

As the bright green cliché puts it, the Stone Age did not end because we ran out of stones.* Nor will the Oil Age end for lack of oil. Perhaps it is more instructive to reflect that the world did not exhaust its capacity to manufacture chlorofluorocarbons (CFCs) either. Scientists discovered the destructive impact these compounds were having upon the Earth's ozone layer and – aided and abetted by the environmental movement – raised the alarm. Governments negotiated and signed a binding international protocol limiting CFC use, and industry set

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* *The well-worn "Stone Age" cliché is usually attributed to Saudi Arabia's OPEC minister Sheik Yamani in the 1970s.*

to work developing alternatives. This success, while admittedly on a much smaller scale than the energy revolution we face, provides an inspirational model for concerted global actions.

The five factors mentioned above are creating a perfect storm, in which dramatic and irreversible change to the global energy system is unavoidable. We can choose to face up to this change, even embrace it, and stride purposefully towards an energy system which is clean, secure, and equitable. Or we might attempt to ignore it, eventually be overwhelmed by it, and suffer catastrophic consequences as a result of our collective lethargy. If politicians, business leaders, and civil society are able to summon the courage necessary to proactively transform our energy system, there will undoubtedly be winners and losers. If they do not, it is extremely difficult to envision any winners at all.

This book is intended as a positive contribution to the debate as to how we may begin to manage this challenge, particularly with respect to climate change. The focus is firmly on the *transformation* of the transport sector, which is ninety-five percent dependent on crude oil today. There is no other sector which suffers from this high degree of fuel specificity, thus transport represents a unique threat to both environmental integrity and energy security. We begin by asking: how on Earth did we get here?

LESSONS FROM HISTORY

As mortgage and pension fund managers are quick to point out in their tiresome disclaimers: “Past performance is no guarantee of future results”. The operative word here is *guarantee*: there is always an element of risk in predicting what the future might hold. While we await the invention of a reliable crystal ball, the best way for us and the fund managers to mitigate such risk is through the analysis of historical trends.

We persist, therefore, in acquiring data, performing literature surveys, compiling and distributing information. However, thanks to Mr. Google and those of his ilk, the currency of information is fast depreciating: today we can all afford to ‘find out more’. And how much more there is; we are positively drowning in data. We may be living in the Oil Age but, as we are frequently reminded, this is also the Information Age.

Data might be ever cheaper, but wisdom – that is, a profound understanding of what lurks behind the data – is not. It may be getting easier to obtain historical information, but it takes much more effort to really comprehend why something happened the way it did, particularly if it didn't happen to us. Perhaps that is why we seldom seem to pay enough attention to the experiences of our predecessors: when we face new challenges, we content ourselves with grasping 'the key points', filling in any gaps with broad assumptions, and then we make our decisions and act on them with conviction, secure in the knowledge that we are doing 'the right thing'.

Wisdom might be rare, but *conventional* wisdom is not; if anything it is the cheapest commodity of all. *"Energy efficiency is the easiest way to reduce greenhouse gas emissions." "Oil companies should increase their investments in alternative energies." "High oil prices are good for the Renewable Energy industry."* These statements are all uncontroversial in today's environmental movement – and on first inspection they may appear to provide a sound basis upon which to build our climate change strategies – but, as this book will illustrate, a statement is not guaranteed to be accurate just because it is widely accepted or frequently repeated.

Might we dare to learn from what has happened in the past? Are there any precedents for the huge challenges that we now face? The answer to both questions is yes: in fact, the rich history of crude oil conjures a tantalising vision of an alternative energy path. We have been here before, the future has already happened. We simply need to make it happen again.

Wonderful Crude Oil

In a world indifferent to environmental issues, not least carbon dioxide emissions, it is safe to say that crude oil is a vastly superior source of primary energy to any we have yet imagined. Oil's great advantage lies in its physical state at ambient temperature and pressure: it is a liquid. This property bestows the combined strengths of energy density and ease of application. And it's also incredibly cheap, considering the extraordinary benefits human beings have enjoyed since the dawn of the Oil Age some one hundred and fifty years ago. It is easy to see how we have allowed ourselves to become so completely dependent on it.

Oil is the yardstick by which other energy sources are measured. We continue to use 'barrel of oil equivalent' (boe) as a unit of primary energy, and we reference the market price of crude oil in economic assessments of energy alternatives from coal to biomass. Oil has created a lifestyle of opportunity and privilege which would have been inconceivable prior to E. L. Drake's 1859 discovery of 'rock oil' in Pennsylvania. Today, crude oil provides more of the world's primary energy than any other resource – roughly forty percent of the global total – and that leading position looks unassailable for the foreseeable future, as figure 1 illustrates.

Human civilisation, as we understand the term, has been surfing a thick black wave of petroleum ever since commercial whaling became the oil industry's first casualty.[2] Kerosene, initially distilled from bituminous tar, began to displace whale oil – or biofuel[*] – from the lighting sector as whales became increasingly scarce and the market price of blubber rose. Whale products had themselves displaced tallow, an earlier form of bioenergy derived by rendering bovine fat,[3] from the 18th Century candles that once dominated the lighting sector. Ironically, in creating a cheap and plentiful source of kerosene, the birth of the oil industry coincidentally saved many species of whale from extinction and was therefore a major environmental coup at the time. There are some astonishing parallels between the rise and fall of the commercial whaling industry and the challenges faced by the oil industry today, and we would do well to pay them heed.[4]

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[*] *'Biomass' is broadly defined as the totality of living matter, including plants and animals. The term 'bioenergy' refers to the subset of biomass which is used to derive energy. In this book, the term 'biofuel' refers to liquid transport fuels derived from biomass.*

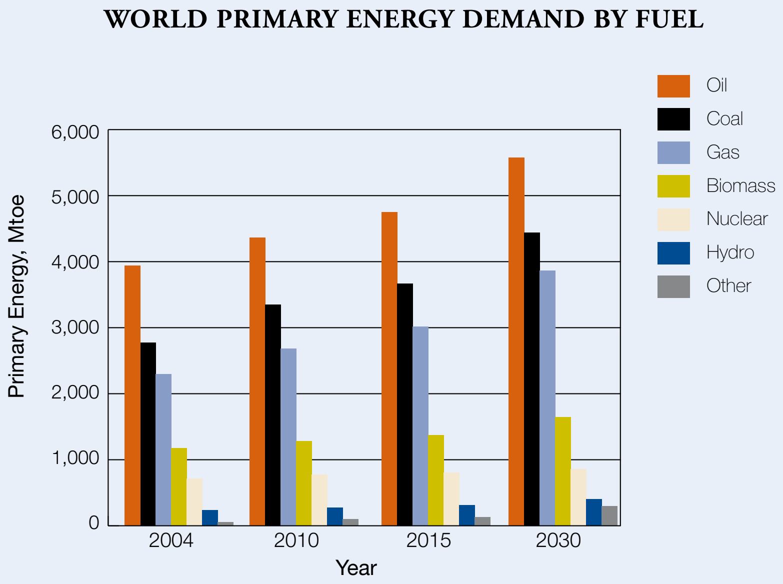


Figure 1. Projected evolution of the world's primary energy demand by fuel, according to the IEA World Energy Outlook 2006 "reference scenario" (data for 2004 are actual).[5]

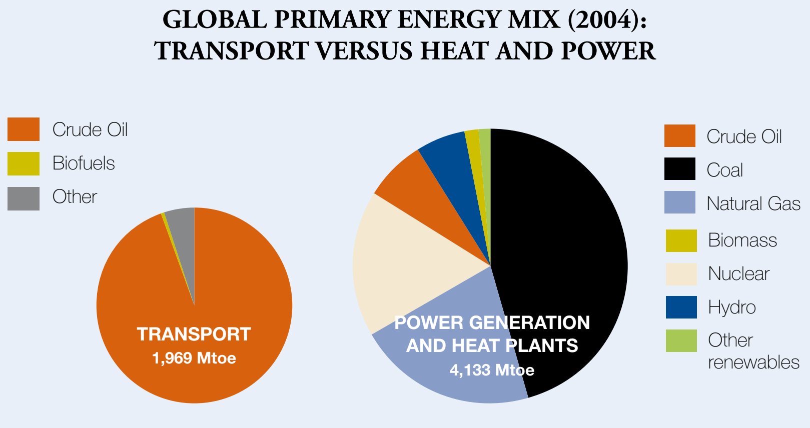
Transport Equals Oil

Crude oil's dominance of the lighting sector was relatively short-lived. With the advent of the electrical era in the late 19th Century, the kerosene lamp was itself displaced by Thomas Edison's electric light bulb, which offered manifold advantages not least in terms of safety and convenience. This was in fact the oil industry's first crisis: it found itself virtually on its knees as crude oil prices hit rock bottom due to rapidly falling demand for its primary product. It is no exaggeration to say that the timely arrival of the automobile saved the oil industry, and the fortunes of these two industrial behemoths have been inextricably linked ever since. As Rob Routs, Executive Director of Shell's Downstream business, told an automotive conference in Amsterdam recently:

> *[S]ince the marriage of fossil fuels and the internal combustion engine some hundred years ago, the fortunes of our industries have been tied together.*[6]

Today, approximately ninety-five percent[*] of the primary energy consumed in transport derives from crude oil,[7] so it is safe to conclude that the transport sector[†] is utterly reliant on crude oil. In fact, it would be more accurate to say that the transport sector is utterly reliant on *liquid hydrocarbon fuels* (such as gasoline,[‡] diesel, and jet fuel) which have, until recently, been most economically derived from conventional crude oil.

This level of fuel specificity (i.e. dependency on a single primary energy source) is unique to the transport sector, which is consequently immune to the type of competition that characterises the heat and power sectors (figure 2).



Data source: IEA World Energy Outlook 2006

Figure 2. Comparison of the global primary energy demand mixes of the tranport sector and heat and power plants, highlighting the unique fuel specificity of transport. This oil dependency is highly problematic as it represents an enormous barrier to achieving energy security through diversification.[8]

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[*] *The remaining five percent is shared between liquefied petroleum gas (LPG), compressed natural gas (CNG), and biofuels.*

[†] *The United Nations Framework Convention on Climate Change (UNFCCC) defines 'transport' according to greenhouse gas "[e]missions from the combustion and evaporation of fuel for all transport activity, regardless of the sector." Thus, in terms of primary energy consumption and therefore GHG emissions, 'transport' does not include electrified modes of mobility such as rail-based rapid transit systems, nor non-motorised forms of transportation. For more on UNFCCC sector definitions, see the website http://unfccc.int/ghg_emissions_data/information_on_data_sources/definitions/items/3817.php*

[‡] *The term 'petrol' is also used in some markets, such as the U.K.*

The underlying reason for transport's dependence on liquid hydrocarbon fuels is that the overwhelming majority of powered vehicles in use today rely upon the internal combustion engine (ICE) – which adores liquid hydrocarbons – to convert stored chemical energy into motion.

It was not always so. In the years 1899 and 1900, the electric car outsold its two competitors in the US: steam-driven cars and gasoline-powered internal combustion engine vehicles (ICEVs).[9] The reason was simple: electric cars were better. They did not suffer the vibrations, the smell, and the noise which accompanied gasoline cars, nor did they require gear changes which were considered the most difficult part of driving. For their part, steam-driven cars suffered from cold-start problems and range limitations when compared with their electric rivals, an early example of which is illustrated in figure 3.

Why, then, are electric vehicles (EVs) now consigned to relatively marginal or niche applications such as golf carts, forklift trucks, and airport terminal buggies? Firstly, the US road network expanded beyond towns and cities, so that long-distance inter-city travel by private automobile became both possible and desirable. At that point, the superior range afforded by gasoline cars relegated their electric counterparts to short-distance commuter travel. Secondly, and ironically, electricity itself helped to undermine the EV. The invention of the electric starter in gasoline-powered vehicles eliminated the need for the hand crank and thereby neutralised a unique selling point that EVs could previously claim: ease of use, especially for female drivers unwilling to operate the physically demanding crank. An additional side-effect of the electric starter was that it encouraged automotive battery manufacturers to focus on mass production of small, low capacity auxiliary batteries rather than on increasing storage capacity, which would have benefited the range of EVs.

Finally, the greatest innovation of the manufacturing industry hammered a sizeable nail into the coffin of EVs: in another ironic twist, a former employee and great friend of Thomas Edison by the name of Henry Ford introduced the production line, whose economies of scale brought the price of a gasoline-powered ICEV within the reach of ordinary American wallets. Strategic marketing errors on the part of both electric and steam car manufacturers sealed their fate: to give one example, as ICEVs became cheaper, EVs actually grew more expensive as manufacturers chose to target the luxury market.[10]

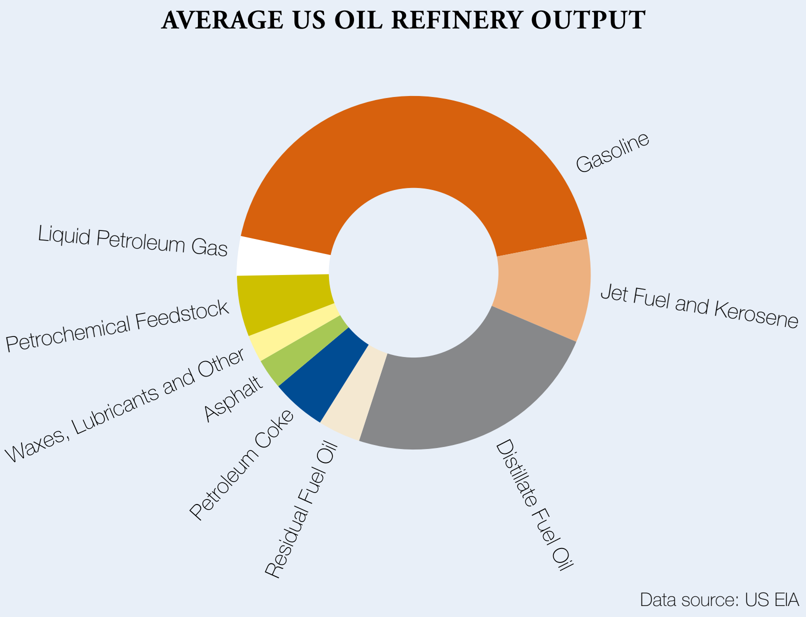
Thus, the marriage of the oil industry with the automobile industry was consummated. But the world in 2008 is no longer indifferent to carbon dioxide emissions, and as we will see, dwindling crude oil supplies are now, more than ever, a potent source of political and military conflict. This one hundred year-old marriage could be about to hit the rocks.

© Archives Center, National Museum of American History.

Figure 3. Thomas Edison photographed with an electric car in 1913.[11]

On average, roughly half of each barrel of crude oil worldwide is converted into transport fuel,[12] meaning that oil industry activity is to a great extent dictated by demand from transportation. In OECD countries, which have more advanced economies and therefore greater reliance on the transport sector, this proportion approaches two-thirds, as illustrated in figure 4. The precise quantity of transport fuels will vary depending on the chemical composition of the crude 'slate', the configuration of the oil refinery, and local market demand, all of which combine to determine processing economics.

From the remainder of each barrel of crude oil which is not refined into gasoline, diesel, or jet fuel, many of the non-energy ancillary product streams may also be destined for transport-related applications, such as lubricants (engine oils, gear oils, greases), asphalt (road surfacing) and petrochemicals (plastics, elastomers, solvents). In theory, one hundred percent of the hydrocarbons in each barrel of crude can be processed into transport fuels, notwithstanding process economics. As demand for transportation fuel keeps rising relative to overall refining capacity, so the economics tend to favour fuel production over alternative pathways. In response, refineries optimise their operating conditions in order to maximise economic fuel output.



Data source: US EIA

Figure 4. Average US refinery output in 2005, showing the strong orientation towards transportation fuels. Diesel fuel belongs in the ‘Distillate Fuel Oil’ category, together with heating oil.[13]

Oil Equals Power

Revenue is a useful measure of the size of a business or sector. It's not the only one, of course: when analysing the performance of companies, it is also informative to compare such metrics as net income, assets, market capitalisation, return on capital employed, and the slightly less tangible brand equity. But raw economic power is best measured in terms of total sales. We currently rely on Gross Domestic Product (GDP), which approximates to the sum of all sales, to compare the relative size of national economies.* We can similarly use total sales – or revenue – to assess the contribution of individual companies to economic activity.

In revenue terms, of the top ten global corporations today,† six operate in the oil business and three in the automotive industry.[14] Could there ever be a more striking indicator of the economic power inherent in the transport sector? This point is so important it bears repetition: nine of the most powerful businesses on the planet directly derive their economic might from the consumption of liquid hydrocarbon fuels in ICEs. Incidentally, the 'odd one out' is Wal-Mart, the discount retailer whose wildly successful business model is contingent on ready access to automotive transport: distribution centres and superstores located on cheap out-of-town real estate, connected to extensive highway infrastructure, accessed by suppliers and customers alike by means of the ICEV. Figure 5 shows how the 'Petroleum Refining' and 'Motor Vehicles' sectors – as defined by Fortune magazine's Global 500 – completely dominate the ranking of global corporations by revenue. Aggregated, these two sectors contributed forty-six percent of all revenues generated by the top fifty companies in 2006.[15]

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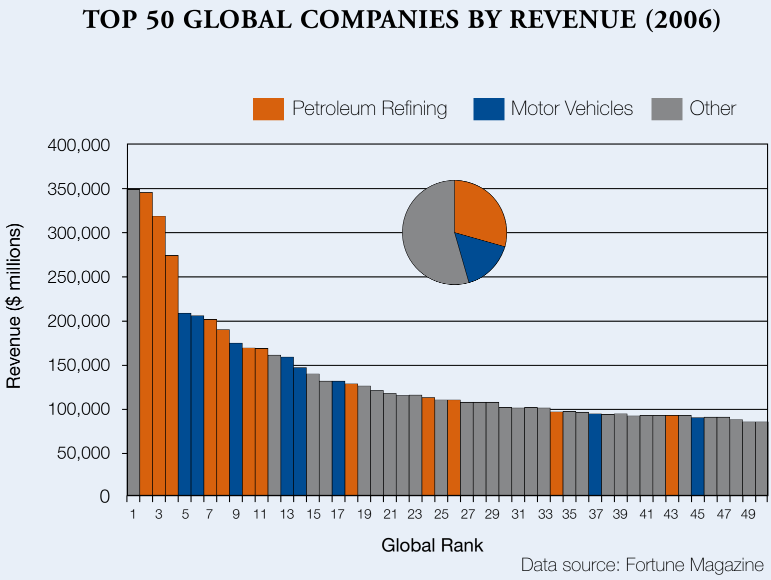
* *This is not to say that GDP is an accurate measure of economic development. Market externalities – such as water contamination, land degradation, and human health impacts – are not comprehended by traditional economic models.*

† *The 2006 edition of Fortune magazine's Global 500 lists the top ten corporations, by revenue, as follows: 1) Wal-Mart, 2) ExxonMobil, 3) Royal Dutch/Shell, 4) BP, 5) General Motors, 6) DaimlerChrysler, 7) Chevron, 8) Toyota, 9) Total, 10) ConocoPhillips. Wal-Mart stands out as being the only one whose core business is neither oil nor automotive transport.*

By comparing revenues side-by-side with the GDP of nations, we may reveal the extent to which modern multi-national oil companies have become state-like in their contribution to the global economy. The US$ 347 billion which ExxonMobil raked in during 2006 eclipsed the GDP of Poland.[16] If it were a nation state, ExxonMobil's 'economy' would rank twenty-second in the world, beating the GDP of many oil-rich nations including Norway, Saudi Arabia, Iran, and Venezuela. Taken together, the combined revenues of the 'Big Six' – roughly US$ 1.5 trillion in 2006 – would come eighth in the global ranking, ahead of Canada, Brazil, Russia, India, and Australia. If money does indeed make the world go round, then the oil sector alone exerts irresistible torque.


TOP 50 GLOBAL COMPANIES BY REVENUE (2006)

Data source: Fortune Magazine

Figure 5. The ranking of the top fifty global corporations by revenue in 2006 shows the economic dominance of petroleum-based automotive transport. Nine of the top ten and nineteen of the top fifty companies operate in either 'Petroleum Refining' or 'Motor Vehicles', contributing 46% of revenue.

National governments understand the importance of the transport sector, and therefore crude oil, as a primary driver of their economies. The transport sector continues to expand roughly in line with economic growth. One might reasonably ask: which is the cause and which the effect? Most likely it's a combination of the two – a positive feedback loop – since the mobility of goods, services, and people enables an increased level of economic activity to take place.

It is not just about the economy, however. Since the First World War, governments everywhere have recognised oil as a key safeguard to national security. In 1912, a young Winston Churchill, then First Lord of the Admiralty, took (in his own words) the "fateful plunge" of commissioning a fleet of battleships running on oil.[17] Until then, coal furnaces powered the naval fleets of Britain and Germany, two nations locked in an escalating arms race. Oil offered the advantages of faster acceleration, superior cruising speeds, and higher energy density which allowed more room onboard for armaments and personnel. With no domestic oil resources known at the time, Britain thus became the first nation to tie its national security to foreign oil, and subsequently embarked on a strategy of interference in Middle Eastern affairs leading to the formation of Anglo-Persian Oil, which later became BP.

In retrospect, World War I can now be considered history's first 'Oil War'. If oil was not the cause of the conflict, it was certainly a defining factor in the war's prolongation, geographical reach, projection of mechanised force, and eventual result. Germany's meagre petroleum supplies were comprehensively overwhelmed by the Allies' access to plentiful American reserves. At the end of the hostilities, Lord Curzon, a member of Britain's War Cabinet, famously claimed:

> *The Allied cause had floated to victory on a wave of oil.*[18]

The remainder of the 20th Century is littered with examples of political and military conflict, discussed in fascinating detail elsewhere,[19] in which oil provides a compelling context. One episode from US history is, however, particularly instructive: President Jimmy Carter's State of the Union address in 1980, prompted by the Soviet invasion of Afghanistan.

> *Let our position be absolutely clear: an attempt by any outside force to gain control of the Persian Gulf region will be regarded as an assault on the vital interests of the United States of America, and such an assault will be repelled by any means necessary, including military force.*[20]

This statement came to be known as the Carter Doctrine, the application of which has been demonstrated by the US (and its allies) most recently in Iraq. In simple terms, the US publicly considers petroleum to be absolutely critical to its national security, and therefore a justification for military intervention. One wonders whether a political administration which has gone so far as to enter wars in the pursuit of oil would have any qualms about opening up its own National Parks and other protected areas to exploration activity. Humanity's ongoing thirst for oil thus represents a direct threat to the integrity of the Earth's few remaining wilderness areas, such as the Arctic National Wildlife Refuge (ANWR).[21] While oil continues to supply the overwhelming majority of the world's transportation services, advocates of drilling in the ANWR may never abandon their efforts. It goes without saying that this would not solve anything, merely prolong our increasingly painful dependency while simultaneously threatening the integrity of a vital ecoregion.

OIL SECURITY

As the major consuming nations see their domestic crude oil resources shrivel in the face of ever-increasing demand, the world's remaining proved reserves are gradually concentrating in relatively few countries, as figure 6 shows. By the end of 2006, more than seventy-five percent of proved reserves were located in the eleven OPEC member states,[*] with a further seven percent to be found within the Russian Federation.[22] It is no coincidence that oil-rich countries are far more likely than most to suffer from political volatility, particularly when those resources have been discovered prior to the establishment of robust political institutions.

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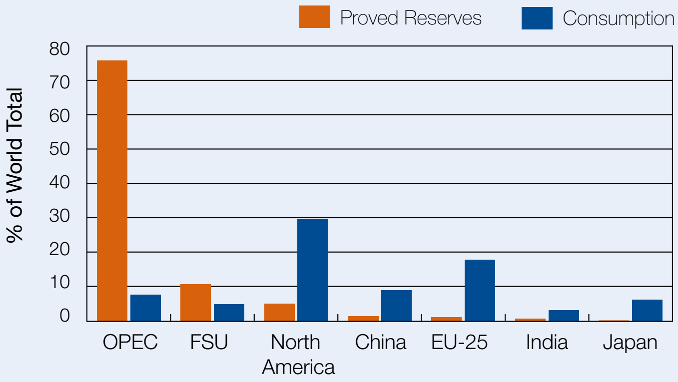
[*] *Members of OPEC, the Organisation of Petroleum Exporting Countries, are as follows: Saudi Arabia, Iran, Iraq, Kuwait, Qatar, United Arab Emirates, Algeria, Libya, Nigeria, Indonesia, and Venezuela.*

The destabilising effect of resource wealth on poor countries is well documented, and has come to be known as the ‘Paradox of Plenty’.[23]

The International Energy Agency (IEA) projects that the US, China, and India will be the top three oil consuming nations in 2030.[24] Taken together, these three countries currently account for just four percent of proved reserves, and all are significant net importers today. Meanwhile, the European Union’s share of proved reserves amounts to less than one percent. Transport represents the EU’s fastest growing energy demand sector, and the largest overall. For each of these dominant demand markets, diversification of supply is the secret to security of supply, but the uneven geographical distribution of conventional crude oil resources represents a considerable barrier to diversification. The recent spate of resource nationalism (discussed below) merely adds to political concerns around oil security. This geopolitical reality leads to market uncertainty and price volatility, with infrastructural bottlenecks – due to decades of under-investment – only serving to exacerbate the problem. It is this emerging dynamic which is the primary motivation behind growing government support for so-called ‘alternative’ transportation fuels.



CRUDE OIL GEOGRAPHY IN 2006: RESERVES VS CONSUMPTION

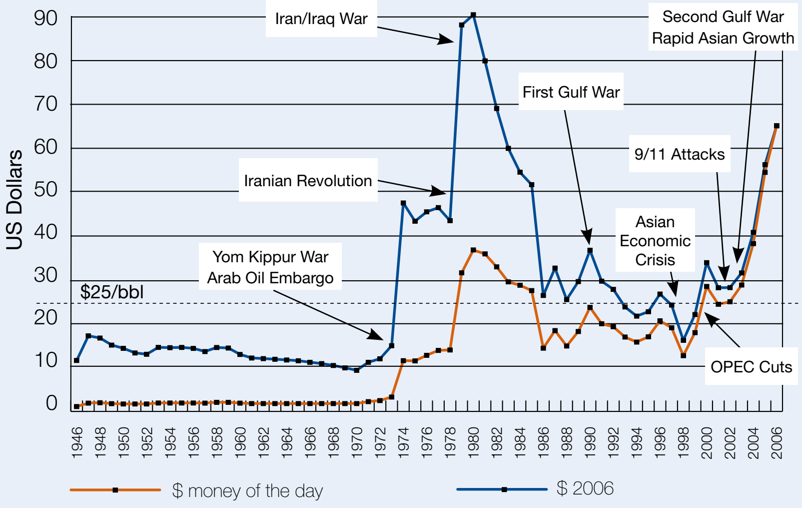
Data source: BP Statistical Review 2007

Figure 6. The geographical distribution of conventional crude oil resources bears no relationship to the areas of high consumption. Remaining proved reserves are gradually concentrating in relatively few countries: OPEC member states and the nations which comprise the former Soviet Union (FSU).

High Oil Prices and Their Effects

Figure 7 illustrates how oil prices tend to fluctuate in response to significant global events. Oil price shocks, such as that witnessed following the Iranian Revolution of the late 1970s, have historically stimulated massive increases in exploration and production, concerted energy conservation drives, and investment in alternative technologies. For example, coal-to-liquids (CTL) research programmes were widespread in OECD nations during the early 1980s, which saw the establishment of the short-lived Synthetic Fuels Corporation in the US.[25] Brazil's biofuels industry, based on ethanol derived from sugarcane, also traces its origins to the same period in history.*

POST-WWII CRUDE OIL PRICE EVOLUTION



Data source: BP Statistical Review 2007

Figure 7. Evolution of post-WWII crude oil price, annotated with major world events.[26]

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* *For a more detailed account of the history of biofuels development, see* Biofuels for Transportation: Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century *(Worldwatch Institute, June 2007).*

It is worth reflecting that the driving force behind the development of oil substitutes has never been concern for the environmental impact of crude oil: rather, it has been energy security, which itself underpins national security.

Sustained periods of high oil prices have forced a structural change in the market which persists today: the displacement of crude oil from applications for which a practical economic alternative existed. Principally, this has meant the gradual substitution for crude oil in electricity generation (by coal, gas, nuclear, hydropower, renewables) and heating (gas), but also non-energy uses such as petrochemicals (coal, gas, and even vegetable oils). To take one example, between 1973 and 2004, oil's share of global electricity generation dropped from 24.7% to 6.7% as oil became far too valuable to 'waste' in the power sector.[27] The IEA projects that this trend will only continue, with oil contributing just three percent of the world's electricity supply by 2030, essentially limited to markets where natural gas is not available.[28]

Crude oil has thus retreated further and further into applications for which there has been no widespread, cost-effective, technically competent substitute, namely automotive, marine and aviation fuels. Meanwhile, overall transport demand has itself been steadily growing. This displacement effect is illustrated in figures 8 and 9.

In the late 1980s, the combination of these factors – energy conservation and fuel switching – gradually eased the global demand for crude oil, with the consequence of excess supply as new production came on stream. This sent prices plummeting to lows of around $10/bbl towards the end of the 1990s. Exploration efforts were subsequently scaled back as it became unprofitable to continue adding new production. Bloated International Oil Companies (IOCs) then embarked on a series of mega-mergers: Exxon with Mobil, Chevron with Gulf and Texaco, BP with Amoco and ARCO, Total with Fina and Elf. This industry consolidation led to a number of refinery shutdowns, worker redundancies and other cost-cutting measures, as operating margins became thinner.

With oil cheaper than ever, many state-sponsored energy conservation efforts were abandoned – the low-hanging fruit having already been harvested – and in some case were even reversed. The most spectacular example of this has been the explosion in so-called Sports Utility Vehicles (SUVs) in the US over the last two decades,* more recently infecting Europe. The US automobile industry had successfully lobbied for a loop-hole in the federal Corporate Average Fuel Economy (CAFE) standards, which enabled SUVs to be classified as 'Light Trucks'. This exempted SUVs from the more stringent CAFE regulations which applied to passenger cars. American consumers embraced the perceived safety and power advantages of driving an SUV despite the inferior fuel economy, because the *incentive* to conserve oil had diminished; the market signalled that oil was inexpensive. It is important to understand and learn from this lesson: cheap energy deflates efforts to drive efficiency improvements.

CRUDE OIL APPLICATIONS

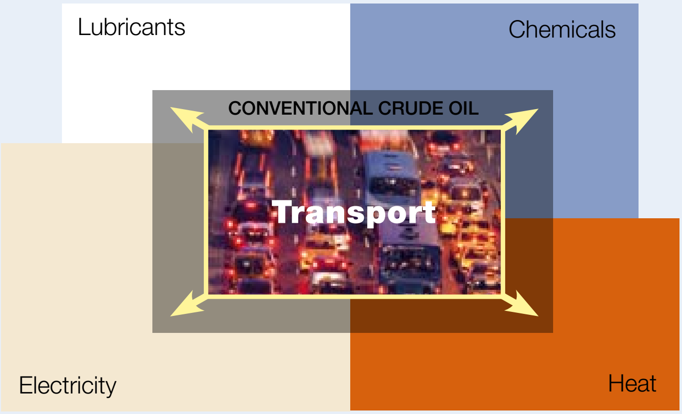

Figure 8. Liquid hydrocarbon fuels, most economically derived from conventional crude oil, completely dominate the transport sector. As global demand for transportation fuel grows in the absence of widely available economic substitutes, oil is gradually displaced from applications for which viable alternatives exist (e.g. coal, gas, and renewables for electricity and heat generation).

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* *According to Paul Roberts in* The End of Oil, *just one in twenty SUVs has ever been driven off-road… intentionally!*

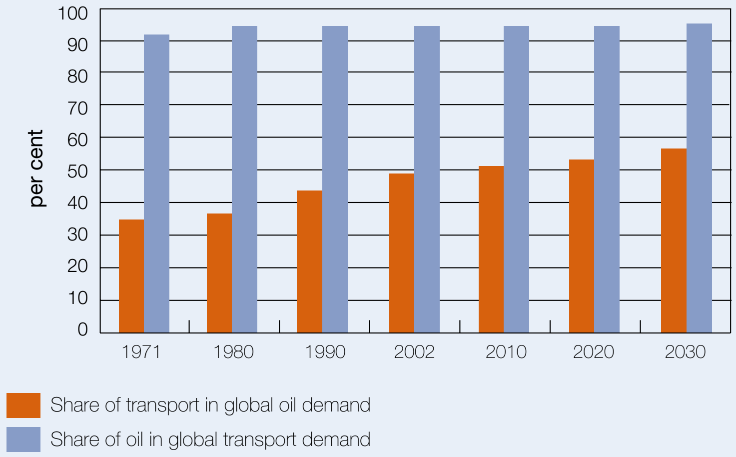
Peak Oil

For a few years following industry consolidation, oil prices hovered close to the $25/bbl mark, considered to be the long-term industry average, and still used as a reference point by many oil analysts and investors today. However, relentless growth in demand for personal mobility, massive increases in air travel, and maturation of the North Sea and US oilfields started testing the limits of supply infrastructure, causing the market to tighten. The phenomenal economic rise of China and India coupled with the aftermath of the September 11th terrorist attacks on the US tipped the scales, and prices sky-rocketed.

A debate is currently raging as to whether the extraordinarily high oil prices of 2006/07 are an indicator that 'Peak Oil' is upon us. Peak Oil theorists argue – correctly – that crude oil is a finite resource which cannot be extracted indefinitely. It is only a matter of when, not if, the global production of crude oil will reach a maximum rate – or peak – and then decline. And with demand continuing to grow, the post-peak world will be characterised by high oil prices. Peak Oil deniers point to the fact that rising oil prices enable the production of reserves which were previously considered uneconomic, which pushes the peak further and further away.

Protagonists from both sides of the debate are at least able to agree on one thing: whether or not Peak Oil theory is at work here, there is certainly a Peak *Easy* Oil effect. Worldwide, the remaining proved reserves of conventional crude oil *may* be sufficient to last for forty years or more at current levels of demand, though no one knows for sure.[29] However, as with any other resource harvesting activity, the oil which is easiest to reach is the first to be exploited. Thus, with the declining rate of significant new discoveries of easily available deposits, barrels of oil will become successively more difficult, expensive, and energy-intensive to extract and process.

Moreover, the physical location of the remaining reserves is of fundamental importance. Geopolitical constraints – oil reserves concentrated in states which do not place the concerns of big Western consuming nations high on their list of priorities – combine with infrastructural bottlenecks to create the market insecurity which results in price volatility. That's why Christophe de Margerie, Total's head of exploration said in 2006, the world is mistakenly focusing on oil reserves when the real problem is capacity to produce.[30]



SHARE OF TRANSPORT IN OIL DEMAND

Data source: IEA World Energy Outlook 2004

Figure 9. Transport's share of global oil consumption has been growing steadily to roughly fifty percent today, and is projected to further increase as oil is continually displaced from applications which have viable alternatives. The share of oil in global transport demand for primary energy remains flat, at around ninety-five percent.[31]

The Rise of National Oil Companies

Petrostates, which are nations 'blessed' with – and economically dependent upon – an abundance of petroleum reserves, have been quick to recognise the renewed strategic significance of their oilfields. Whereas once they courted the IOCs, offering generous concessions in return for project management and engineering expertise, they now feel increasingly confident in the ability of state-owned National Oil Companies (NOCs) to steward their resources effectively.[32] This creeping 'resource nationalism' is becoming intolerable for many net importers, particularly the US, whose international political clout is in danger of being sacrificed on the altar of oil dependence. Expensive oil imports may fund unsavoury political regimes, so if for no other reason it is easy to see why energy independence now dominates the agenda in Washington. According to Thomas Friedman's *First Law of Petropolitics*, the price of oil and the pace of freedom always move in opposite directions.[33] Put simply, leaders of petrostates are insensitive to how they are perceived by outside forces, when oil prices are high.

