Powertrain 2020 –
The Future Drives Electric
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Executive summary

Increasing discussions about global warming and oil dependence are leading to a massive push to reduce fuel consumption and emissions. All G8 countries have pledged to limit the increase in global warming to 2°C, requiring significant efforts from all sectors, and the automotive industry in particular.

Just improving the existing internal combustion technology is not enough. Although the potential to reduce emissions from gasoline and diesel engines will reach up to 40% and 30% respectively by 2020, there is still a gap of more than 10 g/km CO₂ to the European target of 95 g/km.

Therefore, more serious efforts in powertrain electrification are required. The main question is not if, but when (near) zero emission vehicles will penetrate the market. For the most part, technical issues for battery and key electrical components have been resolved, but major challenges remain regarding cost, infrastructure and regulations. This will determine how fast the market will develop.

Two scenarios are presented in this study to forecast the market development for EVs (electric vehicles) and PHEVs (plug-in hybrid electric vehicles or EVs with range extenders), taking different development paths into account. Our more optimistic “The future drives electric” scenario foresees 8-10 million PHEVs and EVs in global sales by 2020. This assumes higher oil prices, accelerated reduction of battery cell costs up to 200 EUR/kWh, stronger government support and a broader product range offered by the OEMs. But even in the less aggressive scenario, there is a massive increase in powertrain electrification.

Powertrain electrification will reshape the current mobility value chain, forcing con-solidation and new partnerships as well as opening up new revenue and profit pools for existing and new players. The future will be decided on four major battlefields, most of them heavily influenced by industrial policy:
1. High-power and high-energy batteries (a EUR 10 bn to 30 bn market by 2020):
While Western companies such as Phostec Lithium (Süd-Chemie), 3M, BASF and others have a strong position for active battery materials, players from Japan and Korea are dominating cell manufacturing. And Chinese players are fast closing the gap, leveraging extensive government support and unique access to critical raw materials. Because of the massive R&D and CAPEX needs, fast consolidation is likely, with probably fewer than ten companies dominating cell manufacturing by 2020.

2. Equipment for battery cell manufacturing (a EUR 3 bn to 8 bn market by 2020 for automotive applications alone):
This market is currently dominated by Japanese and US manufacturers. Due to the high automation of cell manufacturing, European countries such as Germany can participate only if their companies are able to leverage their expertise in precision engineering.

3. Electric motors/e-machines (a EUR 4 bn to 9 bn market by 2020):
Incumbent manufacturers are today’s leaders in terms of technology. However, they face a major threat from Chinese newcomers who have better access to the rare earths needed for electric motors that rely on permanent magnets. Suppliers from triad markets therefore need to increase their efforts to develop alternative technical solutions and must not lose that business.

4. Energy, infrastructure and additional services (electricity alone is a EUR 2 bn to 10 bn market by 2020, plus several times that in additional revenue opportunities):
Utilities all over the world are currently jockeying for position – and are being challenged by new players such as Better Place. These newcomers take advantage of global reach and invest heavily in additional services and new technologies to increase customer value. OEMs need a clear strategy to participate here as well, so as not to be marginalized by a long-term shift from selling cars to providing mobility services.

Governments and industrial policies play a crucial role in market penetration and technology development, as they are required to support market development and facilitate the necessary investments. Here, the US government is leading the way with a support package worth almost EUR 20 billion. China is providing EUR 1 billion. While the Japanese players are already strong, European governments need to increase their efforts in order to not fall behind.
Companies need to define a robust strategic roadmap to benefit from the upcoming changes. We propose a structured approach to answer the five most important questions:

1. Evaluate the strategic importance of the topic for yourself – How aggressive do we need to be to enter this field?

2. Assess your resources – How much can we afford to put into this new market?

3. Synthesis: Define your general strategic roadmap – Where is our technology focus and what is our implementation plan?

4. Define your position in the new electric mobility value chain – Where should the future focus of my business be? Are there opportunities for creating additional value?

5. Adapt your current business – Where do we need to reallocate resources?

The challenges are daunting, but the potential rewards are enormous. There is no better time to start the change than today!
Introduction

There can be no doubt that the current economic crisis will have a lasting impact on the automotive industry, possibly reshaping its landscape entirely. But the jury is still out on what the effect of current turmoil will be on one of the most important developments in the industry: powertrain electrification. Will the crisis put the entire process on hold, or give it new impetus?

As sales decline in major markets worldwide, OEMs find themselves forced to realign their product portfolio and production footprint. In many ways this is the ideal time for them to incorporate new technology into their products. Moreover, the financial support being provided by governments to OEMs around the world is at least in part linked to specific investments in the development of new propulsion technologies.

Of course, automotive manufacturers have been aware of the need for powertrain electrification for quite some time. But their strategy in the past has been to introduce the new technology little by little, supporting it with stable financial returns from their regular business.

The current crisis means that this financial basis has been pulled from under their feet. On top of this, the governments of OECD countries are putting increasing pressure on OEMs to act as pioneers in the development of carbon-free road transportation. Technology has also made significant advances recently. All in all, the time seems ripe for the automotive industry to rethink its previous slowly-slowly approach.

In our 2007 study "Solving the Powertrain Challenge: The Automotive Industry at the Crossroads," we examined the challenges facing the automotive industry in the period up to 2012. Our findings with regard to powertrain technology still hold true today. Improvements in conventional technology – including hybridization, the first step towards powertrain electrification – are sufficient to meet the mid-term emissions standards set out by current regulations. Indeed, we are already experiencing the mass-market introduction of technologies such as start-stop systems and engine downsizing by OEMs.
Our 2007 study also identified the major hurdles facing OEMs with regard to challenges for 2012, in particular how to meet the 130 g/km fleet emission target in Europe. Many of our findings have been addressed by the major players. With customer willingness to pay for new technology being limited, OEMs have adopted a proactive market development strategy, mopping up the extra costs themselves.

Most OEMs have expanded their in-house competences and engineering capacities in the field of hybridization and pure electric drive. They have tried to simplify the growing complexity of their powertrain portfolios. Organizational structures have been adjusted. Although oligopolistic supplier structures continue to exist, increasing competition and growing competence in the supplier industry are gradually leading to more advanced components and a broader range of options to choose from.

The present study takes our initial analysis a step further, analyzing the challenges that automakers face in the longer term. It also reflects the major changes that have occurred since the publication of the report.

Battery technology is in many ways the key to successful powertrain electrification. This area has seen considerable technological advance in the last two years, accompanied by increased commercial activity.

Growing concern about global warming is leading to more and more restrictive governmental regulations, particularly with regard to CO₂ and particulate matter emissions. This development is putting OEMs under greater pressure to develop cleaner vehicles.

The spike in oil prices in 2008 strengthened the intent of governments to decrease their countries’ dependence on oil. At the same time, global competition in the area of green vehicles is growing, often challenging established positions.
These developments have resulted in some modest but significant changes in the business landscape. New players have appeared along the new mobility value chain: battery suppliers such as A123 and LiTec, OEMs such as BYD or Tesla, distributors such as Nice in the UK. Utilities such as RWE and EDF are providing the recharging infrastructure. New types of mobility providers such as Better Place have emerged on the scene. Together, these players are challenging the way that the automobile business has traditionally operated.

Incumbent OEMs such as Daimler, GM, Mitsubishi, Toyota and Renault have also recognized the change in the wind. The major players have announced the launch of pure EVs and PHEVs by 2012 at the latest.

The present study extends our analytical timeframe up to the year 2020. This allows us to present our insights into longer-term developments. It also enables us to focus on the second step towards powertrain electrification – PHEVs and pure EVs.

Our aim in the study is to shed some light on a number of pressing issues. First of all, how will regulatory standards on vehicle emissions develop in the foreseeable future? Second, what are the longer-term technological options available to OEMs for meeting emissions requirements? Third, what is the market potential for pure EVs and PHEVs in key automotive markets? And finally, what impact will this have on the current automotive value chain – what new players will emerge, how will business models change, and what will OEMs’ core activities and competences be in the future?

The potential impact of these developments on OEMs and suppliers cannot be overstated. How they decide to prepare for these challenges today will determine their success in the future. Once again, as was the case two years ago, the automotive industry finds itself at a crossroads. But this time the stakes are even higher.
1. Global policy and regulatory framework

1.1 Global policy

On July 8, 2009 at the G8 Summit in Italy, all eight country leaders – including US President Obama and Chancellor Merkel of Germany – pledged to limit any increase in global temperature to just 2°C compared to pre-industrial levels. They emphasized that industrialized countries should take a leading role in combating climate change, and strive to convince major non-OECD countries such as China and India to join them in this endeavor.

The World Energy Outlook 2008 published by the International Energy Agency (IEA) forms a valuable contribution to the ongoing debate. The report outlines a number of different scenarios for the future development of global CO₂ emissions and their impact on the rise in global temperature. Its "Reference Scenario" describes what will happen if business continues as usual, extrapolating from current trends and efforts. The result? A 45% increase in annual CO₂ emissions by 2030, most likely leading to a global temperature rise far in excess of 5°C.

The IEA report also presents an alternative scenario: "Scenario 450." This scenario is based on targets for global emissions and emissions by individual sectors and regions that would limit the increase in global temperature by 2030 to roughly 2°C. These targets would mean not only avoiding the increase forecast in the Reference Scenario, but also bringing global CO₂ emissions down to below today’s levels.

![Figure 1.1.1: Global policy framework based on forecasts in the World Energy Outlook 2008](image)
To achieve this ambitious goal, all sectors, including power generation and transportation, would need to make a significant contribution. In the transportation sector, light-duty vehicles (LDVs) would be particularly strongly affected. At present, LDVs are the biggest emitters of CO$_2$ in the transportation sector, accounting for 44% of total CO$_2$ emissions.

The average CO$_2$ emission target for the LDV vehicle stock in OECD countries outlined in Scenario 450 is 90 g/km by 2030. This is almost 50% below today’s level of 176 g/km. The emission target for non-OECD countries is 110 g/km. The IEA makes this distinction so as to underline the leading role to be played by industrialized countries.

In terms of new car sales, the European Union, US and Japan must achieve a dramatic reduction in fleet emissions soon after 2012. They need to act early because of the significant time lag before new car sales impact on overall vehicle stock emission figures.