> *When I heard Venezuela's President Hugo Chávez telling British Prime Minister Tony Blair to "go right to hell" and telling his supporters that the U.S.-sponsored Free Trade Area of the Americas "can go to hell," I couldn't help saying to myself, "I wonder if the president of Venezuela would be saying all these things if the price of oil today were $20 a barrel rather than $60 a barrel, and his country had to make a living by empowering its own entrepreneurs, not just drilling wells."* [34]

A full dissection of the foreign policy implications of the crude oil market is beyond the scope of this book. What *is* pertinent to this discussion is the impact of this new dynamic on IOCs and their future strategic direction. The Big Six – or 'oil majors' – who today dominate the Fortune Global 500 revenue summit are, in fact, relatively small fry when it comes to proved reserves. US super-giant ExxonMobil is by far the world's largest corporation in *any* sector by market capitalisation and net income, posting all-time record profits of US$ 39.5bn in 2006. However, ExxonMobil's 11.6 billion barrels of liquid reserves amount to just one percent of the Earth's total. At current production rates,[35] ExxonMobil has less than twelve years of liquid reserves remaining, hence the critical importance placed by the investment community on oil companies' ability to replace reserves year after year. Without doubt, the real resource wealth lies elsewhere, with the petrostates and their agent NOCs; by this measure, the world's largest oil company is Saudi Aramco with reserves estimated at 260 billion barrels, more than twenty times those of ExxonMobil.[36]

Bolstered by government support, it is now common to see self-assured NOCs even from relatively resource-*poor* countries like China and India stepping far beyond their traditional national boundaries. This phenomenon is creating a whole new competitive landscape in the global market once dominated by Big Oil, especially since these state-owned adversaries are driven as much by national policy objectives as commercial ones. The acquisition in 2005 of PetroKazakhstan by China National Petroleum Corporation (CNPC) is one example among many.[37] An intriguing episode earlier that year involved China National Offshore Oil Company (CNOOC)'s attempted takeover of American oil firm Unocal, owner of coveted hydrocarbon assets in Indonesia, Thailand, and Myanmar. The move prompted a muscular response from Washington, as the US administration well understood the strategic implications of the proposed move. In the event, CNOOC's offer of US$ 18.5bn was withdrawn under intense political pressure, leaving the board of Unocal free to opt for an inferior rival bid of US$ 17bn from American giant Chevron.[38] Perhaps even more significant is the story of a joint acquisition by CNPC and India's Oil and Natural Gas Corporation (ONGC) of PetroCanada's Syrian assets. This unprecedented partnership of rival state-owned oil companies was considered by many analysts to be the shape of things to come in global energy markets, as China and India attempt to co-operate rather than compete for dwindling resources.[39]

Faced with the combined challenges posed by resource nationalism and state-sponsored NOCs, the oil majors will have to adapt in order to survive this emerging threat to their hegemony. How they choose to adapt might to a large extent determine the rate at which we are able to decarbonise our economy. The early indicators are not encouraging, as we will learn in Part II.

PART II

OIL, TRANSPORT AND CLIMATE CHANGE

Global warming is one of the biggest challenges facing the world today. By 2005, the average global temperature had reached 0.74 degrees Celsius (°C) higher than a century ago, and according to data from the Intergovernmental Panel on Climate Change (IPCC), eleven of the twelve years from 1995 to 2006 were among the twelve warmest years on record. Scientists attribute the planet's increasing temperature to excessive concentrations of greenhouse gases (GHGs) in the atmosphere, which are largely caused by the global economy's dependence on fossil fuels.[40]

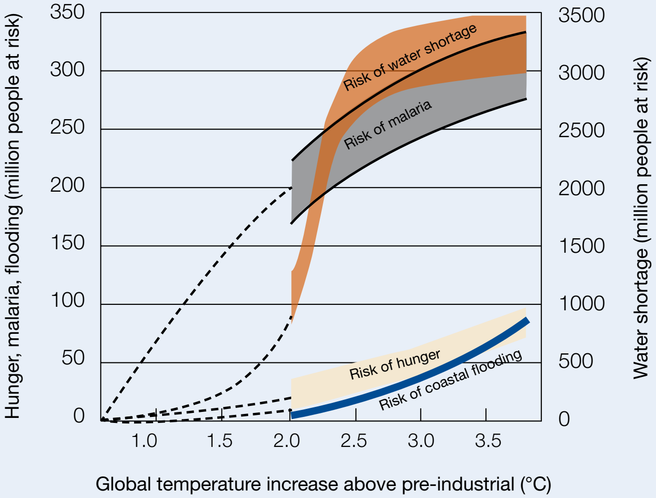
Research strongly indicates that as the planet's average surface temperature climbs, so too will sea levels as glaciers and ice-sheets melt, potentially flooding coastal areas; the global sea level has already risen four to eight inches (ten to twenty centimetres) in the past century. Scientists' best estimates are that sea levels will rise an additional nineteen inches by 2100, and perhaps by as much as thirty-seven inches,[41] or approximately one metre. While some areas of the world will have too much water, others will have too little: hotter temperatures will generate intense heat waves and drought, causing wildfires, exacerbating air pollution and facilitating the spread of tropical diseases.

It is now generally accepted by the scientific community that in order to avoid dangerous climate change, the average increase in global surface temperatures must stay below 2°C compared with the pre-industrial era. This threshold has not been chosen arbitrarily: beyond 2°C, the risks to human population posed by the worst impacts of climate change increase sharply, in particular the combined threats of disease, coastal flooding, and food and water shortages. The importance of this temperature threshold is graphically described in figure 10. If the average global temperature increase exceeds 2°C, it is predicted that by the 2080s more than three billion people worldwide could be at risk due to water shortages; increased droughts in Africa and elsewhere will lead to lower crop yields; and three hundred million people will be at greater risk of malaria and other vector and water-borne diseases.[42]

These drastic environmental changes are expected to disrupt ecosystems and result in significant biodiversity losses. The first comprehensive assessment of the extinction risk from global warming found that more than one million species could be committed to extinction by 2050 if global warming pollution is not curtailed.[43] In purely economic terms, the UK's Stern Report in early 2007 concluded that the costs of unchecked climate change could reach anywhere from five to twenty percent of global GDP by 2100.[44]

In early 2007, the Fourth Assessment Report of the IPCC gathered together and summarised the fruits of hundreds of scientific studies since 2001 which have investigated the causes and potential impacts of global warming.[45] The IPCC report drew the conclusion that it may yet be possible to prevent disastrous climate change if worldwide GHG emissions – which are currently rising at a rate of around three percent per year – peak and then begin to decline before 2015. To maintain a safe climate, as much as eighty-five percent of global CO_2 emissions must be eliminated by the middle of this century.[46] What do these stark conclusions mean for the prevailing transport paradigm, based wholly on the combustion of liquid hydrocarbon fuels?

MILLIONS AT RISK IN 2080s



Adapted from Parry et al. (2001), Global Env. Change

Figure 10. Beyond the 2°C warming threshold, the number of people at risk from many negative impacts of climate change rises sharply. The risks posed by water shortage cannot be over-stated (note the ordinate scale here is an order of magnitude greater than the other risk factors).[47]

STRUCTURE OF THE OIL INDUSTRY

Since the roaring success of John D. Rockefeller's Standard Oil in the late 1800s, the oil majors have been the archetype of vertically integrated corporations, asserting control over virtually every aspect of the crude oil supply chain from Upstream (exploration, production, and crude oil conveyance via pipeline or tanker) to Downstream (refining, blending, storage and distribution of finished products, and retail activities). Indeed, it is noteworthy that five of the Big Six – the odd one out being Total of France – comprise elements of the original Standard Oil Trust, which had been forcibly dismantled into thirty-four spin-off companies in 1911 to counter anti-competitive practices. A succession of mergers and acquisitions during the last one hundred years has seen many of those thirty-four entities subsumed in the development of the IOCs with whom we are so familiar today.

Standard Oil of New Jersey became Exxon, which merged with Mobil, formerly Standard Oil Company of New York (SOCONY). On the US West Coast, Standard Oil of California (SOCAL) acquired Standard Oil of Kentucky and renamed itself Chevron, which later amalgamated with Gulf and Texaco. Another Standard Oil fragment called the Continental Oil Company became Conoco, which joined with Phillips Petroleum to form ConocoPhillips. BP's US arm swallowed first Standard Oil of Ohio and later Amoco, formerly Standard Oil of Indiana, before then adding ARCO, an entity comprising another daughter of Standard Oil called Atlantic Refining. Even Royal Dutch Shell got in on the act when it acquired Pennzoil, previously the South Penn Oil Company, yet another of the thirty-four Standard Oil spin-offs. Given that these giant companies frequently enter Upstream joint-ventures with one another, it is hard to imagine a more incestuous industry.

The vertical integration which characterises the oil sector enables companies to ride the peaks and troughs of the cyclical oil market much more smoothly than would otherwise be possible; high oil prices equate to strong Upstream earnings, while the converse means lower costs and higher retail margins for the Downstream arm, which softens the blow during leaner years. Although today's IOCs vary from one another in terms of their relative interests in Upstream and Downstream operations, their geographical strengths, and their respective fringe activities, they still share much in common. In particular, they face the very urgent challenge that conventional crude oil resources – the headline measure by which financial markets value oil companies – are becoming less and less accessible for the reasons discussed earlier.

IOCs are also important players in natural gas markets. Natural gas was once considered a nuisance by-product to be flared off during crude oil production. It is today recognised as a highly marketable, lower carbon product for heat and power generation: methane (CH_4), the main constituent of natural gas, holds more than twice the energy per unit of carbon than coal.[48] Liquefied natural gas (LNG) – whereby gas is cooled under atmospheric pressure into the liquid state for ease of conveyance, then regasified on arrival – is a game-changing development, creating a global market for natural gas which was previously restricted to essentially three regional markets: North America, Europe, and Asia, all accessed via expensive and vulnerable pipelines. Now that maturing LNG technology is able to overcome the physical inconvenience of handling gas, formerly 'stranded' fields are being connected to far away customers via ocean freight. Giant gas deposits such as Qatar's North Field at Ras Laffan, thousands of pipeline-kilometres from the major consumption centres, instantly become commercially viable thanks to a combination of simple physics and engineering prowess. In terms of climate change mitigation, the ability to bring stranded gas to distant markets is most welcome, provided the impacts of marine and coastal development can be minimised, and to the extent that gas is used to displace polluting coal.

Despite this promise and fast growth in recent years, LNG currently remains a small subset of the wider natural gas business, which itself accounts for roughly one-third of the IOCs' production.* What really drives IOCs today is the same thing which has driven them since the 1890s: finding and extracting more and more liquid resources, and adding value by converting them into transportation fuels.

Oil versus Transport

From the outset, it should be noted that oil industry *operations* (i.e. everything required to obtain and deliver the end product into the hands of the customer) currently have relatively minor impacts on the climate. The GHG emissions associated with the conventional crude oil life-cycle are heavily biased to the usage phase. Roughly eighty-five percent of oil-related CO_2 emerges during combustion (i.e. from vehicle exhaust tailpipes and oil-fired furnaces), with the remaining fifteen percent comprising the combined industrial activities of exploration,

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* *Aggregated data for the Big Six IOCs indicate that natural gas contributed 36% of oil-equivalent production in 2005.*

production, refining, distribution, and retail.[49] This fact is often quoted by IOCs in defence of the climate impact of their businesses, and they are technically correct. On the other hand, product suppliers in all sectors are increasingly expected to shoulder some degree of responsibility for the impact of their products in use. It should be obvious, even to senior public affairs personnel in the oil industry, that customers purchase their fuels with the explicit intention of burning them to release energy.

The small, widely dispersed, mobile nature of transport emissions represents an intimidating challenge in the global battle against anthropogenic CO_2 which causes climate change. It also partly explains why most efforts to reduce energy-related GHG emissions to date have focused on the large, stationary sources which characterise the power sector.

The transport sector as a whole, which includes the sub-sectors of automotive, aviation, and marine transportation, is responsible for some twenty-three percent of energy-related CO_2 released worldwide, the second largest sectoral contribution after power generation.[50] Roughly three-quarters of these emissions come from road vehicles: primarily cars, trucks, and buses. Despite these alarming statistics, mobility itself is not a threat to our survival; on the contrary, it is essential to our existence. However, mobility which is dependent on the exothermic reaction of hydrocarbon molecules with oxygen, in hundreds of millions of internal combustion engines, is placing at risk the continuation of human civilisation, not to mention many of the species with which we share Planet Earth. We must quickly embark on a pathway towards transport decarbonisation. Unfortunately, the signs are not good. If anything, we're heading in the other direction.

A Boost for Renewables?

Throughout 2007, oil prices continued to rise to reach records highs – in nominal terms – approaching $100/bbl. At this level, conventional wisdom has it that renewable energy technologies will receive a spontaneous boost, because their commercial development becomes economically favourable relative to crude oil. There are two good reasons why this assertion does not necessarily hold in practice.

Firstly, there is currently no viable alternative to ICEs for transport,[*] meaning that non-depleting renewable technologies, such as wind, solar, geothermal, hydro, wave, and tidal energy – all based on physical rather than chemical processes – receive no economic benefit from high oil prices.[†] In simple terms, there is no substitution potential; we will never produce gasoline from wind energy, we will never refine diesel from the ocean, and we will never derive kerosene from solar power.[‡] When crude oil contributes such a minor share of power generation, we might just as well claim that high oil prices benefit the sale of toothpaste and cream cheese. Until we are able to run our motor vehicles on toothpaste and cream cheese, this statement will remain absurd.

Liquid hydrocarbons can only be obtained from a material which itself contains carbon. One renewable energy option alone fits this profile: bioenergy. Indeed, the development of biofuels from biomass *is* a direct beneficiary of today's high oil price, evidence of which can be seen in the US and Europe, as governments and businesses turn to biofuels to reduce oil imports which are costly in both economic and political terms. In a sense, the wheel has turned full circle because crude oil first gained a foothold in the global energy economy by displacing biofuels – in this case, wholly *un*sustainable whale oil – from the lighting sector. In an early automotive example of biofuel use,

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[*] *The notable exception is electrified rail-based mass transit, for which primary energy consumption does not appear under the transport sector in the UNFCCC definition because the fuel combustion step takes place in the power sector.*

[†] *To the extent that the oil and natural gas markets are related, it can be argued that high oil prices drive higher gas prices, which in turn benefit the development of renewable energy. However, there is no fundamental reason why oil and gas prices should be linked to one another, as they serve the entirely separate sectors of transport (oil) and heat and power (gas). Where it exists, the pricing relationship between the two fossil fuels is an historical artefact, from the early days when natural gas was little more than a by-product of the petroleum industry.*

[‡] *A counter-argument runs that bioenergy is effectively a form of solar energy, i.e. sunlight which has been stored as plant matter via photosynthesis. This is technically true, but is not relevant to the discussion. The same can be said for wind and wave energy, both of which carry energy which first reached the Earth in solar rays. Even fossil fuels are solar-derived, being the remains of ancient plant and animal matter, decomposed in a geological pressure cooker for millennia.*

Rudolph Diesel's first engine, demonstrated at the Paris World Exposition of 1900, ran on peanut oil.[51]

However, biofuel development, particularly in the dominant 'first generation' technologies, is not necessarily sustainable in either the short- or the long-term. Photosynthesis – the biochemical process by which plants convert sunlight into chemical energy – removes CO_2 from the atmosphere which is then rereleased upon combustion of the biomass. Thus the carbon life-cycle of biomass is, in theory, neutral. In practice, when biomass is put to energetic use, the GHG balance will vary widely, depending on which crops are produced, how and where. The cultivation and harvesting of biomass requires the input of energy and other raw materials, such as water and fertiliser. And in worse cases, biofuel production might have no net positive energy balance and may cause significant environmental and social impacts, such as deforestation, biodiversity loss, soil erosion, water over-abstraction, land-use conflicts, food shortages and staple food crop price fluctuations.

Opponents of biofuels – vociferous as they are – cannot argue with fact that certain bioenergy crops do offer genuine and sometimes substantial benefits to the environment and society when cultivated and manufactured according to strict sustainability criteria. By way of example, the Brazilian bioethanol industry has demonstrated that, under the right conditions, biofuels may be produced sustainably in significant quantities with a highly positive GHG balance. In 2006, bioethanol from sugarcane represented forty percent of Brazil's transport fuel supply, according to a report by the German Marshall Fund of the US.[52] In the best case, on a full life-cycle basis, a barrel of oil equivalent (boe) of Brazilian bioethanol may emit 87% less $CO_2$when burned than the same energetic quantity of gasoline.[*]

Irrespective of the benefits and potential disadvantages, it is in any case misleading to label liquid biofuels – primarily biodiesel and bioethanol – as 'alternative fuels', since the fuels themselves are

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[*] *In practice, the full GHG balance will strongly depend on agricultural practices (e.g. application of fertilizer), land use change, process and distribution efficiency, etc.*

nothing of the sort. The biomass feedstock is an alternative, renewable, and potentially sustainable *source* of hydrocarbon molecules. Thus biomass offers an alternative *route* to the manufacture of transport fuels, but the fuels themselves are not materially different to those which we derive from crude oil.

This is not simply a semantic issue, it is central to the problem at hand: biofuels are liquid hydrocarbons that must be burned at the point of use. Today, we have no alternative to the burning of liquid hydrocarbons in small, mobile ICEs, and while this situation prevails we continue on our journey towards environmental catastrophe.

The 43rd President of the United States spoke too narrowly when he announced in 2006 that America was addicted to oil.[53] As we have seen, America (and the rest of the industrialised world) is addicted not to oil but to liquid hydrocarbon transport fuels. As figure 11 illustrates, this category includes conventional petroleum and a range of so-called alternative fuels: those derived from biomass, oil sands, coal-to-liquids (CTL) and gas-to-liquids (GTL).

We should be in no doubt: the *principal* argument in favour of biofuels, from day one of Brazil's foray into sugar-to-liquids, still rings true today. The primary reason biofuels are so appealing to governments and businesses in 2008 is that they are broadly compatible with the existing fuels infrastructure and engine systems,[*] and therefore offer the path of least resistance towards reduction of expensive and politically inconvenient crude oil imports while simultaneously appeasing the powerful farming lobby. For transport fuel providers it is a relatively trivial task to blend liquid hydrocarbon 'additives' to their fuel pool. This is essentially business as usual: just as chemical dyes are added to distinguish gasoil from road diesel for taxation purposes, so biofuels may be blended with conventional fuels to lengthen the supply and potentially, as a beneficial side-effect, lower the overall carbon footprint of the transport fuel pool.

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[*] *Some minor modifications may be necessary, e.g. to accommodate high concentrations of ethanol such as E85, but the basic operation of the internal combustion engine remains largely unchanged.*

TRANSPORT = LIQUID HYDROCARBON FUELS

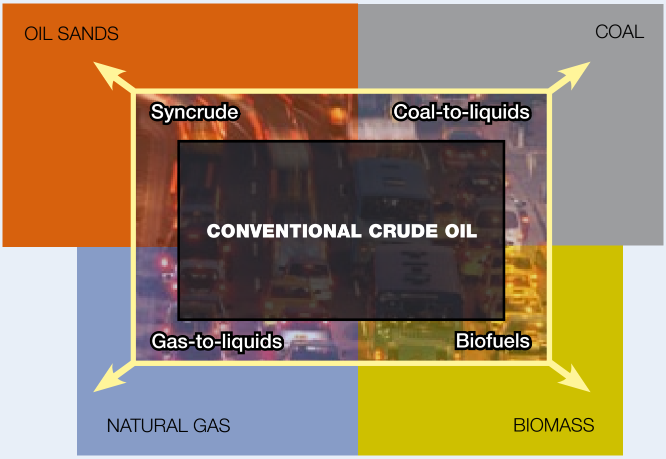

Figure 11. As demand for transport fuel pushes beyond the economic limits of conventional crude oil supply, the shortfall is filled with unconventional hydrocarbon resources which become economically viable as oil prices remain high. Environmentally, some of these options (e.g. sustainably produced biofuels) are significantly better than others (e.g. coal-to-liquids). However, the range of oil substitutes does not lead to an alternative transport paradigm; conventional fuels are displaced within the existing infrastructural model, therefore we experience incremental change.

Liquid biofuels produced from *sustainable* biomass will certainly play an important role in the future of transport, just as they already do in 'sweet spot' countries like Brazil where tropical conditions are ideal for cultivating energy crops. However, in the long-term it is imperative that such a valuable and limited resource be utilised in such a way as to *maximise* GHG reductions in the battle against climate change, rather than simply to sustain the liquid hydrocarbon status quo. In many countries and markets, this will likely mean prioritising the development of bioenergy for combined heat and power generation. As for the role of biofuels in transport applications, we will return to this important subject later.

Core Business

The second reason why renewable energy technologies do not necessarily benefit from high oil prices is that financial markets value oil companies according to the success with which they replace their reserves, while annual profits directly correlate with the market price of crude oil. This powerful relationship is illustrated in figure 12.

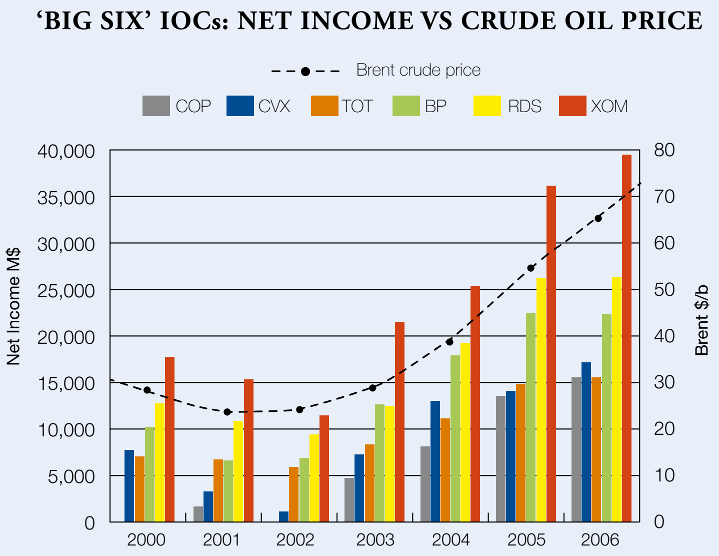

Figure 12. The direct correlation between Big Oil earnings and crude oil price is striking: as the crude oil price rises, oil companies are compelled to find, extract, and sell more and more crude oil in order to increase the financial returns for their shareholders. The chart shows the net income of the top six publicly traded IOCs: ExxonMobil (XOM), Royal Dutch Shell (RDS), BP, Total (TOT), Chevron (CVX) and ConocoPhillips (COP). All data is sourced from company financial reports.

While oil prices are high, producers are *required* to extract and sell as much as possible, to "make hay while the sun shines". To do anything else would be to ignore a *raison d'être* of all corporations, which is to maximise return on shareholder investments. When Rex Tillerson, Jeroen van der Veer, and Tony Hayward – the respective CEOs of ExxonMobil, Shell, and BP – step out of the shower at the start of their day, might they be contemplating the fractions of a percent of their capital which is invested in renewable technologies, or are they more likely preoccupied with their core business of finding more hydrocarbons as efficiently as possible? Given the framework within which corporations are *bound by law* to operate today, it is unsurprising that Big Oil CEOs focus on replacement of reserves. If we would prefer that they prioritise their fringe activities of carbon-free energy, then we ought to initiate the mighty endeavour of redesigning their operating parameters and levelling today's tilted playing field.

One might expect a surge of exploration and production activity to drive oil prices down, as it has done in the past. That this has not yet happened to any great extent simply reinforces the argument that the market is structurally tight, and will likely remain so for the foreseeable future as supplies struggle to keep pace with growing demand. Certainly there will be a considerable lag effect as new exploration activities today will not bear fruit for many years, but the sustained high prices of recent years strongly indicate that there is no slack in the system, no spare capacity. Furthermore, since the oil industry enjoys an oligopoly over the transportation fuel market, we should not expect the answers to our liquid hydrocarbon addiction to flow freely from that sector. It is in the oil executives' interests – and the interests of the shareholders to whom they answer – to sustain the existing paradigm for as long as possible. And as we have seen, achieving that does not necessarily require conventional crude oil.

UNCONVENTIONAL OILS

The continuing reliance on (and persistent growth in demand for) liquid hydrocarbon transport fuels provides a compelling reason for oil companies to go further, deeper, and faster to replace proven oil reserves. In the face of increasing competition from NOCs, resource nationalism, and rapidly depleting 'easy oil', more and more IOCs are turning to 'frontier' resources of oil sands, CTL, and GTL to bolster their hydrocarbon assets. These species, not renewables, are the prime beneficiaries of high oil prices, since conventional crude oil is the benchmark against which investors assess the commercial feasibility of potential substitutes. To put it another way: as the oil price rises, more and more hydrocarbon resources become financially viable and the 'frontier' is rolled back. In the 2006 edition of the Shell Sustainability Report,[54] the company projects that 10-15% of its overall oil and gas production could come from unconventional sources as early as 2015. If the oil price were to climb high enough, it would make economic sense to turn even a Persian rug into transportation fuel.

Unfortunately, the vast majority of unconventional oils, which have until now been economically or politically out of reach, make regular crude oil look almost benign – especially in terms of greenhouse gas emissions. That the history of the CTL industry correlates temporally with the development of biofuels is highly instructive. The driving force behind crude oil substitutes – whether geological or biological – has always been a crude oil supply crisis, while the decisive selection parameter has been local resource availability.

Though many of the unconventional oil technologies – notably the family known as Fischer-Tropsch synthesis[*] – deliver fuels which are undeniably clean in terms of tailpipe emissions (lower SO_2, NOx, CO, heavy metals, and particulate matter), the broader footprint of extraction, processing, and distribution represents a catalogue of direct threats to the biosphere: freshwater consumption, CO_2 emissions, increased mining activity, habitat destruction, local pollution, despoiling of marine ecosystems, introduction of invasive species and loss of biodiversity. Moreover, the development of these unconventional oils brings with it a massive parallel investment in additional liquid hydrocarbon fuel infrastructure and engine systems. And the longer society continues to tolerate the expansion of liquid hydrocarbon fuel apparatus, irrespective of the type of organic matter we use to derive our fuels, the harder it becomes to do anything about it.

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[*] *Developed by German researchers Franz Fischer and Hans Tropsch in the 1920s, the technique involves a catalysed chemical reaction of carbon monoxide (CO) and hydrogen* (H_2) *gases to synthesise liquid hydrocarbon compounds.*

The IEA estimates that US$ 4.3 trillion of investment is required in the petroleum industry between now and 2030, of which seventy-three percent will be in the Upstream.[55] The expansion of exploration and production activities, refining capacity, oil tankers, terminals, pipelines, blend plants, and retail service stations which is necessary to keep pace with rising transport demand will further lock us into a desperate future. This future can be averted only if we summon the courage to divert a significant proportion of those investments into the creation of a 'new transport paradigm'.

Oil Sands

Also referred to as 'tar sands' or 'extra-heavy oil', oil sands are a filthy combination of clay, sand, silt, water and about 10-12% bitumen,[56] which may be located relatively close to the surface. It is the semi-solid mixture of hydrocarbon compounds, resembling tar, which is of interest. Due to its high viscosity and physical entrainment in the mineral matrix, the bitumen cannot be pumped from the ground directly as crude oil. Instead the oil sands must be mined before being either refined directly into petroleum products such as gasoline, or upgraded into a synthetic crude oil – or 'syncrude' – prior to further processing in conventional refineries elsewhere.

The sheer size of the oil sands deposits is staggering, both in terms of land surface area and energy content, and is matched by the scope of the operations necessary for extraction. The vast majority of the world's oil sands are located in Alberta, Canada and Venezuela's Orinoco Belt; these two areas combined account for three-quarters of the world's known oil sands reserves.[57] It is Alberta which is attracting the greatest interest from IOCs, which some commentators have likened to a new Gold Rush,[58] and the reasons why should be familiar by now. Compared to Venezuela, Canada is politically a far less risky place for IOCs to embark upon new capital investments. Legitimate fears of resource nationalism prompting sudden policy changes have already been realised in mid-2007.[59]

Alberta offers a stable investment environment in a highly prosperous OECD nation; proximity to the world's number one oil consumer, the US; and based on today's technology and economic conditions, recoverable oil sands deposits totalling 164 billion barrels – roughly equivalent in energy terms to two-thirds of Saudi Arabia's proved oil reserves.[60] For IOCs desperate to replace their proved reserves, the oil sands thus present an obvious escape route. ExxonMobil has projected that up to one trillion barrels may be ultimately recoverable from oil sands worldwide, which would be equivalent to the total of all conventional crude oil produced globally to date.[61] Once again, it should be clear that the Oil Age will not end for lack of oil, and in spite of the Peak Oil theory, we have more than enough geological hydrocarbons within our grasp at some price to decimate the climate system.

As for geographical reach, Alberta's three main oil sands deposits of Athabasca, Peace River, and Cold Lake underlie 149,000 square kilometres of boreal forest.[62] Expressed in the unofficial but widely used international unit of measure, this area approximates to five 'Belgiums'.[*]

Two different techniques are employed to extract the oil sands: open-cast mining whereby vast quantities of overburden are removed to expose the hydrocarbon deposits, or heating of the oil sands 'in situ' to enable the bitumen to flow more readily. For open-cast mining, the oil sands must be situated within one hundred metres of the surface. Before mining can commence, wetlands must be drained, rivers diverted, and all trees and vegetation removed. About four tonnes of material must be mined to produce a single barrel of syncrude – a yield of just 3.5 percent by weight. This activity is possible thanks to the largest hydraulic shovels ever built, moving over forty cubic metres of material with every scoop. These work in tandem with purpose-built 'monster trucks', fifteen metres in length and seven metres tall, weighing forty percent more than a Boeing 747.[63] Examples of these extraordinary machines are shown in figure 13.

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[*] *The CIA's World Factbook records the surface area of Belgium as 30,528 square kilometres.*

To access deeper deposits, in situ recovery methods are used. In this technique, the injection of steam and/or solvents at high pressure lowers the viscosity of the bitumen such that it separates from the sand and flows to a well, and is then pumped to the surface. According to the Albertan government, around 82% of the oil sands reserves are recoverable using the in situ method, with the remainder accessible through surface mining practices.[64]

Despite the fact that the destructive impact of in situ technologies such as Steam Assisted Gravity Drainage (SAGD) are less dramatic, the above-ground footprint remains considerable as well pads, cleared of all vegetation, spread out over vast areas, connected by surface pipelines carrying steam in one direction and the water/bitumen mix in the other. Meanwhile, huge lakes known as tailings ponds* – large enough to be visible from space – are constructed to accommodate the toxic process residues, which migrate into the groundwater system and leach into the surrounding soil.[65]

OIL SANDS IN ACTION

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Figure 13. Oil sands in action: (a) hydraulic shovel moving $40\,\mathrm{m}^3$ of earth with every scoop; (b) 'monster trucks' on the move; (c) the wheel alone is 4 m tall.

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* *The term 'tailings' is used to describe liquid waste from mining activities.*

Both extraction processes – and the subsequent upgrading and refining steps – require large amounts of water and energy, which is highly problematic while we are battling to gain control of anthropogenic CO_2 emissions. Surface mining requires between two to five barrels of water for every barrel of bitumen produced, while SAGD consumes from 2.5 to 4 cubic metres of steam per cubic metre of bitumen.[66] In addition, the equivalent of up to one-third of the energy contained in the oil must be expended during extraction, equating to three times as much as conventional crude oil production. On a life-cycle basis, this makes the fuels derived from oil sands roughly twenty percent more carbon-intense than petroleum fuels. Any use of these fuels is a backward step, since we have to reduce global CO_2 emissions if we are to stand any reasonable chance of staying below the 2°C threshold.

If all of the above does not sound alarm bells, then consider the fact that in Alberta natural gas is used as fuel to generate the steam required in the extraction process, and to provide a source of hydrogen for bitumen upgrading to syncrude. According to the National Resources Defense Council (NRDC), every 24 hours the industry burns enough natural gas to heat four million American homes in order to produce a million barrels of oil.[67] One infamous proposal – currently the subject of frenzied political debate – is to bring gas from the Beaufort Sea in the Canadian Arctic via pipeline, through the Mackenzie River valley, a globally significant wetland eco-region, to power the Athabasca oil sands operations. Dr. Robert Skinner, an expert in unconventional oils from the Oxford Institute of Energy, summed up the oil sands folly most eloquently on a US radio programme in November 2003:

> *It is sometimes helpful to 'stand on the moon' and observe what we do on Earth… I hope that I don't have the following conversation with my granddaughter twenty years from now:*
>
> *"Grandpa, did you really do that?"*
>
> *"Do 'what', Masha?"*

"Did you take natural gas from the Arctic down to Alberta to boil water to make steam to melt tar out of the oil sands, then use more natural gas to produce hydrogen to make the tar molecules into gasoline so North Americans could drive four tonne vehicles five kilometres to sports clubs to spend fifteen minutes riding stationary bikes; did you really do that, Grandpa?"

"Ahhhh…, yes, Masha, I am afraid we did."[68]

If the Mackenzie pipeline and other natural gas supplies do not suffice to produce the steam, some have proposed that nuclear power be called upon to make up the shortfall.[69] Should we not be truly shaken upon learning that business leaders and politicians are seriously discussing new nuclear power stations as a means to satisfy a growing demand for liquid hydrocarbon transport fuels? Nuclear proponents point to the carbon-free nature of fission-based power as its major advantage over fossil fuels. The bizarre prospect of utilising nuclear power to produce gasoline, diesel, and jet fuel should scream that we are seriously in trouble. Before entertaining such proposals, might we not consider less Herculean efforts to redirect our transport paradigm away from liquids?

Nevertheless, all of the oil majors are heavily investing in Alberta at the time of writing. Shell recently acquired the twenty-two percent of Shell Canada that it did not already own, enabling it to integrate the business fully with its US refining and marketing operations.[70] Imperial Oil, ExxonMobil's Canadian arm, champions itself as "a pioneer in the development of Alberta's vast oil sands resources for many decades – both in situ and mining projects",[71] while Chevron, Total and ConocoPhillips all have growing interests in the field. BP had been absent until very recently, though the company was already participating in a Venezuelan extra-heavy oil joint-venture at Cerro Negro,[72] and had also tabled plans to reconfigure its Indiana refinery to process syncrude from Alberta.[73] BP finally followed its contemporaries upstream into Albertan oil sands when it announced in December 2007, to widespread disappointment in the environmental community, a multi-billion dollar tie-up with Canadian firm Husky Energy.[74] BP really is moving "Beyond Petroleum", though not in the direction its public relations campaign would have us believe.

Alongside Big Oil are resource-hungry NOCs such as China's state-owned trio – Sinopec,[75] CNOOC[76] and CNPC[77] – all of which have shares in Albertan oil sands projects. Even the self-styled 'responsible oil company' Statoil recently entered the business,[78] much to the dismay of environmental groups who hoped that the Norwegian outfit might provide a different development model for the industry.

From today's levels of about 1.2 million barrels per day (mb/d), the industry estimates production could easily reach 4 mb/d by 2020, potentially making Canada the world's fourth biggest oil producer, surpassed only by Saudi Arabia, Russia and the US.[79] The IEA expects Canadian production to climb further still, reaching as high as 5 mb/d by 2030.[80] To put this into today's context, 5 mb/d is equivalent to the entire oil consumption of Japan, exceeding the combined requirements of France and Germany.[81]

Among the many serious problems associated with oil sands expansion discussed above, the use of valuable and limited natural gas resources to extract oil sands from Alberta has been likened to a kind of reverse alchemy: turning gold into lead.[82] However, this inherently wasteful process is not the only way that numerous IOCs propose to use methane to generate liquid hydrocarbon transport fuels.

Gas-to-Liquids (GTL)

We learned earlier how LNG technology has enabled stranded gas – that is, natural gas which exists in reservoirs far enough from end users to make traditional pipeline transit uneconomic – to be transformed into the liquid state for long distance distribution to markets. In this case, the liquefaction step is a *physical* process which requires an energy input to condense the gaseous methane before loading onto purpose-built vessels. Upon arrival at the destination, the product is then regasified prior to distribution and/or use.

The act of liquefaction means that LNG suffers an energy debit of around fifteen percent versus pipelined gas, although this still makes the overall carbon balance significantly positive compared with coal,[*] which is the main fossil fuel alternative in heat and power applications. In other words, despite losing some energy in the transformation process, LNG remains a highly promising technology for easing the transition to a low carbon economy, by displacing coal in heat and power generation, in markets which are not accessible via gas pipeline.

By contrast, gas-to-liquids (GTL) technology converts natural gas into a synthetic liquid fuel, primarily diesel, via a *chemical* process which alters the molecular nature of the hydrocarbon. This Fischer-Tropsch GTL synthesis is energy intensive, meaning that at best only sixty-six percent of the primary energy input is retained in the liquid fuel output.[83] As such, the life-cycle carbon footprint of GTL fuels is essentially no better than diesel derived from conventional crude oil, despite starting with a feedstock which is the least carbon-intense of all the fossil fuels. Notwithstanding the associated local air quality benefits of synthetic fuels – suppression of SO_2, NOx, CO and particulate emissions – this carbon giveaway represents an appalling waste of munitions in humanity's fight against climate change, and it is entirely driven by our dependency on liquid hydrocarbon transport fuels.

Furthermore, since the world's proven natural gas reserves are similarly encumbered by the uneven geographical distribution which makes crude oil problematic, the widespread development of GTL transport fuels achieves very little in terms of energy security; we simply shift the geopolitical problem from one finite, imported fossil fuel resource to another. Almost fifty-six percent of proved gas reserves are located in just three countries: Russia, Iran, and Qatar,[84] who will all be keen to extract the maximum value from those resources. As Business Week reported in May 2005:

> *There are troubling signs that natural gas producers are moving toward forming their own version of OPEC. While not an immediate threat, such a move could eventually drive up prices for an*

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[*] *Natural gas contains roughly half as much carbon per unit of energy as coal, therefore an energy debit of fifteen percent due to the LNG process makes LNG fifty-nine percent less carbon intense than coal.*

> *indispensable element of the U.S. long-term energy supply: in January, the Energy Dept. predicted that gas imports from outside North America will increase more than 700% and account for a quarter of U.S. consumption by 2025.*[85]

Companies in possession of proprietary synthetic fuel technology are intent on monetising that competitive edge. In the early years of the 21st Century, ExxonMobil, Shell, and GTL joint-venture Sasol Chevron were all converging on Qatar – a byword for stranded gas – pumping capital into projects of extraordinary scale. Despite ExxonMobil's decision in February 2007 to shelve their 150,000 b/d Palm GTL project – reportedly due to escalating costs[86] – both Shell and Sasol Chevron appear undeterred. Shell's Pearl project, in cooperation with the state of Qatar, is set to become the world's largest integrated GTL plant with 140,000 b/d of fuel output, roughly ten times larger than Shell's existing Bintulu facility in Malaysia, which has been fully operational since 1993.[87] Sasol Chevron's 34,000 b/d joint-venture with Qatar Petroleum, known as Oryx, began shipping its first production in April 2007.[88] If successful, the capacity of Oryx could eventually rise threefold to 100,000 b/d.[89] Smaller scale projects either announced or underway in Nigeria[90] and Australia[91] will help to take the world's GTL supply from 100,000 b/d in 2005 to 2.3 mb/d in 2030.[92]

In order to prepare the ground for GTL's assault on the European market, Shell and Sasol Chevron recently came together with Volkswagen, DaimlerChrysler, Renault, and Bosch to form the Alliance for Synthetic Fuels in Europe (ASFE), a political lobby group which is promoting the notion that turning low carbon natural gas – the ideal candidate for displacing coal in power generation – into liquid transport fuels is a good idea.[93] The following quote from ASFE's website demonstrates the lack of joined-up thinking in energy companies:

> *Europe's challenge is to meet future mobility needs while reducing the environmental impacts of vehicle use and delivering the lowest possible emissions cost effectively. This is why the synthetic fuels represent a critical step on the path to a European future of sustainable mobility.*

This statement has two immediate problems. Firstly, as the ASFE's own publicity material correctly points out,[94] on a life-cycle basis the GHG emissions from GTL fuels are comparable to those produced in a conventional refinery system. So where are the emissions reductions? Certainly, GTL fuels can help to suppress the non-CO_2 tailpipe emissions which are detrimental to local air quality. However, as we discuss in detail later, there exists a simpler and far more efficient way to eliminate tailpipe emissions altogether: eliminate tailpipes.

Secondly, in the European Union, the CO_2 emissions from coal-fired power stations alone exceed those from oil-based transport. "Europe's challenge", as the ASFE puts it, is actually to reduce the environmental impacts of the energy system as a whole, including *inter alia* the emissions from transport as well as those (which are far greater) from the power sector. It makes sense to deploy all the weapons at our disposal in the battle against climate change as effectively as possible. In the case of natural gas, this means maximising its inherent carbon advantage by using it to displace coal in heat and power generation.

What, then, of the future of coal? Disturbingly, even coal is being seriously considered as a replacement for crude oil in transport.

Coal-to-Liquids (CTL)

Of all the methods humankind has ever devised for turning carbonaceous materials into liquid hydrocarbon transport fuels, coal-to-liquids (CTL) merits special attention because it has the most negative implications for climate change mitigation. The basic technology is nothing new, having been developed in the early 1900s. Essentially, the C:H ratio in solid coal must be modified, through the addition of hydrogen, into order to synthesise molecules which are liquid under ambient conditions.

CTL is commercially proven, viable, and even inevitable whenever the following three conditions are met:

(i) abundance of domestic coal (or ready access to cheap coal resources)

(ii) limited access to crude oil (or sustained high oil prices)

(iii) policy support (on the grounds of national security)

These criteria were satisfied on two notable occasions during the 20th Century: in Nazi Germany and South Africa under Apartheid. In the former, acute crude oil shortages during World War II prompted the Nazis to establish a network of CTL plants manufacturing transport fuels to sustain the war machine. By the end of the conflict, as much as ninety percent of German gasoline was derived from coal.[95] In the post-war period, once oil supply lines had been re-established, the economics of CTL collapsed and facilities were either reconfigured for other purposes or decommissioned.

In the case of South Africa, international sanctions against the Apartheid regime forced the country's leaders to embark on a CTL programme in 1955 which still has lingering consequences. By the mid 1980s, CTL technology supplied sixty percent of South Africa's transport fuel requirements.[96] The programme survives to this day thanks to the paucity of South Africa's domestic oil resources. The lasting legacy is that the former state-owned oil company Sasol is now the world leader in the CTL field, and is aggressively promoting it around the world.

The renaissance of a technology which was developed by the Nazis, deployed by an Apartheid regime and is burdened by so many other negatives would be incongruous, to say the least. If independence from OPEC oil is what coal-rich nations desire, then CTL offers a tempting but dangerous short-cut.

For the coal industry, CTL represents a tremendous new business opportunity: diversification and upgrading of their low value-added raw material for power generation into a high-grade fuel for the automotive and aviation industries. As if that wasn't good enough, it's all under the banner of 'Clean Coal' – a loose but increasingly fashionable oxymoron which owes much to the inherent filthiness of coal – since the synthetic nature of CTL fuels delivers a reduction in overall tailpipe emissions versus conventional diesel, gasoline, and jet fuel. While this is definitely a welcome benefit in the urban environment, especially in rapidly developing Asian nations where local urban air pollution seriously impacts public health, this benefit accrues only at the point of use.

The overall life-cycle CO_2 emissions of CTL – from the coal mine through to the wheels of the vehicle – are at least twice as high as their crude oil counterparts. In other words, all else being equal, a single litre of CTL diesel has a climate change impact equivalent to two litres of conventional fuel.

Proponents argue that CTL deployment remains consistent with a global effort to mitigate climate change impacts, through the parallel application of Carbon Capture and Storage (CCS) technology which aims to permanently bury CO_2 in geological reservoirs deep underground. However, even with the inclusion of CCS, coal-derived liquid fuels are no better than break-even in terms of CO_2 impact compared with conventional fuels.[97] We are far away from ever capturing and burying vehicle tailpipe emissions, which are virtually identical – around 2.5 kilogrammes of CO_2 per litre – regardless which carbonaceous feedstock we use to derive our virtually identical liquid hydrocarbon fuels.

On top of this horrendous carbon footprint, CTL processes are incredibly water-intensive; between six and twelve tonnes of water are consumed for every tonne of liquid fuel output.[98] And the growing scarcity of freshwater resources may be second only to climate change as a defining environmental and geopolitical issue of the 21st Century.[99]

Figure 14 shows the key CTL candidate countries, based on the first two criteria mentioned above: ready access to coal coupled with net imports of crude oil. Given that CTL has barely prospered in two countries facing States of Emergency, the recent resurgence of interest around the world should sound the very shrill warning that we are now entering a *planetary* State of Emergency.

As custodian of the world's largest coal deposits and given its apparently unassailable position as number one oil importer, the US is clearly a potential CTL front-runner. As Montana Governor Brian Schweitzer told TIME Magazine:

> *America is the Saudi Arabia of coal … We can achieve energy independence in ten years, create a whole new industry with tens of thousands of high-paying jobs. We'll never have to send our grandchildren to war in the Middle East.*[100]

Russia's massive coal deposits occupy second place in the global ranking, yet it is extremely *un*likely that CTL technology will emerge there since Russia is relatively rich in oil and holds the world's largest proven reserves of natural gas.

China takes the bronze medal for coal reserves, and the gold for coal production which powers the Chinese economic 'miracle'. Given that it's also the world's third largest importer of petroleum – soon to overtake Japan for second place – China is virtually guaranteed to follow the CTL path to oil security; coal is cheap, oil is dear, and China's demand for liquids shows no sign of abating.

COAL-TO-LIQUIDS CANDIDATES

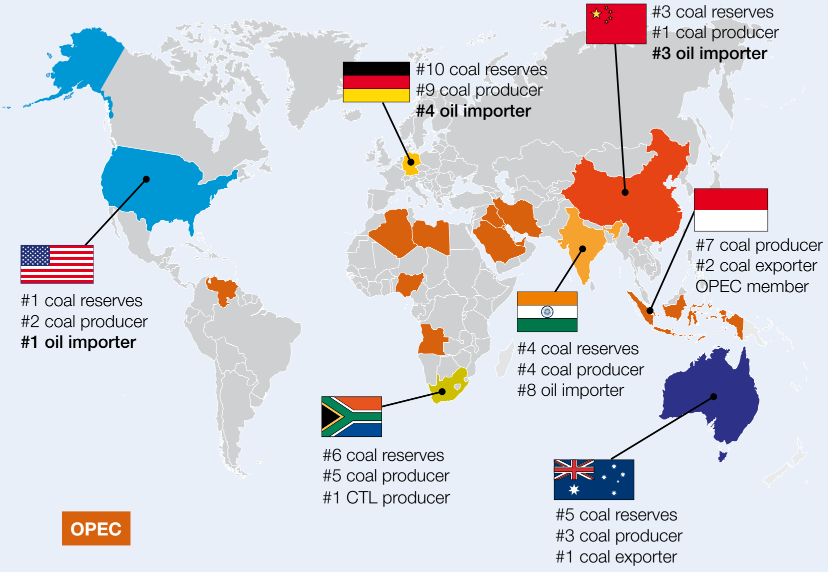

Figure 14. CTL development programmes are now underway in China, the US, Australia, India, and Germany. Indonesia is rumoured to be considering this path since it is now a net importer of crude oil. South Africa is the world leader and will likely expand its production capacity in the near future.

China's near neighbour India finds itself in a similar position with booming economic growth, generous coal deposits, and scarce domestic oil resources. Some commentators doubt whether India's coal reserves will be sufficient to sustain a long-term CTL programme due to competition with the power sector over finite resources. However, one of the great advantages of CTL is that virtually any grade of coal may be used to produce the same high quality synthetic fuel, whereas power generators favour harder coal. More importantly, while domestic coal offers a clear strategic and economic advantage when performing the CTL feasibility study, it is not a prerequisite. A thriving international coal market does not suffer from the same geopolitical constraints as liquid and gaseous fossil fuels. Coal resources are widely dispersed in more than seventy countries – offering energy security through supply diversification – and estimated global coal reserves are sufficient to last approximately one hundred and fifty years at current production rates.[101]

Australia is another net importer of crude oil, albeit a relatively minor consumer in global terms. However, the great promise of CTL for Australia extends far beyond energy security. Australia is the world's largest *exporter* of coal, with market proximity to oil-thirsty Asia Pacific neighbours China, India, and Indonesia which recently became a net importer of crude oil despite also being an OPEC member. CTL technology proliferation thus opens up new and profitable business opportunities for Australian coal interests.

South Africa remains the world leader in CTL since the days of Apartheid. With such a wealth of commercial experience, Sasol is keen to license its proprietary techniques to the wider market, as well as expand operations on home soil. Wherever there are discussions around potential CTL developments, Sasol is a possible partner.

Even Germany, despite its booming renewable energy industry and its own murky history of CTL operation, is capitalising on the resurgence of interest in the technology. CHOREN Industries GmbH optimistically declares its coal gasification technology will accelerate the development of climate-friendly second generation biofuels, also known as biomass-to-liquids (BTL).[102] While this claim may contain a kernel of truth, it is somewhat disingenuous when the greatest near-term potential for the technique is certainly coal liquefaction.

In summary, we should not be in the least surprised when CTL plants start to become an established feature of the industrial landscape in the US, China, India, Australia, Indonesia, South Africa, and possibly Germany. The 'business as usual' CO_2 emissions baseline will soon have to be redrawn with a much steeper gradient. All that remains to accelerate CTL's expansion is the third criterion of governmental policy support. It is close to being met in all three heavyweight markets: US, China, and India.

In the US, a lobby group comprising several mining, railway, and energy interests was formed in early 2007. According to its website,[103] the mission of the Coal-to-Liquids Coalition is "to articulate policies, educate policy makers and advocate congressional and administrative actions to advance the construction of state-of-the-art coal liquefaction facilities." The formation of this group came hot on the heels of the Coal-to-Liquid Fuel Promotion Act of 2007,[104] draft legislation which proposes loan guarantees from the Department of Energy, tax credits (of the type currently enjoyed by the exploding US biofuel industry), and Department of Defense funding. Once again, the implication – energy security winning out over climate security – should be abundantly clear.

In China, the CTL game is even more advanced. For those who wonder whether CTL will ever amount to more than a 'boutique' fuel, China's National Development and Reform Commission (NDRC) may provide a clue: its official target for CTL fuels is thirty million tonnes by 2020.[105] In the context of China's oil demand trajectory, thirty million tonnes represents relatively small potatoes at just 6.4% of projected imports.[*] However, when compared with the NDRC's biofuel target of ten million tonnes by 2020, we can see the deeper ramifications for any goal of reducing CO_2 emissions: for every one step forward, we take three steps back. Both Sasol and European oil major Shell have entered into strategic partnerships with local giant Shenhua Coal in an effort to bring coal-derived transport fuels to the Chinese by the end of this decade.

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[*] *According to the IEA World Energy Outlook 2007, China's net oil imports are projected to rise from 7.1 mb/d in 2015 to 13.1 mb/d in 2030. Assuming linear growth, this translates to net imports of 9.1 mb/d – or 468 million tonnes – by 2020.*

Despite this gloomy outlook a glimmer of hope may exist, thanks to water scarcity: an official from the NDRC recently expressed doubts about China's CTL potential, given the stress on freshwater resources in the coal-rich northern provinces.[106] Acute water shortages are already driving enormous hydro-engineering projects, aimed at diverting water from the Yangtze River northwards via three new canals.[107] It remains to be seen whether this sceptical voice will translate into a shift in official government policy, but so far concern for escalating CO_2 emissions has not been a driving force in the Chinese CTL debate.

India appears to be following rather than leading the CTL development path, but with no less enthusiasm. In early 2007, India's Investment Commission sent the Prime Minister a recommendation that CTL "should become an integral part of India's strategy for oil security".[108] This statement was quickly followed by an announcement that Sasol would be opening an office in Mumbai to search for viable CTL projects.[109]

THE CONVERGENCE OF TRANSPORT AND POWER

The escalating interest in GTL and CTL 'alternative fuels' (or 'liquid hydrocarbons', by another name) is one way we can envision a convergence between the traditionally discrete transport and power sectors. As we have seen, oil's great advantage over its fossil fuel cousins – the reason it became so dominant in small, mobile combustion applications – is its physical liquidity which imparts the combined benefits of high energy density and ease of application.

Methane (CH_4), the main constituent of natural gas, has a relatively high energy content per unit of carbon which makes it a highly effective tool in the power sector's efforts to reduce CO_2 emissions. Per unit of carbon, natural gas contains roughly one-third more energy than crude oil, and double the energy of coal. However, at ambient temperature and pressure for the same energy equivalent in gaseous form it occupies roughly one thousand times as much space as crude oil.[110] GTL technology overcomes this density drawback, but with an energy debit – owing to the 66% thermal efficiency of the process – which entirely neutralises its carbon advantage.

At the other end of the scale, solid coal has a low energy content per unit of carbon, and is more difficult to convey than either of its fluid hydrocarbon counterparts. In transport applications, coal has thus been confined historically to shipping and steam locomotives, both of which could afford to carry huge payloads of fuel. Today, the main energy use of coal is of course in the power sector. The upshot of commercial Fischer-Tropsch synthesis is that both natural gas and coal have found a viable pathway from the heat and power sectors into the transport sector.

Convergence between the transport and power sectors is not necessarily a bad thing. On the contrary, it may be desirable, provided we can carefully define the point of convergence. For the foreseeable future, it appears inevitable that in a carbon constrained world we will continue to consume fossil fuels to some extent. In this context, we will need to answer a straightforward question: what is the most carbon efficient way of deriving energy services from those fossil fuels? As we will see, it is certainly *not* by expending additional energy to convert solids and gases into the liquid state.

PART III

A DIFFERENT ROAD

THE END OF THE ICE AGE

As we have seen, the early part of the 20th Century did not suffer from the overwhelming dominance of the internal combustion engine (ICE) which characterises the transport sector in 2008. Electric cars were at one point outselling their gasoline-powered competitors, but they have – with the exception of niche applications – almost entirely disappeared from our roads.

It is interesting to note that the few niches in which electric vehicles (EVs) remain dominant are those in which ICEVs simply won't do: their performance is found wanting, despite a century of continuous development. In fact, they will *never* do. These EV strongholds fall into two main categories: indoor applications which require zero vehicular emissions (e.g. warehouses, airport terminals, railway station concourses), and specific outdoor applications such as golf carts and neighbourhood vehicles in retirement communities, where virtually silent operation is a valued feature. Both of these performance parameters – emissions and noise – are important in all automotive applications, yet we have grown tolerant of the inherent shortcomings of ICEVs.

However, the rules of engagement are changing: we have seen how transport's dependence on liquid hydrocarbons and ICEs represents a serious threat to the Earth's climate system, the integrity of valuable ecosystems under attack from exploration and production activities, and to global political stability as a result of the uneven distribution of reserves. None of these concerns could have been considered legitimate in 1900, when the atmosphere was treated as an inexhaustible waste receptacle for all anthropogenic emissions, black gold flowed freely from giant US oilfields, and the world supported roughly one-quarter of today's human population. In the vastly different context of the 21st Century, we need to revisit the case for the electric vehicle with some urgency.

In 1990, the California Air Resources Board (CARB) courageously introduced legislation known as the Zero Emissions Vehicle (ZEV) Mandate, setting percentage sales targets for US automakers to meet with electric cars. The original ZEV Mandate began to make mass-produced electric vehicles a reality: General Motors' EV1, Toyota's RAV4-EV, Ford's Ranger EV pick-up truck and Th!nk City car are memorable examples of fully electric vehicles which appeared briefly, in small trial numbers, on California's roads by the late 1990s. They did not survive in sufficient numbers to utterly transform the automotive sector for reasons that remain a matter of debate for industry commentators and EV advocates alike; the saga is recounted in the documentary film *Who Killed the Electric Car?*[111] This fleeting renaissance of EVs provides many lessons for future market development,[112] as well as solid performance data, albeit based on technology which has since been superseded.

Escaping Lock-in

Once a particular technology has achieved dominance in a given market, it becomes very difficult to dislodge. The dominant technology itself improves over time, reaches economies of scale and benefits from societal preferences, subsidies and incentives, making it hard for subsequent – perhaps better – alternatives to compete fairly. In the automotive industry, the real killer is that the prevailing dominant technology – in this case, the ICE – effectively defined an entire infrastructure ecosystem, which itself required extraordinary capital investment. The 'path dependency' of dealerships, spare parts manufacturers, service facilities, fuelling stations, long-distance highways and even insurance policies adds considerable inertia to the dominant technology. Thus, we experience 'lock-in' to a liquid hydrocarbon paradigm, which is so pervasive that six of the top ten corporations in the world (by revenue) are predominantly suppliers of liquid hydrocarbon fuels. Yet as we have seen, the biosphere which provides our life-support systems can no longer sustain this paradigm. This conclusion reverberates in the board rooms of Big Oil and Big Auto, and in the wider investment community whose future returns are firmly in the firing line.

How do we escape this lock-in? By finding new sources of carbonaceous material to liquefy? No, that won't do it. That's the very best way to *reinforce* the lock-in. What other options might we have at our disposal? Increase the energy efficiency of our vehicle fleet? Choose other modes of transport? Reduce the need for personal mobility?

In fact, we can already do much along these lines to enhance our surface transportation system. We can eliminate unnecessary journeys by improving urban planning regulations, encourage modal shift from private vehicles to public transport, from road to rail or sea, and implement policies such as congestion charging which generate economic incentives for behavioural change.

We can increase the energy efficiency of our vehicles, for example by reducing the rolling resistance of tyres, or by lowering the weight of automotive bodies and components. We can lower maximum speeds to permit engine downsizing, which enables the engine to run closer to optimal efficiency. We can take other efficiency steps: deactivating some cylinders when cars reach cruising speed, and, of course, hybridize cars to eliminate idling and recapture braking energy. We can also attempt to decarbonise our fuels, by mandating a minimum percentage of sustainable biofuels[113] while simultaneously penalising the carbon-intensive unconventional oils,[114] as is being proposed within the European Union at the time of writing.

We can – and should – expedite all of these measures and more, for they are all worthy in their own respects. They would certainly reduce crude oil demand in comparison to the BAU scenario, while simultaneously improving the local and global environment and lead toward the political holy grail of energy independence. However, even if successful in our efforts, we would still be effecting incremental change: our overall transport system may turn out to be more efficient and effective, but our hundreds of millions of automotive vehicles would remain shackled exclusively to the burning of liquid hydrocarbons in ICEs. Tailpipe emissions, smog, incessant noise, pressure on pristine ecosystems from hydrocarbon activities, all would continue. There is no getting away from it: if we want to escape the lock-in – which we must, if we are to maintain a living planet – then we need to initiate *transformational* change, which requires disruption to the ICE-dependent status quo.

Transformational Change

Perhaps the greatest hurdle we encounter when discussing transformational change lies in the fact that people really do struggle to envision something which has not happened yet. Here is an imaginary but plausible conversation from the mid 1980s, which illustrates the point:

> A: "Within twenty years we will be able to afford portable telephones which are smaller than a packet of playing cards, usable anywhere in the world, which can also be used to take photos, create movies, listen to music, even watch television."
>
> B: "That's ridiculous! We've got telephones already, and cameras, personal cassette players, and portable TVs. And anyway, what about the batteries? To do what you suggest, they'd be so big you'd have to carry them round in a suitcase. It'll never happen."
>
> A: "Hmmm, perhaps you're right. By the way, have you ever heard of a company in Finland called Nokia?"
>
> B: "Yes, they make car tyres. What have they got to do with it?"

It seems preposterous to think that today we could be carrying around Michelin mobile phones![*] Yet Nokia is a rare exception that

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[*] *Conversely, 'Motorola' does sound like an appropriate name for car tyres! This is no accident: the moniker was chosen when Motorola specialised in automotive electronics.*

proves the rule: corporations are spectacularly unsuccessful at *transforming* their core business. Nokia, the world's largest manufacturer of mobile phones, started the 20th Century as a paper and rubber company, later diversifying into telecommunications, and today has one-third of the mobile phone market.[115]

Mobile telephony has utterly transformed the way in which we communicate, in the space of a single generation. It is an excellent case study in transformational change and offers a glimpse of what could be achieved in the automotive sector, if we indulge our collective imagination. The incumbent suppliers – frequently state monopolies – of the dominant 'fixed line' services underestimated the potential impact to their bottom lines, and as a result were in many cases slow to see the emerging opportunity for – or indeed threat to – their own businesses. To the incumbents, the fixed line infrastructure represented capital investment – or 'lock-in' – and they were understandably keen to deliver maximum return on that investment.

The emergent service providers which brought us affordable mobile telecommunications were able to bypass the fixed line infrastructure. Initially, the costs of the new mobile technology were high, while performance was compromised by range, as well as battery size, weight, and lifetime. Thus sales were restricted to niche applications and markets. Early adoption of mobile phones was enabled by first using them in fixed locations: cars and trucks, powered by the vehicle's auxiliary battery.

As mobile technology rapidly improved and sales steadily climbed, the cost of performance declined to the point where fixed line telephony with its inherent limitations no longer made perfect sense for many ordinary people. New business models emerged, whereby customers could select between term contracts or 'pay-as-you-go' tariffs, tailored to different patterns of use. And developing markets in south-east Asia and Africa – realising the clear advantages offered by this revolutionary new technology – were able to 'leap-frog' directly to mobile phones, skipping a generation of wired telecommunications infrastructure investment rather than blindly repeating the evolutionary steps that the developed world had taken to reach the same point.

The global telecoms landscape has changed beyond all recognition in a couple of decades. If the automotive sector were to undergo a similar transformational change, or paradigm shift, would the dominant vehicle manufacturers and fuel suppliers be fundamentally immune to the type of external threats which overhauled the telecommunications sector? If the oil industry draws pertinent lessons from history, it will recall that it was once displaced from a seemingly unassailable dominant position in the lighting sector, through the introduction of a disruptive technology: electricity.

Disruptive Technologies

Automobile manufacturers (and fuel suppliers) frequently claim that their job is to provide what their customers demand. "Customers want larger, more powerful SUVs, we simply supply them", or so the story goes. But this line of argument begs a few probing questions. If customers always knew what they wanted, would marketing departments exist? What would be the purpose of advertising, and why would companies spend huge amounts of money on this apparently futile activity?* How do you define what it is that your customers demand? Isn't it a core competency of successful businesses also to *create* demand, for *new* products, that is: products which don't yet *exist* in the consciousness of consumers?

As potential automotive consumers, do we demand heavier cars capable of attaining speeds which are three times faster than the law permits, consuming ever greater quantities of increasingly expensive liquid hydrocarbon fuels which provoke bloody conflict, human suffering

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* *A survey conducted by environmental group Friends of the Earth analysed car adverts placed in UK national newspapers over a two week period leading up to the new car registration date in March 2007. Over half were for cars in the most polluting Vehicle Excise Duty bands E to G, corresponding to cars that emit over 165 grammes of carbon dioxide per kilometre (gCO_2/km). Only three percent of adverts promoted cars which emitted below the 120 gCO_2/km threshold for 2012 which was set by the EU in the mid 1990s. Friends of the Earth estimated that the total spending on advertising in the two-week period of the survey amounted to almost £5.5 million (US$10 million).*

and directly cause environmental catastrophe? Or do we rather demand appropriate personal mobility solutions which will take us from A to B safely, efficiently and conveniently, with due consideration to our neighbours and the environment? At the moment, we're not exactly spoiled for choice. Eavesdropping on another imaginary conversation, this time from one hundred and fifty years ago, we might have heard the following:

> A: "I'm a transport service provider. What do you, my customer, demand from me?"
>
> B: "I want a faster horse that never gets tired."
>
> A: "Oh, so you don't want a car then?"
>
> B: "What's a 'car'?"

Evidently, it was not the horse-traders of the 19th Century who invented that disruptive technology called the motor car. But that's not to say that customers didn't *want* the manifold advantages of non-biological transport solutions; they just hadn't imagined them! In a similar vein, returning to the mobile phone industry, it was not the fixed line telecommunications monopolies who brought mobile telephony to the world, but no one alive today would seriously argue that there is no demand for mobile phones.

If precedent shows that incumbent suppliers of dominant technologies are usually unreceptive to disruptive solutions, what are the chances that the combined might of the oil and automotive industries will be able – not to mention willing – to provide us, the demanding consumers, with breakthrough alternatives to the internal combustion engine? These vested interests are likely, accidentally or intentionally, to *hinder* the development and widespread adoption of any solution which is outside their core expertise, and which therefore represents a threat to their future business success. There is nothing remotely sinister or nefarious about this response; the framework in which corporations operate *requires* that they do battle to eliminate threats to the profitable status quo, unless they have the specific internal capacity to embrace those threats as opportunities.

So, what about electric cars? When the likes of Ford and Honda claim that commercially available automotive grade lithium ion batteries are several years away, we should wonder if their managers are the right people to judge. Shouldn't we rather ask companies whose core expertise is battery development? Of course, we may encounter an equal but opposite bias in *their* projections, but that's not to say they are any less trustworthy than Detroit, nor does it mean that the actual truth lies equidistant between these highly polarised perspectives.

Similarly, when Shell espouses its hydrogen demonstration projects in the Netherlands, Iceland, Washington DC, and Tokyo,[116] keeping the world's conscientious energy consumers hoping and believing in a technological breakthrough which will require incredible investment in an entirely new parallel infrastructure – an infrastructure that would almost certainly be owned and operated by companies that are expert in the synthesis, storage, and delivery of combustible fluids – we should start to ask some fundamental pertinent questions. For starters: what does it mean when a major corporation decides to invest in a disruptive technology?

The Great American Streetcar Scandal

Los Angeles is surely one of the most depressing examples of automobile-centric urban planning, even by American standards. Visitors to this sprawling mess of suburbs and low-rise commercial districts strung together along endless gridlocked highways are right to inquire how such a fascinating failure of human ingenuity came into being. How could such a vast expanse of steel and concrete have evolved in the absence of any meaningful mass transit infrastructure? It turns out the answer is in the question: it evolved *because* there was no meaningful mass transit infrastructure!

In a now legendary example of corporate self-interest winning over public 'general interest', General Motors is widely credited with the destruction of Los Angeles' extensive streetcar network.* Senior GM

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* *The city of Los Angeles was not alone in suffering this fate, but it remains the best case study. Other examples include Chicago, Philadelphia, Baltimore, Washington, St. Louis, Salt Lake City, Sacramento, San Diego and Oakland.*

figures in the 1920s correctly identified public transport as the major barrier to increasing sales of motor vehicles – initially buses. And so, together with Standard Oil of California (now Chevron), Phillips Petroleum (part of today's ConocoPhillips), and Firestone (the tyre manufacturer now owned by Bridgestone), they established a separate entity called National City Lines to acquire the competition and then systematically deconstruct electrified rail-based mass transit in favour of road-based motor vehicles. GM's now infamous statement: "What's good for the country is good for GM, and vice versa" illuminates the almost egocentric way in which powerful corporations sometimes view their contribution to society.[117]

The lesson to be drawn from the Great American Streetcar Scandal (which is described in fascinating detail elsewhere[118]) is that businesses respond entirely rationally, from their point of view, to external threats. Furthermore, it serves as a warning that when companies invest in product technologies which directly *compete* with their core business, it is not necessarily a moment to celebrate.

"Beyond Petroleum"

Take, for example, BP's acquisition of Solarex (a leader in solar energy), half of which it already owned, in April 1999.[119] The US$ 45 million which BP reportedly paid for the remaining fifty percent effectively transformed BP into "the world's largest solar energy company". Everything is relative. Exactly one year later, BP concluded its US$ 27.6 *billion* takeover of Atlantic Richfield Company (ARCO),[120] an integrated oil and gas operation with extensive fossil fuel reserves and a network of service stations across the US. Needless to say, investing six hundred times more dollars on hydrocarbons than on solar energy in the space of twelve months is understandable when you're a dyed-in-the-wool oil company, but as with BP's recent oil sands incursion, it casts an unflattering light on the "Beyond Petroleum" public relations campaign.

THE CHINA FACTOR

By 2006, China was home to approximately twenty-two million private motor vehicles.[121] Around 6.4 million passenger cars were sold in 2007, with a further 2.5 million commercial vehicles, making a rise of 22% on the previous year.[122] At this staggering rate of growth, the total fleet could increase more than ten-fold to 250 million by 2030, with the automotive sector considered by the NDRC to be one of the key pillars supporting Chinese economic development.[123] China is already the second largest car market in the world, after the US.[124] Domestic automobile manufacturing capacity is expanding at an incredible rate; by the end of 2007, China had overtaken Germany as the world's third largest auto maker behind USA and Japan.[125] Chinese manufacturers will start exporting to European and US markets very soon,[126] following a trail from Asia blazed by Japanese, Korean, and Malaysian companies before them. Chery Automobile recently announced its intention to build assembly plants in Russia, Romania, and Poland, meaning that we will soon be driving Chinese cars such as the 'QQ' on Europe's roads.[127] As small and efficient as the QQ undoubtedly is, it will simply help us to continue our ICE-powered road trip into the Abyss.

250 Million Vehicles

Today, the US automobile fleet numbers roughly 250 million.[128] By 2030, China's vehicle population could therefore resemble the US in 2008, albeit in a nation with pitiful domestic crude oil supplies, vast coal reserves, stressed freshwater resources, advancing deserts, and a population of perhaps 1.5 billion to feed. The implications should be clear, not to mention shocking.

If we were to travel back in time to the point when US car numbers were approximately the same as in China today, we would find ourselves somewhere between the two World Wars. Knowing what we now know about the unsustainable nature of our present transportation model, how would we choose to redesign the future?