Moreover, significant differences exist between actual, on-road CO$_2$ emissions and vehicles’ certified values. Certified values are based on a vehicle’s official driving cycle and can differ from the actual levels by as much as 30%, depending on the driving cycle used and the driving and traffic conditions. Thus the IEA estimates that today’s actual average CO$_2$ emissions per vehicle for the LDV stock of OECD European countries is 165 g/km.
This figure compares with a global OECD average of 176 g/km and an estimated actual average value for the new car sales fleet in Europe in 2006 of 180 g/km (a correction factor of at least 10% compared to the certified values). The IEA estimate takes into consideration the large number of older vehicles in today’s vehicle stock that weigh less and have smaller engines. Taking into account other published estimates, we believe that the IEA estimate is toward the lower end of the actual possible range.

Initial simulations based on the (optimistic) IEA figures for the vehicle stock indicate that the 2020 emission targets for certified values of the new car sales fleet should be well below 95 g/km for Europe. Requirements for the US and Japan are very similar.

The debate about targets for different sectors and the role of different regions in reducing emissions is likely to become more intense in the coming months and years. The next important calendar date in the discussion will be the World Climate Conference to be held in Copenhagen in December 2009.
1.2 Regulatory framework

The world’s leading economies have developed a wide range of instruments aimed at reducing emissions and lessening their dependence on oil imports. Their approach has two prongs. On the one hand, they are trying to force OEMs to come up with more fuel-efficient vehicles. They do this by means of tighter regulations, harsher penalties, subsidies for research and development and industrialization programs. On the other hand, they are trying to steer demand from end customers toward forms of private transportation that are less damaging to the environment. This they do with the help of tax incentives, subsidies and other local instruments.

1.2.1 Government targets for new vehicle sales

**CO₂ emissions and fuel efficiency regulations**

Several major countries across the world have established targets for CO₂ emissions and/or fuel efficiency. The European Union currently has the most stringent targets. By 2012 the average CO₂ emissions of an automaker’s annual new car sales should not exceed 130 g/km in the EU (applies to 65% of the fleet, gradually increased up to 100% by 2015). By 2020 the target is likely to be 95 g/km. This represents an average fuel consumption of roughly 4 liters of gasoline, or 3.6 liters of diesel, per 100 km.
In the US, the current CAFE fuel-efficiency targets for passenger cars and light trucks in 2020 are just 35 miles per gallon of fuel, the equivalent of almost 6.7 liters of fuel per 100 km. However, the Obama administration has announced that it will be bringing this target forward to 2016. In California, the Air Resources Board (CARB) has set the 2020 fuel-efficiency target at 42.5 mpg (5.6 liters per 100 km).

California was also the originator of the Zero Emissions Vehicle (ZEV) Mandate, which requires OEMs to produce a certain percentage of ZEVs for sale in the state. By the end of 2008, more than ten US states had adopted this legislation. Under the ZEV Mandate, an OEM with a 10% market share in these states would have to sell 3,000 ZEVs or 7,500 enhanced advanced technology partial zero emission vehicles (AT-PZEV) – vehicles utilizing fuel that can be used in a ZEV, i.e. PHEVs and hydrogen internal combustion engine vehicles (HICEVs).

The Japanese government first established fuel economy standards for gasoline- and diesel-powered light-duty passenger and commercial vehicles in 1999 under its “Top Runner” energy efficiency program. Current fuel economy targets for 2015 are in line with those established in Europe. Fuel economy targets are based on weight class. Assuming that the ratio of each segment remains constant, the fuel efficiency target for 2015 is 16.8 km per liter (5.9 liters per 100 km).
The Chinese domestic automotive industry still lacks competitiveness in internal combustion engine (ICE) technology. Consequently, the government has opted to establish short-term fuel efficiency targets that are not as strict as those found elsewhere. Nevertheless, the government is aware of the increasing importance of limiting oil imports to the transportation sector. In January 2008, it increased the regulation on fuel consumption by an average of 10% for each weight class used in the Chinese system. This tightening up is expected to result in an estimated average fuel efficiency target of 7.25 liters per 100 km (assuming segment ratios will remain at the 2008 level).

For example, in 2008 a passenger car with a curb mass of 865-980 kg had to show fuel consumption of less than 7.4 liters per 100 km. For comparison, a 1.2-liter 44-kW Volkswagen Polo with a curb mass of 1,014 kg has an average fuel consumption of 5.8 liters per 100 km.

How effective fleet emission targets are depends very much on the severity of the penalties imposed. The European Union is currently in the process of introducing penalties for OEMs that fail to meet the targets. The level of these penalties increases with every extra gram of CO₂ emission above the target, and will soon be the toughest in the world.

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**FIGURE 1.2-3: Current CO₂ fleet emission penalties for OEMs in key automotive markets**

<table>
<thead>
<tr>
<th>CO₂ fleet emission penalties for OEM (EUR per vehicle)</th>
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<tbody>
<tr>
<td><strong>EU</strong></td>
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<tr>
<td>EU penalties per vehicle (EUR/g)</td>
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<tr>
<td>1st g</td>
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<td>3rd g</td>
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<tr>
<td>Every other g</td>
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<tr>
<td><strong>US</strong></td>
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<tr>
<td>US penalties per vehicle (EUR/g)</td>
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<td>1st g</td>
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<td>3rd g</td>
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<tr>
<td>Every other g</td>
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<tr>
<td><strong>JAPAN</strong></td>
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<tr>
<td>Japan penalties per vehicle (EUR/g)</td>
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<tr>
<td>Every other g</td>
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<tr>
<td><strong>CHINA</strong></td>
</tr>
<tr>
<td>China adapted EURO standards in 2000</td>
</tr>
</tbody>
</table>

1) Target for 65% of the fleet from 2012 on; gradually increased up to 100% of the fleet until 2015
2) On average approx. 600,000 vehicles sold per Japanese OEM in 2008

Source: EU Commission, Parliament, and Council; JAMA; ICCC; I.D. Power; Roland Berger
**NOx and particulate matter emissions**

The European Union and Japan lead the pack in terms of legislation for other tailpipe emissions such as particulate matter (PM) and NOx. Europe brought in the EURO 5 norm in September 2009, under which PM is reduced by 80% and NOx by 20% compared to EURO 4 for diesel vehicles. EURO 6 will be introduced in 2014, bringing with it still further reductions. In Japan, the 2009 target values for NOx and PM emissions are roughly equal to those of EURO 5.

In the US, the Environmental Protection Agency has dramatically reduced NOx and PM emission targets. Its aim in doing so has been to close the gap with Europe and Japan.

In the case of China, we expect further convergence of toxic emission targets in the coming years. However, as the price of fuel in China is controlled by the state, oil companies do not have a strong interest in upgrading their refining facilities. This lack of incentive to offer better fuel quality currently hinders the introduction of stricter emission regulations. In the future, as automobile exports from China increase, the pressure to bring regulations into line with global standards will doubtless grow. A similar pattern is likely to be observed in India.

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**FIGURE 1.2-4: Convergence of NOx and particulate matter emission targets**

| NOx/PM emission standards for passenger cars^{1,2}, 2000-2015 (g/km) |
|---|---|---|---|---|---|---|---|---|---|---|
| **EURO 3** | | | | | | | | | | | | | | | | |
| **EU** | 0.5 | | | | | | | | | | | | | | | |
| **EURO 4** | | 0.25 | | | | | | | | | | | | | | |
| **EURO 5** | | | 0.18 | | | | | | | | | | | | | |
| **EURO 6** | | | | 0.08 | | | | | | | | | | | | |
| **US EPA\(^1\)** | 1.0 | | | | | | | | | | | | | | | |
| **Japan** | 0.98 | 0.8 | | | | | | | | | | | | | |
| **EURO 1** | 0.06 | | | | | | | | | | | | | | | |
| **EURO 2** | | | 0.14 | | | | | | | | | | | | | |
| **EURO 4** | | | | 0.02 | | | | | | | | | | | | |
| **CHINA** | | | | | | | | | | | | | | | | |
| **NOx** | 0.15 | 0.05 | | | | | | | | | | | | | |
| **Particulate matter** | | | | | | | | | | | | | | | | |

1) Diesel engines
2) Environmental Protection Agency

**Note:** EURO 1 and EURO 2 had no NOx emission targets.

**Source:** EU: national regulations; Roland Berger
1.2.2 Support for research into alternative powertrains

Many governments currently offer support to the automotive industry in its efforts to develop alternative powertrains by helping them with the large initial investments needed in R&D. In many cases, governments are also helping build the national infrastructure needed for recharging EVs.

Germany is a good example. The German government has recently announced a EUR 500 million program for developing e-mobility in the country. This program includes subsidizing R&D, in particular for batteries and other components, and building the infrastructure for EVs in selected geographical regions. France has announced a similar program worth over EUR 400 million to support the development of EVs and hybrid vehicles, and Spain, Denmark and the UK have also launched support programs.

In the US, the government plans to invest up to EUR 113 billion in developing clean energy technology over the next ten years. An additional EUR 24 billion will be provided to improve, expand and upgrade the electric transmission infrastructure. The new capacity in green power generation and upgraded grids will help to meet the extra demand posed by EVs. To boost the development of PHEVs, the US plans to spend the equivalent of EUR 3.4 billion on smart electric grid development. The new technology will enable PHEVs to generate revenues for their owners when the vehicles are plugged in, serving as "capacity buffers" during peak hours.

To overcome problems in battery technology, the US plans to provide EUR 2 billion for battery-related research and a further EUR 150 million in grants for research focused on EVs. At the same time, it will give EUR 17 billion in loans to automakers to accelerate the retooling of automotive plants to enable the production of fuel-efficient vehicles. The federal government is planning to spend some USD 600 million on outfitting its fleet with alternative propulsion vehicles.

The Japanese government is subsidizing the development of high-performance batteries for HVs/EVs to the tune of EUR 150 million. Its aim is to cut the cost of battery cells in half by 2010.
And China? Its plans are even more ambitious. EVs are the key pillar of the Chinese automotive industry strategy, which focuses on the industrialization of EVs/PHEVs and key vehicle components. Pilot projects will run between 2009 and 2011 in several large cities as part of the “Ten Cities, One Thousand Cars” initiative, aimed at enabling cities to put energy-efficient vehicles into operation quickly. To foster technological advances, the Chinese government is also providing approximately EUR 1 billion for research into powertrain technologies.

The governments of industrialized countries around the world have recognized that technological leadership in the field of new electric powertrains is vital if they wish their auto industry to remain competitive. Consequently, they are willing to support their industries with significant investment programs. Such programs can make a significant contribution to overcoming the hurdles that stand in the way of new technologies becoming fully commercially viable.
1.2.3 Steering demand

In the attempt to steer customer purchasing behavior toward vehicles with low CO₂ emissions, governments have started to implement tax regimes that penalize CO₂ emissions. By the end of 2008, 15 European countries had adopted such taxation systems.