Between 2003 and 2020, it is anticipated that three to five hundred million Chinese will migrate from rural areas to towns and cities.[129] Such a rapid rate of urbanisation – which equates to the construction of a new Shanghai every year* – offers the potential to deploy new sustainable transport solutions which is conspicuously lacking in OECD countries. However, this window of opportunity is strictly time-limited; within the next two decades, we may be faced with another global economic powerhouse locked in to liquid hydrocarbon transport fuels. The Chinese have roughly one hundred years of Henry Ford behind them. In a way, this positions China one hundred years ahead of the US.

China's leaders fully understand their country's predicament. It is experiencing an unprecedented rate of growth in demand for transportation services, coupled with hopelessly inadequate domestic oil resources. The reserves-to-production (R/P) ratio of Chinese proved oil reserves is estimated at just twelve years,[130] based on the current rate of consumption which, as we know, is increasing fast. These two factors – incredible demand growth and steeply declining reserves – conspire against China at a time when the world is beginning to acknowledge the potentially terrifying consequences of unrelenting anthropogenic GHG emissions. Reports that China recently passed the US to become the world's leading emitter[131] will only increase the international focus on China's development trajectory. While per capita emissions remain relatively low compared with typical OECD levels, owing to China's enormous population, the global climate system is unsympathetic to such metrics, responding only to absolute emissions.

History teaches us that threats can often be turned into opportunities, and that necessity is the mother of invention. Challenged to raise the living standards of its 1.3 billion people while simultaneously reducing its carbon footprint, China paradoxically offers some of the brightest prospects for redesigning our automotive transport paradigm. In early 2007, the Chinese Academy of Sciences (CAS) published a list of suggestions for the development of alternative energy systems,

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* *According to the website www.citypopulation.de, the population of Shanghai stood at 16.4 million in 2000.*

paying particular attention to “petroleum substitutes”. In addition to ominous proposals for continued research and development of oil shale resources, liquefaction technology, and second generation biofuels, the statement published on the CAS website makes the following recommendation:

> *First of all, positive efforts should be made to promote the adoption of new power systems for the automobiles, which are good at energy saving and diversified for energy sources. Priority should be given to electrified power systems with zero discharge of exhaustive gases. There is the need to vigorously carry out the research and development of highly efficient, low-cost systems of fuel cells and lithium ion batteries.*[132]

In Tianjin, a port city some 125 km to the east of Beijing, an electric vehicle factory is currently under construction which will boast a capacity of twenty thousand units per annum.[133] When completed, the Tianjin-Qingyuan Electric Vehicle Company will be the largest electric vehicle manufacturer in the world by some distance, and – it is worth repeating this point – it will be a Chinese company using Chinese technology, with plans to export half of its annual production to the US and Europe. Once again, as with the 19th Century horse-traders, it is frequently not the incumbent suppliers of the dominant technology who are successful in developing the disruptor. At the 2004 Challenge Bibendum, Jean-Marie Folz, the CEO of French carmaker Peugeot-Citroën, told reporters that “if anyone has a breakthrough in electric vehicles it will be China.”[134]

PART IV

THE ELECTRIC POWERTRAIN

LIFE-CYCLE ANALYSIS

As an energy conversion device, the internal combustion engine coupled with a mechanical drivetrain* – the conventional ICEV – is desperately inefficient. Whether fuelled by gasoline (spark ignition ICE) or diesel (compression ignition ICE), the vast majority of today's cars, light trucks, buses, and heavy-duty vehicles operate on a four-stroke cycle, namely: i) intake of air and fuel into the cylinder; ii) compression of the air and fuel mix; iii) combustion and expansion of the fuel; and iv) expulsion of the hot exhaust gases.

In this thermo-mechanical process – whereby chemical energy is converted into mechanical energy via fuel combustion – expansion of fuel in the confines of the cylinder causes the piston to reciprocate, which drives the crankshaft, which turns the axle, which rotates the wheels which propel the vehicle. A large proportion of the energy that is released ends up as waste heat transferred to the exhaust and cooling water. The engine and mechanical drivetrain – thanks to an abundance of moving parts in each – offer ample opportunity for further

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* *The term 'drivetrain' typically refers to the transmission system from the engine output shaft to the wheels, whereas 'powertrain' is a more comprehensive term encompassing the energy storage device and, possibly, a prime mover (ICE or fuel cell).*

unproductive energy dissipation in the form of friction losses and noise.

According to the US Department of Energy (DOE)'s website dedicated to fuel economy – in a gasoline-dominated market – only 15-20% of the chemical energy stored in the fuel is put to work moving the vehicle (and powering the accessories).[135] This assessment has nothing whatsoever to do with vehicle size, shape, or weight; it is simply a measure of how much energy is available to turn the wheels. Of course, lighter bodies with superior aerodynamics, reduced tyre rolling resistance, and efficient auxiliary components will enable more of that motive energy to be converted into propulsion, but those complementary measures do nothing to improve the efficiency of the *powertrain* itself.

Diesel-fuelled ICEs are inherently more efficient converters of chemical energy than their gasoline counterparts. Indeed, in a 2002 study comparing the performance of light-duty vehicles in Europe,[136] diesels were five to fifteen percent more fuel efficient than their direct gasoline equivalents, with turbo direct injection (TDI) technology able to increase that advantage to thirty percent. For our discussion, we therefore take efficiency benchmarks of 18% for gasoline – the mid-point of the US DOE range – and 23% for diesel engines, which represents a thirty percent efficiency advantage over gasoline.

After one hundred years of continual product development and technological advances, vehicle efficiencies of the order of 18-23% should strike us as being quite dreadful! And this omits the energy losses that occur before the fuel even reaches the engine, to extract, transport (via marine tankers or pipelines), refine and deliver it. In the commonly used well-to-wheels (WTW) convention of automotive life-cycle analysis, illustrated in figure 15, these combined oil company activities are termed the well-to-tank (WTT)* segment, while the operation of the vehicle – converting stored chemical energy into motive energy – is called the tank-to-wheels (TTW) portion. When assessing the relative merits of alternative vehicle technologies, it is vitally important to fairly compare their energy consumption over the life-cycle, not just at the point of use, to truly evaluate their respective GHG emissions.

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* *Or mine-to-tank, in the case of coal.*

It is also crucial to define at which point the life-cycle analysis should begin. The resource extraction and distribution process *upstream* of the plant (mining for coal or drilling for oil and gas) is the same, irrespective of whether the plant then goes on to generate electricity or to produce liquid fuels. In many cases the energy consumption and emissions involved in the resource extraction process are minor compared to what happens at the plant and beyond. For these reasons, it may be most appropriate to consider the plant as the starting point for life-cycle analysis when comparing alternative vehicle technologies.

We will thus focus on the plant-to-wheels (PTW) portion of the full life-cycle, which can be further sub-divided into plant-to-tank (PTT) and tank-to-wheels (TTW).

CRUDE OIL WELL-TO-WHEELS LIFE-CYCLE ANALYSIS

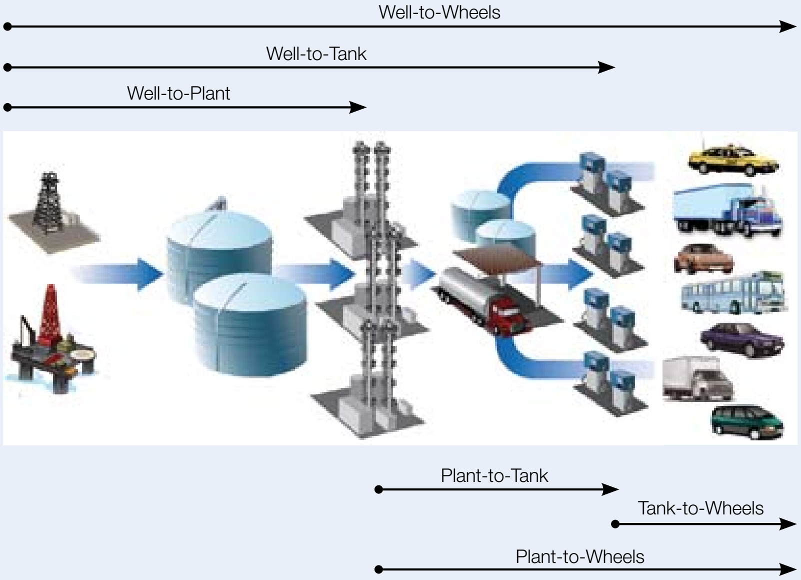

Figure 15. Graphical representation of the well-to-wheels (WTW) life-cycle analysis. This discussion focuses on the plant-to-wheels (PTW) portion, which we further separate into plant-to-tank (PTT) and tank-to-wheels (TTW).

Electrons versus Liquids

Why is the mechanical powertrain so dismally wasteful? An underlying characteristic of the ICE is that maximum efficiency is attained near the maximum load point. Automotive engineering consultant Ricardo estimates that modern gasoline and diesel engines operating at full throttle typically achieve efficiencies of around 28% and 33% respectively; most of the wasted energy is transferred to the exhaust, coolant, lubricant, and radiated heat.[137] However, automotive engines seldom function at maximum power due to variable speeds and idling – especially in the urban environment – which makes their mean operating efficiency much lower in practice. At partial load, those automotive engine efficiencies drop to around 23% for gasoline and 30% for diesel.[138] This explains why, for conventional vehicles, official fuel consumption figures are far more impressive in the extra-urban rather than the urban test cycle. Further losses mount up: according to energy expert Vaclav Smil, idling at red lights and in congested traffic can easily account for 5-10% of the initial energy input, with a further 5% cannibalised by friction in the transmission.[139] Hence, in practical terms, it is reasonable to assume mechanical powertrain efficiencies of 18% for gasoline and 23% for diesel.

In distinct contrast to the ICE, electric motors are inherently energy efficient – across a much broader load range – converting some eighty-six percent of the chemical energy stored in batteries to power the wheels. An electric powertrain incorporates not only an electric motor but also a generator, battery, control system, and transmission, and these combine to lower the overall TTW efficiency.* A 2001 study by Sweden's Lund University[140] estimated a battery-electric vehicle (BEV) efficiency of 57%, based on the component technology of the day. The study saw the potential for considerable gains through realistic technology advances – including

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* *Note that 'tank' is used in the broadest sense of a storage medium, since we are comparing liquid fuels with electricity.*

lithium-polymer batteries currently penetrating portable application markets such as laptop computers, mobile phones, and power tools – taking the overall BEV efficiency as high as 76%. The same study placed the mean efficiency of ICEVs at around 18%, which aligns with our working assumption for gasoline discussed above. A recent IEA report[141] on the prospects for hydrogen and fuel cells[*] presents a comparison of future automotive transport platforms in which the efficiency of electric vehicles is estimated to be 74%. For the purposes of this discussion, we will conservatively assume that a BEV's electric powertrain could achieve 65% efficiency.

To test the validity of these figures against real world performance data, it is helpful to compare vehicles which are identical in all respects, save for the powertrain technology which propels them. That way, we can control for energy losses arising from vehicle aerodynamics and other idiosyncrasies. Thanks to California's ZEV Mandate, it is possible to evaluate such data from the recent past.

The most famous electric vehicle spawned by the Mandate is probably the General Motors EV1, which was developed from the bottom up as an electric vehicle and consequently has no ICEV equivalent against which to compare. However, the Toyota RAV4-EV and the Ford Explorer USPS Electric both had direct gasoline-powered equivalents. According to the US DOE's fuel economy website,[142] which enables side-by-side comparisons of historical vehicle performance data, the RAV4-EV (model year 2000) was 4.4 times more efficient than its ICEV contemporary over the combined test cycle. Meanwhile, the Explorer USPS Electric (model year 2002) returned fuel economy figures 3.2 times better than its conventional sibling. These two data points indicate that, all else being equal, the practical energy efficiency of the electric powertrain can exceed that of its gasoline-powered mechanical counterpart by at least a factor of three to four.

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[*] *The prospects for hydrogen and fuel cells are discussed in more detail later in this report.*

This finding validates the working assumptions which form the basis of our discussion: an estimated electric powertrain efficiency of 65% is 3.6 times greater than the 18% assumed for a mechanical powertrain fuelled by gasoline, suggesting that our respective efficiency benchmarks are reasonable, at least insofar as they relate to one another.*

It is clear that the electric powertrain is a vastly more energy efficient device *in principle* than its conventional mechanical counterpart, thanks in some measure to having far fewer moving parts to invoke friction losses, no idling while stationary, and the possibility to recapture some of the motive energy via regenerative braking. Most of all, the electric motor draws on a high quality form of energy – electricity – which is extremely well ordered in comparison to the chaotic chemical-thermal energy conversion which drives the pistons of an ICE. The superiority of the electric powertrain comes despite comparatively limited research and development that has occurred over the course of a century which has been dominated by ICEVs. However, the supremacy in tank-to-wheels (TTW) energy efficiency is only part of the story: the electric powertrain still requires the production of electricity, so what about the plant-to-tank (PTT) portion?

Starting with the liquid pathway, the best conventional oil refineries are actually highly energy efficient. In simple terms, this is because the feedstock – in this case, crude oil – is essentially *refined* into liquid fuel products via distillation. This separation of the crude oil mixture into its constituents does demand energy input, in order to heat the feedstock in a distillation tower, but does not require that the feedstock *itself* be burned. Further energy expenditure occurs during catalytic cracking at temperature and high pressure, which is necessary to convert heavy, long-chain hydrocarbon molecules into the lighter components found in gasoline. And to meet increasingly

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* *In fact, this comparison is rather generous to the internal combustion engined variants. The RAV4-EV and the Explorer USPS Electric utilised older nickel metal hydride (NiMH) and lead acid (Pb-Ac) batteries respectively, which are less efficient than the lithium-based cell technology which appears in modern electric vehicles.*

stringent fuel quality standards, such as ultra-low sulphur diesel – from crude oils of diminishing quality – additional energy-intensive processing is required. Finally, the liquid fuels must be conveyed via pipeline and/or road tanker to the point of sale, such as the roadside retail service station. Nevertheless, the full petroleum refining and distribution efficiency, as referenced by the US DOE,* maintains a respectable 83%.[143]

Turning to the electron pathway, operators of conventional power stations based on hydrocarbon fuels can only dream of the 83% energy efficiency achieved by crude oil refiners. Power stations burn mostly coal and natural gas (as we have seen, crude oil is considered too valuable to 'waste' in such facilities) to heat water, to create steam, which drives the turbines that generate electricity. According to the IEA, the efficiency of the world's coal-fired power plants in 2003 was just 35%, with natural gas performing somewhat better at 42%.[144] Typical grid transmission and distribution (T&D) losses of around 8% further lower the efficiency of the electron pathway.

Based on these assumptions, how do the electric and mechanical powertrains compare in pure energy efficiency terms? For the mechanical variant, we multiply the refining and distribution efficiency of 83% by the two extremes of the ICEV energy efficiency range – 18% for gasoline and 23% for the more frugal diesel engine – to arrive at plant-to-wheels (PTW) efficiencies of just 15% and 19% respectively. For the electron pathway we take the average power station efficiencies of 35% for coal and 42% for natural gas, attenuate for T&D losses of 8%, then multiply by the estimated BEV efficiency of 65% to deliver PTW efficiencies of 21% and 25% for coal and natural gas respectively. These results are summarised in Table 1.

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* *It is reasonable to accept the US figure for our purposes, since the US refines more transport fuel from crude oil than any other single nation, consumes one-quarter of the world's crude oil, and forty percent of the world's gasoline.*

Primary energy efficiencies		Liquid Pathway (ICEV)	Electron Pathway (BEV)
Plant-to-Tank	Plant efficiency	83%	35-42%
	Transmission & Distribution		92%
Tank-to-Wheels		18-23%	65%
Plant-to-Wheels (life-cycle)		15-19%	21-25%

Table 1. Comparative primary energy efficiencies of ICEVs and BEVs across the plant-to-wheels life-cycle.

Despite those wretched power plant inefficiencies and the fact that electric powertrain technology is relatively immature, the battery electric vehicle can be over sixty percent more energy efficient than today's conventional ICEV, across the entire plant-to-wheels life-cycle. Considering the potential for technological advances over time – which will inevitably favour the less developed electric powertrain – this efficiency advantage is likely to increase.

CO_2 Emissions

Of course, the PTW primary energy efficiency does not tell the whole story; we must also consider the life-cycle CO_2 emissions of the electron and liquid pathways. Great care must be exercised in order to make direct comparisons, because the power generation 'mix' of different nations – or of states within nations – varies substantially. For example, California's electricity is among the cleanest in the US, due both to the relatively high contribution of natural gas – almost sixty percent in 2005 – and to the share of carbon-free energy technologies (nuclear, hydro, and renewables), together with a coal component of less than one percent.[145] This carbon-light generation mix delivers a slender CO_2 intensity of 273 grammes per kilowatt-hour (gCO_2/kWh)

overall.* Meanwhile, Indiana in the US Midwest relies heavily on coal – a massive seventy-three percent in 2005 – for its power supplies. Consequently, its CO_2 emissions per unit of electricity are an eye-popping 937 gCO_2/kWh: more than three times greater than in California and more than fifty percent higher than the US national average of 620 gCO_2/kWh.[146] Roughly forty-nine percent of US electricity comes from burning coal.

Across the Atlantic, the EU's electricity generation mix varies similarly from one Member State to another. For California, read Austria (221 gCO_2/kWh), with fifty-nine percent of electricity supplied by renewables; while for Indiana, read coal-heavy Greece (781 gCO_2/kWh). The EU-25 average CO_2 intensity of electricity (and heat) production in 2004 stood at 370 gCO_2/kWh.[147]

These figures quantify the amount of CO_2 emitted per kilowatt-hour of electricity produced. Fortunately, it is easy to convert the CO_2 intensity of liquid hydrocarbon energy into the same units, to enable a direct comparison with any given power mix.

Based on typical physical and chemical data supplied by US government websites,[148] the amount of elemental carbon per unit of energy is around 67 grammes for gasoline and 68 grammes for diesel. A molecule of carbon dioxide weighs 44/12 times more than a carbon atom.† Therefore, assuming an oxidation factor of 99% to account for the small portion of fuel which is not oxidised to form CO_2,[149] we multiply those carbon contents by 0.99 x 44/12 to arrive at 242 gCO_2/kWh for gasoline and 248 gCO_2/kWh for diesel. Note that these numbers refer only to the physical-chemical properties of the fuels themselves, and do not take into consideration the efficiency of the process by which the fuels are manufactured and delivered to the point of use. To complete the picture, we must account for the refining and distribution losses,

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* *Electricity imported from neighbouring states raises the CO_2 intensity per kWh of energy consumed within California. However, the GHG data provided by the US DOE refers to generation by state. The US average remains unchanged by interstate sales of electricity.*

† *The atomic weights of carbon (C) and oxygen (O) are 12 and 16 respectively. Therefore, molecular weight of carbon dioxide (CO_2) is 12 +16 + 16 = 44.*

and also calculate how effectively those liquid fuel kilowatt-hours are converted into automotive kilometres. We must convert the CO_2 intensity of the energy supplied to the vehicle into CO_2 intensity of motive energy which turns the wheels.*

This is where our earlier analysis of ICEV and BEV energy efficiency comes in. Table 2 shows how the full story plays out for typical gasoline and diesel ICEVs, compared with our hypothetical BEV running on average power mixes in each of the sample US states and EU nations: California, Indiana, Austria and Greece. In the case of liquid fuels, we make the assumption that the energy consumed in the refining and distribution steps also derives from crude oil. The final column of table 2 – the CO_2 intensity of motive energy – is depicted graphically in figure 16.

		CO_2 intensity of energy supply	(Refining &) T&D efficiency	Vehicle energy efficiency	CO_2 intensity of motive energy (lower = better)
		gCO_2/kWh	percent	percent	gCO_2/kWh
ICEV	Gasoline	242	83%	18%	1,619
	Diesel	248	83%	23%	1,300
US BEV	California	273	92%	65%	457
	Indiana	937	92%	65%	1,567
	US average	620	92%	65%	1,037
EU BEV	Austria	221	92%	65%	370
	Greece	781	92%	65%	1,306
	EU average	370	92%	65%	619

Table 2. Comparison of the CO_2 intensity of motive energy at the wheels of ICEVs and BEVs, for representative US states and EU nations.

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* *In this analysis, we assume that the weight and aerodynamic attributes of the ICEV and BEV are identical, such that energy supplied at the wheels equates to automotive kilometres.*

The calculations illustrate that, in terms of CO_2 emissions, BEVs offer tremendous advantages over ICEVs where the electricity is derived from carbon-light generation sources. Even in coal-rich Indiana, the BEV significantly outperforms gasoline – which dominates the US automotive market – in terms of gCO_2/kWh. More importantly, based on the *average* power mixes of both the US and the EU, the data indicates that BEVs perform dramatically better on CO_2 emissions than conventional ICEVs, whether fuelled by diesel or gasoline.

This finding should lay to rest the so-called 'long tailpipe theory' which argues that the electrification of automotive transport merely transfers problematic emissions from the vehicle exhaust to the power plant. EV sceptics who subscribe to this view – evidently bereft of quantitative analysis – will frequently claim that 'zero emissions vehicles' are more accurately 'emissions elsewhere vehicles'. This is true, of course, except that it neglects to mention that single point source emissions are far easier to control and clean – and the rather important fact that those emissions elsewhere are substantially reduced, as figure 16 illustrates.

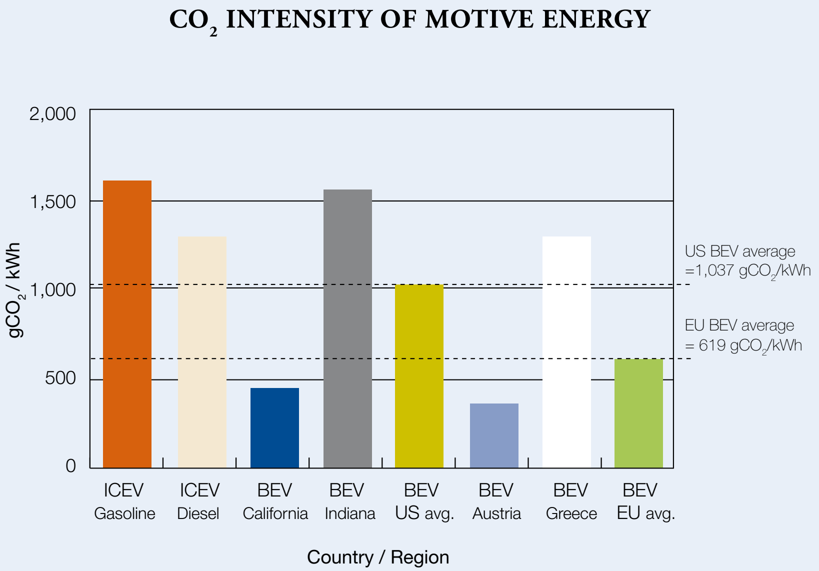

Figure 16. CO_2 intensity of motive energy supplied at the wheels of ICEVs and BEVs in US and EU.

The conclusion is clear: despite the variation in today's power generation mix across states and nations, electrons beat liquids in terms of life-cycle CO_2 emissions. Moreover, that advantage will unquestionably grow as power supplies become progressively cleaner, while the CO_2 intensity of liquid fuels is likely to increase as we are forced – through inability to escape the liquid hydrocarbon paradigm – to exploit more and more unconventional resources.

This point is central to our understanding of the dynamic energy system: we have at our disposal a broad – and expanding – range of sustainable renewable technologies for generating electricity. Wind, solar-thermal, solar-photovoltaic, geothermal, hydro, ocean (wave and tidal) power generators all exploit non-consumptive natural physical processes to produce electrons. Any such electrons may be put into service powering an electric vehicle, but they can never fuel an ICEV: hydrocarbons can be converted into electricity, but the reverse is not true. For this reason, only grid-connected vehicles can get cleaner as they get older.

So if BEVs beat ICEVs in terms of life-cycle CO_2 emissions *with the energy source mix as it is today*, it is safe to say that the gulf will only widen if sustainable renewable energy options become a greater part of that mix. And that is destined to happen: as CO_2 emissions attract increasing financial penalties through climate change policies such as the European Emissions Trading Scheme (EU-ETS) and similar state-level instruments in the US and elsewhere, renewable energy options will steadily become more and more competitive versus fossil fuels.

Consequently, the CO_2 intensity of our power supplies will certainly decline over time, as they must if we are to avert catastrophic climate change. The EU's target that twenty percent of primary energy must be derived from renewable sources by 2020, as agreed by the March 2007 Spring Council,[150] translates into roughly forty percent renewable energy in the power sector. China has recently made a highly ambitious pledge to spend around one-tenth of its GDP in 2006 over the coming decade on renewable energy – equivalent to US$ 265 billion – a massive investment by any standards, albeit commensurate with the challenge.[151] Meanwhile, our transport sector remains firmly shackled to the combustion of liquid hydrocarbon fuels which are increasingly derived from energy-intensive unconventional resources, meaning that the CO_2 intensity vector is pointing in the wrong direction.

And yet the data presented here demonstrate that even now, with an energy system dominated by fossil fuels, there are significant GHG benefits to be realised through the electrification of automotive transport. Electric vehicles need not wait for the coming renewable energy revolution, though they will automatically reap the rewards when that does indeed happen.

Automakers today find themselves under growing pressure to design ICEVs which consume less fuel per kilometre (and therefore emit less CO_2), as legislation tightens in the face of climate change and energy security concerns.[152] Of course, most of the areas in which significant gains will be made – weight reduction through the use of lighter construction materials and downsizing, improved aerodynamics, energy efficient air conditioning units, reduced tyre rolling resistance, better road design and traffic management systems – apply in precisely equal measure to EVs. And the latter will further benefit from advances in electric powertrain technology which plainly do not apply to conventional vehicles.

One should be mindful of the challenges involved in comparing the electron pathway with liquid hydrocarbon fuels precisely, since we are forced to rely on the aggregation of regional or national data from a dynamic power sector. Nevertheless, meaningful conclusions may be drawn at the appropriate level, as our analysis of life-cycle CO_2 emissions has shown. However, given signs that the power and transport sectors are beginning to converge, it is perhaps more instructive to compare 'apples with apples': to assess which automotive powertrain permits the greatest *resource* efficiency.

Resource Efficiency

Let us return to China. With an abundance of coal reserves – one hundred and fifty years, at present consumption levels – and a dearth of crude oil resources, China is understandably looking to derive much of its energy security from domestic coal. For the reasons already discussed, it is highly tempting for China to turn to coal liquefaction to satisfy a transport system which is ninety-five percent dependent on liquid hydrocarbons, despite the extraordinary carbon footprint and water-intensity of coal-to-liquids (CTL) technology. If we take it as 'given' that China will, one way or another, derive transportation energy services from coal, then the real question we must answer is: what is the most resource efficient way to turn coal into kilometres?

In their 2005 book *The Bottomless Well*,[153] Peter Huber and Mark Mills paint the compelling picture of a 1GW coal-fired power station running at full capacity, while in the adjacent parking lot ten thousand stationary Pontiacs are being revved to the red line in neutral gear. The combined power output of the ten thousand 'plants on wheels' is roughly the same as that of the power station, but with far lower efficiency. This is hardly surprising; when it comes to the burning of hydrocarbons these truths are, as Thomas Jefferson so eloquently said,[154] self-evident:

(i) Large is better than small

Gigawatt (GW) scale power plants are able to run hotter, and thus more efficiently, than kilowatt (kW) scale engines of the type which propel motor vehicles. This truth has its roots firmly in the basic laws of thermodynamics, which are not subject to revision;*

(ii) Constant load is better than variable load

As mentioned earlier, a property of internal combustion engines is that maximum efficiency is achieved at maximum load. A power plant can run at maximum load for longer periods than an automotive engine (whose operating profile is dictated by the driving conditions), thereby achieving much greater thermal efficiency;

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* *Distributed CHP (combined heat and power) plants based on natural gas combined cycle technology are highly energy efficient – up to ninety percent – and therefore appear to buck this trend. However, the laws of physics remain immutable: the efficiency advantage of CHP derives not from the reduced plant size, rather from the fact that heat which would otherwise be wasted is instead put to useful work by industrial, commercial and residential consumers.*

(iii) Stationary is better than mobile

In practical terms, it is considerably easier to manage, collect, and process emissions from stationary power plants than from mobile vehicle exhaust tailpipes;

(iv) Few is better than many

The greater the number of emissions sources, the harder it becomes to do anything about them.*

Faced with these four starting points, we have little option but to favour the combustion of a given resource in thousands of large, stationary power plants running at constant load, over millions of small, mobile automotive engines running at variable load. This assertion can be proved mathematically by comparing the liquid pathway with the electron pathway for our chosen resource: Chinese coal. As before, informed estimates must be made regarding the primary energy efficiency of each conversion step.

The IEA quotes the average efficiency of Chinese coal plants as 33% in 2003.[155] Assuming grid transmission and distribution losses of around 10% (developing country grid losses tend to be higher than in OECD nations), and taking our hypothetical battery-electric vehicle operating at 65% efficiency, we arrive at a PTW life-cycle efficiency of 19%.

How does the CTL pathway fare? Remember: we are comparing apples with apples, since the starting premise is that China will use its coal to derive transportation energy services. Sasol, the world leader in CTL technology, operates three indirect coal liquefaction (ICL) plants in South Africa with thermal efficiencies ranging from 37-50%.[156] Sasol's initial plans for China involve two brand new plants, for which we will assume operating efficiencies at the top of this range.[157] Even without considering energy losses in the fuel distribution phase, the ICEV burning CTL diesel fuel with an efficiency of 23% therefore delivers a PTW

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* *A possible exception here is the use of biomass for CHP, where small decentralized plants reduce energy losses in the supply chain by eliminating the need to transport biomass over long distances. It remains true that the fewer the number of plants which can achieve this supply chain optimisation, the better.*

life-cycle efficiency of just 12%. Thus, the electron pathway generates 1.7 times more kilometres than the liquid pathway for every tonne of coal consumed or, alternatively, for every tonne of CO_2 emitted.

It must also be recognised that this figure is particularly harsh on the electron pathway, since it derives from a relatively inefficient Chinese power sector, combined with an immature electric powertrain which will improve over time, as the renascent electric vehicle industry inevitably climbs the experience curve, already travelled for one hundred years by the ICEV.

There is nothing remotely cutting-edge or aspirational about the technology and efficiency assumptions presented here. If China were to deploy the latest integrated gasification combined cycle (IGCC) coal-fired power stations – a reasonable supposition, given that the brand new CTL facilities currently under construction represent multi-billion dollars of investment in the very same coal gasification technology which underpins IGCC plants – then the efficiency of electricity generation climbs from 33% to around 50%.[158] Factor in additional gains through improved battery technology and management systems – up to around 75% according to some sources – and we quickly achieve PTW efficiencies exceeding 30%, close to three times greater than using coal liquefaction to sustain the liquid hydrocarbon paradigm. In other words, for every tonne of CO_2 emitted from coal use, electricity has the potential to deliver three times more energy at the wheels than the liquid pathway. With respect to climate change and energy security, the electron pathway is therefore a no-brainer.

This is certainly true for coal, but what about its fossil fuel cousins, natural gas and crude oil? We can apply the same methodology to compare gas-fired power with gas-to-liquids (GTL) diesel, and to compare oil-fired power with conventional fuels. In both cases the trend remains the same, as table 3 shows: *for any given hydrocarbon resource, electrons will always have the potential to beat liquids in terms of energy efficiency and therefore CO_2 emissions.*

The data demonstrate that turning natural gas into diesel via Fischer-Tropsch synthesis is an extraordinary waste of the least environmentally damaging fossil fuel. While GTL proponents such as the ASFE are quick to highlight improvements in urban air quality through suppression of other vehicular combustion by-products, conventional ICEVs burning GTL fuels can never hope to match the *non-existent* emissions of BEVs on this metric, and the additional energy consumed in the GTL process effectively spends the carbon advantage natural gas holds over crude oil, thereby equalising the CO_2 footprint on a life-cycle basis. As we saw earlier, the best possible use of natural gas in the fight against climate change is to displace dirty coal from power generation. The very latest combined cycle natural gas plants which combine heat and power generation (CHP) can achieve primary energy efficiencies of up to 90%.[159]

		Plant-to-Tank	Tank-to-Wheels	Plant-to-Wheels
Coal	CTL diesel	50%	23%	12%
	Electricity (average)	32%	65%	21%
	Electricity (IGCC)	46%	65%	30%
Crude oil	Diesel	83%	23%	19%
	Gasoline	83%	18%	15%
	Electricity (average)	36%	65%	23%
Natural gas	GTL diesel	66%	23%	15%
	Electricity (average)	39%	65%	25%
	Electricity (CHP)	83%	65%	54%

Table 3. Plant-to-wheels analysis of primary energy efficiencies comparing electrons and liquids, starting with different fuel resources. Note that plant-to-tank electricity efficiencies already account for average T&D losses of 8%.

Even crude oil fares better on a plant-to-wheels basis when turned into electricity. The notion that crude oil is too valuable to waste in power generation is in fact a paradox. Crude oil is prioritised for liquid fuel production only because the transport sector is ninety-five percent dependent on liquid fuels, which are most economically derived from crude oil. If life-cycle efficiency fundamentals held sway, then crude oil would go the same way as coal and natural gas: heat and power production.*

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* *This analysis does not take into account the non-energy by-products of crude oil refining, such as petrochemical feedstocks, lubricating oils, waxes, and bitumen, which together make up around 12% of a barrel of crude oil.*

The ‘electrons-beat-liquids’ trend is not limited to fossil fuels. Within Europe, the EU is setting a target that the transport sector must derive ten percent of its energy from renewable sources by 2020.[160] Given the transport sector’s prevailing dependence on the internal combustion engine, this has been widely interpreted as corresponding to a *de facto* biofuels target of ten percent. The proposed directive is a matter of some controversy and ongoing debate, since it may be forcing the market towards an inefficient use of a valuable renewable resource. In mid-2007, in a paper titled *Climate Change by Biomass*, the German Advisory Council on the Environment (SRU) wrote that biomass “can be used up to three times more efficiently in heating and CHP than in producing the currently used biodiesel and bioethanol.”[161] The European Commission’s own scientific body, the Joint Research Centre (JRC), issued a working paper in December 2007 which concluded that in terms of GHG reduction per hectare of land, “it is substantially more efficient to use the biomass to generate electricity than to produce [first generation] biofuels”.[162] This is not to say that biofuels are themselves a bad idea, especially when compared to fossil fuels; rather it is because ICEVs are inherently inefficient at turning stored chemical energy into kilometres, regardless from where that chemical energy originated.

So-called second generation biofuels are a potential game-changer as they promise to greatly improve both the sustainability and the CO_2 balance of biofuels. The technique aims to produce liquid fuels from ligno-cellulosic plant matter, of the type which is found in stalks and woody residues. Indeed, the EU’s ten percent target is contingent upon second generation technology – currently in the pilot plant development stage – playing a significant role. As we will see, the contribution of next generation biofuels may actually far exceed the ten percent which is currently imagined, provided we can dramatically redirect the automotive development trajectory.

Stationary Emissions

Returning to the self-evident truths, there is another significant benefit of the electron pathway: stationary emission sources lend themselves to a future in which Carbon Capture and Storage (CCS) becomes technically and commercially viable. This means it is conceivable that even in an energy system firmly rooted in fossil fuels, *the full life-cycle emissions of electric vehicles can be close to zero*.