In the past, many tax regimes were based on cylinder displacement. This approach more or less penalized high fuel consumption. The new taxation systems, by contrast, charge directly for CO₂ emissions. In several instances, vehicles with emissions below 120 g/km are exempt from taxes altogether. This creates a powerful incentive for customers to buy fuel-efficient vehicles.

As well as reducing taxes, many countries are trying to promote the sales of vehicles with low CO₂ emissions by giving buyers direct monetary incentives or subsidies. This is the case in Denmark and France, for instance. While these programs will probably be scaled down or abolished once EVs gain significant market share, they are a viable way to help low-emission vehicles get started.
Similar programs are also found outside Europe. Japan’s incentives to buy fuel-efficient vehicles have been inconsistent to date, with a reduction in acquisition taxes of 2.7% and a reduction in vehicle ownership tax of 50%. More recently, however, the Japanese government has announced a major overhaul of the country’s vehicle tax regime with the goal of completely exempting vehicles with low CO\textsubscript{2} emissions from acquisition and tonnage taxes.

China has not as yet announced any plans for a CO\textsubscript{2}-based taxation system. However, the government is aware of the major opportunity represented by new powertrain technologies as a way for the country’s automotive industry to gain a competitive edge over established players. The current Chinese taxation system is based on cylinder displacement. This has only an indirect influence on CO\textsubscript{2} emission levels.

Nevertheless, in the new tax regime introduced in 2008, taxes on vehicles with cylinder displacement of less than 1 liter were lowered from 3% to 1%, while those for vehicles with cylinder displacement of more than 3 liters were raised from 25% to 40%. The new system also heavily subsidizes the purchase of fuel-efficient vehicles. For example, the government offers subsidies of RMB 60,000 (approximately EUR 6,000) for the purchase of EVs for public use, such as taxis and buses.

The US is taking a different approach to changing customer behavior. Rather than penalizing vehicle owners with high taxes on CO\textsubscript{2} emissions, the US encourages them to acquire fuel-efficient vehicles by providing benefits to drivers. These benefits include income tax credits (up to USD 3,400) on a federal level and numerous other monetary incentives in certain states. Moreover, the recent economic stimulus package includes a USD 7,500 tax credit available to buyers of the first 500,000 PHEVs, giving an additional boost to demand. The government aims to get 1 million PHEVs with at least 150 mpg into service nationwide by 2015.
1.2.4 Authorities and local communities

In addition to national programs and tax incentives, many authorities and local communities have begun taking action against CO\textsubscript{2} emissions. In Europe, London has implemented a congestion charge of GBP 8 per day for all vehicles entering the inner-city area. Vehicles such as EVs and certain hybrids are exempt from this charge. More than ten other cities in Europe are currently considering introducing similar measures.

In Japan, many cities offer free parking, discounts on tolls, special automobile insurance and low-interest loans to buyers of low-emission vehicles. In the US, buyers of environmentally friendly cars are rewarded with special benefits, usually non-monetary. Benefits include allowing the drivers of these vehicles to use high-occupancy vehicle lanes (e.g. in California), giving them free parking and even granting discounts on the electricity used to charge EVs during off-peak times (both incentives offered in Los Angeles).

The private sector also plays a vital role in promoting environmentally friendly vehicles. Several large companies including Google and Hyperion in the US and major fleet operators such as UPS and Deutsche Post actively support the acquisition of fuel-efficient cars.

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**FIGURE 1.2-7: Current incentives for drivers of fuel-efficient vehicles**

Selected incentives for driving fuel-efficient vehicles

- **No congestion charge – London**
  - In London, electric vehicles and alternative-fuelled vehicles are exempt from the congestion charge of GBP 8 (approx. EUR 8.71) levied for entering the city.

- **Use of HOV\textsuperscript{PL} lanes – California**
  - In California, drivers of qualifying vehicles such as selected hybrids, compressed natural gas, hydrogen and electric vehicles can use High Occupancy Vehicle lanes.

- **Free parking – Los Angeles**
  - Free parking in designated parking lots in cities such as Los Angeles, private parking areas at IKEA, etc.

- **Discounts on electricity – Los Angeles**
  - Los Angeles Department of Water and Power offers a discounted rate of 0.0021 USD/kWh for electricity used to charge EVs during off-peak times.

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1) EUR/GBP currency exchange 1:0.9 - April 4, 2009  
2) High Occupancy Vehicle

2. Powertrain technology options

Faced with growing environmental concerns and more stringent government regulations, OEMs find themselves forced to make dramatic improvements in fuel efficiency. They can do this by reducing vehicle weight, improving vehicle aerodynamics or developing advanced powertrain technologies. On the one hand, this means optimizing the potential of current ICE-based powertrains, for example via downsizing or hybridization. On the other hand, it means developing zero-emission pure electric propulsion, with or without on-board range extenders – i.e. pure EVs and PHEVs.

Below we examine both technological options and how they can be turned into viable market products. In each case we also determine the potential they offer for reducing emissions.

2.1 ICE-based powertrain optimization

2.1.1 Introduction

In April 2007 we published our first powertrain study, entitled “Solving the Powertrain Challenge: The Automotive Industry at the Crossroads.” The study looked at the potential of conventional ICE and hybrid powertrains and whether they could help meet the EU CO₂ fleet emission targets of 130 g/km by 2012.

The 2007 study identifies three key levers for further optimizing the conventional ICE powertrain: thermodynamic improvements, reduced mechanical friction, and optimized calibration of the overall powertrain system. Downsizing and gasoline direct injection (GDI) are already becoming increasingly popular with OEMs, with the likes of Volkswagen and BMW already using these technologies in many of their vehicles. Diesel engines with multi-stage turbochargers are also starting to replace larger displacement engines, for example in Mercedes and BMW vehicles.

Hybridization is a different story. Full hybrids remain a niche technology due to their unattractive cost-benefit ratio. The vehicles currently available are mainly flagship technology products with very low volumes and high sticker prices. Only Toyota, which has integrated full hybrids into its overall vehicle and platform strategy, is able to sell full hybrids on a larger scale.

OEMs are currently introducing micro-hybrids and mild hybrids in all vehicle segments. Such vehicles offer much lower component costs, combined with significant potential to boost efficiency.
In Japan, Honda’s new mild hybrid model, the "Insight," was the best-selling car in April 2009. In Europe, micro-hybrids or start-stop systems with brake energy recuperation are poised to enter the mass market.

Alternative fuels, including biofuels, remain present on the market. However, they are not seeing substantial growth as was previously forecasted. This lack of progress is mainly due to social concerns and the fuels’ limited potential to reduce CO₂.

### 2.1.2 Key ICE optimization levers and their CO₂ reduction potential

The following paragraphs summarize the key ICE improvement technologies. We have added our latest insights. For more detailed information on individual technologies, please refer to the 2007 study.

Thermodynamic improvements within the combustion process and an optimized overall powertrain calibration are the most important means of improving partial load efficiency. Reducing mechanical friction also has a substantial influence on engine and overall powertrain efficiency in all load stages. A number of technologies relating to each of these three levers are currently in development or already in series production.

![FIGURE 2.1-1: Overview of key ICE optimization technologies and their CO₂ reduction potential](image)

CO₂ reduction potential (%)

<table>
<thead>
<tr>
<th>LEVER</th>
<th>TECHNOLOGY</th>
<th>CO₂ REDUCTION POTENTIAL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THERMODYNAMIC IMPROVEMENTS</td>
<td>Internal exhaust manifold</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exhaust gas regulation</td>
<td></td>
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<tr>
<td></td>
<td>Optimized cooling</td>
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<td></td>
<td>VVT</td>
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<td></td>
<td>VVL</td>
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<td></td>
<td>1st generation GDI</td>
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<td></td>
<td>2nd generation GDI</td>
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<tr>
<td></td>
<td>Advanced DI</td>
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<tr>
<td>REDUCTION OF FRICTION</td>
<td>EPS</td>
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<tr>
<td></td>
<td>Low-friction engine</td>
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<td></td>
<td>Low-friction piston</td>
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<tr>
<td></td>
<td>Cylinder deactivation</td>
<td></td>
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<tr>
<td></td>
<td>Mild downstaging</td>
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<tr>
<td></td>
<td>Strong downstaging</td>
<td></td>
</tr>
<tr>
<td>POWERTRAIN CALIBRATION/ HYBRIDIZATION</td>
<td>0.5L gasoline engine</td>
<td></td>
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<tr>
<td></td>
<td>Micro-hybrid</td>
<td></td>
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<tr>
<td></td>
<td>Mild hybrid</td>
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<tr>
<td></td>
<td>Full hybrid</td>
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</tbody>
</table>

CO₂ = gasoline direct injection; DI = diesel direct injection; VVT = variable valve timing; VVL = variable valve lift; EPS = electric power steering

Source: Expert interviews; Roland Berger
Taken individually, many of these technologies offer only minor savings: integrated exhaust manifolds, optimized cooling with an adjustable water pump, electric power steering and optimized gearbox ratios, for example. However, in combination they can reduce CO₂ emissions significantly.

Beside the incremental improvements outlined above, emerging technologies offer major CO₂ reduction potential: downsizing (with or without turbocharging) and GDI. It is likely that these two technologies will become standard in the coming years in established car markets such as North America, Europe and Japan.

But there’s a flipside. Using turbochargers and GDI with lean combustion has a negative effect on the exhaust gas quality of ICES. Turbochargers hamper the rapid warming of the catalytic converter, with the result that CO₂, HCx and NOₓ emissions are higher. The GDI lean combustion process creates further problems. The oxygen surplus in the combustion chamber causes high NOₓ emissions, which requires additional exhaust gas after-treatment.

With respect to the latter problem, homogenous charge compression ignition (HCCI) technology could be a solution in the long term. HCCI is a completely new combustion process technology that has the potential to reduce CO₂ emissions still further. The technology is currently still in the development stage. It combines the low NOₓ emissions of gasoline engines (homogeneous charge spark ignition) with the efficient lean combustion process of diesel engines (stratified charge compression ignition).

Compared to second-generation GDI and advanced diesel combustion, the additional saving potential of HCCI is small. However, the lower soot and NOₓ emission levels could help avoid expensive NOₓ exhaust gas after-treatment – especially for large, powerful vehicles.

A major challenge for HCCI is the delicate combustion process. This process is hard to control in a multi-cylinder engine and requires a highly advanced control system and specific conditions in each cylinder (such as engine temperature, air intake volumes and temperatures). For this reason, it is questionable whether we will see HCCI in large-scale production for gasoline or diesel engines before 2020.