CTL players such as Sasol and Shell claim that the CO_2 emissions associated with their processes – up to ten times greater than conventional refining – should not worry us: CCS will provide the answer. This is a peculiar argument, for it essentially means that we should not be troubled by *existing* vehicular CO_2 emissions. Fortunately, it is easy to see through this nonsense. Expensive and inherently risky 'end-of-pipe' abatement technologies such as CCS should be employed to deliver *net emissions reductions*, not simply enable us to tread water on climate change. The electric powertrain effectively transplants the fuel combustion phase – and thus emissions – from the moving vehicle to the stationary plant, at which point they can be captured. Any future application of CCS can therefore deliver a virtually zero emissions automotive transport paradigm if we follow the electron pathway.

Furthermore, if sustainable biomass is used to generate electricity (and heat) with CCS, we might dare to imagine a future in which every kilometre driven equates to *negative* emissions, that is: geosequestration of atmospheric CO_2. As the bioenergy crop grows, the photosynthetic process removes CO_2 from the atmosphere, which can then be stored away in geological formations; but this is only true if combustion occurs in stationary power plants. If we were to follow the liquid pathway, and turn sustainable biomass into liquid hydrocarbon transport fuels, we would miss a twofold opportunity: first, the clear energy efficiency advantage offered by the electron pathway for *any* given resource; second, the possibility to capture and store emissions.

TECHNOLOGY OPTIONS

The discussion has until now been limited to conventional vehicles – comprising an ICE linked to a mechanical drivetrain – and battery electric vehicles (BEVs) such as those rare species which briefly appeared on the roads of California in the late 1990s. The evidence presented so far highlights the superiority of BEVs over ICEVs, at least in terms of energy efficiency and CO_2 emissions. However, conventional vehicles outperform their electric rivals against three critical parameters, which have helped – together with the technology lock-in discussed in Part III – to limit widespread public acceptance of EVs: one is driving range; another the amount of time needed to recharge (or refuel); and the final one is vehicle cost, which is strongly linked to battery cost.

Limitations of Battery Electric Vehicles

The fact is inescapable: liquid hydrocarbon fuels provide far greater energy density (or specific energy) and flexibility than even the most advanced batteries. Gasoline packs a specific energy of 13.0 kilowatt-hours per kilogramme (kWh/kg), while diesel weighs in at 12.7 kWh/kg.[*] By comparison, nickel metal hydride (NiMH) batteries of the type employed in the second-generation GM EV1 and the Toyota RAV4-EV are capable of achieving a specific energy of around 0.07 kWh/kg, while the latest lithium ion (Li-ion) cells provide up to 0.16 kWh/kg, more than twice as much as NiMH yet still two orders of magnitude less energy per kilogramme than conventional fuels.[163]

The energy density advantage of liquid hydrocarbons grants dramatically superior driving range per kilogramme of energy carrier, despite the woeful inefficiency of the mechanical powertrain in converting that stored energy into kilometres. Moreover, the physical nature of liquids is matched by the extensive network of roadside service stations specifically developed to support them; it takes only a few minutes

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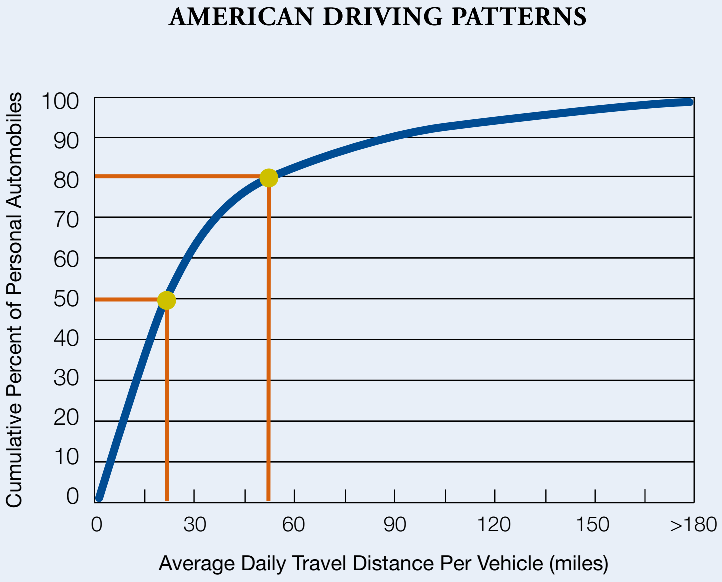
[*] *The higher physical density of diesel means that it contains roughly eleven percent more energy per litre than gasoline (10.7 kWh/l for diesel versus 9.6 kWh/l for gasoline), despite having a slightly lower specific energy density.*

to pump forty litres of gasoline or diesel into the tank, as opposed to spending several hours plugged into an electricity outlet.

These two attributes combine to offer a far greater comfort level for motorists, even though for the majority of mobility requirements the comparatively short distances covered by BEVs before charge depletion do not represent any practical limitation: a high proportion of journeys undertaken by road vehicles are well within the 150-200 km range afforded by BEVs such as the General Motors EV1 and the Toyota RAV4-EV. Many advocates for EVs as second family cars refer to a federal government survey on US transportation statistics, undertaken in 1990, which found that half of all American motorists travel 25 miles (40 km) per day or less, with eighty percent driving a maximum 50 miles (80 km) per day.[164] These data are presented graphically in figure 17.



Source: EPRI Journal, Fall 2005

Figure 17. Half of all personal automobiles in the US travel 25 miles (40 km) or less each day, while eighty percent travel a maximum of 50 miles (80 km).[165]

Despite being almost two decades old, there is little reason to suspect that these statistics lack relevance today: the 2007 edition of the Transportation Energy Data Book reports that the average household vehicle trip length grew from 8.9 miles (14.3 km) in 1990 to 9.9 miles (15.9 km) in 2001.[166] Over the same time period, the average daily vehicle miles rose from 28.5 to 32.7, an increase of fifteen percent due to continuing urban sprawl which lengthens commuting distances, yet still comfortably within the range afforded by proven BEV technology.

According to the European Commission's statistics body Eurostat, the passenger mobility data for Europe are broadly similar to the US. Since statistical surveys in the EU are frequently conducted at the Member State level, the methodologies applied vary from one nation to another, which makes it difficult to generalise. A summary compiled by Eurostat in 2007 of the most recent national travel surveys found that people in most countries make on average three trips per day, totalling between 30 and 40 km across all modes of transport.[167] These passenger kilometres are predominantly satisfied by the use of private cars: in the EU-25, close to 460 million citizens travel a daily average of 27 km by car.[168] Taking a specific national example, we find that in 2002/03 more than three-quarters of car journeys in the UK were less than 10 miles (16 km) in length, while a massive 93% were below 25 miles (40 km).[169]

Considering the private vehicle usage patterns in the US and EU – with no reason to suppose dramatic differences in other regions – it is clear that BEVs are technically capable of satisfying the majority of personal mobility requirements currently met by ICEVs. In practice, the barriers to electric vehicles are much more psychological than technological. *"What if I forget to recharge and I'm late for that meeting?" "What if I want to visit my relatives at the other end of the country?" "What if I need to run my child to hospital in the middle of the night and I find the battery to be dead?"* ICEVs running on liquid hydrocarbons provide a security blanket to almost all eventualities, however infrequent or unlikely. How else, but with an ICEV?

Of course, the *perception* that autonomy of 150-200 km limits the practicality of the BEV would evaporate entirely if batteries could be recharged almost anywhere, in minutes rather than hours. It would be no more than a mild inconvenience – on the rare occasions that the driving range is exceeded – to have to pull over twice as often to 'refuel', providing the whole process could be accomplished in the time it takes to buy a cup of coffee and a newspaper. Presently, it seems that batteries have some way to go before reaching this level of performance. Even so, why should we immediately leap to the assumption that recharging 'our' batteries is even necessary?

Another lesson from history (there really are no new ideas): The Economist recently printed an intriguing article which told of the brief rise and unfortunate demise of the London Electrobus Company, one hundred years ago.[170] The popular electric buses were relegated to a footnote in public transport history apparently because of systematic fraud, not owing to any insurmountable technological barriers. On the contrary, they outperformed rival ICE-powered buses on several metrics including reliability, longevity, and of course substantially reduced noise and zero vehicular emissions. But the pertinent lesson to be drawn here is how they overcame the range restriction of sixty kilometres on a single charge. At lunchtime, the buses returned to a depot whereupon they drove up a service ramp. The one and a half tonne lead acid batteries – stowed underneath the vehicle – were lowered onto a trolley for removal, enabling the installation of a fully charged replacement. The whole process took about three minutes.

Can we not imagine a similar scheme working now, at least for fleets, which lend themselves to standardisation? We should. Project Better Place was set up in 2007 by former SAP executive Shai Agassi.[171] The concept revolves around the idea that the battery of an electric car is merely the gasoline or diesel of a conventional vehicle. Just as ICEVs speed from one roadside filling station to another, so would electric cars run between battery exchange outlets. The Project's website explains the business model as follows, drawing yet another parallel with the mobile telecommunications industry:

> *Project Better Place's business model for electric cars will look like the model used for mobile phones. Mobile phone operators arrange cell towers to create coverage areas. Similarly, electric cars will be able to travel throughout a network of charging spots and battery exchange*

> *stations, with easy access to electricity. Our partnerships with car manufacturers and battery suppliers will create huge benefits for our network subscribers, including lower car prices and batteries that cost far less than conventional fuel.*[172]

Early in 2008, Project Better Place announced the signing of a Memorandum of Understanding (MOU) with the government of Israel and Renault-Nissan to prepare the market for mass produced electric vehicles and wean the nation off imported oil.[173] Under the terms of the MOU, the Israeli government would provide tax incentives to customers, Renault-Nissan would supply the electric vehicles, and Project Better Place would construct and operate an Electric Recharge Grid across the entire country.

Innovative schemes like Project Better Place should help to overcome the perceived limitation of EV autonomy, while also reversing another piece of conventional wisdom which currently hampers the EV: high battery cost. In fact, it remains true that the upfront capital cost of high-tech EV batteries represents something of a barrier to widespread acceptance, especially in the consumer market where buyers appear unwilling or unable to embrace the concept of 'total cost of ownership'.[*] If the battery need not be purchased outright, merely leased, then those higher capital costs may be spread out over the lifetime of the device.

On the subject of costs, it must also be recognised that economic fundamentals have rarely featured strongly in the purchasing criteria of private consumers, especially in the automotive sector where brand values and optional extras often appeal to emotional rather than rational decision making processes. Evidence of this abounds: one need only consult the price list of automotive retailers within a given model

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[*] *The glacial market penetration of high-initial-cost/low-operating-cost compact fluorescent light bulbs (CFLs) versus conventional incandescent bulbs – not so much lighting devices as miniature heating elements – bears testimony to this point. The installation cost of CFLs – which are typically four or five times more 'expensive' than incandescent bulbs – can be recovered in a matter of months through lower energy bills. This is a classic market failure among many which hinder the adoption of superior technologies.*

range.* What is the payback period for heated leather seats? It's a silly question; heated leather seats are chosen for reasons of comfort and style, not economics. Does a more powerful engine pay for itself over the lifetime of the vehicle? On the contrary, in terms of fuel economy, insurance, and taxation it usually works out even more expensive, but that doesn't stop many motorists from favouring more horsepower. Likewise, irrespective of purely economic considerations, an initial price premium for vehicles running on electricity taken from a domestic wall socket overnight could make perfect sense to millions of drivers who either value the 'environmental feature' or dislike time-wasting visits to fuelling stations. Such a unique and convenient performance feature need not withstand a rigorous economic analysis in order to appeal to the private motorist, provided it is affordable.

Mental barriers which limit the widespread acceptance of EVs are surmountable through education and innovation. Infrastructural and technological hurdles are trivial by comparison; no significant new infrastructure is required, and *existing* technology can be more than adequate for the majority of our mobility requirements.

But for all the apparent opportunity and benefit, we cannot simply assume that the market will transition to an electric transport paradigm of its own accord. As we have seen, businesses suffer from technology lock-in, and as far as consumers are concerned old habits die hard.

Nobody alive today witnessed the year in which EVs outsold ICEVs, while few are even aware of it. We have grown thoroughly addicted to the convenience for individuals – expressed in both flexibility and cost – of transport based on the combustion of liquid hydrocarbon fuels. As with all addictions, this one brings with it a series of penalties to society which are neither reflected in the economics, nor are they immediately obvious to the user. Consumers purchase gasoline or diesel from sterile retail outlets far removed – both geographically and psychologically – from the dirty end of the oil industry.

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* *In November 2007, Volkswagen offered its Golf to the UK market priced from £12,127 to £26,427, a difference of 118% across the full model range (www.vw.co.uk). In Germany, the list price of the Opel Astra from General Motors ranged from €16,360 to €30,150, a difference of 84% (www.opel.de).*

One technology option has emerged in recent years, which attempts to combine the convenience of liquid hydrocarbon fuels with the energy efficiency potential of the electric powertrain. The hybrid, in its initial incarnation and in its full development, can bridge the gap between ICEVs and BEVs.

The Rise of the Hybrid

As with many automotive industry innovations, the idea of combining mechanical and electric powertrains in one vehicle is not new. In 1901, Ferdinand Porsche developed an early hybrid electric vehicle (HEV) in which a gasoline generator produced electricity to charge batteries which in turn powered in-wheel electric motors.[174] Two years earlier, the Woods Motor Vehicle Company was established in the US and became one of the leading manufacturers of electric cars. Reacting to a decline in the popularity of all-electric BEVs, partly due to range limitations compared with gasoline-powered vehicles, Woods developed its 'Dual-Power' automobile in 1916, including both an electric motor and an ICE.[175] By means of a lever on the steering wheel, the driver could select between electric and mechanical drive according to the vehicle speed. On reflection, the Dual-Power was a neat engineering solution to problems which did not exist: gasoline was inexpensive so fuel economy did not exert any influence on buyer behaviour, while the environmental impacts of tailpipe emissions were to all intents and purposes invisible. The US$ 2,650 price tag was therefore difficult to justify to would-be motorists who could purchase Henry Ford's 'Model T' for just US$ 750. Thus, the Dual-Power disappeared, together with the Woods Motor Vehicle Company, in 1918.

Fast-forward to December 1997, when Toyota of Japan introduced to its domestic market the Prius, a family-sized car combining mechanical and electric powertrains in parallel to deliver a breakthrough in terms of energy efficiency and vehicular emissions. Three years later, Toyota took the award-winning Prius overseas for the first time, and its subsequent success – particularly in the gasoline-dominated US market

– is testimony to the truism that timing is everything: an idea which fails is not necessarily a failed idea.

Unlike the Woods Dual-Power, which required manual switching between combustion engine and electric motor, the Prius has a computerised management system which automatically selects and blends propulsion systems depending on the driving conditions. Substantial efficiency gains are realised through regenerative braking technology, whereby motive energy is recovered to recharge the battery as the vehicle coasts or brakes, instead of simply being lost to the brake pads as waste heat. In addition, the engine management system is able to shut down the ICE in an instant when the vehicle is stationary or travelling at low speeds, thus eliminating unnecessary fuel consumption through idling. Consequently, the Prius demonstrates its greatest advantages in the stop-start cycle of urban driving – where conventional ICEVs suffer most – as these conditions maximise the benefits of regenerative braking and zero idling. Further efficiency gains are made through downsizing of the engine, made possible with no measurable loss of performance by the instantaneous power-assist utility of the electric motor.

The success of the Prius – by far the most recognised and best-selling hybrid model today – encouraged other major automakers, eager to tap into a 'new' segment of environmentally conscious motorists, to pursue the commercialisation of HEVs. Of course, demand has been helped along by record high gasoline prices which have occasionally risen above US$ 3 per gallon in the US;[176] with some hybrid models offering up to forty percent greater fuel economy than comparable ICEVs,[*] many customers felt motivated to reduce their use of gasoline.

This is the mirror image of what happened in the 1980s, when one enabler for the explosion in popularity of SUVs was a significant drop in the oil price. Ironically, this was caused in part by successful efforts to *conserve* crude oil, in response to the price shock of 1979. Recall that the other key factors in a declining oil price were the displacement of

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[*] *According to US DOE website www.fueleconomy.gov, for the model year 2007 the Honda Civic Hybrid returned a combined fuel economy of 42 miles per gallon (mpg) versus the non-hybrid gasoline variant's 29 mpg.*

crude oil from heat and power applications, coupled with a redoubling of exploration and production efforts. As a consequence, the global energy system underwent an irreversible structural change: there are today very few opportunities left to displace oil. The 'easy' oil is drying up, demand for transport fuels continues to rise, geopolitical tensions exacerbate energy security concerns; these pressures within the oil market drive up the price.

By the end of May 2007, Toyota had recorded cumulative worldwide HEV sales of one million,[177] with the Prius accounting for more than seventy percent of that total.[178] Japanese rivals Honda and Nissan now offer HEV variants of established models, as do US automakers General Motors and Ford. That the Prius commands such a disproportionate share of the hybrid market owes partly to the 'first-mover advantage', but there is perhaps a more subtle explanation which once again hints at what drives human beings to act in a certain way. The distinctively shaped Prius is unique among the current crop of HEVs in that it was designed *exclusively* as a hybrid car; all of its competitors are hybrid variants of existing models, impossible to distinguish from the ICEV platform save for a discreet badge on the vehicle. What is the relevance of this point? Being seen to own and drive a Prius is equivalent to making a highly visual and public statement – however contentious – that "I care about the impact of my driving".

The European automotive sector has been reluctant to be swept along by the hybrid wave, in part because the regulatory and market acceptance of diesel vehicles in Europe seems to offer a cheaper pathway to fuel economy than gasoline-electric hybrids. However, this lethargic response to hybrid technology is starting to resemble feet-dragging by European industry: there is no fundamental reason why *diesel*-electric hybrid vehicles should not catch on and deliver substantial efficiency and emissions benefits. Indeed, French carmaker PSA unveiled two demonstration models boasting diesel-electric hybrid powertrains in early 2006.[179] Despite posting impressive performance data, including a fuel economy advantage of twenty-five percent versus comparable conventional diesels, the PSA group claims that the cost of hybrid technology is still too high for commercialisation before 2010.

Hybrid cars starting with the Prius have transformed the automotive market. And yet we still experience incremental change. Notwithstanding the significant fuel economy benefits of HEVs, it is worth remembering that one hundred percent of the energy which reaches the wheels of the vehicle is derived from liquid hydrocarbon fuels – mostly gasoline, to this point – which are burned in an ICE. It is a wicked irony that an oft-expressed benefit of the HEV architecture – “It’s an electric car, and you don’t even need to plug it in!” – speaks directly to its inherent limitation. True, the electric powertrain is utilised for some proportion of each journey, but all of that electrical energy has been recovered from onboard fuel combustion, either directly (by the ICE generating electricity to recharge the battery) or indirectly (through regenerative braking). This point is so important that it bears repetition: the automotive *market* may have been transformed in some way by the HEV, but our broader paradigm – ninety-five percent dependency on liquid hydrocarbon fuels – remains essentially unchanged. Until those electrons can be supplied from sources other than onboard combustion – such as the electricity grid or even rooftop solar-PV arrays – we are destined to continue along more or less the same lines as before.

The Ultimate Flexible Fuel Vehicle

The ‘plug-in’ hybrid electric vehicle (PHEV), frequently described as the logical end-point for the evolution of the HEV, installs a more sophisticated battery system and the electronics to permit the car to be charged from the power grid. This technology allows the first tens of kilometres of every journey – covering the majority of commuting distances – to be all or partly powered by electricity taken from a wall socket. Beyond a pre-determined level of charge depletion, an onboard generator kicks in which either recharges the battery in the ‘series’ hybrid architecture, or else powers a mechanical drivetrain in the ‘parallel’ configuration. As with the conventional HEV, both modes of operation are possible in what is referred to as ‘blended’ mode.

The onboard range-extending generator will initially take the form of a downsized ICE running on liquid hydrocarbon fuels and is thus compatible with the same refuelling infrastructure upon which ICEVs and HEVs depend. The all-electric range is determined by the battery characteristics and technology – which is advancing apace thanks to the fast-moving ICT industry – as well as the particular driving conditions and ambient temperature.

Although it is tempting to view the PHEV as occupying an evolutionary step from the HEV, it is more useful to think of PHEVs as a development of the BEV. After all, the PHEV is at heart an electric vehicle that has been improved with the addition of a range-extending onboard generator, which eliminates the fear factor of running out of electrons mid-journey. Whether legitimate or not, as discussed above, BEVs remain hampered by the market perception that limited range and long charge times equate to limited utility. These concerns entirely disappear with the PHEV, which capitalises on the energy efficiency and emissions advantages of the electron pathway while providing the flexibility associated with liquid fuels. Figure 18 compares schematically the different electric vehicle architectures, ranging from hybrid to plug-in to full battery-electric.

In terms of GHG abatement potential, the PHEV lies somewhere between the BEV and the HEV, depending on the all-electric range and vehicle usage patterns. A joint study undertaken by the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC) in 2007 compared various scenarios from 2010-2050, in which the well-to-wheels impacts of different PHEV fleet penetration rates were modelled in conjunction with varying CO_2 intensities of electricity production in the US.[180] Even for the worst case, in which PHEV penetration rates were modest and total CO_2 emissions from electricity production were allowed to *increase* by 25%, the annual and cumulative CO_2 emissions were still reduced. Annual emissions reductions in 2050 ranged from 163 million tonnes in the low penetration / high CO_2 scenario, to 612 million tonnes in the high penetration / low CO_2 case. In percentage terms, with respect to GHG savings, PHEVs delivered a 40-65% improvement over conventional vehicles and a 7-

46% improvement over HEVs. As with full battery electric vehicles, the cleaner the electricity supplied, the greater the benefit in terms of lower CO_2 emissions on a well-to-wheels basis.

THE ELECTRIC POWERTRAIN

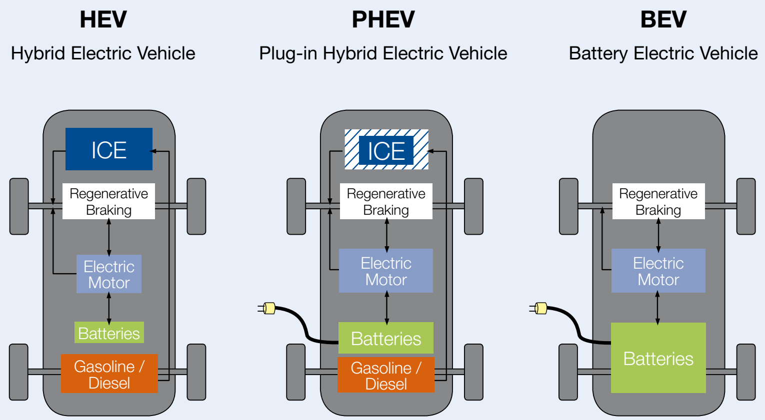

Figure 18. Comparison of different electric powertrain configurations. The HEV essentially derives all of its motive energy from the combustion of hydrocarbon fuels onboard; regenerative braking offers potentially significant but incremental energy efficiency gains. The alternative PHEV and BEV variants derive up to one hundred percent of their motive energy from batteries, which are charged by connecting to the electricity grid when stationary, and similarly benefit from regenerative braking.

The PHEV is in fact the ultimate flexible fuel[*] vehicle, able to operate with electrons produced from any power generating technology, whether chemical or physical, in tandem with liquids derived from any carbonaceous material, whether mineral or biological. Therefore, PHEVs truly represent a *transformation* – from HEVs which obtain their motive energy wholly from liquid fuels to PHEVs that displace

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[*] *The term 'flexfuel' is used in the US specifically to describe a gasoline-powered vehicle which is capable of running on a blend of up to 85% ethanol with 15% gasoline (E85). In Europe, due to the high dieselisation of the automotive fleet, the term is used more generally to include diesel/biodiesel and gasoline/ethanol blends. Here we use the term 'flexible fuel' more broadly to indicate flexibility with respect to primary energy sources.*

liquid fuels with electricity. In the ‘parallel’ PHEV, the internal combustion engine and electric motor both drive the wheels, and both powertrains can be fully optimized. The ‘series’ PHEV architecture decouples the thermo-mechanical device from the wheels of the vehicle, thereby enabling the generator to run at constant load to achieve optimal efficiency, and simplifying the vehicle construction by eliminating the mechanical powertrain entirely.

To reflect the fact that the mechanical powertrain has been removed, General Motors refers to its planned series PHEV as an ‘Extended Range Electric Vehicle (EREV)’ and, indicating that its ten years of hydrogen fuel cell research may be put to use someday, suggests that the ICE can in principle be replaced by a fuel cell. Alternatively, in a scenario where battery technology advances to such an extent that range and recharging limitations disappear entirely, the onboard generator may be dropped from the configuration, thus returning to the pure BEV. It is no exaggeration to say that the series PHEV concept is essentially future-proof, while simultaneously being compatible with today’s infrastructure.

A Boost for Renewables?

The ability to ‘refuel’ by connecting to the electricity grid – or even off-grid sources of electricity – would finally allow the following snippet of conventional wisdom to ring true: *high oil prices directly benefit the development of renewable energy*. It all boils down to substitution potential: if enough vehicles were capable of connection to the grid, the oil industry’s oligopoly over road-based transport would fracture, the elasticity of the transport ‘fuel’ market would increase, and the price of crude oil would decline, over time, toward its electricity equivalent. Private and commercial vehicle operators alike would no longer be willing to pay more for liquid fuels than for electrons in the face of genuine competition between energy carriers. A homeowner who drives a grid-connected vehicle might well favour the relatively high upfront fixed cost of rooftop solar-PV cells over the ongoing and volatile variable cost of liquid hydrocarbon fuels. Where solar-PV is not an option, today’s liberalised energy markets in many regions enable users to purchase renewable electricity directly from the grid.

From the perspective of the green energy sector, the prospect of connecting PHEVs (and BEVs) to the grid should be a tantalising one. In fact, it could be a match made in heaven, just as the birth of the ICEV provided a much-needed boost for the flagging oil industry as it struggled to recover from the body blow dealt by Thomas Edison's light bulb. The reason is quite simple: car batteries can act as distributed energy storage devices, which is exactly what the renewable energy sector needs to help increase its scale. Equipping electric vehicles with a bi-directional relationship to the power grid paves the way for the fuller integration of the power generation and transport sectors, leading to many new opportunities.

Physical energy sources such as wind and solar are, by their very nature, variable. Offshore wind often blows strongest at night, when electricity demand is lowest. On cloudy days, solar cells cannot be relied upon to supply base load power. Wave energy is similarly subject to the vagaries of the climate system. Essentially, the peak of renewable electricity production is outside of the control of the power utility, therefore it cannot be matched to the peak of demand. By contrast, chemical energy sources such as coal, oil, and especially natural gas are much more flexible to the demands of the grid; power production at thermal plants can be modulated to a certain extent.* This fact is often cited by critics of renewable energy as a serious limitation which can only be overcome with breakthroughs in energy storage technology. Thoughts frequently turn to hydrogen, which may be produced via electrolysis when renewable power is in excess, stored in tanks, distributed via pipeline if necessary, and recombined as required in fuel cells to produce electricity. It's a neat idea which, as we discuss later, suffers atrocious energy efficiency losses – governed by fundamental physical laws which will not be breached by human ingenuity – in

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* *The extent to which power generation can be modulated depends on the generating technology. For example, gas-fired power stations can be switched off and restarted quite easily without severe efficiency losses, whereas coal-fired and nuclear plants are less amenable to complete shut downs.*

the conversion steps to and from hydrogen. Advanced automotive battery storage may make it a moot point.

The extensive adoption of electric vehicles can create enormous and widely distributed energy storage capacity, particularly at night when most vehicles are stationary and therefore capable of being connected to the grid. This is precisely when electricity demand is lowest, and when the potential of wind power is often highest. 'Vehicle-to-Home' (V2H) and 'Vehicle-to-Grid' (V2G) technology enables the storage and retrieval of electricity from automotive batteries to power home appliances during peak hours, to feed the grid during peaks of demand and provide other generation services to utilities.[181] The convergence of power and transport – around energy efficient electrons, not carbon-intensive liquids – draws a step closer, as utilities begin to realise the grid management potential of EV batteries, which can smooth the peaks and troughs of cyclical electricity demand, and thereby enhance the efficiency of the energy system as a whole. Better still, V2G technology would in theory enable EV owners to charge up overnight, benefiting from cheap off-peak tariffs, and sell that power back to the grid during peak hours when electricity commands a higher price. In mid-2007, the Ford Motor Company and Southern California Edison announced a cooperation to explore V2H systems;[182] we are thus witnessing the legacies of Henry Ford and Thomas Edison reuniting through the electrification of automotive transport.

GRID-CONNECTED VEHICLES IN PRACTICE

Battery Electric Vehicles

A range of BEVs which are either available today or scheduled for the very near future are illustrated in figure 19. Unlike many technology options for climate change mitigation, the electrification of automotive transport is not contingent on a unidirectional West-to-East transfer of intellectual property. On the contrary, the existing global BEV market is noteworthy for being led by an Indian company.[183] Bangalore's Reva (figure 19a), which recently debuted on UK roads wearing the G-Wiz nameplate, was reportedly the best selling on-road electric vehicle in 2006. Although the G-Wiz is classified as a quadricycle rather than a car by UK authorities, this technical distinction makes little difference to London-based owners who enjoy an exemption from the daily congestion charge, free parking in designated bays, and even free electricity from adjacent charging posts. Suffice it to say, the financial incentive offered by these combined policy measures has provided the catalyst for electric personal mobility in the City of London. In late 2007, the G-Wiz was retailing at around €11,500 (equivalent to $17,000) in the UK.[184]

BATTERY ELECTRIC VEHICLES

© RECC
© MILES ZX40S Advanced Design
© Th!nk City
© Tesla Motors

Figure 19. A range of full battery-electric vehicles including (a) India's Reva, (b) Chinese made Miles ZX40S, (c) Norway's Th!nk City, and (d) US's Tesla Roadster.

China, too, shows encouraging signs in this field. As mentioned earlier, the largest electric vehicle factory in the world is currently under construction in Tianjin with a projected capacity of twenty thousand units per annum, half of which are earmarked for US and European markets.[185] An example of the ZX40S, built in China and distributed by Miles in the US, is illustrated in figure 19b. Meanwhile, the Brazilian automotive sector is reportedly getting in on the act. As a complement to their flexible fuel system, Obvio! Automotoveiculos are partnering with British firm Lotus Engineering to produce a BEV suitable for export to California.[186]

BEV manufacturers are not limited to the so-called BRICS[*] countries. Norwegian EV company Th!nk resurrected the small electric city car abandoned by Ford following a relaxation of the California ZEV Mandate. Aiming for a commercial launch date of March 2008 in Europe, the Th!nk City (figure 19c) will offer a driving range of 180 km on a single charge.[187] The NICE[†] Car Company, based in the UK, has already begun marketing its BEV from around €15,000 (or $22,000), in competition with the Reva G-Wiz, aimed at commuters eager to beat the London congestion charge.[188]

If the above examples confirm the image of battery cars as little more than motorised shopping trolleys, or over-dressed golf carts, then the $98,000 (or €67,000) Tesla Roadster (figure 19d) takes electric automobility into entirely new territory. Weblogs the world over are buzzing with excitement ahead of the Tesla's debut in 2008. Judging by the early performance data, it is easy to understand why: acceleration from zero to sixty mph (equivalent to 100 km/h) in just four seconds, with a top speed of 130 mph (210 km/h) and an estimated range of 245 miles (395 km) per charge. This car promises to demonstrate what EV enthusiasts have long been advocating: driving electric is simply a superior experience to anything offered by outmoded internal combustion engines. In this important respect – transforming popular opinion of what electric vehicles can be – it is no exaggeration to say that high performance cars like the Tesla Roadster have the potential to change the world. Disruptive technologies first appear at the extremes of the performance and cost envelope, from where they gradually make inroads to the mass market. So it was with computing, mobile telecommunications, digital

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[*] *The term BRICS refers to the group of fast developing nations comprising Brazil, Russia, India, China, and South Africa.*

[†] *The cleverly chosen name stands for 'No Internal Combustion Engine'.*

photography, plasma-screen televisions; so it will be with electric vehicles.

As we are frequently told, there are no silver bullets with which to solve the world's complex environmental problems. If we could wave a magic wand today and instantaneously electrify the world's vehicle fleet, we would still be left with a far from perfect transportation system. There would still be energy waste through unnecessary journeys and low vehicle occupancy levels (or load factors), time lost and stress gained due to traffic congestion, ugly concrete urban landscapes with too little regard for the majority (lest we forget) non-motoring population, to mention just a few of the problems which will not be solved through automotive electrification.

However, when society does eventually decide that tailpipe emissions of any kind – coupled with the incessant hum of those thermo-mechanical devices which fill our roads – are no longer tolerable, we may even find that the very idiosyncrasies which hindered public acceptance of electric vehicles reveal themselves as *strengths*. Mark Anslow, a journalist writing in The Ecologist magazine, had this to say about his first BEV experience:

> *Walking away from [it], I begin to realise that an electric car is more than the sum of its parts. Owning one, and coming to terms with its limitations, foibles and differences, teaches you to re-assess the fossil fuel mobility which we have too easily come to take for granted. Driving electric leads you to develop a new appreciation of fuel costs and emissions. You accelerate slowly and brake gently to eek power out of the battery. You travel more slowly, more safely, and more efficiently. You re-evaluate your journey lengths, which in turn makes you question whether the journey is even necessary. You search out local services, within easy reach and away from out-of-town dual carriageways. Driving electric is more than owning a new car – it should become a commitment to a less intensive form of motoring.*[189]

For those remaining sceptics who still associate electric motoring with golf carts and airport terminal buggies, we close our discussion of BEVs in practice with this excerpt from an interview with Donald Sadoway, a professor in the department of materials science and engineering at the Massachusets Institute of Technology (MIT):

> *I opened the sun roof, rolled down the windows, and I pulled out. It was like a magic carpet. You hear people laughing, talking, and you're interacting with the city. I returned the vehicle to the fellow at Boston Edison, and I came back here and said, "I've got to work harder. I've got to make this thing happen." The only reason that car isn't everywhere: it couldn't go more than 70 miles on a charge. But you make it 270, game over. Anybody who drives it will never go back to internal combustion.*[190]

Plug-in Hybrids

So far, real world examples of PHEVs are even fewer and farther between than BEVs. The modern plug-in hybrid was developed by Professor Andy Frank at the University of California at Davis, who converted a number of passenger cars from ICEV to PHEV starting in the 1990s. French automaker Renault developed and briefly commercialised two grid-connected versions of its Kangoo light-duty van from 2002-2003. The original BEV version known as the Electri'cité was adapted in March 2003 with a small range-extending generator, thereby creating a series PHEV which was named the Elect'road. Renault's press release at the time described the concept as follows:

> *Kangoo Electri'cité, the "all electric" version, is intended mainly for urban use. It achieves a range of 60 to 100 km depending on operating conditions. Elect'road does away with the hassles of pure electric power thanks to an onboard electric generator which extends its range to as much as 150 km in the urban cycle. With the introduction of Elect'road, Renault's electric vehicle range combines three advantages: low emissions, economy, and sufficient range for urban and suburban use.*[191]

The Elect'road was withdrawn after around five hundred units were sold,[192] presumably due to lack of demand. It is not clear to what extent timing, lack of policy support, Renault's marketing strategy, or the vehicle's own performance played a part in its premature demise.

Reinforcing the notion that PHEVs are the natural successors of the HEV, 'unofficial' plug-in conversions of the Toyota Prius have been cropping up in recent years. The California Cars Initiative (CalCars.org) describes itself as "a non-profit startup formed by entrepreneurs, engineers, environmentalists and consumers".[193] CalCars is dedicated to raising public awareness, educating policy makers about the benefits of grid-connected vehicles, and hopefully influencing the automotive industry to bring PHEVs to large-scale production. In 2004 it was the first to make waves and attract widespread media attention to the idea of a car which can deliver in excess of one hundred miles per gallon, or less than 2.4 litres per 100 km. The organisation's website lists the location of more than fifty plug-in Priuses currently plying the US highway network, among which is the car of founding member Felix Kramer (figure 20a).

Another outfit dedicated to the conversion of Toyota's hybrid flagship is Amberjac Projects, based in the UK, which provides a commercial service to Prius owners keen to realise the benefits of refuelling with electrons from the grid.[194] Amberjac's engineers replace the standard-issue NiMH battery pack with an advanced lithium iron phosphate ($LiFePO_4$) substitute, together with a battery management unit, for a fee of around €14,000 (roughly $20,000). These retrofitted plug-in Priuses have been clocking up fuel economy of 2.2 litres per 100 km. At typical urban driving speeds, below 33 mph (53 km/h), the all-electric range is estimated at 35 miles (56 km),[195] enough to eliminate a large proportion of liquids demand from each vehicle.

Whether credit is due to the likes of CalCars and Amberjac Projects or not, there are signs that Big Auto is beginning to move, albeit gingerly, towards commercialisation of PHEVs. General Motors stunned the automotive industry in January 2007 when it presented the Chevrolet Volt concept car (figure 20b) at the North American International Autoshow in Detroit.[196] Many commentators recalled that GM's most recent foray into electric vehicles with the EV1 ended in tears, bitter accusations of foul play, and a public relations disaster for GM which culminated in the provocative documentary film *Who Killed the Electric Car?* in 2006. However, far from being an oddly shaped BEV seemingly designed to fail, the sleek Chevy Volt series PHEV concept – with an expected all-electric range of 40 miles (64 km) – stole the show and created major excitement the world over.

PLUG-IN HYBRID ELECTRIC VEHICLES

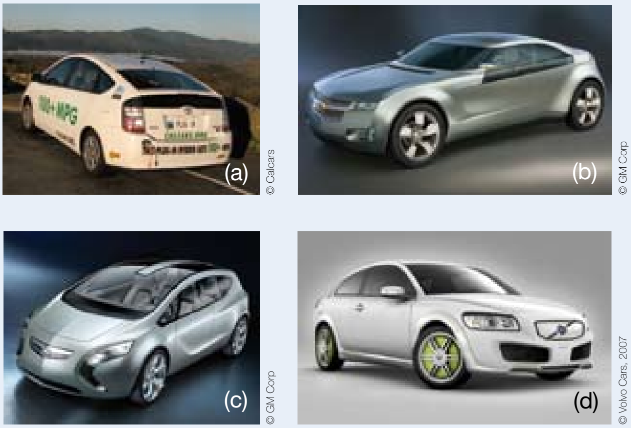

Figure 20. A selection of PHEVs, ranging from (a) Prius+, driven daily by CalCars founding member Felix Kramer, to various concepts which have debuted in recent Motor Shows: (b) Chevrolet Volt, (c) Opel Flextreme, (d) Volvo ReCharge.

We have been here before, the future has already happened: GM presented a plug-in concept car called the XP-883 in 1969.[197] We simply need to make it happen again. On this occasion, it seems as though GM is in agreement, having announced a target launch price of $30,000 (€21,000) and an ambitious production date of November 2010.[198] And not without good reason: in April 2007, for the first time in more than seven decades, GM could no longer claim to be the world's largest automobile manufacturer, having been overtaken by Toyota.[199] At this watershed in the company's history, the excitement and media attention surrounding the Volt and its European cousin the Opel Flextreme (figure 20c), which debuted a few months later at the Frankfurt International Motor Show, have potentially turned the series PHEV into one of GM's most important projects ever. Top executives began to say that they are betting the company's future on electrification of automotive transportation.[200] Vice president for research and development Larry Burns explained the 'E-Flex' platform – around which the Volt and the Flextreme are designed – on the company's website:

> *With our new E-Flex concept, we can produce electricity from gasoline, ethanol, biodiesel or hydrogen. We can tailor the propulsion to meet the specific needs and infrastructure of a given market. For example, somebody in Brazil might use 100 percent ethanol (E100) to power an engine generator and battery. A customer in Shanghai might get hydrogen from the sun and create electricity in a fuel cell. Meanwhile, a customer in Sweden might use wood to create biodiesel.*[201]

Speaking of Sweden, at the 2007 Frankfurt International Motor Show the Swedish automaker Volvo also unveiled a series flexible fuel concept called ReCharge, based on the existing C30 model (figure 20d). Ford-owned Volvo's performance claims even overshadow GM's Volt: in-wheel motors propel the ReCharge up to 100 km on electricity alone, following which the fuel consumption may range from zero to 5.5 litres per 100 km.[202] For a 150 km drive starting with a full charge, the effective fuel economy of the ReCharge would be 1.9 litres per 100 km (equivalent to 124 miles per gallon). In all-electric mode, Volvo projects operating costs around eighty percent lower than those of a comparable petroleum-powered vehicle.

With GM having largely stolen the PHEV limelight, Toyota is now publicly pursuing grid-connected technology as the logical evolution of the Prius. In July 2007, Toyota announced that it had become the first manufacturer to have a prototype PHEV certified for use on public roads in Japan.[203] This was followed six weeks later with the news that French utility EDF had signed a technology partnership with the Japanese automaker, designed "to develop practical solutions for the commercialisation of Toyota's prototype vehicle technology".[204] According to the press release, the two companies have developed an innovative charging and invoicing system to be compatible with a new generation of public charging stations, which aim to make electric power more accessible on public roads and car parks. Initially Toyota stated it would engage GM's challenge to be first to mass-produce PHEVs, but the company later delayed its plans, claiming "while we would love to be first, we're determined to be best".[205] In any case, the two American and Japanese rivals may be blind-sided by China's BYD Auto, who boldly announced in early 2008 its intention to bring a plug-in hybrid to production before the end of the year.[206]

PHEVs with all electric ranges of anywhere between fifty and one hundred kilometres, and charging stations available in public places, make it conceivable that many motorists would seldom have to visit a conventional service station to refuel. Crucially, that option would remain available – based entirely on existing infrastructure – if and when the necessity arose. And for those rare occasions that liquid fuels *are* required, our thoughts return to biofuels.

FUELLING THE PLUG-IN

Residual Liquid Demand

The potential for grid-connected vehicles to decimate our demand for liquid hydrocarbon fuels should be clear. Freed from the psychological barriers which hinder widespread market acceptance of pure battery-electric vehicles, plug-in hybrids with an all-electric capability of just fifty kilometres would slash liquid fuel consumption, since such a high proportion of journeys undertaken are well within this range. Beyond 50 km, a significant share of the 'residual' liquid demand may be met with next generation biofuels. Suddenly, the European Union's target that renewable energy must meet ten percent of transport fuel demand by 2020 which, up to now, has been widely considered as rather ambitious, may even prove somewhat conservative.

While we still lack consistent data for Europe, the US National Household Travel Survey (NHTS) of 2001 provides great insight and offers the best departure point for our analysis of the potential to reduce liquid fuel demand. Assuming that the PHEV starts each day fully charged and operates solely on battery power until reaching its all-electric range, the key parameter we must consider is the fraction of daily kilometres that the average driver could travel on electricity alone.

A recent study by the American Council for an Energy Efficiency Economy (ACEEE) attempted this analysis using the distribution of daily travel distances found by the NHTS, and demonstrated that an all-electric range of 30 miles (48 km) should be sufficient to cover fifty percent of mileage, on average.[207] If and when the all-electric range is exceeded, as a first approximation it is reasonable to suppose that a Prius-sized PHEV would revert to a Prius-like 46 mpg,* or 5.1 litres per 100 km. Therefore, with half of all kilometres derived from electricity, we can expect the liquid fuel consumption to be around 2.5 litres per 100 km, or double the fuel economy of the Prius. Indeed, the existing PHEV concepts such as the Chevy Volt, the Opel Flextreme, and the Volvo ReCharge, as well as those Prius conversions discussed above, support this hypothesis.

To put this fuel economy into perspective, in 2006 the average new car sold in Europe consumed roughly 6.5 litres per 100 km. In other words, all else being equal, a Prius-sized PHEV would require little more than *one-third* of the liquid hydrocarbon fuel consumed by the average passenger car sold in Europe today. In the context of the EU's renewable energy targets, any strategy which accelerates the adoption of PHEVs in the European market is therefore entirely consistent with the stated goal of raising the proportion of biofuels in the transport fuel mix. The biofuel share would of course increase further still with a generous sprinkling of BEVs, which deliver mobility services with no consumption of liquids at all.

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* *Based on new US EPA estimate for model year 2008, combined driving cycle (www.fueleconomy.gov).*

However, the maximum liquids reduction potential of grid-connected vehicles can be realised only if they start each journey with a full charge. And that means additional electricity demand, over and above the 'business as usual' scenario.

How Much New Electricity?

In 2006, the Pacific Northwest National Laboratory (PNNL) performed an impact assessment of PHEVs on electric utilities and regional power grids in the US.[208] The headline conclusion of the study is astonishing: with the installation of no new electricity generating capacity, if charging off-peak, it would be possible to 'fuel' eighty-four percent of the nation's cars, pickup trucks, and SUVs – roughly 198 million vehicles – driving an average of 33 miles (53 km) per day. Of course, this does not mean no new electricity would be required. It is simply an indication of the degree to which today's electricity system is sub-optimal. Grids are designed to cope with peak demand – which occurs during the day, when large numbers of power-consuming appliances are operational – meaning that significant spare grid capacity exists in the demand troughs, frequently at night when the majority of vehicles are stationary.

The PNNL study found that greenhouse gases and other criteria emissions would reduce overall, while noting that particulates and SO_2 emissions may increase due to the predominance of coal in the existing US power mix; in the PHEV scenario, those coal-fired plants would be called upon to supply more electricity, more of the time. While this is clearly a potential negative side-effect of automotive electrification, which must be given due consideration, it is in principle much easier to deal with static rather than mobile emission sources, which are also much more threatening from a public health perspective. Furthermore, this conclusion does not take into account future developments in the power mix stimulated by tightening environmental legislation. The ACEEE report discussed above also notes the rise in SO_2 emissions based on today's US power mix, while making the valid point that since grid-connected vehicles will not appear in large numbers for several years, the power plant emissions most relevant to their environmental performance will be those of the future.[209]

As with the assessment of residual liquid demand, a number of basic assumptions are necessary before attempting to estimate how much new electricity will be required. We start with the approximation that fifty percent of all kilometres will be powered by electricity alone, based on current US driving patterns. In the European Union, the electricity requirement would be considerably reduced because the average daily driving distance is only half of that in the US.

Secondly, we must estimate the PHEV efficiency in all-electric operating mode; for that we rely upon the real-world experience of CalCars with their 'Prius+' conversion, which consistently delivers 3.85 miles* (6.2 km) per kWh,[210] equivalent to just 0.16 kWh/km. Finally, we make an assumption for the average distance travelled by a passenger car per year. In the US, we know from the NHTS that the daily average is 33 miles (53 km), which equates to around 19,000 km per year, of which half could be derived from electricity. By combining these assumptions we can estimate that to power a typical PHEV in the US for one year would require 50% x 19,000 / 6.2 = 1,500 kWh of electricity.

What does this quantity of electric power mean in real terms? Kilowatt-hours are not instantly intuitive for most people – unlike the unit of 'Belgium' as a measure of land surface area – so it is helpful to put this additional electricity demand into some meaningful context.

Simple arithmetic shows that one million PHEVs consuming an average of 1,500 kWh per year would require 1.5 terawatt-hours (TWh) of electricity annually. In Germany alone, the total electricity consumption in 2005 was 586 TWh.[211] Therefore, one million PHEVs introduced to the German automobile fleet would collectively consume around 0.25% of the country's annual electricity demand. In the US, where electricity consumption is an order or magnitude higher at

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* *Note that this figure is probably conservative, since the CalCars Prius+ is essentially a retrofitted PHEV as opposed to being designed from the ground up. While the Prius+ is a worthy vehicle in its own right, we might expect that a mass-produced PHEV, benefitting from concerted optimisation in product development, would exceed this efficiency.*

4,047 TWh in 2005,[212] one million PHEVs would demand a negligible 0.04% of the nation's power. The clear message is that significant numbers of grid-connected vehicles would not have a significant impact on national electricity consumption.

Focusing only on renewable power, a typical large modern onshore wind turbine has a generating capacity ranging from 2,500-3,500 kW.[213] Since wind energy is variable, the proportion of time each turbine spends generating electricity – or 'load factor' – is between twenty-five and thirty-five percent, depending on location. For the sake of simplicity, we assume an onshore wind turbine capacity of 3,000 kW and an average load factor of thirty percent. Thus, our representative turbine outputs 3,000 kW x 30% x 365 days x 24 hours = 7,884,000 kWh every year, making it capable of supplying carbon-free energy to over five thousand PHEVs operating according to the average US driving cycle. Alternatively, the electricity required to power one million PHEVs would be satisfied with one hundred and ninety typical onshore wind turbines.

In the offshore environment – more challenging from an engineering perspective – the wind power potential is far greater. According to its website, the 'London Array' offshore wind project currently underway will deploy up to 341 turbines generating 1,000 MW in total.[214] Such a scheme would be capable of powering six million PHEVs on the average US driving cycle, or perhaps double that number in the EU.

For another visualisation of 1,500 kWh of renewable electricity, we might consider a practical solution for the homeowner who drives a grid-connected vehicle – or the manager of a light-duty commercial vehicle fleet, for that matter. What is the surface area of rooftop solar-PV panels which would be required to supply 1,500 kWh per year? Like wind power, the geographical location and orientation of solar panels is critical; the potential to generate electricity from the sun depends to a very great extent on the hours of sunlight incident at the chosen site. Moreover, the rapid development of PV technology, as with the somewhat related ICT sector, means that solar cell performance is improving almost by the month. Nevertheless, we can draw from the real world experiences of commercial PV developers like Solar Century in the UK. Based on the latest commercially available technology – even in northern temperate zones which are not blessed with long hours of sunlight – it is possible to achieve a power output of 150 kWh per square metre per year.[215] A solar-PV array of ten square metres – easily accommodated by a typical residential rooftop – is therefore capable of delivering the requisite 1,500 kWh.

Whether the right answer is five, ten, or fifteen square metres, the important message here is that we would not need to erect solar-PV panels the size of tennis courts in order to supply each individual grid-connected vehicle with carbon-free energy. Nor would we need to construct wind farms covering an area of land, say, the size of Belgium, in order to power tens of millions of PHEVs. In fact, if the US electricity grid is anything to go by, then we may not *need* to install a single kilowatt of new generating capacity for many years to come.

ELECTRICITY IS NOT JUST FOR CARS

As the transition evolves, retro-fit solutions may include modifying the second axle of existing vehicles or adding in-wheel motors to power many of the hundreds of millions of vehicles already on the roads partially with electricity. The mayor of Mexico City announced an initiative to improve air quality and general health and quality of life in the city, part of which included the conversion of one thousand gasoline-powered vehicles from the municipal fleet into electric vehicles.[216]

Light-duty passenger vehicles such as cars, pickup trucks, and SUVs are not the only methods of automotive transport which today consume liquid hydrocarbons, and which tomorrow might easily be powered – partially or totally – by electrons from the grid.

Electric Buses, Trucks, and Vans

As we have already seen, one hundred years ago the London Electrobus Company introduced fully battery-electric buses to popular acclaim. The modular battery system pioneered by the Electrobus is ideally suited to fleets of vehicles operating relatively short-distance service cycles, typical of public transport, parcel couriers, and other urban delivery vehicles. Noteworthy contemporary examples may be found in the US, China, the Netherlands, and France.

In the early nineties, as part of a strategy to improve air quality, reduce congestion, and reverse urban decay in Chattanooga, Tennessee, two parking garages were established at either end of the downtown corridor to 'intercept' private cars, from where a free electric shuttle bus service was installed, to convey passengers to their final destination. Evidently without knowing it,[217] the Chattanooga Area Regional Transport Authority (CARTA) had developed a battery replacement system – taking ten to fifteen minutes – which was virtually identical to the one operated by the London Electrobus Company a century ago. What's more, in comparison with CARTA's diesel vehicles, the electric buses turned out to be three to four times cheaper to fuel, and more than twice as cheap to maintain.[218]

In China, the Beijing Olympic Games Organising Committee (BOGOC) has commissioned fifty buses powered by Li-ion batteries to ferry athletes and officials between venues during the 2008 Games.[219] Three loop lines will connect the Olympic village, press village, and various arenas, while the BOGOC has allocated an area of five thousand square metres for recharging and parking.

Under the auspices of the Rotterdam Climate Initiative, in August 2007 logistics provider TNT trumpeted plans to test two zero-emission trucks in and around central Rotterdam, recharged solely from carbon-free hydropower.[220] According to the company's press release, the 3.5 tonne Smith Edison EV and 9 tonne Smith Newton EV, with expected driving ranges between 120 and 220 km, will be the first electric delivery vehicles in mainland Europe. Aside from the clear environmental benefits, TNT expects to realise cost savings over the projected five year lifetime of a commercial vehicle, thanks to reduced fuel and maintenance expenses more than offsetting the high upfront cost of the trucks.

French state-owned postal service La Poste announced in April 2007 its intention to order *ten thousand* electric delivery vehicles following a highly successful trial.[221] La Poste Chairman Jean-Paul Bailly was reported as saying: "According to our tests, it is six times cheaper to run an electric vehicle than a diesel vehicle". An invitation to tender for the first five hundred vehicles has already been issued to prospective suppliers.

Finally, a trans-Atlantic project trial involving up to thirty plug-in hybrid Sprinter vans, supplied by DaimlerChrysler, is being coordinated by the Electric Power Research Institute (EPRI).[222] Daimler has been especially interested because of the increasing numbers of cities that are limiting the access of ICE delivery vehicles from urban centres. The programme is designed to collect performance and field test data while verifying the durability of a number of different engine / battery combinations, including both gasoline and diesel engines with NiMH and Li-ion batteries.

Electric Two-wheelers

In increasingly crowded urban landscapes, and especially in the fast emerging Asian economies such as China, India, Malaysia, Vietnam, and Indonesia, electric bicycles may offer an alternative solution to motorised personal mobility with zero vehicular emissions. Highly congested cities such as Beijing and Shanghai have witnessed an explosion in electric bicycles in recent years. Petrol-driven scooters are outlawed in many Chinese cities – Beijing and Shanghai included – due to severe air pollution. Electric bikes have consequently been embraced by commuters wishing to graduate from pedal power while avoiding the cost (and, increasingly, immobility) associated with four-wheeled transport. By 2010, China is expected to be producing thirty million electric bikes per year, compared to an already impressive nine million in 2005.[223]

Electric bikes, scooters, motorcycles, and the unique self-balancing Segway Personal Transporter – examples of which are illustrated in figure 21 – all offer virtually silent personal mobility, a very high degree of energy efficiency, and zero emissions at the point of use. They afford the user far greater flexibility than is possible with rigid public transportation services and far greater opportunity for work and leisure activities due to their extended range and speed compared with non-motorised forms of transport. To the extent that they can replace journeys made by ICEVs – until now the *de facto* alternative to public transport for suburban commuters – electric two-wheelers can dramatically improve the local environment and contribute to lowering greenhouse gas emissions.

ELECTRIC TWO-WHEELERS

© Urbanmover

© VectrixEurope

© Brammo Motorsports

© Segway Inc

Figure 21. Fully electric personal mobility options: (a) Urban Mover electric bicycle, (b) Vectrix electric scooter, (c) Enertia electric motorcycle, (d) Segway Personal Transporter.

PART V

OTHER ALTERNATIVE FUELS

As the previous section demonstrated, the electrification of automotive transport holds the immediate potential to deliver on four primary objectives simultaneously: a reduction in CO_2 emissions, a step-change improvement in energy efficiency, a dramatic increase in urban air quality, and enhanced energy security through diversification away from petroleum. All of these benefits come without any significant infrastructural changes.

Liquid hydrocarbon fuels derived from unconventional frontier resources such as tar sands, coal-to-liquids (CTL), and gas-to-liquids (GTL) cannot hope to address all four challenges. They are essentially desperation measures which apply a short-term balm to the global liquids crisis, but offer nothing to tackle the root cause of the problem. In terms of climate change, they even exacerbate an already alarming situation. Sustainably produced biofuels are the exception which proves the rule; they can, and likely will, make a growing contribution to the transport fuel pool, displacing geological sources of liquid fuel and supplying environmentally benign range extension to plug-in hybrid electric vehicles.

It is not strictly correct to reduce the problem to a straight choice between liquid hydrocarbon fuels and electrons. There are other possibilities which merit consideration; a comprehensive discussion of alternative energy carriers should also consider gaseous fuels.

HYDROCARBON GASES

Liquefied Petroleum Gas

Liquefied Petroleum Gas (LPG) is a mixture of short-chain hydrocarbon gases, primarily propane (C_3H_8) and butane (C_4H_{10}), which is derived either as a by-product of conventional crude oil refining or occurring naturally within geological oil and gas deposits. The gaseous hydrocarbon mixture liquefies under light pressure, hence the name LPG.

LPG is used for stationary applications such as heating, cooking, and as an industrial feedstock, as well as substituting for conventional petroleum fuels in modified internal combustion engines. In automotive applications, LPG is frequently termed ‘autogas’. During the crude oil crises of the 1970s, autogas gained favour in some countries, notably Australia, as a pathway to reducing the crude oil dependency of transport. As ever, the primary driving force behind alternative fuels is energy security linked to an oil supply pinch. By 2004, around ten million vehicles globally were capable of running on autogas, with South Korea the world’s leading consumer.[224]

From an environmental perspective, autogas offers some benefits over conventional fuels. According to the World LP Gas Association, on a well-to-wheels basis the CO_2 emissions from autogas may be twelve percent lower than gasoline and four percent lower than diesel.[225] Like natural gas, LPG is relatively clean burning, thus may contribute to a marginal improvement in urban air quality by suppressing NOx and particulate emissions. In heavily congested Hong Kong, by the end of 2004 more than 99% of the 18,000-strong taxi fleet was running on autogas as part of an effort to reduce urban pollution emerging from vehicle tailpipes.[226]

Finally, LPG supply is somewhat diversified due to the fact that it may be derived from both crude oil and natural gas. Currently, around sixty percent of global LPG supplies come directly from field production, with crude oil refining accounting for the remaining forty percent.[227]

Compressed Natural Gas

Earlier in this book we learned how the energy intensive GTL process – manufacturing synthetic diesel from methane – effectively wastes the carbon advantage which natural gas holds over crude oil. In the context of climate change mitigation, GTL represents nothing less than a reckless use of the least polluting fossil fuel. It is far better for stranded gas reserves to be physically liquefied into LNG, rather than chemically modified to form GTL diesel. Optimally from a CO_2 abatement perspective, LNG will then be shipped to countries with no access to pipelined gas, where it will be used to displace dirty coal from power generation.

As an alternative transport fuel (i.e. not simply an alternative *source* of familiar liquid fuels), natural gas may be compressed to around 200-250 atmospheres (atm) and stored in a high pressure metal cylinder onboard the vehicle, to fuel an adapted internal combustion engine.[228] Emissions of CO_2 and other criteria pollutants are significantly lower than gasoline, diesel, and even LPG. According to the US DOE, vehicles running on CNG may emit 25% less CO_2 and between 35-60% less NOx per kilometre than gasoline equivalents.[229] However, methane is itself a greenhouse gas – one which is twenty-one times more potent than CO_2 – thus even small leakages[*] prior to combustion may neutralise the effectiveness of CNG as a weapon in the battle against climate change.[230]

Worldwide growth in CNG vehicles has been rapid in recent years. Data provided by the International Association for Natural Gas Vehicles show that in the period from January 2000 to June 2007, annual growth rates have exceeded thirty percent.[231] Interestingly, the sharpest increases during this period have been in Asia (50%), South America (28%), and Africa (21%) – three regions which do not suffer the same degree of liquid hydrocarbon lock-in which afflicts Europe and North

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[*] *The same is true of pipelined gas and LNG of course, though leakages or 'fugitive emissions' will be more difficult to avoid from thousands of small filling stations and millions of onboard storage tanks than from relatively few stationary industrial facilities.*

America. Ranked by percentages of total fleet, the countries with the highest proportion of natural gas vehicles in the world are Bangladesh (27%), Armenia (25%), Pakistan (25%), Iran (24%), and Argentina (22%). With 3.6 million between them, these five countries accounted for 52% of the global population of natural gas vehicles in 2007.

Growth and Dependency

In the short-term, a reduced dependency on expensive crude oil imports coupled with moderate CO_2 abatement and air quality benefits may appeal to city leaders and politicians. Ultimately, however, the contribution of LPG and CNG will be modest and transitional at best. If we are looking for sustainable solutions to the challenges posed by transport to the environment and energy security, then we do not find any answers in LPG or CNG.

Nations with domestic gas resources may find relief, but for how long? Like crude oil, natural gas is a finite resource which cannot last forever. Latest estimates that proven reserves are sufficient to last another 63 years are based on current rates of consumption.[232] Gaseous hydrocarbon fuels cannot make any sustained impression on the global transport sector without 'stealing' CO_2 abatement potential from the power sector, where the environmental gains are far greater if natural gas is used to displace coal. With almost fifty-six percent of remaining gas reserves located in just three countries – Russia, Iran, and Qatar – the long-term implication is clear: a switch to gaseous hydrocarbon transport fuels will be fraught with the same kind of geopolitical problems which crude oil users face now. All of the main energy consuming nations of today (US, EU, Japan) and tomorrow (China, India) are already net importers of natural gas.

Moreover, the combustion of LPG and CNG still results in the release of geological carbon to the atmosphere. From an energy efficiency perspective, the consumption of hydrocarbons in millions of small, mobile, internal combustion engines will always be sub-optimal compared with their burning in thousands of large, stationary power plants which may generate combined heat and power at efficiencies up to ninety percent.

In transitioning away from liquid hydrocarbons, if we are to grow 'dependent' on a new energy carrier for automotive transport, then far better for that to be an energy carrier which is maximally diversified for its primary energy source, is inherently energy efficient, and delivers automotive mobility with zero vehicular emissions. In this regard, electricity has only one possible challenger: hydrogen.

OIL COMPANIES AND THE HYDROGEN HIGHWAY

Readers of oil company publications may be forgiven for wondering why this entire discussion has not been framed around the future hydrogen economy. Take the Shell Sustainability Report 2006, for example.[233] In a section titled "Security through diversity", the document explains that:

> *[Shell] is exploring ways to promote hydrogen as a longer-term fuel option and in 2006 operated five demonstration refuelling stations around the world.*

With five hydrogen filling stations already functioning in 2006, one might be left with the impression that the hydrogen economy is just around the corner; certainly something worth waiting for. Sounding a somewhat cautionary tone later in the same report, under the heading "Lower CO_2 transport", the outlook for hydrogen is framed thus:

> *The large-scale rollout of hydrogen-powered vehicles is uncertain and at least 10-20 years away. That means transport will continue to rely mainly on oil for many years to come.*

No matter how many times this statement is read, it refuses to make sense. The problem here is that the second sentence is not a logical or indeed inevitable consequence of the first, which does happen to be accurate. As we have seen, based on *existing* infrastructure and technology, there is already an alternative form of energy, which need not wait for the "large-scale rollout of hydrogen-powered vehicles", and which has the potential to erode the oil dependency of transport within the next few years. Nevertheless, the Shell Sustainability Report 2006 continues to lead the reader astray:

> *In the meantime, reductions in GHG emissions in the transport sector will need to come mainly from blending biofuels into petrol and diesel, from technologies to improve the fuel efficiency of conventional fuels and vehicles, and from efforts to manage people's demand for transportation.*

These are the words of the company which publicly aims to become the world leader in the development of Albertan oil sands – with all its associated environmental impacts – as well as vigorously promoting a market for costly, impractical, and environmentally unsound synthetic fuels derived from coal and natural gas. In its forty-two page sustainability report, Shell does not once mention the genuine potential of grid-connected vehicles to deliver "Lower CO_2 transport" or to achieve "Security through diversity". And why should it? From the unique perspective of Big Oil, the electrification of automotive transport would not provide any cause to celebrate. On the contrary, it represents a direct challenge to the oligopoly currently enjoyed by the oil industry over the transport sector, just as electricity once virtually eliminated kerosene from its seemingly unassailable position in the lighting sector. And as we know, corporations are required to do battle with competitors, to extinguish any emerging threats which could undermine their shareholders' investments.

In fairness, Shell is not alone in perpetuating the myth that until we manage to leap the series of high hurdles which stand between us and the hydrogen economy, we have no alternative but to continue pretty much business-as-usual: more liquids, a bit of energy efficiency, and a cursory nod towards demand reduction. For more than a decade, US automakers in particular have asked the public and government to 'excuse' them from improving the performance of their current vehicles, on the grounds that they were directing the bulk of their research and development dollars towards hydrogen.

As for what the future holds, it is no accident that IOCs are particularly keen to see the global energy system revolve around the H_2 molecule, for it is they who currently occupy the box seat. Who else, other than the oil industry, possesses a century of expertise in producing and handling large quantities of flammable fluids, distributing them over long distances via pipelines or tankers, and selling them through a firmly established network of roadside filling stations? These are capital intensive activities to which the barriers to new market entrants are extraordinarily high.

Again, given the contextual framework in which businesses operate, there is nothing remotely nefarious or sinister about an incumbent supplier steering its customers towards a new product that it is best positioned to deliver. However, recognising the extraordinary financial and political muscle which the oil industry may bring to bear, we must exercise great care in maintaining an intellectually honest discourse. Recall that six of the world's ten largest corporations, measured by revenue, are vertically integrated oil companies. This realisation should not, in itself, lead directly to the conclusion that hydrogen is the wrong answer; it is merely that the public and decision makers must understand the powerful vested interests which are promoting hydrogen as the only viable future for automotive transport.

Blinkered to the Range of Solutions

The electric automotive paradigm is systematically ignored by those who profit from the status quo. For instance, a 'comprehensive' well-to-wheels study in 2007 by CONCAWE,* EUCAR,† and JRC – the Joint Research Centre of the European Commission – attempted to assess the relative merits of "a wide range of automotive fuels and powertrains relevant to the EU in 2010 and beyond".[234] This worthy objective was unfortunately undermined by the deliberate exclusion of grid-connected vehicles from the assessment. Inexplicably, the vehicle performance criteria which defined the boundaries of the study specified a top speed of greater than 180 km/h and a minimum range of six hundred kilometres. With the exception of Germany, no European nation has a legal speed limit in excess of 130 km/h, while the average

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* *CONCAWE is a European association of oil companies dedicated to environmental, health, and safety issues relating to the oil industry.*

† *EUCAR is the European Council for Automotive Research and Development.*

daily driving distance in Europe is just twenty-seven kilometres, or less than five percent of the range threshold chosen by CONCAWE and its partners. In any case, plug-in hybrids have precisely the same range potential as conventional ICEVs, so their exclusion from the study – with no justification – is particularly puzzling.

In 2004, the World Business Council for Sustainable Development (WBCSD) issued a weighty report titled *Mobility 2030: Meeting the challenges to sustainability*.[235] Introducing a discussion on propulsion systems and fuels, the report graphically presents "Possible transport fuel pathways" as coming down to a straight choice between liquids and gases; the 'alternative' propulsion systems considered were internal combustion engines and fuel cells. Unsurprisingly, the WBCSD did not conclude that grid-connected vehicles would contribute anything towards meeting sustainable mobility requirements, because grid-connected vehicles were neglected from the study.

Two years earlier, another group comprising General Motors, the Argonne National Laboratory, and the big three IOCs – ExxonMobil, Shell, and BP – cooperated on another 'comprehensive' well-to-wheels study which aimed "to help inform public and private decision makers regarding the impact of the introduction of such advanced fuel/propulsion system pathways from a societal point of view".[236] The report examined thirty different fuel pathways, of which six were ostensibly based on electricity. However, in each of those six, electrons were used to produce hydrogen via electrolysis, not to charge the batteries of grid-connected vehicles. The conclusions naturally made comfortable reading for oil companies keen to maintain their position of supremacy over the automotive transport sector.

Is the future hydrogen? Perhaps it will prove to be. But first it is essential that we deconstruct a few of the myths which have enveloped the hydrogen debate.

The Hydrogen Car is an Electric Car

Some analysts will claim that the jury is still out as to whether the future of automotive transportation will be based on electricity or hydrogen. Both are clean energy *carriers* rather than naturally occurring primary energy *sources* – meaning that both require an initial production step – and both represent pathways to zero-emissions vehicles.

However, the jury seems to be deliberating over the wrong problem. Unequivocally, the future of automotive transportation will be based around electricity. Hydrogen fuel cells are essentially electricity generators. The car, SUV, bus, or truck powered by a hydrogen fuel cell is, in fact, an electric vehicle, in which the wheels are powered exclusively by electric motors, just as they are in battery-electric vehicles and series plug-in hybrids. To emphasise the point, fuel cell vehicles are frequently abbreviated to FC*EV*s.

Now that we have correctly reframed the subject matter under discussion – different electric vehicle architectures – the pertinent question should be: what is the most environmentally effective way to get electricity onboard the vehicle?

The Hydrogen Economy

To anyone who cares about the future of the planet, the 'hydrogen economy' certainly sounds appealing. Hydrogen is the most abundant element in the universe, and it reacts with oxygen – either via combustion or in a fuel cell – to release energy and produce pure water. Imagine a future in which cars emit nothing but drinking water from their 'tailpipes'. This is the attractive vision painted by advocates of the hydrogen economy, which for some inexplicable reason appears more alluring than battery-powered vehicles which emit nothing whatsoever.

Despite its universal prevalence, nature rarely supplies elemental hydrogen for free; aside from some hydrogen-producing bacteria and algae, the vast majority of the Earth's hydrogen atoms are tightly bound up in water molecules (H_2O) and hydrocarbon compounds such as coal, oil, and methane (CH_4). From these stable naturally occurring substances, an energy input is required to liberate hydrogen, whether via electrolysis of water, or through thermo-chemical processes such as hydrocarbon reforming or gasification, both of which release CO_2.

The tantalising term 'hydrogen economy' becomes meaningful only when the energy system is based around hydrogen derived from sustainable renewable resources, such as wind, solar, or geothermal power. Producing hydrogen from fossil fuels, by definition, perpetuates the 'fossil fuel economy' in which we find ourselves today. In this respect, hydrogen is really no different from electricity: there are clean sources, and there are dirty sources. Moreover, it is utterly nonsensical to promote hydrogen on the basis of its physical abundance, for hydrogen atoms are not destroyed by their energetic use; they merely bond with oxygen atoms to form water.