Mild hybridization involves a stronger electric motor than that found in micro-hybrids, one that can not only restart the ICE but also assist in higher load stages. This technology will see a high penetration rate, at least in the large vehicle and premium segments. Other segments will also benefit from micro-hybrid technologies such as start-stop.
Full hybrid powertrains are not the most cost-efficient way to enhance fuel efficiency. They will therefore remain a niche technology, at least in markets with a high share of diesel. We foresee a trend toward developing full hybrids into PHEVs (see section 2.2), owing to the significant extra potential for reducing CO₂ and limited extra costs for a slightly larger battery.

If automakers apply the technologies described above in advanced gasoline powertrains, they can potentially achieve savings of more than 40% compared to standard powertrains with a naturally aspirated, four-valve port injection engine.

The first step in this process would be to make a number of smaller enhancements, such as reduced engine friction through optimized bearing, an integrated exhaust manifold, a cooling system with an adjustable water pump, optimized gearbox ratios and so on. This would lower CO₂ emissions by up to 9%.

![Diagram](image)

Future best-in-class gasoline engines will be significantly downsized, with much less displacement and fewer cylinders than today’s engines. They will feature direct injection and a variable valve train, and will be supported by a micro-hybrid or mild hybrid powertrain.
We believe that in 2020, HCCI will still be a niche technology used only in a small number of displacement engines, typically large ones. Most other engines will rely on advanced direct injection systems.

The full efficiency gain of more than 40% can only be achieved in larger engines that rarely operate in high engine loads. Smaller engines applying the same technology portfolio will not achieve the full saving potential outlined above. The lower amount of power and torque available requires such engines to operate at higher engine load levels, which have less efficiency improvement potential.

As discussed above, future gasoline engines need to not only improve efficiency, but also meet stricter exhaust gas emission requirements. In most cases this should be possible without more expensive exhaust gas after-treatment. Only engines with stratified direct injection and lean combustion will find it difficult to meet the stricter NO\textsubscript{x} limits.

Compared to gasoline powertrains, diesel powertrains will most likely have less potential to reduce CO\textsubscript{2} emission. Best-in-class diesel engines in 2020 will be about 30% more efficient than the standard diesel engines today.
Most of the technologies described above will make gasoline and diesel engines more expensive. The relative cost increase will be higher for gasoline engines as they will use a broader portfolio of new technologies.

Nevertheless, diesel engines will remain the more expensive engine type, especially since stricter NOx limits under new exhaust gas regulations will lead to significant add-on costs for exhaust gas after-treatment.

Estimating costs for the individual emission reduction technologies is very difficult. This is especially true for the period up to 2020. For reference figures, please see to our 2007 study.

### 2.1.3 Potential fleet emission reductions

The application rate of the ICE optimization technologies discussed above will very much depend on the willingness of OEMs or customers to bear the extra costs. This willingness will differ for each vehicle segment and market region.

Three- and four-cylinder gasoline engines will be able to answer the majority of customer performance needs. The very small vehicle segments will even see the introduction of two-cylinder engines. Beyond 250 hp, six-cylinder engines will be the dominant application. V8 engines will most likely form part of the flagship powertrain, produced purely for marketing and image purposes.

We see a similar picture emerging for diesel-powered vehicles. Here, three- and four-cylinder engines will serve as the standard motorization across the volume segments. With up to 250 hp, they will cover a very large share of the required performance range. Six-cylinder engines will answer higher performance needs (up to 330 hp) with a much lower fitment rate than today.

Additional costs are likely to be the restraining factor in the smaller vehicle segment. The opposite will be true for larger vehicles and SUVs in the premium segment. In 2020, as today, larger/premium vehicles and bigger SUVs will be bought mainly for image reasons. This means that they are likely to display superior technology and performance. Sticker prices are less important in the customer decision-making process for such vehicles. Technologies such as downsizing with multi-stage charging systems and mild hybrids will most likely become standard in these vehicle segments.
Large/premium vehicles and bigger SUVs are likely to be the only vehicles enjoying the maximum CO₂ reduction potential for conventional, ICE-based powertrains, due to their premium positioning. Average CO₂ emissions of E-segment vehicles (e.g. the BMW 5 series) will fall to about 140 g/km on average, and those of luxury cars (e.g. the Mercedes S-Class) to about 160 g/km. However, large SUVs are likely to still emit more than 180 g/km on average.

In the smaller and volume vehicle segments, customers’ willingness to pay for efficiency-boosting technologies will be much lower. Moreover, cost competition is in general much stronger. As a result, much less new technology will be used. Cost-intensive technologies such as mild hybrids and fully variable valve trains will have only limited fitment rates in these segments. Consequently start-stop, downsizing, and advanced direct injection systems will have to provide most of the CO₂ emission reductions.

The technologies outlined above will be applied in all the key markets. However, timing and implementation rate will differ between Europe, North America, Japan and other geographical areas. We discuss these differences in detail below.

EUROPE

Europe will strengthen its leading technological position by means of a strong trend toward downsizing. Three-cylinder engines, both gasoline and diesel, will most likely become standard in European mid-size vehicles (such as the VW Golf and Renault Megane) by 2020. Three-cylinder engines are also likely to be the entry-level motorization for large conventional cars (such as the Citröen C5 and Opel Insignia) and compact SUVs. Turbo- or supercharged four-cylinder engines will be used only in the upper performance range (above 130 hp), while six-cylinder engines will have a very limited fitment rate in volume car segments.

The result of these developments will be that European gasoline vehicles will emit 30-40% less CO₂ than today on average. Diesel engine emissions will fall by 20-30%.

If the powertrain technologies described above are implemented in the different vehicle segments across Europe, fleet emissions will drop significantly over the next decade. They are likely to fall below 130 g/km, but not as far as 95 g/km, the proposed target for 2020. Here we expect to see a gap of at least 10 g/km that will need to be met by other means.
**FIGURE 2.1-4:** In Europe, downsizing will be standard in all segments by 2020 – Premium segments show a higher technology level

**Europe: Key powertrain technologies by segment, in 2020**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Small (A/B-segment)</th>
<th>Mid-size (C-segment)</th>
<th>Large (D-segment)</th>
<th>Compact SUV (D-segment)</th>
<th>Premium (E/F-segment)</th>
<th>Large SUV (E-segment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (hp)</td>
<td>80</td>
<td>120</td>
<td>150</td>
<td>180</td>
<td>350</td>
<td>250</td>
</tr>
<tr>
<td>Cylinders</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Injection</td>
<td>1st-gen. GDI</td>
<td>2nd-generation GDI</td>
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<tr>
<td>Valve train</td>
<td>VVT</td>
<td></td>
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<tr>
<td>Hybrid</td>
<td>Micro-hybrid</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Gearbox</td>
<td>M/T or AMT 5</td>
<td></td>
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<tr>
<td>Saving pct</td>
<td>30%</td>
<td>35%</td>
<td>35%</td>
<td>35%</td>
<td>40%</td>
<td>40%</td>
</tr>
</tbody>
</table>

**FIGURE 2.1-5:** ICE powertrain optimization is unlikely to be enough to meet European CO₂ emission limits of 95 g/km by 2020

**European CO₂ fleet emissions - 2008 and forecast for 2020**

- **CO₂ fleet emission targets**
  - 2020: 95 g/km
  - 2012: 130 g/km
  - Expected ICE optimization by 2020:
  - Large SUV: 110 g/km
  - Compact SUV: 110 g/km
  - Premium: 110 g/km
  - Large: 110 g/km
  - Mid-size: 110 g/km
  - Small (A/B): 110 g/km

1) For 65% of the fleet from 2012 on, gradually increased up to 100% of the fleet until 2015
2) Not considering EV/PHEV

Source: J.D. Power; Roland Berger
NORTH AMERICA

In 2020, North American volume models will on average still be larger and more powerful than European models. However, in terms of technology they will probably have caught up with Europe.

Four-valve cylinder heads with variable valve timing, turbochargers and downsizing, direct injection technologies, double-clutch transmissions and automatic gearboxes with six or more speeds will most likely become standard in the US market. Only stratified direct injection and cylinder deactivation are likely to have very different fitment rates from those seen in Europe. Lean combustion GDI will have a lower penetration rate due to lower fuel qualities. At the same time, cylinder deactivation will be more common than in Europe – larger pickups and SUVs are likely to use bigger engines than in Europe, but with deactivation technology to compensate for some of the higher CO₂ emissions.

Three-cylinder engines in general will remain a niche application in North America. Mid-size vehicles will use four-cylinder engines almost exclusively. Large conventional models and compact SUVs will use turbocharged four-cylinder engines at the entry level and will rely on six-cylinder engines for high-end power needs. In large SUVs and pickups, six-cylinder engines will be standard.
If most of the powertrain technologies described above are applied in the different vehicle segments in the US over the next decade, OEMs are unlikely to face difficulties meeting the recently announced CO₂ emission targets for 2016. In fact, these targets only translate into 174 g/km for passenger and light-duty vehicles combined, and the potential for technological improvement remains very high. Cost burdens will be the toughest hurdle to overcome for manufacturers. It also remains unclear what the Obama administration will set as its next CO₂ emission target for the period beyond 2016.

**JAPAN**

North American vehicles on average are bigger and more powerful than European ones. The opposite is true for Japanese vehicles. Yet despite the high share of small engines in Japan, the penetration rate of leading-edge powertrain technologies in the Japanese vehicle fleet will be comparable to that of Europe. In some technologies such as hybrids, it will even be superior. The result may be CO₂ emissions below those of Europe in the coming years – although a direct comparison of CO₂ emissions in Japan and Europe is not possible due to different driving cycles used in CO₂ emission certification.
Japan may remain out in front in the future, even with its lower penetration rates for some of the main CO₂ emission reduction technologies. Key reasons for this superiority are the higher share of partial engine loads in Japan’s driving cycles (10-15 mode and JC08 mode) and the very large share of gasoline engines – which generally have a higher CO₂ savings potential – in the country’s vehicle fleet.

CHINA, INDIA AND OTHER REGIONS
In India, South America, Southeast Asia and parts of China, low vehicle prices and low production costs remain more important than efficiency improvements. In these markets, low-cost powertrains (with engines costing EUR 600-700 and manual gearboxes costing about EUR 200) will retain a sizeable market share. The current lack of strict CO₂ emission regulations means that automakers will not have to make the same level of investments in reducing fuel consumption and CO₂ emissions as in Triad markets. Instead, technical improvements will be driven by the introduction of stricter exhaust gas regulations.