Much has been written and said about the technological and economic barriers facing the hydrogen economy, from production, to storage, to distribution, to safety, and to the performance of the fuel cells which convert molecular hydrogen into electricity. It is beyond the scope of this book to evaluate how far into the future a practical hydrogen highway might be. In fact, the 'barrier analysis' approach which is often applied may be unhelpful in the long run, since it presupposes that hydrogen is the right answer, concentrating only on what needs to be done to surmount each successive barrier. Instead, this discussion will focus on the relative merits of hydrogen and electricity as the carrier of our sustainable energy future. Essentially, it boils down to how hydrogen will be produced, and how it will be used.

Hydrogen Production

Proponents of the hydrogen economy are quick to highlight the significant quantities of the gas which are already produced for industrial purposes, totalling around forty million tonnes per year worldwide in 2003.[237] Roughly ninety-six percent of this production comes directly from fossil fuel sources – half from natural gas – with the remainder produced electrolytically. Industrial hydrogen is mainly consumed as a *feedstock*, for the synthesis of ammonia (NH_3) in the manufacture of fertiliser, and for various hydro-treatment processes in crude oil refining which help to eliminate impurities such as sulphur.

While it is useful to know that synthetic hydrogen production is widely practiced, it is important to understand the scale of the industry in terms which are meaningful to this discussion. Expressed in *energy* units, the combined global hydrogen output translates to 866 million barrels of oil equivalent (boe), or six percent of the annual oil demand from the transport sector. In other words, for hydrogen to make any significant contribution to the global energy system, production capacity would have to be ramped up dramatically from present levels. By contrast, global electricity generation stands an order of magnitude higher at approximately 11 *billion* boe, or three-quarters of the total energy consumption in the transport sector.* Furthermore, since electricity infrastructure is scaled to handle the peaks of demand, the actual installed generating capacity of over 4,000 GW is capable of supplying twice the existing output without any significant new investment.[238]

Notwithstanding the relative production capacities of hydrogen and electricity, we must not lose sight of our overarching challenge: in order to avoid the worst impacts of environmental degradation – not least climate change – as well as enhancing global political stability through achieving energy security, we must rapidly engineer the transition to a *sustainable* energy future which, by definition, does not depend upon the extraction of finite geological deposits. Irrespective of our chosen energy carrier, our primary energy must eventually originate from sustainable renewable sources, including wind, solar, geothermal, wave, tidal, hydro, and biomass.

However, the short- to medium-term outlook for commercial hydrogen production revolves around natural gas reforming and coal gasification. Thus we find ourselves standing once again at the doorstep of Big Oil, where we begin to understand the broader strategic context in which BP[239] and Shell[240] recently announced their respective joint-ventures with giant coal companies Rio Tinto and Anglo-American. But that's OK, argue the fossil fuel companies, by manufacturing hydrogen

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* *If the figure of 11 billion boe for electricity seems low, it is because this refers to the electricity output (i.e. after plant efficiency losses), whereas the 14 billion or so barrels of oil consumed by the transport sector is energy input.*

from natural gas and 'clean coal' (i.e. coal gasification with CCS) we will ease the transition to a hydrogen economy by establishing supply lines, refuelling infrastructure, and vehicle stock, which will eventually be filled with sustainably sourced hydrogen. This justification is also used by some automakers who are promoting hydrogen-powered ICEVs despite their many flaws (discussed below).

On first hearing, it sounds reasonable. However, if we follow this line of argument closely, there is a very real danger that we will unwittingly create for ourselves another path dependency in the transport sector, resembling that which we currently experience with liquid hydrocarbons. What's more, we may find ourselves again 'locked in' to another transport paradigm which is sub-optimal from an energy efficiency point of view, from which it will be extraordinarily difficult for subsequent generations to escape due to the huge vested interests and sunk investment. In order to correctly assess the relative merits of hydrogen and electricity as our future energy carrier of choice, our departure point must be the sustainable renewable energy system.

With the exception of biomass, which may be gasified to separate hydrogen from carbon (with far less efficiency than the manufacture of range-extending bioethanol or biodiesel), the most realistic pathway for H_2 production from renewable energy involves the electrolysis of water, i.e. the conversion of electrical energy into chemical energy stored within the H_2 bond. But here's the catch: the first law of thermodynamics dictates that the efficiency of any energetic conversion can never exceed one hundred percent; in practice it is always lower. This is another way of saying the chemical energy stored in the hydrogen molecule will always be less than the electrical energy input.

In fact, the production of hydrogen gas by electrolysis of water can be relatively efficient; literature surveys reveal a wide range of values from as low as forty percent to over eighty percent.[241] Though most analysts use fifty percent as a working assumption, even if we are optimistic and project electrolyser efficiencies at the upper end of the range, unless we have at our disposal a *surplus* of sustainable renewable electricity, can we ever justify throwing some of it away in order to produce hydrogen? Perhaps we can, but only in very specific circumstances such as off-grid renewable electricity generation with no access to energy storage facilities.

From the outset, therefore, in the competition between potential carriers of sustainable renewable energy, hydrogen lags behind electrons in terms of existing generating capacity and energy efficiency. Next, we must consider what happens once the hydrogen gas has actually been produced.

Hydrogen Distribution and Storage

Of the forty million tonnes of hydrogen gas which are currently manufactured globally, the majority is produced on-site in oil refineries and chemical plants. The primary reason for locating production close to the point of use is that hydrogen, being the lightest gas in the universe, is notoriously troublesome to handle. Dedicated stainless steel pipelines must be constructed because existing pipes designed to convey natural gas are frequently too porous to contain tiny hydrogen molecules, thus becoming brittle and prone to fracture. The investment cost of hydrogen pipelines of a fixed diameter is about twice that of natural gas pipelines.[242]

Despite having a high specific energy (i.e. energy content per unit mass) of 142 MJ/kg, the physical density of hydrogen is just 84 g/m^3, which means that one kilogramme of the gas occupies around 12 m^3 at normal temperature and pressure (NTP[*]).[243] By comparison, one kilogramme of natural gas displaces 1.4 m^3 and packs a specific energy of 54 MJ/kg. This means the volumetric energy density of hydrogen is only one-third that of natural gas, making the cost of a hydrogen pipeline around six times higher than a natural gas pipeline of equivalent energy capacity.[244] The IEA projects that worldwide investment required to develop a hydrogen pipeline network might be in the order of US$ 2.5 trillion, while noting that the energy required transporting hydrogen via pipeline is on average 4.6 times higher per unit of energy than for natural gas. This equates to an efficiency loss of ten percent over a distance of 1,200 km; the same energy would move natural gas 5,000 km.[245]

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[*] *NTP = 20°C and 1 atmosphere.*

As an alternative to pipeline distribution, like natural gas, hydrogen may be either compressed to around 200 atm or chilled close to absolute zero for transportation via truck or ship. Both processes are energy intensive, resulting in additional efficiency losses in the hydrogen supply chain, and super-cooling requires venting that can further deplete the stored fuel. According to one study, it takes 22 tube trailers at 200 atm or 4.5 liquid hydrogen tankers to carry the energy contained in a single gasoline tanker of the same gross weight.[246]

Comparing the hydrogen distribution efficiencies with our electron pathway, we know that electricity grid transmission and distribution (T&D) losses of around 6-8% are typical in OECD countries. Whether carried by pipeline, tanker or ship, it is therefore inconceivable that centrally-produced hydrogen will ever match the efficiency of the electricity grid. Only if it is synthesised at or close to the point of use would hydrogen avoid significant energy losses associated with distribution. Even then, mindful that our guiding principle is the exclusive use of energy from sustainable renewable resources, hydrogen produced in localised facilities would still need to be compressed for storage and/or delivery directly to the vehicle, which would of course incur further energy losses.

Hydrogen Fuel Cells

Once the hydrogen has been delivered to the fuel cell electric vehicle (FCEV) – skirting over the significant technical and economic barriers to onboard storage – the chemical energy in the H_2 bond must be converted into motive energy to turn the wheels. In essence, the fuel cell performs the reverse function of the electrolyser which produced the hydrogen in the first place. Fuel cells generate electricity, heat, and water by catalysing the reaction of hydrogen and oxygen. They differ from batteries in one very important respect, and the clue is in the name. Fuel cells consume a reactive material, or fuel, in their operation, which must be periodically replenished. In this case, the fuel is of course hydrogen. By contrast, batteries simply *store* electrical energy as chemical energy within a closed system.

Whereas the battery electrodes will degrade over time with charging and discharging – thus limiting the useful lifetime – the fuel cell components remain relatively stable. In simple terms, we may think of batteries as electricity storage devices, while fuel cells are electricity generators.

Where earlier we compared the primary energy efficiency of the electric powertrain with the conventional mechanical powertrain, we must now consider the relative efficiencies of batteries and fuel cells when it comes to dispensing electricity; our task is simplified by the fact that the vehicle's electric drivetrain is essentially identical in both cases.

As with batteries, a range of fuel cell technology options exists, though the current favourite for automotive applications appears to be the proton exchange membrane (PEM) fuel cell. Unlike other alternatives such as molten carbonate (MC) fuel cells and solid oxide (SO) fuel cells, they have the advantage of relatively low operating temperatures of around 80°C which allows them to start quickly. MC and SO fuel cells are the most promising candidates for stationary applications, where they might well find a niche in the distributed supply of combined heat and power to commercial and residential consumers.

In its 2005 assessment report titled *Prospects for Hydrogen and Fuel Cells*, the IEA assigns a theoretical energy efficiency of 64% for PEM fuel cells, while noting that practical operating efficiencies tend to be lower.[247] Still, PEM fuel cells can be up to three times more efficient than internal combustion engines when operating at partial load. It has to be said, compared with an automotive sector dominated by ICEVs, the energy efficiency of the PEM fuel cell sounds highly encouraging. How do FCEVs square up, on a well-to-wheels basis, against grid-connected vehicles?

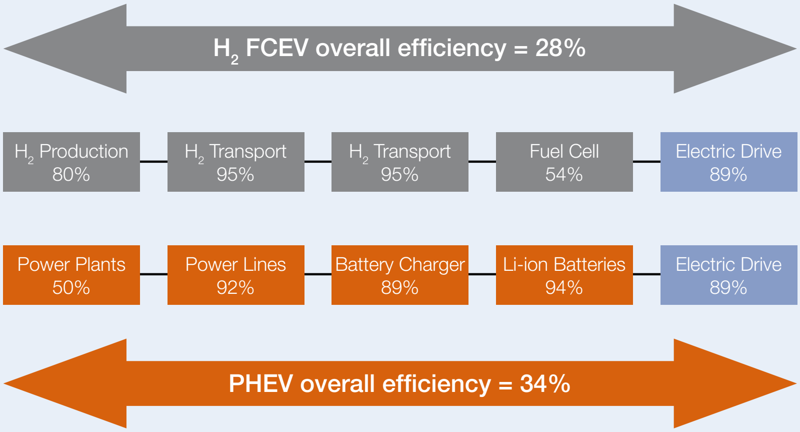
Well-to-Wheel Comparison of Fuel Cell and Plug-in Electric Vehicles

The most obvious advantage of FCEVs over battery electric vehicles (BEVs) is their range potential and refuelling speed. Yet their use is predicated on a future in which we have equipped a significant proportion of roadside service stations with hydrogen pumps for this advantage to be realised. Until that time, the practicality of FCEVs will remain distant. In contrast, plug-in hybrids (PHEVs) do not experience range limitations, nor do they require the installation of an entirely new and highly expensive refuelling infrastructure. Moreover, PHEVs running on a combination of renewable electricity and sustainably produced biofuels would meet our requirement of a future energy system compatible with a healthy planet.

Figure 22 reproduces a well-to-wheels analysis which appears in the IEA report on hydrogen prospects discussed above.[248] Unlike the well-to-wheel comparison of BEVs and ICEVs presented earlier in this book, the IEA assessment is based on cutting edge technology, which is appropriate considering the nature of the study; FCEVs and PHEVs are essentially next generation technologies, commercially unavailable at the time of writing. As such, the assumptions may appear somewhat indulgent: power plant efficiencies of 50%, H_2 production efficiencies of 80%, and electric drivetrain efficiencies of 89% (the same for both pathways). Nevertheless, these estimates stand up to scrutiny: the chosen methodology is entirely fair in the sense that if we are allowed to assess a currently non-existent hydrogen paradigm then it is reasonable to take the best available technology approach to the electric paradigm.

Based on the IEA assumptions, the theoretical WTW efficiency of the H_2 FCEV is 28% overall, compared with 34% for PHEVs running on electricity alone. This is a very important conclusion, as it indicates that the battery pathway delivers electrons to the motor 23% more efficiently than the hydrogen pathway. In other words, the primary energy required to propel a grid-connected vehicle a distance of one hundred kilometres will carry an equivalent H_2 FCEV just seventy-seven kilometres. Of course, practical limitations in the all-electric range of the PHEV mean that this advantage will not be sustained throughout long journeys; the efficiency of the PHEV will likely drop to that of a comparable HEV once the battery has been discharged.

IEA WELL-TO-WHEELS COMPARISON OF FCEVS AND PHEVS



Data source: IEA Prospects for Hydrogen and Fuel Cells

Figure 22. WTW analysis of FCEVs and PHEVs based on primary energy efficiencies, assuming PHEV use only grid-supplied electricity which implies limited range.

However, in the context of our vision for a sustainable renewable energy system, a closer look at the underlying assumptions is highly revealing. What does a power plant efficiency of 50% actually mean in a scenario where electricity is generated exclusively from sustainable renewable resources? Does it mean anything at all? Power plant thermal efficiencies are consequential only when primary *fuels* – coal, oil, gas, uranium, or biomass – are converted into electricity, not when using physical energy sources such as wind, solar, geothermal, wave, and tidal. On the other hand, when hydrogen is manufactured via electrolysis, using the same renewable electricity which might otherwise feed into the grid, the efficiency of *that* process remains critically important to our evaluation.

In figure 23, the IEA assessment is reconstructed assuming that our starting point is sustainable renewable power from physical energy sources. This is a simplification of course, since a portion of our sustainable energy future will likely include electricity (and heat) generated from the combustion of biomass. Nevertheless, it remains instructive for our comparison.

To anyone with a basic grasp of physics, the result should not be all that surprising: as an energy *carrier*, hydrogen can never compete with its own energy *source*. The electron route – with an overall efficiency of 69% – is almost three times more efficient than the hydrogen pathway. Expressed in terms of driving range, the energy required to propel a PHEV (or BEV) one hundred kilometres would only carry an equivalent H_2 FCEV a distance of thirty-five kilometres.

WELL-TO-WHEELS COMPARISON OF FCEVS
AND PHEVS USING RENEWABLE ELECTRICITY

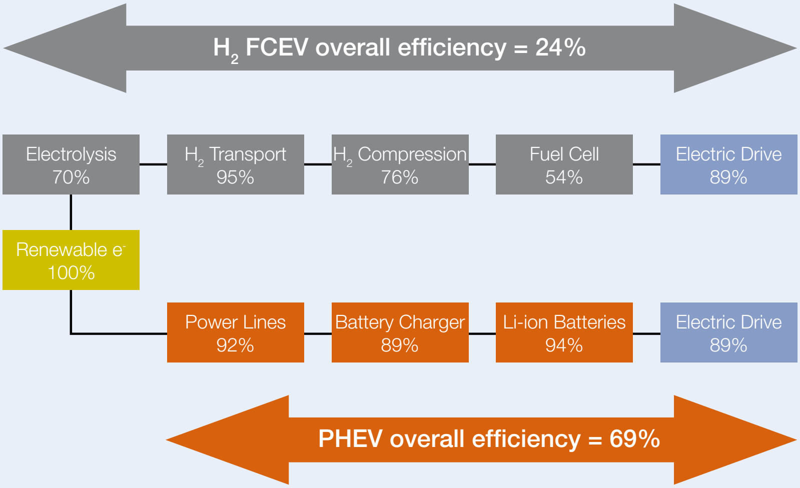


Figure 23. WTW analysis of FCEVs and PHEVs repeated, assuming all electricity supplied from sustainable renewable (physical) sources, such as wind, solar, geothermal, wave, tidal.

Assuming future generations – in a more populous world, barring unprecedented natural disasters or armed conflicts – will be keen to use their energy resources wisely, we can only imagine how they would judge their forebears for blindly pursuing the inefficient hydrogen economy, especially when faced with such persuasive arguments to choose otherwise.

Hydrogen in Internal Combustion

An alternative use of hydrogen in automotive applications has been attracting some attention, thanks largely to BMW's 'Hydrogen 7' concept car and several H_2 ICEVs produced by Ford. With relatively minor modifications to the internal combustion engine, and assuming the problem of onboard storage can be solved economically, hydrogen may be burned instead of hydrocarbon fuels to power an otherwise conventional vehicle. Advocates claim that the concept is a short-cut to hydrogen-powered vehicles – side-stepping the high cost of H_2 fuel cells – thereby easing the transition to the hydrogen economy. However, on closer inspection it makes no sense from an energetic perspective.

The inherent inefficiency of the conventional mechanical powertrain prevails – despite an improvement of perhaps twenty-five percent versus gasoline ICEVs – thus the appreciable efficiency advantages of the fuel cell are not realised and consequently the vehicle range is shortened (assuming the same onboard storage capacity).[249] A recent article in Future Fuels, a periodical published by the Energy Institute, described the idea of hydrogen in an ICEV as the "daftest fuel on the planet", going on to argue that with hydrogen produced from fossil fuels its well-to-wheels CO_2 balance is the automotive equivalent of flying a Jumbo jet from Europe to the US with just one passenger onboard.[250]

If hydrogen is to play any role in the future sustainable energy system, it is extremely unlikely that it will be as a substitute for petroleum in ICEVs. Those who argue that this was never the point, that H_2 ICEVs are merely intended to smooth the transition to H_2 FCEVs, are guilty of presupposing that H_2 FCEVs represent the best long-term vision for automotive transport.

The Hydrogen Future

Electricity will *always* hold the potential to be a more efficient carrier of energy than hydrogen molecules, on a life-cycle basis. The most efficient vehicle platform is likely to be the pure battery-electric vehicle, albeit with autonomy restrictions (which may eventually be overcome with modular battery replacement schemes, if not further breakthroughs in battery technology itself). Where long range and fast refuelling times are essential, FCEVs potentially offer advantages over BEVs – albeit inefficiently – but that competitive edge is not maintained over PHEVs.

As an energy *storage* medium, especially to provide stationary back-up power, hydrogen may play a role in the long-term. It is not likely to be a commercially viable automotive transportation fuel, unless we witness a technology breakthrough whereby hydrogen gas can be 'distilled' locally with no carbon inputs from tanks of water combining algae and sunlight close to the point of use. Where renewable energy cannot be fed directly to the grid or stored in automotive batteries for some reason, electrolysis of water to create hydrogen could make more sense than the alternative of simply shutting down generating capacity. However, this is not in itself sufficient justification for ploughing massive investment into the creation of a hydrogen-based automotive paradigm. From an efficiency perspective, hydrogen from excess renewable energy may be better off powering large stationary distributed fuel cells which can provide carbon-free heat and power services to residential, commercial, and industrial customers.

This is not to say that hydrogen will *never* play a role in the future sustainable transport paradigm; only that it *does not make sense* according to fundamental physical laws and based on all of the information available to us today. By far the most promising automotive platform is the grid-connected vehicle: depending on application, a high proportion of our future road-based mobility requirements may be satisfied with either BEVs or PHEVs.

From time to time, the PHEV range-extender will be called upon to supply some fraction of the vehicle's motive power. In keeping with our sustainable renewable energy vision, this onboard generator will likely be fuelled with sustainably produced liquid (or even gaseous) biofuels from second or third generation techniques. However, the great beauty of the PHEV architecture is that it is essentially future-proof: the ultimate flexible fuel vehicle. Should it ever make sense to synthesise hydrogen from sustainable renewable energy, and should we manage to overcome the remaining technological and economic challenges associated with its distribution and storage, then it would be easy to replace the PHEV's onboard generator with a hydrogen fuel cell.

The final word on hydrogen goes to Dr. Ulf Bossel of the European Fuel Cell Forum:

> *Without the slightest doubt, the technology for a hydrogen economy exists or can be developed in reasonable time. Also, hydrogen is an appropriate energy carrier for particular niche applications, or it may become an important medium for electricity storage with reversible fuel cells. But hydrogen can never establish itself as a dominant energy carrier. It has to be fabricated from high grade energy and it has to compete with high grade energy in the market place. Hydrogen cannot win this fight against its own energy source. Physics is eternal and cannot be changed by man. Therefore, a "Hydrogen Economy" has no past, no present and no future. The road to sustainability leads to an "Electron Economy".*[251]

PART VI

HOW TO GET THERE

The challenge we face is enormous. In order to avoid the worst impacts of climate change, the Earth's average surface temperature must stay below 2°C of warming compared to the pre-industrial era. To stand any chance of meeting this objective, global greenhouse gas emissions must peak and decline within the next decade, which means we must rapidly embark upon a pathway which leads towards the decarbonisation of our energy system. In addition, geopolitical issues linked to the global hydrocarbon economy represent a clear and present danger to the stability of our planet.

As a central part of this effort, we must engineer a smooth transition towards a transport system which is both highly efficient *and* compatible with a future in which all of our energy derives from sustainable renewable resources. Due to powerful vested interests in the business and industry community, coupled with a natural reluctance on the part of consumers to embrace change, this is not something which can be entrusted entirely to the forces of the market. However, with concerted action from multiple stakeholders – visionary politicians, innovative business leaders, and influential advocacy groups – it will be possible to write some remarkable success stories in the coming years.

POLICY OPTIONS

A number of policy interventions will be necessary in order to overcome the many barriers which we will encounter on the road to decarbonisation.

Picking winners?

When it comes to competing technology options, one of the favourite mantras of business is that "policy makers must resist the temptation to pick winners." The rationale here is that the economy can only move towards sustainability if policies are established which act upon the entire market, not just one part of it. Thus the setting of technology-neutral standards is generally favoured over technology-specific mandates. In practice, the outcome will be that certain options are automatically excluded by the setting of standards, but this is essentially weeding out the losers, which is not the same as 'picking winners'. New technological solutions may emerge at any time – whether by chance or through targeted research and development – which may not be foreseen by technology-specific legislation. Technology-neutral policies and measures are therefore necessary to avoid erecting unintentional barriers to the adoption of as yet unimagined solutions. A key component of 'not picking winners' is to establish a level playing field among the existing competitors, which may require taking steps to recognise and/or compensate for the hidden or overt subsidies and preferences which are often afforded to the incumbent technology.

To give an example, in order to hasten the necessary decarbonisation of the power sector, policies which impose strict emissions standards to fossil fuelled power plants (e.g. mandatory limits on grammes of CO_2 emitted per kilowatt-hour of energy supplied), should in principle be favoured over directives which insist upon specific CO_2 abatement technologies such as Carbon Capture and Storage (CCS). Enacting strong emissions legislation may mean that coal-fired power plants, for example, cannot legally function *without* CCS, but the policy itself does not stipulate one technological solution over others. In the act of policy making, it is therefore vital to carefully define the parameters of interest – in this example, the reduction of CO_2 emissions per unit of energy supplied – according to which the winning technologies will emerge. Simultaneously, policies which internalise the external costs of polluting practices, such as cap and trade schemes or pollution taxes, will have the effect of removing a subsidy which is otherwise granted to activities deemed undesirable.

An Integrated Approach

As a matter of principle, chosen policies must also attribute responsibilities appropriately across the various actors. Consider the example of energy-consuming domestic appliances, such as televisions, refrigerators, or light bulbs. The equipment manufacturers may reasonably be requested – or incentivised – to produce the most energy efficient appliances possible. How they choose to achieve that aim may be open to their own interpretation and skills of innovation. Light bulb manufacturers may discover new efficient lighting technologies which are presently unknown to policy makers and to their competitors. For their part, customers may be offered incentives to favour the purchase of more energy efficient appliances over inefficient alternatives, thereby creating a 'market pull' for superior products. Meanwhile, electrical utilities would be held responsible for reducing the CO_2 intensity of the energy they supply, which ultimately powers the appliance. This may be achieved through supply side efficiency improvements, through increasing the proportion of renewable energy in their generating mix, or through end-of-pipe abatement solutions like CCS.

Taken together, a suite of policies which are appropriately targeted at (i) suppliers of energy, (ii) manufacturers of energy-consuming appliances, and (iii) purchasers and operators of those appliances would come together to form an *integrated approach* to reducing CO_2 emissions per unit of energy service consumed.* Figure 24 shows how this principle applies to automotive transport policy.

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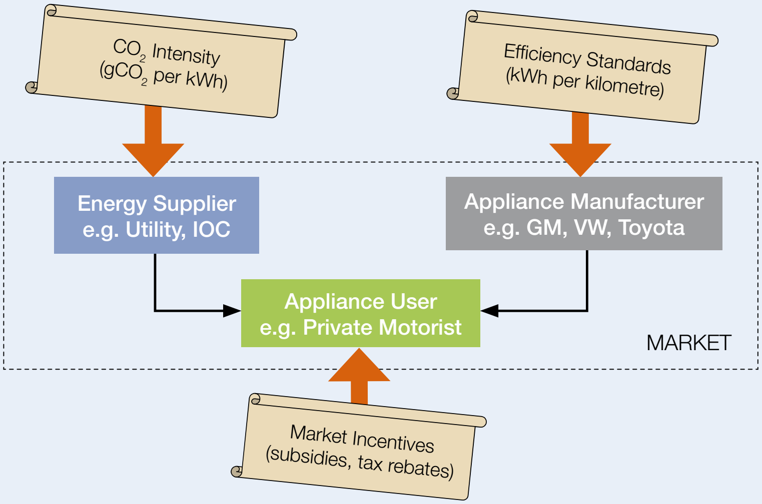
* *An 'energy service' may be thought of as the useful product of an energy input, such as lighting, heating, cooling, telecommunications, kilometres.*



AN INTEGRATED POLICY APPROACH

Figure 24. An integrated approach to policy making in the automotive transport sector. Policies are applied which assign appropriate responsibility to meeting the combined objectives of raising energy efficiency and reducing CO$_2$ emissions.

Appliance Energy Efficiency Standards

Regardless of the vehicle class, chosen powertrain technology, energy supply chain, or mode of operation, automotive vehicles are energy-consuming appliances in exactly the same way as televisions, refrigerators, or light bulbs. The energy service of interest is distance travelled. In the integrated policy framework described in figure 24, vehicle manufacturers sit firmly in the upper right-hand box: their responsibility should be to produce the most efficient energy-consuming appliance possible, while continuing to satisfy additional legislative requirements such as minimum safety standards, maximum noise levels, and so on. In other words, vehicle manufacturers must be held to account for the tank-to-wheels (TTW) portion of the automotive energy life-cycle.

How might vehicle efficiency standards be best expressed, in order to ensure that policy makers do not unwittingly erect barriers to superior technologies? The world's largest automotive market, the US, expresses its Corporate Average Fuel Economy (CAFE) standards in units of liquid fuel consumption: miles per gallon (mpg). That seems quite technology-specific; the mpg metric presupposes that gallons – a measure of liquid volume – must be consumed in order to deliver the energy service of interest. Mpg is indeed a measure of vehicle efficiency, but *only* when that vehicle is a powered by a device (e.g. ICE) which consumes liquid fuels.

Equally presumptuous is the kilometres per litre (km/l) metric favoured by Japan and South Korea, and its reciprocal – litres per 100 km (l/100km) – adopted by China and Australia. Of course, based on today's automotive fleet demographic, these performance indicators appear to be entirely reasonable from a policy perspective. But remember that policy makers must not fall into the trap of picking winners; gallons and litres are both essentially meaningless for grid-connected vehicles (what does a litre of electricity look like?). And the purpose of improving vehicle efficiency standards is to influence the characteristics of the *future* automotive fleet; the powertrain technologies which dominate the *existing* fleet should be irrelevant. So policy makers must focus on providing a level playing field such that any technology – whether incumbent or emerging – is free to compete on its own merits, with its success or failure ultimately determined by its ability to meet the policy objectives.

As a climate change crusader, the EU favours a measure of the global warming impact as a function of distance travelled, which is expressed in grammes of CO_2 per kilometre (gCO_2/km). On first inspection, this appears rational: the focus is kept firmly on the objective of mitigating the climate change consequences of the transportation system, so CO_2 standards seem to represent the obvious way to go. However, by definition, this approach is irrelevant for ZEVs, which will necessarily score zero on the tank-to-wheel gCO_2/km metric. This is not to say that ZEVs consume no energy, or that they are infinitely energy efficient! A battery-electric Hummer – by virtue of its enormous size, weight, and power – would likely expend more energy per kilometre than a diminutive battery-electric Smart Fortwo, yet the gCO_2/km metric would not discriminate between the two. Evidently, gCO_2/km is a *proxy* for vehicle fuel efficiency, which again is only valid for vehicles which consume hydrocarbons onboard.

So what's the answer? Maybe we could attempt to express gCO_2/km on a full life-cycle basis, such that the emissions from the production of energy – or energy carrier – are also accommodated by the vehicle efficiency standard. That way, ZEVs running on electricity or hydrogen produced from dirty coal would be subject to comparable emissions standards, thus placating the 'long tailpipe' theorists. But this doesn't work, either. As we have seen, the CO_2 emissions from the power sector vary substantially from region to region, due to the differing shares of low carbon and renewable energy in the electricity generating mix. As a matter of principle, vehicle manufacturers should not be penalised for the CO_2 intensity of the energy which powers their vehicles, whether that energy is supplied in the form of liquids, electrons, or hydrogen. For one thing, it just doesn't feel right that a vehicle sold in coal-rich Greece would carry a different gCO_2/km label than an identical vehicle sold in Austria. It would certainly provoke confusion for customers, and would simultaneously cause market distortions and undermine policies which incentivise the purchase of inherently energy efficient vehicles.

In precisely the same way, we do not apply complicated life-cycle calculations to all other energy-consuming appliances, such as televisions, refrigerators, or light bulbs, and then hold the manufacturers of those appliances to account for the local energy mix at the point of sale. An energy efficient refrigerator sold in California does not suddenly become less efficient when relocated to Indiana. If policy makers are to maintain technological neutrality and avoid picking winners, there is no reason to treat the automotive sector as a special case. Vehicle manufacturers in the EU – who are presently legally responsible for meeting targets expressed in gCO_2/km – would hardly be impressed if their products were penalised on account of fuel suppliers electing to pursue energy-intensive hydrocarbons such as coal-to-liquids or oil sands. Conversely, they should not expect to profit from oil companies meeting their obligations to increase the share of sustainable biofuels in the fuel pool, just as manufacturers of electrical goods do not claim additional credits when utilities invest in wind power.

According to the principle of the integrated policy approach, which requires that responsibilities be assigned justly, instead of a CO_2 proxy or an indicator of liquids consumption, we must select a *direct* measure of vehicle efficiency, expressed in units of *energy consumed per distance travelled*, such as kilowatt-hours per kilometre (kWh/km).[*] As discussed earlier (Part IV), it is a trivial exercise to convert a litre of gasoline, diesel, and biofuel into kWh, similarly electricity and hydrogen produced from any source. With a kWh/km metric, the market would be equipped to select the most efficient vehicles from a range of technology options, including ICEVs, BEVs, PHEVs, FCEVs, and anything else which we have not yet imagined. This would not be possible if zero-emissions vehicles were simply labelled 'zero gCO_2/km', 'zero mpg', or 'zero l/100km'.

The unit of kWh may seem somewhat abstract to automotive consumers at first, but it will soon be understood by anyone who has ever read their electricity bill. And as a measure of efficiency to underpin policy formulation, it addresses the need to provide a level playing field upon which all possible automotive technologies can compete.

Once the principle of appliance efficiency standards has been established – including the adoption of an appropriate test cycle which is also technology blind – the targets must be both enforced and progressively tightened over time in order to be effective. Thus, the ultimate policy objective for the automotive manufacturers should be to deliver a steady reduction in the amount of energy required to deliver the energy service of interest.

CO_2 Intensity of Energy

Raising appliance efficiency standards will of course play a vital role to curb rising energy demand and therefore restrict the growth of CO_2 emissions. However, we will fail in our broader objectives if efficiency gains of, say, twenty percent are accompanied by proliferation of CO_2-intensive energy carriers derived from coal and oil sands. In the integrated approach, policy measures to improve vehicle efficiency must go hand in hand with legislation aimed at tackling the carbon content of the energy itself.

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[*] *The reciprocal km/kWh will do just as well.*

The well-to-tank (WTT) emissions associated with the delivery of the energy carrier to the vehicle need not – or rather, *must* not – be comprehended by the vehicle efficiency standards against which automakers are held to account, for those *process* emissions are entirely outside of their control. It has been argued, principally by the European automotive sector, that automakers who offer flexible fuel vehicles (FFVs), which are capable of running on blends of biofuel and conventional fuel, should receive credits toward meeting their efficiency targets. This would wrong in principle, for it is not the automaker which determines the production pathway or the composition of fuels available at the filling station, nor is it the automaker which pulls up to the pump and purchases the fuel which powers the FFV. As discussed earlier, many so-called alternative fuels are not alternative at the point of use: diesel is diesel, whether derived from crude oil, dirty coal, sustainable biofuels, or an unspecified blend of all three. An automaker claiming credits for producing FFVs is akin to an oil company seeking reward for every energy-efficient vehicle sold.

In the integrated approach, policy instruments targeting fuel suppliers – or more broadly, energy suppliers – should drive an emissions reduction in the well-to-tank portion of the energy life-cycle, expressed in grammes of CO_2 per kWh (gCO_2/kWh). In parallel, legislation acting upon the consumer should incentivise the purchase of the least environmentally-damaging energy carrier, as well as the most efficient energy-consuming appliance. Thus, the true power of the market to select winning technologies may be unleashed.

For example, the California Low Carbon Fuels Standard[252] might offer a new legislative opportunity for questioning the rampant development of Canadian oil sands, which is almost entirely driven by the US's demand for automotive fuels. A parallel to California's proposal is being discussed in the EU at the time of writing, under the auspices of the Fuels Quality Directive, Article 7a.[253] The idea is to impose a requirement on fuel suppliers that the life-cycle carbon footprint of transport fuels sold within the EU will decline by ten percent by 2020. In terms of how to implement this Directive, the devil will be in the detail, but few can deny the merit of – or the need for – such policy approaches.

Meanwhile, various policy options exist to address the power sector, from emissions trading schemes such as the EU-ETS, to renewables obligations and feed-in tariffs. The range of approaches available for reducing the carbon footprint of electrons speaks volumes for the inherent strength of the power sector – security through diversity – in comparison to the dearth of policy instruments which lend themselves to the 'liquids' sector.

Zero-Emission Vehicle Mandates

The term 'mandate' is opposed in particular by many in the auto industry, who protest that mandates are equivalent to picking winners. This need not be the case: there exist at least three potential alternative technology platforms for the delivery of zero-emissions vehicles (ZEVs), all of which present countless degrees of freedom in meeting the zero-emissions requirement: BEVs, H_2 FCEVs, and even compressed-air vehicles[254] (also grid-connected, in the sense that air must be compressed through the expenditure of energy most likely supplied via electricity). It is fully legitimate for policy makers to specify that automotive fleet sales must comprise a certain percentage of ZEVs by a given date. This is precisely the kind of regulatory certainty – neutral with respect to competition – which industry calls for on a frequent basis.

The ZEV Mandate approach has enjoyed some success in the past, notably in California during the 1990s which prompted the development of many BEVs discussed earlier. That the Mandate was subsequently watered down – in the face of intense industry lobbying – does not detract from its value as a policy tool. Had they not allowed mass-produced HEVs and token numbers of FCEVs to substitute for EVs, the California Air Resources Board (CARB) who administered the Mandate might well have hastened the transformation of automotive transport that we so desperately require today.