The low-cost approach seen in these markets requires a less complex motor design and low-cost production technologies. Three- and four-cylinder engines with cast-iron motor blocks and two-valve cylinder heads will remain common. Even two-cylinder engines will not be unusual for low-cost vehicles. Expensive technologies such as turbocharging, variable valve trains and mild hybrids will only appear in higher-segment vehicles. Even start-stop will not be standard – although it would be a welcome innovation in urban driving in these regions, given the high traffic density and congestion.

Of course, this does not mean that vehicle fleets in these countries will not improve CO₂ emissions. The level of technology at present is very low, so efficiency gains of more than 25% are possible. OEMs here can reduce CO₂ emissions by adopting technologies and components that are already standard in Triad markets today. Thanks to economies of scale, this will involve only very minor additional costs, if any.

The other factor driving the introduction of new technology in these markets is export. If manufacturers wish to compete globally, they need to invest in new, cleaner technology.

2.1.4 The financial burden for OEMs

Even assuming that most of the technologies outlined above will be standard by 2020 – which means that manufacturers will benefit from significant economies of scale – the average extra cost per vehicle in the future will be several hundred euros or US dollars.
OEMs selling in the European market and aiming to achieve fleet emissions in line with existing regulations will need to bear an average of EUR 800 in extra powertrain technology costs per vehicle. The exact level depends on the specific product mix. Some models, in particular in the luxury segment, may actually enjoy lower powertrain costs due to the increased use of mass-market technology (e.g. V6 diesel with turbocharging instead of V8 diesel). However, the average cost increase will be between EUR 400 for the small car segment and EUR 2,500 or more for gasoline-powered premium cars.

How can OEMs recoup some of this extra expenditure? Providing customers with 30% or more fuel savings and lower annual tax payments based on CO₂ consumption may make them willing to bear part of the extra costs through a higher sticker price. But OEMs selling on the European market will probably have to mop up more than EUR 12 billion of annual extra component costs themselves, with a limited additional profit pool.

We foresee the same level of financial burden in the US market. Here, the willingness of end customers to pay a higher sticker price is even more limited than in Europe. Given the fragile financial condition of the key US players, coping with the estimated extra annual component cost of more than USD 10-15 billion will represent an enormous challenge for the industry, especially on the supplier side.
2.1.5 Conclusions

Optimizing the conventional ICE powertrain (including mild hybridization) offers the potential to reduce CO\textsubscript{2} emissions by up to 40%. But OEMs are bound by two factors: the limitations of physics, and rigid customer expectations regarding vehicle size and performance – expectations that are unlikely to change over the next decade. These two factors mean that the level of fleet emissions realistically achievable is likely to remain well above 100 g/km. For European markets, this will not be enough to achieve the CO\textsubscript{2} emission targets for 2020.

Even the improvements outlined above are possible only if OEMs make the investments required to adapt all their vehicle platforms and production lines in line with the new, improved powertrain technology. They will also have to find a way to cope with the additional material costs. Support from government for this is unlikely to be forthcoming.

That's quite a challenge. It means that OEMs must take a closer look at a potential new set of powertrain technologies that could provide an even bigger step forward in CO\textsubscript{2} reduction. These technologies may have appeared unrealistic a few years ago, but the situation today has changed dramatically, particularly with respect to battery technology. Accordingly, in the following section we turn our attention to powertrains for PHEVs and EVs.

2.2 EV and PHEV powertrains

2.2.1 Introduction

PHEVs with an electric driving range of more than 25 km (15 miles) can significantly reduce the CO\textsubscript{2} emissions from road transportation. Certified CO\textsubscript{2} emissions for PHEVs compare very favorably with those of standard full hybrids. Thus PHEVs with a pure electric driving range of more than 25 km achieve a 50% reduction in CO\textsubscript{2} emissions on paper.

In reality, however, much of this reduction is probably achieved by drivers charging PHEVs externally or at home on a regular basis and then driving more than 50% of the daily distances in pure electric mode. Some drivers in metropolitan areas may even use their PHEVs as pure EVs 90% of the time, only using the ICE powertrain for occasional journeys or in specific situations. For this reason, in the analysis below we group PHEVs with an electric driving distance of more than 25 km together with EVs.
PHEVs can take a number of different forms in terms of their technology. They range from upgraded versions of today’s full hybrids to pure EVs with an additional ICE-powered generator for recharging the battery – called a "range extender." Because of their unlimited driving range, it is widely assumed that PHEVs will become the dominant technology until such time as manufacturers introduce more powerful batteries for EVs. However, EVs are not necessarily just limited to small car segments. In practice, drivers make short trips within cities in bigger vehicles too, even in SUVs and vans. This is particularly the case for larger households with more than one car.

PHEVs and pure EVs have very different powertrains from those of today’s vehicles. This has a significant impact on the overall vehicle layout. In the following sections we give a brief overview of the key components, technological challenges and potential cost impacts involved.
### 2.2.2 Vehicle layout requirements

Cars with pure electric powertrains require a very different vehicle packaging than cars with conventional powertrains. This is due to the different spatial and physical requirements in terms of vibration, noise, cooling, aerodynamics and so forth. The compact design of the electric components (except the battery) provides an opportunity for OEMs to redesign the body-in-white, introducing new lightweight materials and innovative interior solutions, for instance. Toyota’s “1/x” concept car is a good example. Adding a small, ICE-powered generator as range extender doesn’t necessarily exclude the option of such a redesign. The picture changes, however, where fully-fledged ICE powertrains come into play (e.g. in parallel hybrid designs) or where the vehicle platform needs to suit both electric and ICE applications.

In the period up to 2020 – in other words, for the first and second generation of PHEVs/EVs – most manufacturers will continue to use established vehicle packages that follow conventional powertrain layouts. This will allow them to leverage component synergies with ICE-powered versions. Upper-end premium vehicles (conventional E-segment and F-segment vehicles and large SUVs), which have relatively low production volumes, will not feature a dedicated EV layout.
The new versions will most likely be PHEVs based on a parallel hybrid powertrain layout that can utilize the body and crash structures as well as the gearbox and axles of conventional ICE-powered models.

In terms of packaging, integrating a PHEV powertrain into a large vehicle with a longitudinally placed engine should not be a problem. The electric motors and power electronics are only marginally larger than their conventional equivalents and will fit into the existing parallel hybrid powertrain. The medium-sized battery will probably fit into the trunk area.

This is not the case with smaller, mid-size vehicles with transversely mounted engines. For these vehicles, designing a PHEV version with a parallel hybrid system will involve major packaging problems. Serial hybrid, mixed parallel-serial hybrid and pure EV layouts will most likely be the preferred solution. Doing without the multi-stage gearbox will save on some of the limited packaging space.

A dedicated vehicle platform will probably be designed first for pure EVs in the smaller car segments, where there are higher volumes and greater customer acceptance for pure electric driving. A good example is Renault’s new “City EV”, to be launched in 2012.

### 2.2.3 Key powertrain components

For pure electric driving, the powertrain consists of just three major components: an electric motor (possibly with a multi-gear transmission), power electronics, and an energy storage system. Complexity increases if a range extender system is added.

#### 2.2.3.1 Electric motors

Electric motors have a completely different torque characteristic to that of ICES. They reach their maximum torque at very low motor speeds. By contrast, ICES usually need at least one-third of their maximum engine speed to reach peak torque. The Tesla Roadster is a good example of the additional driving pleasure that this creates for end customers – a pleasure that will probably be available not only in high-performance cars, but in all vehicle segments.
Electric motors are already a mass-market product with a wide range of applications. They are produced by well-established manufacturers. However, the requirements for electric motors for vehicles differ from those for regular electric motors. In particular, electric motors for vehicles are subject to greater weight and packaging restrictions, have higher efficiency needs (due to the limited energy supply), superior power requirements and need a broader speed range.

For industrial applications, the induction motor (or AC asynchronous motor – see box feature) is by far the most common type of electric motor. This is largely because of its simple design and low production costs. As compact electronic inverters became available in the 1980s, engineers first started using this type of motor in vehicles.
For high-end applications, most car manufacturers use permanent magnet synchronous motors (PMSMs). The main design difference between these and induction motors is that PMSMs feature permanent magnets in the rotor that generate the second magnetic field. This allows the rotor to rotate at the same speed as the revolving magnetic field generated in the stator (hence the "synchronous"). The entire supply current can be used to generate the stator field, providing more torque per power input than induction motors, especially at low motor speeds. PMSMs also have disadvantages, however. These include higher production costs (due to the expensive permanent magnets and more complex manufacturing process), lower efficiency at higher speeds (due to undesired currents in the stator created by the permanent magnets) and a high braking torque in case of short circuit.
Current-excited synchronous motors are a design alternative to PMSMs that avoid using permanent magnets which require rare earths, mainly sourced from China at great cost.

Besides induction motors and PMSMs, the two main types of motor currently used in automotive applications, engineers are currently investigating a number of other types of electric motors. In fact, DC motors are the only type of motor that is generally ruled out from vehicle application, as their low specific power and efficiency make them very unattractive for application in vehicles. Only innovative, brushless DC motors could potentially make a difference here.

Two other types of motor in particular are currently in development. These are switched reluctance motors (SRMs) and transverse flux motors (TFMs). SRMs enjoy very low production costs, even lower than those for induction motors. This is thanks to their very simple rotor structure and lack of permanent magnets. SRMs use magnetic reluctance to generate torque. The stator magnetic field causes a magnetic flux through the specially designed rotor.
To follow the path of least magnetic resistance (i.e. magnetic reluctance), the rotor starts to move and generates torque. However, the reluctance phenomenon also causes micro-motions within the structure of the rotor iron – making them quite noisy – and high fluctuations in torque.

TFMs face similar noise and torque fluctuation problems, but they outperform SRMs in terms of their specific power and efficiency. Unfortunately, they also have a very complex motor design and are currently very expensive to produce.

Manufacturers and suppliers are just beginning to invest in developing special electric motors for vehicle applications. Due to their high power density, compact PMSMs are the best choice for PHEVs in a parallel or power-split hybrid layout with strong powertrain package constraints. However, export restrictions on rare earths recently announced in China have put up a major hurdle for using permanent magnets. Electric motor suppliers outside China therefore need to focus on developing alternative solutions to avoid high costs and losing the market to Chinese players.

The lack of high-speed performance is a challenge for PMSMs in serial layout PHEVs with higher vehicle top-speed requirements, and in EVs with tough cost constraints. In these vehicles, current-excited synchronous motors and induction motors will most likely be the dominant application.

Increasing R&D budgets will lead to further advances in the specific power of all motor types. At the same time, better market penetration rates will bring the cost of a standard 50 kW electric motor (permanent power) well under EUR 1,000. This will make producing such motors highly competitive compared to ICEs.

### 2.2.3.2 Power electronics

The power electronics of an electric powertrain comprise four main components: a traction inverter to control the electric motor and provide the required power from the battery; a battery charger to connect the battery to an external power supply for recharging; a DC/DC converter to provide the required power level for the standard electric system in the vehicle; and a generator inverter in case a range extender is used on-board to recharge the battery. We look at each of these components below.
Traction inverter

The electric motors used in vehicle applications will be mainly AC motors. A traction inverter therefore needs to convert the high-voltage DC coming from the battery into AC for the motor. An electronic motor controller – normally part of the inverter and similar to an ICE engine management system – translates the required power level from the driver (at the gas pedal) into the necessary levels of current amplitude and frequency for each of the three AC phases going to the motor.

The actual control of current sent to the stator windings is performed by three electronic circuits, one for each AC phase, in which semiconductor switches (IGBTs or MOSFETs) and high-power capacitors are key components.

The traction inverter is also responsible for transforming electrical energy recuperated by the electric motor during braking into DC. This is then used to recharge the battery.

Most research at present focuses on developing more compact and cost-efficient designs. In the long run, this is likely to lead to traction inverters made specifically for the automotive industry that weigh well under 10 kg and cost far less than EUR 500 each.
Battery charger

When an EV or PHEV is hooked up to the external grid, a battery charger converts the single or three-phase AC supply to the right voltage level necessary for charging the battery. The AC — now at the right voltage level — is rectified through diodes into DC and smoothed out via capacitors.

Chargers vary significantly in terms of their system specifications, weight and cost. Small chargers can weigh as little as 2.5 kg, while large ones with more than 4.5 kW power can add as much as 11 kg to total vehicle weight. Depending on the maximum power levels required for charging the vehicle, chargers can thus add considerable weight and volume to the powertrain system.

Efforts are currently underway to combine the charging capabilities of the traction inverter with the battery charger in a single component, thus saving both costs and packaging space. Once realized, this achievement would represent a significant step forward, especially as the higher power levels needed for quicker battery charging are likely to make bigger chargers a necessity in the future.

DC/DC converter

The high-power battery in EVs and PHEVs also supplies power to the standard electric system in the vehicle. The DC/DC converter uses semiconductor switches, similar to those in the traction inverter, to convert the battery DC into AC.
It then transforms the high voltage level down to the requested level. In the final stage, the AC is rectified through diodes into DC and smoothed out via capacitors. Ultimately the DC/DC converter will render a "normal" lead acid starter battery unnecessary, as it can supply appropriate power to start the engine and operate the vehicle's internal grid. Depending on the voltages and exact system specification, the weight of the DC/DC converter can vary from approximately 2 to 4 kg.

**Generator inverter**

EVs with an ICE-based range extender need a separate generator inverter to convert the AC produced by the generator into DC for recharging the battery during driving. Even so, the functionality is very similar to the traction inverter in energy recuperation mode. Because generator inverters only work one way, as it were, they offer weight and cost advantages over traction converters.

To summarize, power electronics for automotive applications are still in their infancy. They still show significant room for improvement in terms of their performance, size, weight, integration and production costs. Most past developments in the field of electric motors have focused on other applications and not taken the specific requirements of the automotive industry into account. This will no doubt change as EVs and PHEVs become more common on the market.

To achieve even greater penetration of EVs and PHEVs, important developments are needed in the third major component of electric powertrains, the battery system. It is to this core component that we now turn our attention.

**2.2.3.3 Battery system**

A number of different battery technologies exist at present. The lead acid battery, currently the standard vehicle battery, has been used to supply vehicle electricity for a number of decades.

With the introduction of the first modern EVs in the 1980s, the need for more powerful batteries arose. Nickel-cadmium batteries were originally used, later replaced in hybrid vehicles by nickel-metal hydride batteries. However, none of these battery technologies provide the energy density required for sufficient driving distance in pure electric mode.

The successful launch of Li-Ion batteries for consumer electronic goods such as laptops and mobile phones opened the door to further developments. These batteries are powerful enough to make EVs and PHEVs a viable alternative to today's standard ICE vehicles.
But Li-Ion batteries have not completely solved the problem. The energy density of gasoline is more than 9,000 Wh per liter – more than 40 times that of Li-Ion batteries. The search therefore continues for the next generation of batteries for EVs. In the meantime, we may assume that Li-Ion batteries will be the key technology for PHEVs and EVs in the coming decade.

Other non-chemical energy storage devices include super-capacitors that can reach very high specific power levels for a few seconds, but cannot hold a lot of energy, and flywheels, which store energy in high-speed rotating devices. Neither of these alternatives currently meet the requirements for longer-distance electric driving or use in LDVs.

Below, we examine the technology used in Li-Ion batteries. We also look at the current development focus and the costs involved.

**Li-Ion battery technology**

Today’s Li-Ion batteries are made from a set of subsystems. Some eight to twelve individual Li-Ion cells are put together in a stack with a basic single-cell control system. Several stacks are then connected to make a complete battery pack with a solid housing for crash protection, cooling and a master control device that manages the overall system and the communication with the rest of the vehicle.
A variety of different chemical compositions are currently under investigation, but the basic chemical principle of the cell remains the same. The lithium-based cathode provides the Li-Ions, which travel to the anode during the charging process. A separator foil between the two electrodes prevents unintentional short circuits, while a liquid, gel-like or solid electrolyte between the components makes it possible for the Li-Ions to travel easily from one electrode to the other.
The exact chemical make-up of the cathode and the electrolyte can vary, and precise details are carefully guarded by key players in the field. For the anode, most manufacturers use a copper foil coated with graphite.

Most of today’s Li-Ion batteries produced for consumer electronic goods use CoO$_2$ or MnO$_2$ (cobalt-oxide or manganese-oxide) cathodes. These cathodes have a proven production process technology. For vehicle applications, however, the material has a number of drawbacks. Problems include limited cycle times (the number of charging processes before the battery loses a significant amount of its energy capacity) and thermal instability in case of malfunction. For this reason, manufacturers are putting a great deal of effort into developing an alternative chemical make-up that will meet the requirements of vehicle applications.

**Current focus of R&D**

To reach the usual 150,000 km driving range of vehicles, built-in batteries need to withstand more than 1,000 charging cycles without losing too much capacity. The batteries must also pass crash and malfunction tests. Current development efforts also focus on improving energy density, reducing production costs and speeding up the charging time.

A key lever for improvements is the chemical composition of the electrodes, especially the cathode, electrolyte and separator material. Researchers are looking into using different chemical components in conjunction with lithium.
Another area of investigation is the surface structure of the individual components at a nano level. The hope is that it will be possible to find a way to improve the traveling behavior of the Li-Ions and so optimize cycle and charging times.

Because of the number of cells needed in vehicle batteries, much effort is also going into developing and improving battery management systems. These systems monitor the battery performance on a continuous basis, right down to the cell level.

The first Li-Ion batteries on the market, such as those used in the Mitsubishi iMiEV introduced in Japan in July 2009, already seem to meet the necessary lifetime and safety requirements of car manufacturers. In terms of driving range, we expect to see continuous improvement in energy density over the coming years. This should reach up to 180 Wh/kg on a battery system level by 2020.

**FIGURE 2.2-12:** By 2020 Li-Ion batteries will store almost twice their current energy levels and provide a much longer driving range

<table>
<thead>
<tr>
<th>Capacity of a 200 kg Li-ion battery (kWh) and electric driving range (km)</th>
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<tbody>
<tr>
<td>Ni-MH today</td>
</tr>
<tr>
<td>Specific energy - cell level (Wh/kg)</td>
</tr>
<tr>
<td>Specific energy - battery level (Wh/kg)</td>
</tr>
<tr>
<td>Battery capacity (kWh)</td>
</tr>
</tbody>
</table>

**MAIN ASSUMPTIONS**
- Constant battery weight of 200 kg
- Improvements in battery (e.g., utilization of capacity - battery DoD) and vehicle (air drag coefficient) over time considered

**Costs**
Major battery manufacturers are currently building up production capacity so as to be able to meet the demand expected in the coming two to three years. Production lines have been put in place for several million cells per annum.
Battery costs will mainly be driven by the materials required and their purchasing price. An additional driver is the cost of installed production machinery. In this early phase of technology and market development, Li-Ion cells for automotive applications will probably cost around EUR 500 per kWh.

Two-thirds of the material costs of Li-Ion batteries are currently accounted for by the electrodes and the separator material. Like the battery manufacturers, the major suppliers of raw materials are also currently building up their electrode and separator production capacities.

The situation is exacerbated by ongoing discussions about patent infringement and in some cases even lawsuits. Nevertheless, the range of different chemical compositions possible should mean that there is enough leeway in spite of patent restrictions to create a competitive supplier market.
Further developments with regard to materials will lead to higher yields per kilogram. This, combined with the significant economies of scale in the production process, should provide many opportunities for further cost improvements.

Currently Western suppliers buy most of the production equipment they use for the manufacture of Li-Ion batteries from high-cost countries such as the US and Japan. Due to the high quality requirements, they have few alternatives. However, Chinese competitors have started using equipment developed locally or in-house for less critical production steps. They are also replacing some of the automated steps with manual tasks, due to the low cost of labor in China.

In the coming years, we expect to see the cost of batteries falling substantially from its current level of around EUR 400-500 per kWh for high-energy cells. The target of approximately EUR 200 per kWh (on cell level) may be achievable by 2020.
To summarize, battery technology is by far the most critical factor in determining the success of PHEVs and EVs. Recent technological improvements appear to have done away with most of the obstacles to using Li-Ion batteries in vehicles. However, further improvements are still required in critical areas. To achieve mass-market processes, companies will have to make enormous investments in both R&D and production technology.

There is a good chance that a state-of-the-art EV, with or without a range extender, could feature a compact battery pack weighing not much more than 100 kg by 2020. This would make overall vehicle weight comparable with today’s ICE-powered competitors. It would also provide an electric driving range of about 150 km, with a maintenance-free powertrain and superior driving characteristics. All this could be possible with battery costs of not more than EUR 5,000.

### 2.2.3.4 Range extenders

To achieve similar driving ranges to those of ICE-powered vehicles, EVs require some kind of range extender, at least for the foreseeable future. Range extenders are an additional power source that drives a generator to produce electrical energy to extend the electric driving range. The additional cost for the vehicle as a whole depends on the technical solution chosen and any reduction in battery size that the range extender makes possible.
Initial solutions use proven low-power ICEs, specially adapted to act as range extenders. This is a pragmatic approach for the early market phase, where production volumes are still low. The ICEs are optimized to work across a narrow range of engine speeds. However, they are still over-engineered for their particular purpose and add unnecessary complexity with their traditional design layouts.