It is noteworthy that a working technical group chartered by CARB recently said it saw much-improved near-term prospects for PHEVs. For the purposes of the Mandate, PHEVs are classified as "advanced technology partial zero-emissions vehicles" (AT PZEV).[255] CARB expressed optimism that PHEVs can make a valuable contribution to meeting the overall objectives of the ZEV Mandate, and are thereby deserving of partial compliance credits based on the all-electric range:

> *The Expert Review Panel found that PHEVs foster mass market ZEVs and their commercialization should be encouraged. Blended PHEVs may also provide substantial benefit and further help in advancing ZEV enabling technologies and battery development.*[256]

Consumer Incentives

In parallel to the above measures targeted at suppliers, consumers should be incentivised to purchase the least environmentally-damaging energy carrier and the most efficient energy-consuming appliance.

On 17th February 2003, London introduced a congestion charge which requires drivers who enter a marked central zone to pay a fee, initially £6 (around €9 or $12) per weekday.[257] Though not the first of its type – Singapore[258] has been operating a road pricing scheme since the 1970s – the scale and success of London's system has attracted widespread attention around the world as civic leaders grapple with deteriorating urban air quality. But what makes London so relevant to this discussion is its far-sighted decision to exempt "alternative fuel vehicles" including BEVs from the charge, while simultaneously offering free parking in marked bays with adjacent recharging posts (figure 25).

For the driver of a BEV, the combined savings from congestion charge exemption, parking, and fuel economy can amount to as much as £30 per day, totalling a massive £7,800 (roughly €11,000 or $16,000) per year for daily commuters to central London. These combined financial incentives have created a 'market pull' for BEVs such as the Indian-made Reva G-Wiz, now an increasingly common sight on the city's streets. Retailing at around £9,000 – somewhat expensive for a vehicle of its size and specification – the G-Wiz pays for itself in as little as fourteen months. This makes perfect sense to anyone with a simple grasp of life-cycle cost of ownership – the person who switches from incandescent to compact fluorescent bulbs for environmental and economical reasons. Suddenly, all those protestations that BEVs are too pricey for market acceptance due to high battery costs start to evaporate rather rapidly.

This EV exemption has drawn fire from critics who point out – with some justification – that it is not in keeping with the spirit of a *congestion* charge to strongly incentivise the purchase of motorised four-wheeled vehicles. How does an electric car create less congestion than an ICEV? But this objection rather misses the point: urban congestion is problematic not only because of the productive time lost in traffic queues, but also because of the noise pollution and tailpipe emissions which accumulate as a direct consequence. BEVs have zero tailpipe emissions and are, to all intents and purposes, silent, and are therefore worthy of such an exemption. It is more debatable whether or not HEVs such as the Prius should also enjoy this congestion charge dodge – which they do today – although it is undeniable that the greatest benefits of HEVs accrue in the stop-go low speed urban cycle.

PUBLIC CHARGING POST

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Figure 25. Within London's congestion charge zone, public charging posts are appearing next to dedicated parking bays reserved for BEVs.

Infrastructure

London's decision to install charging posts – from which electricity is currently supplied for free – at dedicated parking bays is another example of barrier removal, even if that barrier is often more psychological than practical. It is also a deft move at raising awareness, as drivers of conventional vehicles are confronted with forbidden parking spaces, prompting the realisation that there must be alternative personal mobility options to the ICEV.

Infrastructural barriers to electric vehicles are trivial, amounting to no more than an extension cord in most cases. Underground and multistorey car parks are already wired to power the requisite overhead safety lighting, so it should not require significant effort to expand capacity and wiring to provide charging points in these facilities. On-street parking is a slightly different matter, though London has demonstrated it can be done safely and unobtrusively. And of course parking meters and street lighting are obvious indicators that electrical installations can thrive at the roadside.

Complementary infrastructural measures such as access to priority traffic lanes or exemptions from bridge and tunnel tolls could also be introduced initially. As with congestion charge waivers, these incentives could be gradually phased out once alternative vehicles have gained a sufficient foothold in the market.

Taxation

The London congestion charge example is not the only way to use financial instruments to stimulate the market for highly efficient EVs. Favourable fiscal regimes, such as road tax and company car tax exemptions, or income tax rebates may also encourage consumer demand for vehicles which are demonstrably less damaging to human health and the environment, thereby compensating their owners for the social benefits their choices provide.

Tax revenues are currently used to underwrite (and effectively to conceal) the true cost of the incumbent liquid hydrocarbon paradigm.

Major oil consuming nations today deploy military forces to protect crude oil flows around the world. Meanwhile, public healthcare spending treats respiratory complaints arising from urban air pollution emerging from vehicle tailpipes. Hidden subsidies of this nature erect economic barriers which hinder the market penetration of superior disruptive technologies.

The provision of tax incentives for alternative vehicle technologies should not be confused with policy makers picking winners. The parameters around which vehicles qualify for exemptions or rebates may be broad enough to allow a range of technology interpretations. This isn't picking winners; it's raising the performance bar to a level which weeds out the losers.

Government Research

Compared to a conventional hybrid, the battery system of a PHEV currently adds around $8,000 - $12,000 (€5,700 - €8,500) to the vehicle cost.[259] This premium will inevitably decline over time as manufacturers achieve economies of scale and targeted research programmes deliver future technology improvements. Given the urgency of the issue and the numerous benefits of grid-connected vehicles, governments should significantly increase public spending on advanced battery research programmes focused on reducing the cost of performance and on demonstration programmes, third-party warranty and other initiatives that foster cost reductions.

Public Procurement

Local and national governments (as well as corporations) wield significant purchasing power since they procure and operate large fleets of vehicles. It makes perfect sense for the strategic objectives of those institutions – increasing efficiency; reducing pollution; mitigating climate change; improving energy security – to inform their buying criteria. Of course, this is true not only for vehicle purchases but for all public procurement activities. Preference for grid-connected vehicles would not only help to meet these strategic objectives, but would also provide much needed investment certainty for manufacturers who may otherwise be hesitant to install production capacity for new – initially more expensive – automotive technologies.

For countries which are net importers of crude oil, favourable tax regimes and public procurement programmes for grid-connected vehicles make a convincing economic argument. High oil prices translate to costly imports and a dreadful drain on the national economy. For example, in 2006, the US imported five billion barrels of crude oil, exactly two-thirds of its total annual consumption of 7.5 billion barrels.[260] The average oil price in 2006 was $65/bbl, meaning that US oil imports effectively channelled $326 billion overseas.

How much of this oil ended up being burned in gasoline-powered ICEVs? According to the US DOE's Energy Information Administration (EIA), the US consumed 3.4 billion barrels of motor gasoline in 2006, meaning that 45% of total US crude oil demand fuelled the nation's light vehicle fleet.[261] Assuming the same fraction of *imported* oil is refined into gasoline, we can calculate that $147 billion worth of crude oil imports emerged from US vehicle tailpipes in 2006.

EMERGING BUSINESS MODELS

In response to the implementation of sensible policies and measures of the type discussed above, innovative business models will emerge to assist in the transformation of automotive transport.

Car Conversions

Commercial ventures such as the UK's Amberjac Projects[262] and Canada's Hymotion[263] already provide a service to convert conventional hybrid vehicles such as the Toyota Prius to plug-in hybrids. US advanced battery developer A123 Systems has announced plans to sell plug-in hybrid conversion kits in 2008, aimed at companies wanting to offer the service.[264] The more cautious Prius owners may be unwilling to void their Toyota service warranties, but hybrids are not the only candidates for grid-connected vehicle conversion.

In April 2007, Canadian firm Azure Dynamics signed a supply agreement with Electro Autos Eficaces (EAE) of Mexico to convert one thousand Nissan Tsurus from conventional ICEV to electric drive.[265] The programme is part of Mexico City Mayor Marcelo Ebrard's initiative to improve air quality and general health and quality of life in the city, with the additional benefits of greenhouse gas emissions abatement and reduced oil dependence. The market for electric drive conversions is, in theory, as large as the existing automotive fleet.

Car Sharing Clubs

On a purely economic basis, buying a car is one of the most disadvantaged transactions a person can make. After the purchase of a home, cars often represent the second largest single financial outlay a private citizen is likely to face. And unlike bricks and mortar, there is no 'return' on the automotive investment,* at least in the majority of cases where the vehicle is used for non-commercial purposes. The capital stock is haemorrhaging money from day one, likely to halve in value over the first four years of its operational life. There must be a better way to pay for personal mobility services.

Some businesses and their growing numbers of customers believe so. Car sharing clubs are springing up across the US and EU. Examples include Zipcar[266] in the US and UK, Cambio[267] in Germany and Belgium, and Mobility Car Sharing[268] in Switzerland. Mobility started operating in 1997, and by 2007 was serving over seventy thousand clients with a fleet of 1,950 vehicles, spanning a broad utility range from the micro Smart Fortwo to minivans such as the Peugeot 807.

And herein lies the great advantage of joining a car sharing club: flexibility. When private citizens purchase cars, they tend to choose a

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* *There are exceptions: classic cars may appreciate over time, for example.*

vehicle which is capable of fulfilling all of their mobility needs, from the mundane – such as the weekly supermarket run, or the daily commute – through to the exceptional. Just as the electricity grid is scaled to cope with peak demand, meaning that significant spare capacity exists 'off-peak', the same is true for the automotive fleet. For instance, a family of four may elect to buy a large estate car or 'multi-purpose vehicle' (MPV) which is sized to manage the 'peak load' – perhaps the bi-annual road-trip to distant relatives – in comfort. The same vehicle is likely to be used on a routine basis where an appliance half its size – with twice the fuel economy – would suffice. According to the IEA, average urban vehicle occupancy rates are 1.50 in Japan, 1.37 in Europe, and 1.40 in the US. For commuting vehicles, these figures drop to an estimated 1.25, 1.15, and 1.10 respectively.[269] Moreover, private cars spend the vast majority of their lives stationary, further increasing spare capacity not to mention visually scarring the landscape. With the car sharing club scheme, members can request – by telephone or internet – the use of a vehicle which is most appropriate to the mobility needs of the moment. Thus, the capacity of the passenger vehicle fleet aligns more closely with the market demand, and the automotive sector becomes more efficient overall as it moves from a product model to a service model.

How does this relate to the discussion of highly-efficient grid-connected vehicles? In fact, BEVs in particular are an excellent solution to the service model of automotive mobility. As businesses, car sharing clubs will be more sophisticated than private motorists in their buying behaviour, able to factor in both the fixed costs and the variable costs of operating a vehicle fleet on a commercial basis. The reduced operating expenses of BEVs – fewer maintenance overheads and significant energy savings – should be highly attractive to service providers who generate revenues per kilometre. Furthermore, the greater purchasing power of fleet operators can help to overcome the higher upfront capital costs which may deter private consumers from buying a BEV.

Mass Transit Partnerships

The car sharing club model will appeal to public transport providers, such as rail and coach operators. Relatively rigid mass transit infrastructure – especially rail-based – is highly efficient and punctual but somewhat inflexible compared to private motoring. By combining mass transit services with car sharing, public transport providers may effectively extend their network coverage far beyond their traditional nodes. Swiss Railways' partnership with Mobility Car Sharing, called 'Click and Drive', gives members access to 800 vehicles located at 350 railway stations around Switzerland.[270]

Once again, the BEV in particular is beautifully adapted to serve such a business model, capable of completing the "last few kilometres", unreachable through public transport, both cheaply and efficiently. Range limitations are of little concern, because the long distance leg of each journey has already been covered by mass transit.

Energy Services

Electric utilities will undoubtedly view the electrification of automotive transport with some excitement: grid-connected vehicles represent an entirely new market for their product, combined with grid management potential through emerging vehicle-to-grid (V2G) technology. Recently formed technology partnerships hint at the continuing integration between the power and transport sectors. The announcement in July 2007 that Southern California Edison and Ford Motor Company will be working together to explore the market potential of grid-connected vehicles represented an important baby step on the road to automotive transformation.[271] This was followed in September by a similar partnership launched between Electricité de France and Toyota.[272]

Project Better Place, discussed in Part IV, aims to establish a network of battery exchange stations – starting with Israel – which would enable motorists to purchase electrons in much the same way as they purchase gasoline or diesel today, thus bypassing high upfront battery costs.[273] Renault-Nissan have already signed a Memorandum of Understanding to supply electric vehicles with exchangeable batteries by 2011.

It is clear that the convergence of power and transport alone is not enough to bring about sustainability. In parallel, it is essential that we engineer a smooth transition towards an energy system which exploits only sustainable renewable resources. Even here, businesses promoting grid-connected vehicles may have an important role to play. Take the example of an electrified two-wheeler: the Segway PT. For every unit sold, Segway pledges to purchase 200 kWh of electricity from sustainable renewable sources, which the company calculates is sufficient to power a typical Segway PT for more than two years of operation.* Thus, the Segway PT rider need not have access to a liberalised electricity market in order to enjoy carbon-free personal mobility. Innovative marketing packages of this nature – explicitly linking green energy with mobility solutions – lend themselves perfectly to grid-connected vehicles of any shape and size.

International Oil Companies

What of the existing incumbent suppliers of automotive fuels, the oil industry? Today, the majority of the companies operating in this sector interpret their primary role as satisfying their customers' growing demand for liquid hydrocarbon fuels. In reality, what their customers actually demand is motorised kilometres. Very few people are interested in purchasing malodorous flammable liquids which must be set on fire in outmoded and inefficient thermo-mechanical devices. What concerns them is the productive output of that activity: mobility.

To ensure the integrity of the Earth's climate system, the wider environment, and global political stability, transport fuel providers must reassess their contribution to economic development. A primary

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* *The Segway PT requires about 1 kWh for a full charge, which is sufficient to propel the device 35 km. Thus, 200 kWh of green electricity provides 7,000 km of carbon-free personal mobility, which is sufficient for two years of operation assuming a daily urban commuting distance of 13 km (or 8 miles).*

objective of all corporations – at least, those who wish to survive – is to generate long-term shareholder value. This principle is increasingly incompatible with a business model which depends entirely on the extraction and processing of finite geological resources which have no long-term future. The fundamental constraint is neither resource availability nor infrastructure; it is ultimately about environmental sustainability. In this context, it is disastrously short-sighted that oil companies are valued by investors according to their ability to replace fossil hydrocarbon reserves. In a carbon-constrained world, the market value of all energy companies should relate more broadly to their respective abilities to supply the energy services required in the future.

Oil companies insistent on perpetuating their core activity of liquid hydrocarbon fuel supply can have no option but to move from geological to biological sources of carbon. However, the Earth's biosphere has finite capacity to produce these biochemical energy carriers sustainably while simultaneously feeding – and hydrating – a growing human population, and supporting essential biodiversity. Thus, energy suppliers must sooner or later turn to renewable *physical* energy resources – wind, solar, geothermal, tidal, and wave energy – or carriers thereof, namely hydrogen or electricity. And if our overarching principle is to use our sustainable renewable energy resources as efficiently as possible, then the basic laws of physics dictate that electricity will win.

The production of electrons in a carbon-constrained world is not inherently at odds with the current development trajectory of the oil and gas sector. As IOCs steadily increase the share of natural gas in their fossil fuel reserve portfolios, and as they invest more and more in LNG facilities, so their interests grow in a steadily decarbonising power sector. As climate change legislation tightens around CO_2 emissions from power plants, so IOCs will find their geological expertise a valuable asset, able to generate revenue by offering CCS services to large static emitters, such as power plants. Finally, where else but the oil and gas sector can anyone claim decades of experience delivering complex engineering projects in challenging offshore environments, where the potential for wind power is greatest, and in deep drilling that will be required for enhanced geothermal systems (EGS)?

UNINTENDED CONSEQUENCES

Solutions to environmental problems occasionally bring with them a series of unintended consequences, which may or may not be positive. While it is impossible to foresee all eventualities, some obvious risks should be assessed and managed prior to the deployment of any new technology.

Battery Impacts

There is a risk that the large-scale deployment of grid-connected vehicles may introduce environmental threats associated with the batteries. Potential risks are attached to each step in the battery life-cycle, and the combined impacts of all phases must be carefully considered when selecting the winning battery technology: i) extraction of raw materials; ii) processing of materials and components; iii) battery operation; iv) sale for secondary use; v) collection for recycling of discarded batteries; vi) final disposal.

The batteries themselves must be manufactured using energy and raw materials which were originally extracted from the Earth's crust. Of course, the same can be said of existing automotive batteries, internal combustion engines, and many other automotive components which will eventually be made redundant by the advancing electric powertrain. To the extent that these raw materials are able to be recycled, the mining of virgin resources and associated impacts can be minimised, as can the discharge of battery waste to the environment.

The most promising technologies for electric vehicles are currently either nickel metal hydride (NiMH) batteries of the type found in the first generation HEVs, or lithium ion (Li-ion) batteries similar to those which power portable electronic devices such as laptop computers, mobile phones, and digital cameras. In other words, the batteries which will most likely power tomorrow's automotive fleet are today mass produced and widely used in familiar applications.

These batteries do not fail; they degrade, meaning that once they are no longer suitable for automotive applications, they can be redeployed for secondary uses. Speciality businesses may emerge to offer stationary energy storage services, which may prolong the useful lifetime of batteries and delay the recycling for many years.

Manufacturing processes and recycling techniques – both NiMH and Li-ion batteries are highly recyclable at the end of their operational lifetimes – are already established; the environmental hazards associated with these batteries are therefore not entirely new. Large numbers of grid-connected vehicles will no doubt increase the *quantity* of raw materials consumed and waste to be managed, and this will require a significant scaling-up of existing programmes.

In the automotive sector, battery collection and recycling is widely practiced and, unlike for consumer batteries, recycling rates are very high. Most existing automotive batteries are based on lead-acid (Pb-Ac) technology, which will be gradually displaced as grid-connected vehicles enter the market. According to the US Environmental Protection Agency, almost 99 million automotive Pb-Ac batteries are manufactured each year, and close to ninety percent of them are recycled through programmes established to comply with state laws.[274] In the UK, recycling rates for automotive batteries are similarly estimated at around ninety percent.[275] By comparison, less than two percent of the UK's consumer batteries are recycled, with the remainder ending up in land-fill sites.

Given that advanced automotive batteries will necessarily have high operating efficiencies, it is not so much the *use* of batteries which poses the major environmental threats; rather it is the extent to which recycling and disposal of battery waste is regulated and monitored. It is therefore essential that in parallel to the adoption of grid-connected vehicles, automotive battery recycling programmes are appropriately scaled and enforced by law, as indeed they are today in many developed markets.

A Boost for Nukes?

Another potential concern linked with widespread electrification of automotive transport is that the additional demand for base load power could be used to further the interests of the nuclear lobby. Nuclear power is difficult to modulate according to demand variations, meaning that off-peak electricity is essentially wasted. The installation of night-time demand and/or storage capacity – millions of automotive batteries connected to the grid overnight – may therefore sit well with the nuclear industry.

While this is undeniably true, it is intellectually dishonest to argue that support for grid-connected vehicles is tantamount to support for nuclear power. These are two separate discussions. There are numerous rational arguments against a nuclear renaissance, none of which are at odds with a vision for automotive electrification. A desire to realise the manifold benefits of highly efficient grid-connected vehicles does not surrender the right to strongly prefer one power generating technology over another.

For one thing, our guiding principle that all future energy supplies must be met with sustainable renewable resources automatically disqualifies nuclear fission, for it is neither sustainable nor renewable. Overnight base load demand created by grid-connected vehicles will also benefit the development of variable renewables such as offshore wind. Secondly, grid-connected vehicles are not a prerequisite for nuclear power to enter the automotive transport sector. Recent developments in the Albertan oil sands demonstrate that even the liquids paradigm is not immune from renewed interest in nuclear power.[276]

In summary, the electrification of automotive transport is compatible with, and supportive of, a strategy to rapidly increase the share of sustainable renewable energy in the power sector.

Induced Demand

History has shown that great advances in energy efficiency are usually accompanied with *increasing* energy consumption. For example, today's internal combustion engines are much more energy efficient than those of, say, thirty years ago, but our overall appetite for energy has grown voraciously. Efficiency gains have been overwhelmed by an expanding fleet of vehicles, increasing in size, weight, and power, coupled with a growing number of kilometres driven. This pattern is repeated in many sectors, such as personal computing; more efficient appliances enable more work to be done, faster and more cheaply, more of the time, by more machines.*

It is conceivable that the proliferation of highly efficient automotive appliances may induce demand growth in much the same way. Risks associated with increasing size, weight and power can be neutralised through strong vehicle efficiency standards expressed in kWh/km, as discussed above. However, complementary measures will be needed to encourage behavioural change (e.g. eliminating unnecessary journeys, telecommuting, ride sharing), promote modal shift (e.g. from individual to mass transit), and improve urban planning regulations (e.g. reversing the trend towards urban sprawl through city regeneration programmes, multi-purpose zoning etc.). A detailed discussion of these measures is beyond the scope of this book.

GEOGRAPHICAL FOCUS

A strategy to transform automotive transport through electrification may not instantly appeal to every country or region on Earth. However, any nation which satisfies one or more of the following six criteria stands to benefit from such a transformation. With the right supporting measures, the promotion of grid-connected vehicle technology has the clear potential to reward any country which…

- is a net importer of crude oil;
- wishes to use indigenous energy resources as efficiently as possible;
- has a large, or fast growing, road transport sector;
- has a large, or fast growing, automotive industry;
- possesses, or intends to invest in, widespread electricity infrastructure;
- is committed to tackle rising GHG emissions.

Based on these six criteria, which countries and regions of the world are the prime candidates for a strategy to electrify automotive transport?

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* *Paradoxically, those same technological advances which enable us to consume more energy also permit the production of more energy: modern oil production platforms, for example, resemble super-computers with a drill bit attached.*

North America

The US is the world's number one consumer of crude oil, accounting for just over 24% of global demand, of which two-thirds is imported.[277] With a population of around three hundred million people,[278] per capita oil use stands at a staggering 25 bbl per year.* Contrary to conventional wisdom, this oil intensity is *not* the product of a diverse climate which ranges from a frigid north to a sub-tropical south, thus placing abnormally high demands on heating and cooling services. Two-thirds of US oil consumption fuels the transport sector.[279] Transport drives oil.

Regarding the automotive sub-sector, thanks to a legislative loophole which enabled SUVs to be classified as 'light trucks', the overall efficiency of the US light vehicle fleet peaked in 1988 and declined steadily thereafter.[280] It is worth reflecting on this point: the peak of efficiency came a full two decades ago. Today, the efficiency of the US automotive fleet lags far behind Japan, Europe, Australia, South Korea, and China (a developing country). The American market therefore offers massive and immediate potential for substantial vehicle efficiency gains.

Moreover, rising US demand for transport fuel drives the highly destructive development of oil sands in North American neighbour Canada. Aside from dealing with the localised environmental impacts, Canada has a legal obligation to reduce GHG emissions as a party to the Kyoto Protocol. This commitment is being compromised by an insatiable thirst for gasoline south of the border. Canadians should therefore have a strong vested interest in the transformation of automotive transport away from liquid hydrocarbons. And Mexico, facing near-insoluble pollution problems, especially in Mexico City, is launching several major EV-related programs including the Nissan Tsuru conversion initiative described above.

Back in the US, non-profit groups and entrepreneurs are vigorously promoting a vision of vehicles which can connect to the nation's electricity grid. Silicon Valley start-up Tesla Motors,[281] Miles Automotive,[282] and A123 Systems[283] are three notable examples of American businesses

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* *By comparison, annual per capita oil consumption stands at 15 bbl in Japan, 12 bbl in the EU-25, 2 bbl in China, and less than one barrel in India.*

looking to drive the market for EVs. Even Detroit behemoth General Motors have put a stake in the ground by committing to commercialise PHEV technology by 2010.[284]

European Union

With the second largest automotive fleet on Earth and very little in the way of domestic oil resources, the self-proclaimed leaders on climate change have recently shown signs of political will in tackling the automotive transport sector. The European Commission's strategy for reducing CO_2 from cars is the subject of fervent debate at the time of writing, not least due to the conflicting interests of automotive manufacturers from Germany, France, and Italy.[285] The future winners will surely be those who embrace the inevitable transformation, not the laggards who unwisely defend the unsustainable status quo.

Kyoto targets have spawned mechanisms like the EU Emissions Trading Scheme (EU-ETS) and renewables obligations, which will combine to substantially reduce the carbon intensity of European electricity supplies by 2020. Gains here will directly benefit the transport sector, but only when vehicles are able to refuel by connecting to the grid. Meanwhile, the EU's ambitious targets for biofuels are consistent with delivering a transport sector running exclusively on sustainable renewable energy resources, through the development of biodiesel- and bioethanol-compatible PHEVs.

Japan

Japan is the world leader in hybrid vehicle technology thanks to the innovation of Toyota and Honda. It claims no significant fossil fuel resources – every drop of crude oil it consumes is imported. And as signatories to the international climate change Protocol which was negotiated in its own city of Kyoto, Japan shares a keen interest in realising an automotive paradigm which is highly efficient, climate-friendly, and is compatible with a sustainable renewable energy future.

Rapidly Emerging Economies

In the rapidly emerging economies, especially in China and India, it should be easy to appreciate that the prospective prize is even greater. Both countries are undergoing an explosion in demand for private motor vehicles, for which there is no historical precedent. The OECD nations of North America, Europe, and Asia-Pacific developed transport infrastructures based entirely on liquid hydrocarbon fuels, because during their 20th Century industrialisation crude oil was cheap and plentiful, with little competition over resources and no concerns for the long-term impacts of CO_2 emissions. In the 21st Century, the rules of engagement have changed, and both China and India recognise this as well as anyone. Better still, as neither country suffers the liquid hydrocarbon lock-in which afflicts the OECD nations, they are perfectly positioned to choose a different road.

In fairness, developing nations retain the right to choose the path followed by the developed economies before them. But it would make for very strange decision making if developing nations elected to invest in fixed line telecommunications infrastructure over the latest mobile technology, when all the indicators suggested that fixed line telecoms would grow more and more disadvantaged over time. That is precisely where China and India now find themselves with respect to automotive transport development.

It has been said that China's coal-intensive energy mix should immediately disqualify it from the pursuit of electric vehicles.[286] A better strategy, we are told, would be for China to develop highly efficient diesel-powered ICEVs, which could outperform electric vehicles on a well-to-wheels (WTW) basis. However, this line of argument fails for reasons that flow from China's desperately inadequate domestic oil resources. As we have seen, China is today developing coal-to-liquids (CTL) technology, which has a CO_2 footprint twice that of conventional petroleum refining. Proponents argue that the inclusion of Carbon Capture and Storage (CCS) technology buries most of the process emissions, bringing the WTW emissions down to a level comparable with conventional diesel fuel, and therefore marginally better for the climate than China's existing coal-fired electricity. The logical flaw in the argument is that if we are to entertain the prospect of CTL *with CCS*, then we must compare the life-cycle emissions to coal-fired electricity *with CCS*. The latter delivers virtually zero-emissions automotive transport with up to three times the efficiency of the former, per unit of coal consumed. The liquids pathway is therefore indefensible, particularly in China.

When discussing technological solutions to global environmental challenges, a recurring problem is one of 'technology transfer', generally articulated as: how to get superior next-generation technologies from the 'advanced North' to the 'developing South'. With grid-connected vehicles, the quandary is if anything reversed. India is home to the world's best selling BEV, the Reva (or G-Wiz) from Bangalore.[287] China's EV industry is enormous, with nine million electric bicycles manufactured in 2005.[288] The world's largest EV factory is currently under construction in the Chinese city of Tianjin, with half of its production earmarked for export.[289] If the recent refusal of the EU to lift anti-dumping tariffs on Chinese compact fluorescent light (CFL) bulbs is anything to go by,[290] the self-serving interests of those who currently profit from the status quo must be overcome before emerging China and India will be able to help save the 'advanced North' from itself.

PART VII

CONCLUSIONS

A century of economic and social development has been made possible by a transport sector – enabling the movement of goods, services, and people – which remains ninety-five percent dependent on the combustion of liquid hydrocarbon fuels derived from crude oil. The circumstances in which this transport sector evolved have changed beyond recognition. Anthropogenic climate change, deteriorating urban air quality, destruction of essential ecosystems, and escalating political squabbles over diminishing crude oil resources are the backdrop to our global energy system. The alarming fuel specificity of transport must end if we are to stand any chance of reversing these negative trends.

Remaining reserves of crude oil are concentrating in relatively few countries. With the exception of Russia, all the major oil consuming nations – US, EU, China, Japan, and India – are significant net importers. They now face a liquid fuels crisis, which can be solved neither by the threat of military action nor by turning to so-called 'alternative' but in fact highly polluting hydrocarbon resources. The only sustainable approach to this crisis is to tackle its root cause: the unchallenged dominance of the internal combustion engine (ICE) which drives transport's ninety-five percent dependency on liquid hydrocarbon fuels.

In the automotive sub-sector, which accounts for three-quarters of all the primary energy consumed by transport, the potential for energy savings is enormous. Unnecessary journeys can be eliminated through smarter urban planning, encouraging behavioural change, and switching from private to public transport modes. Doubling the effective fuel economy of a private car is as easy as carrying a passenger. Vehicle downsizing, lightweighting, aerodynamic improvements, efficient auxiliary components, lower maximum speed limits, reducing the rolling resistance of tyres and simple hybridising are worthwhile in that all will increase the efficiency of the automotive fleet. Yet none will reduce the sector's dependency on liquid hydrocarbon fuels. With eight hundred million vehicles in the world today, potentially doubling by 2030, the longer we focus on incremental improvements – choosing to ignore our fundamental dependency on liquid hydrocarbon fuels – the more we will be forced to confront *additional* challenges: pressure on governments to open up National Parks and other protected areas for oil exploration, widespread support for destructive unconventional 'solutions' like oil sands and coal-to-liquids, increasing geopolitical conflicts and human rights abuses, and the resulting rapidly growing CO_2 emissions from hundreds of millions of vehicle tailpipes.

Automotive transport is ripe for transformational change. We must accelerate the commercialisation of vehicles with diversified primary energy sources, high efficiency *and* compatibility with a sustainable, renewable energy future. The electrification of automotive transport offers a promising way to achieve this objective. Grid-connected vehicle technology – enabling all or part of every journey to be powered by electricity taken from the grid – is available based on existing infrastructure and current technology. Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) – supplemented by sustainable biofuels for range extension – can dramatically reduce the crude oil dependency of automotive transport in an efficient and sustainable manner.

While most of the world's primary energy will be supplied by fossil fuels in the short- to medium-term, the inherent energy efficiency of the electric powertrain means that the electron pathway can be more efficient than the liquid pathway for any given resource, all else being equal. In other words, electric vehicle technology means that there can be no justification for the wasteful and carbon-intensive conversion of coal or natural gas into liquid transportation fuels.

To avert the worst impacts of climate change, the power sector must embark on a pathway towards decarbonisation. Fortunately, a range of low carbon generating options exist today, many of which will become increasingly competitive as climate change policies penalise carbon dioxide emissions worldwide. Electricity can be created from physical renewable energy sources (e.g. wind, solar, geothermal), from which it is impossible to produce liquid hydrocarbon fuels. Only vehicles which are capable of receiving electricity from the grid will benefit from future emissions reductions in the power sector. Thus, over time, grid-connected vehicles will grow successively cleaner, while conventional ICE vehicles become dirtier as greater quantities of liquid fuel derive from carbon-intensive unconventional mineral resources. And yet, even based on today's fossil-rich energy mix, the convergence of power and transport can deliver an overall reduction of greenhouse gases, as well as an improvement in urban air quality and noise levels.

By definition, transformational changes of this type require disruption to the status quo. We cannot depend entirely upon today's dominant transport solution providers to drive – or even support – a shift away from liquid hydrocarbon fuels. Strong policies will be required to dismantle market barriers to superior technologies, and to remove hidden and overt subsidies which perpetuate the liquids paradigm at the expense of competition. As a matter of principle, it is essential that policies accounting for all externalities assign the correct responsibility to each of the actors involved.

As with all energy consuming appliances, vehicle manufacturers should be responsible for improving the efficiency of their products. Existing metrics which refer to liquids consumption (in gallons or litres) or CO_2 emissions are technology specific proxies for energy efficiency, which presuppose that vehicles *must* consume hydrocarbon fuels onboard. Vehicle efficiency standards should therefore be expressed in units of energy consumed as a function of distance travelled, e.g. kWh/km, and successively tightened.

Suppliers of energy, whether in the form of liquids, gases, or electricity, must be held responsible for reducing the carbon content of that energy, expressed for example as gCO_2/kWh. Prospective customers can then be encouraged through financial incentives to choose the most efficient appliances together with the cleanest forms of energy.

National and local governments should take the lead in fostering a market demand for grid-connected vehicles, through public procurement programmes and fiscal policy. Supporting infrastructural measures such as installing public charging facilities, providing access to priority traffic lanes, or offering exemptions from road tolls may play an important part in promoting the use of vehicles which are demonstrably less damaging to human health and the environment.

In the private sector, companies will likely emerge which are today unknown to automotive transport. Innovative business models will come to the fore, which offer integrated mobility services as the sector moves away from the traditional product model. Electrical utilities and renewable energy suppliers will immediately identify the opportunities associated with transport electrification, and not only from the perspective of increasing sales. The grid management potential of electric vehicles will be explored in partnership with technology companies and vehicle manufacturers to further enhance the efficiency – and expedite the decarbonisation – of the power generation and distribution system.

Despite the obvious benefits of automotive electrification, we must remain wary of unintended negative consequences. Advanced battery systems will demand the extraction and processing of raw materials, associated energy consumption, the development of a 'second life' industry for used batteries and a scaling up of existing waste management programmes. Electricity consumption will necessarily rise as liquid fuel demand falls, so technologies to mitigate large static emissions should be implemented; strategies which drive the power sector towards efficient sustainability will go hand-in-hand with the transformation of transport.

History shows that significant improvements in energy efficiency often induce demand; energy efficient devices may be used more often and in greater numbers than their inefficient predecessors, resulting in a net increase in energy consumption. Expanded mass transit and smart growth community planning efforts must be necessary corollary strategies.

In terms of geography, the electrification of automotive transport will appeal to any country or region which (i) is a net importer of crude oil; (ii) wishes to use indigenous energy resources as efficiently as possible; (iii) has a large, or fast growing, road transport sector; (iv) has a large, or fast growing, automotive industry; (v) possesses, or intends to invest in, widespread electricity infrastructure; and (vi) is committed to tackle rising greenhouse gas emissions. Prime candidates include North America, the EU, Japan, China, and India.

As it has done for the last one hundred years, road-based transport will continue to play a vital role in the delivery of essential mobility services which underpin economic and social development. It will be possible to realise the associated benefits without widespread environmental destruction, loss of vital ecosystems, and escalating political conflict, but only if we are able to engineer a transition towards **an automotive transport paradigm which is both highly efficient and compatible with a sustainable renewable energy future**. With concerted action by multiple stakeholders in key regions, it should be possible to write some remarkable success stories in the coming years.

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The oil and transport sectors are inextricably linked.
If we are to stand any chance of reversing climate change, destruction of essential ecosystems and geopolitical tensions, this link must be broken by transitioning to a transport paradigm which is both highly efficient and compatible with a sustainable renewable energy future.

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