New, simpler engine designs with optimized combustion processes and/or fuel alternatives will most likely be the preferred solution in the medium term. These solutions can reduce engine costs, weight, the required packaging space, overall complexity and CO₂ emissions. A number of suppliers have already presented prototypes for such solutions based on internal combustion engines.

Fuel cells have significant potential to establish themselves as the range-extender technology, which even provides zero CO₂ emissions (at least at the tailpipe). Several major automotive OEMs, including Daimler, Ford, GM, Renault-Nissan and Toyota, have recently announced the beginning of joint collaborations for developing, marketing and introducing electric vehicles with fuel cells. Energy and oil companies will support these alliances. Most technological questions with regard to the fuel cells have been resolved. Cost competitiveness and infrastructure availability are the major remaining issues. Whether they can be resolved depends very much on further improvement within large-scale production processes and strong government and private support to provide the required infrastructure density.
2.2.3.5 Conclusions

As we have seen, there is major development potential in the key power-train components of EVs and PHEVs. As in all other high-tech fields, the first generation of products will be big, heavy and costly. But with an industry as powerful as the global automotive sector, things are likely to move fast. In particular, highly competitive components are likely to emerge at attractive prices in the period up to 2020.

![Figure 2.2-17: In the long term, the cost difference between EVs/PHEVs and ICEs is likely to fall below EUR 5,000](image)

Government support programs and global competition for technology leadership will speed up this process. Companies must try to move from successful prototypes in the laboratory to high-quality, mass-production components for the automotive industry. The faster they can do this, the more they stand to benefit.
Of course, the true amount of CO₂ emissions that can be cut by replacing conventional ICE-powered vehicles with EVs and PHEVs depends on how clean the source of the electric power itself is. With today’s average global emissions of less than 600 g of CO₂ per kWh in power generation¹, EVs and PHEVs can provide more than 30% of the CO₂ reduction per vehicle even on a well-to-wheel basis – not taking into account the efforts being put into replacing CO₂-intensive power generation with methods based on renewable power sources.

Replacing 20% of today’s LDV fleet with EVs and PHEVs would mean putting roughly 130 million such vehicles on the road worldwide. This would increase world electricity demand by about 150 TWh or 1%. In other words, the impact would be much less than the expected global increase in electricity generation from renewable sources.¹

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¹ Source: IEA, WEO 2008
3. Scenarios for the development of the EV and PHEV market

3.1 Introduction

Forecasting the development of the market for EVs and PHEVs is a tricky business. As with any disruptive technology that has yet to fully hit the market, predictions are dangerous. What makes them even more difficult in the case of EVs and PHEVs is the fact that governments are fundamentally involved in making the market change happen – and the actions of governments are particularly hard to predict, especially on a global basis.

Despite these reservations, experts generally agree that EVs and PHEVs will represent one of the key options for individual mobility in the future. Where there is less agreement is in the timing of this development.

We saw in Chapter 1 how governments play a key role in the market development for EVs and PHEVs. To fulfill their commitments to fight climate change, they are steering both the supply and demand side. The World Climate Conference in Copenhagen in December 2009 will shed more light on how exactly they intend to do this. Action will be needed if the leading OECD countries are to live up to their "pioneering role." The EU in particular will have to further tighten its CO$_2$ targets for 2020, with the US and Japan following suit. If governments fail to proactively influence the markets for EVs and PHEVs, things will inevitably move much slower.
It is likely that governments will back up their tough targets on the supply side with incentives for customers on the demand side. Incentives are especially important in the initial years of market development: they are a way of getting vehicles off the production lines and onto the roads.

### 3.2 "Pull" – Making EVs and PHEVs attractive for customers

By the beginning of the next decade, car buyers will be able to choose between a wide range of different powertrain technologies: ICEs, hybrids, PHEVs, EVs with range extenders, pure EVs and so on. Before reaching a decision about which option to go for, buyers will no doubt (consciously or subconsciously) compare the different technologies to see how they match up with their own personal requirements. These requirements are essentially their basic mobility needs, price limitations, personal taste and image.

For EVs to be successful they must be able to compete on all of these needs. They need to represent an attractive alternative. Whether they are or not depends on a number of key drivers – which we discuss in detail below.
3.2.1 Meeting customers’ mobility needs

People want to be able to use their vehicles to go where they want, when they want. Although the size and type of vehicle do in fact place some restrictions on this freedom, our perception as car owners is one of almost unlimited personal mobility.

EVs must offer an attractive alternative with regard to this critical factor. They can be successful only if they offer sufficient driving range and are able to take their owners where they want to go.

**Driver 1: Driving range**

PHEVs and EVs with range extenders have a very limited driving range in pure electric mode, approximately 10-60 km. But this does not limit their overall mobility. The reason, of course, is that they can switch to the back-up mode – a gasoline engine. The disadvantage of this technology from the customer's perspective is that the electric driving range, which would be the preferred driving mode, is strictly limited. Interior space may also be restricted due to the package requirements of having two powertrains.

One alternative is a pure EV with its driving range determined by the energy capacity of the battery system. As we saw in Chapter 2, it is unlikely that such vehicles could offer driving ranges comparable to ICE-powered vehicles within the next ten years.
But they do offer sufficient range for city driving, making them a good option for second cars in households with two vehicles. The limited driving range of pure EVs creates what is known as “range anxiety.” This affects drivers as soon as the battery charge falls below 50%. A solution to this problem is needed if pure EVs are to become a mass-market success.

**Driver 2: Charging infrastructure**

The charging infrastructure for vehicle batteries needs to be convenient. The option of charging batteries at home—which we will call Model 1—will not be available for many end customers in major urban areas, even in the US. It would in any case limit the range and possible application of pure EVs. Thus in Model 1, PHEVs and EVs with range extenders would operate in pure electric zero-emission mode only to a limited degree.

What is needed is a public charging infrastructure. This facility would make EVs and PHEVs attractive to a wider range of customers. It would also provide the basis for a market breakthrough.

Experts currently consider two main alternatives for a public charging infrastructure to be feasible from a commercial and technical point of view in the coming five to ten years. We will call these alternatives Model 2 and Model 3.
Model 2: "Like gas stations," i.e. superfast charging infrastructure

Model 2 would at first sight appear to be the natural choice from a customer perspective, as it does not involve any change in mobility behavior. However, this model has major drawbacks on the vehicle/battery and grid side.

To recharge a battery with a 25 kWh capacity in around six minutes – roughly the time taken to fill a vehicle up with gasoline – the chargers would need to provide roughly 250 kW of power. At present this would require a cable thicker than the hose at a gas station. There are also significant safety implications.

Even if it were possible to design a safe and convenient charging station with the required level of power, the battery and the vehicle would have to be able to handle this degree of energy flow in such a short period of time. Battery manufacturers believe that they could devise a battery that could cope with superfast charging; indeed, they have already presented prototypes at the laboratory level. But the key focus of most efforts today, as we saw in Chapter 2, is getting mass production of batteries up and running, reducing costs, maintaining high quality, meeting safety requirements and guaranteeing a lifetime of more than ten years. In other words, there currently are many higher priorities than introducing batteries with superfast charging capabilities.

Vehicles would also have to be able to cope with the extreme influx of heat over a short period of time. The cooling and protection system needed would represent a large and expensive addition to the already expensive vehicle. Current estimates are for more than EUR 2,000 in extra costs.

**FIGURE 3.2-4: Fast-charging of batteries would lead to additional imbalances in the power level in the grid**

- **Pros**: No change of customer mindset needed (refueling as usual)
- **Cons**: Fast recharging leads to further imbalances in the power grid; Increased well-to-wheel CO₂ emissions due to the use of coal- and gas-fired power plants to produce the necessary energy

Source: National Grid; Roland Berger
On the grid side, the general assumption is that charging will mainly take place at night. This would not put additional stress on the system. Indeed, EVs and PHEVs could be the missing piece in the puzzle – the factor that makes a further increase in renewable energy possible. In any case, a comprehensive superfast charging infrastructure would most likely lead to a further increase in grid load at peak times, i.e. mornings and evenings.

Looking at all the arguments, we do not believe that a comprehensive public superfast charging infrastructure will emerge in the next five to ten years. (The charging system developed by TEPCO in Tokyo and currently being tested with the Mitsubishi iMiEV and Subaru is not a superfast charging system in the sense described above; power levels are limited to about 100 kW and recharging times are more than 20 minutes.) After 2015, however, when the second generation of EVs and PHEVs is on the market, some OEMs and infrastructure operators may be willing to give this option a go. This is particularly likely if stakeholders and end customers have built up a certain level of confidence with regard to EVs and the growing customer need for longer driving distances provides the necessary business case.

An alternative to superfast charging could be exchanging the battery at a special station. This approach would be very similar to gasoline stations today in terms of time, with customers swapping the empty battery for a recharged one instead of charging it themselves. As for superfast charging, this option is not technically viable today, with the batteries having different shapes, characteristics, etc. Extensive standardization efforts would be required on the vehicle battery side in order to make the breakthrough happen. We do not expect battery changing stations to become widespread before 2020; extensive investments have already been made in developing and producing different battery technologies, and OEMs are going to insist on retaining their existing EV designs. What’s more, OEMs would lose design liberties regarding battery packaging and management.

**Model 3: "Charging everywhere," i.e. an infinite number of public charging points**

In Model 3, EVs and PHEVs can be charged wherever they are parked – at home, at work or in public parking facilities. This is a technically viable solution even today. Most grids can handle the creation of a large number of charging points at the roadside or in parking lots without major investment being necessary, even if these points need to provide higher power levels of between 10 and 20 kW.
The first generation of EVs and PHEVs will have on-board chargers that can handle up to 10 kW in most cases, with the potential of upgrading to higher power levels in the near future. This would allow end customers to recharge vehicles from a 50% charge level to full during a single stop of one to two hours, e.g. while customers go shopping. In this way, customers could recharge whenever they felt like it, solving the problem of range anxiety.

The key challenge lies in setting up a commercially viable, convenient system for end customers. The difficulty is how to change drivers’ mobility behavior: instead of going to a gas station just before the tank is empty, drivers need to charge their cars every other time they park. In response, some innovative market players are proposing smart features such as automatic authentication, monthly billing (similar to cell phone contracts), upgrades to satellite navigation systems so that they show where the next free charging point is, and so on. These are features that are designed to make the change of mindset easier for end customers.

Commercial viability is largely driven by the level of investment required; in other words, the number of charging points needed to give end customers the feeling that they can charge their vehicles wherever they park, and the level of investment per charging point. A growing number of players around the world are developing innovative solutions, and pilots are being launched.

**FIGURE 3.2-5: Pilot projects around the world are currently testing the acceptance of different infrastructure and business models**

**Overview of main charging infrastructure pilots**

- **North America**
  - Several Californian utilities (e.g. SCE, PG&E) have commercial test fleets.
  - BMW running pilots in Los Angeles and New York, 500 electric Minis and powerful home chargers.
  - Coulomb/Better Place testing public charging infrastructure in San Francisco Bay area.

- **Europe**
  - Leading European utilities running more than 10 pilots in large urban areas (e.g. London, Paris, Berlin, Oslo) to test public charging infrastructure and business models.
  - JDP working with the Danish government to install a nationwide system.

- **Asia**
  - Chinese pilot program in 13 cities (incl. Beijing and Shanghai) to introduce approx. 10,000 new-energy vehicles into public fleets.
  - SCC to accelerate development of charging infrastructure in Beijing, Shanghai and Tianjin.

- **Japan**
  - Japgo to introduce approx. 200 fast-charging stations in Tokyo area in 2009 together with a company test fleet of pure EVs.
While the initial public charging infrastructure will rely on the proven conductive, cable-bound charging technology, the future may be inductive charging. The latter offers higher charging convenience for the customers, is better protected against vandalism, requires less maintenance and is “invisible” – i.e. underground, not disturbing the cityscape. Whether this will happen depends on the upcoming improvements in the efficiency level of inductive charging systems, costs and safety issues. But even if inductive charging were to become reality, we still expect traditional charging to remain in use as this would provide low-cost charging opportunities on private property.

**Rollout of infrastructure**

To minimize investment without constraining market development, the infrastructure rollout will most likely start in areas where the biggest customer densities are expected. As discussed above, the limited driving range of pure EVs make them particularly suitable as second cars for short everyday trips. Early adopters are likely to be technologically minded, concerned about ecological issues and above-average earners. This segment of the population tends to be concentrated in large urban areas. Public infrastructure is thus likely to be built first of all in these areas, with a wider rollout occurring from 2015 onward.

As is generally the case in new markets, first movers are most likely to acquire a large market share. They will then maintain this leading position over a longer period of time.
3.2.2 Attractive pricing

Despite growing environmental awareness in society, studies have repeatedly shown that customers are only willing to pay a limited price for being green. That price is generally put at around EUR 2,000 in developed markets. This means that EVs and PHEVs must be attractively priced, not only in terms of the initial purchase price, but also the ongoing costs each month (i.e. TCO, the total cost of ownership).

We expect vehicle costs for EVs (excluding the battery) to be very similar in the long run to comparable ICEs. The Mitsubishi iMiEV, currently in its first sales year, sells for around JPY 4 million, for instance, but significant price reductions are expected when it achieves bigger sales volumes after 2012.

The key drivers for attractive EV pricing are therefore battery prices, fuel prices and government subsidies or tax benefits. Assuming additional costs of EUR 7,500 (approximately USD 10,000) for EVs after their initial market launch phase, European fuel prices of EUR 1.40 per liter and electricity prices of EUR 0.20 per kWh, the monthly total costs including vehicle lease for an EV would already be comparable to those of ICE-powered vehicles (on the basis of 1,000 km per month). This calculation takes into account a one-time leasing down payment that is approximately EUR 2,000 higher than that of a comparable ICE-powered vehicle, and no subsidies or tax benefits.

In fact, one-time purchase tax benefits of more than EUR 2,000 are either already in place or under discussion in many markets worldwide. Annual tax benefits for EVs, thanks to their zero emissions, are also likely. This could make EVs a very attractive choice in terms of price even in the early phase of their market development. This remains the case even if we assume additional monthly costs for access to the newly-built public infrastructure.

When it comes to PHEVs, the picture is more complex. The monthly fuel price comparison depends on the split between electric and gasoline-based driving. This in turn depends on the electric driving range (i.e. the battery size), the availability of the recharging infrastructure and the customer’s specific pattern of mobility.
Driver 3a: Fuel and electricity prices

The price of fuel is driven by two things: the price of oil and the amount of tax levied on fuel. Crude oil is sold on a global basis, so only minor variations occur between regions. Our assumption here is that the price of crude will increase over time due to growing demand and limited supply.

Tax levels, on the other hand, are set by individual governments. Western European countries tend to have the highest fuel taxes. Germany, for instance, imposes a tax of EUR 0.66 per liter excluding VAT. Other countries such as the US have significantly lower fuel taxes. In January 2009, China introduced a fuel tax of CNY 1 per liter. These differences in tax levels obviously have a significant impact on the overall price of fuel.

Electricity prices also vary significantly. This variation is due not only to country-specific taxes but also to the different sources of production: nuclear, wind, etc. As a result, the monthly cost benefits of switching from gasoline to electricity depend very much on the energy price structure in the region or country in question.
Driver 3b: Battery prices

Battery prices function on a global basis. With growing competition and expanding production volumes, we expect the costs for Li-Ion battery cells to fall to around EUR 400 per kWh by 2011-2012. In the longer term they should fall even further, to EUR 200 per kWh or less.

Yet even assuming battery cell prices of EUR 200 per kWh, the additional costs of an electric vehicle with a 20 kWh battery are at least EUR 5,000-6,000. Significant monthly savings or purchase subsidies would be required to compensate for this additional cost burden. As before, tax incentives would play a major role in the early phase of market development.

Driver 4: Government subsidies/tax incentives

Governments and local authorities have a variety of tools at their disposal to support the market development of environmentally friendly technologies. Here we examine government subsidies and tax incentives in particular.

One-time subsidies are a valuable instrument. They have a powerful impact as the money generally goes directly to consumers. For instance, the French government is subsidizing the purchase of any vehicle that produces 60 g/km or less in CO₂ emissions to the tune of EUR 5,000 until 2012.
One-time subsidies can help ramp up the market. However, we do not include such measures in our long-term forecasts for the selected regions as they will generally be phased out as soon as the market achieves critical mass.

Annual taxation systems favoring EVs and PHEVs have a longer lifecycle. More than 14 countries in Europe have already introduced systems based on CO₂ emissions. We foresee a tendency to increase the rates used in the coming years, and include this measure in our long-term forecasts.

### 3.2.3 Meeting customers' vehicle type and image requirements

It is not enough for EVs to meet customers' mobility and pricing requirements. They must also satisfy their image requirements with regard to body type and size, manufacturer and brand.

**Driver 5: Availability of different vehicle sizes and types**

In the initial years, pure EVs will probably be used mainly for city driving and urban commuting. We can assume that they will be mainly A- and B-segment vehicles, such as the Mitsubishi iMiEV and the planned Pininfarina EV. In this respect the recently announced Nissan Leaf – a C-segment vehicle – is something of an exception.

PHEVs will most likely be available in a wider range of segments, including C-segment and above, and all body types. This is because their use is not restricted. Toyota’s hybrid family will soon include all the larger vehicle segments. We expect the same pattern with their PHEVs from 2010.

**Driver 6: Availability of different brands**

The introduction of high-quality, reliable EVs and PHEVs requires a major development effort on the part of OEMs. Not all manufacturers will be willing or able to invest on this scale in the initial years. Only the most powerful OEMs and those who foresee the biggest strategic gains for their company are likely to offer series production for EVs and/or PHEVs at first.

The more successful EVs and PHEVs become, the greater the pressure on other OEMs to follow suit. Prior to 2012, we expect to see only a limited number of manufacturers with attractive vehicles on the market. By 2015, however, given that battery costs are likely to come down to levels significantly lower than today, we expect most players to have at least one EV or PHEV in their portfolio.
For all intents and purposes, the current economic crisis does not appear to have had a significant impact on the development plans for EVs and PHEVs already announced by manufacturers. Indeed, a number of OEMs have been adamant that their strategic plans with regard to this new technology will not be influenced. The coming months will show whether these statements hold true or not.

### 3.3 "Push" – Encouraging OEMs to produce EVs and PHEVs

Our assumption is that the governments of major OECD countries will live up to their "pioneering role" in reducing CO₂ emissions in all sectors, including road transportation. As we saw in Chapter 1, the IEA’s Scenario 450 reveals that LDVs in OECD countries would have to almost halve their new car fleet emissions by 2020 compared to today’s levels to achieve the proposed vehicle stock emission reductions. In Chapter 2 we saw that the potential improvements to ICEs, although important in themselves, are limited in their overall effect. EVs and PHEVs would therefore need to form a large share of the new car sales fleet by 2020.
We foresee that the governments of OECD countries will introduce major customer incentive programs for EVs and PHEVs in the future. This step will help overcome the price disadvantages of the vehicles in the initial years after market introduction. This is the "pull" effect, stimulating demand.

At the same time, however, we expect European governments in particular to raise the pressure on OEMs to produce EVs and PHEVs. They will do this by further tightening up fleet emission targets in the period to 2020 and offering support programs for R&D and manufacturing. We call this the "push" effect.

The governments of countries with a significant vehicle manufacturing industry will no doubt also use this carrot and stick approach to establish their own OEMs as leading players in the field. With enormous upside potential, especially in the US and China, we expect the global race for leadership of the market to speed up in the coming years. At present, the Japanese are ahead, but key European players see themselves as naturally filling this role.

Leading OEMs such as Toyota, Daimler and GM have already committed their organizations to "re-inventing the automobile." Be that as it may, the financial situation in which the auto industry finds itself today will no doubt trigger intense discussion between OEMs and governments about the necessary government actions and their precise timeline.

3.4 Market forecast for PHEVs and EVs

We expect the market penetration of EVs to develop strongly over the next ten years. The exact speed and strength of this development will depend on the key drivers described above, and how they change over time.

The greatest uncertainties with regard to the future relate to the building of infrastructure and the TCO benefits of EVs. When end customers no longer have to pay a premium and the vehicles meet their mobility needs, the mass introduction of EVs and/or PHEVs is highly likely. Government support in the form of one-time subsidies and annual tax benefits will be a major lever for TCO. However, it is difficult at this stage to say how strong the political will is to implement such measures on a global basis.
Given these uncertainties, we have developed two different scenarios. Our first scenario assumes a slower penetration of EVs and PHEVs in the next 5 to 10 years, and rather a stronger demand for smaller, efficient ICE-powered vehicles. We call this scenario "Downsized mobility."

Our second scenario is rather more optimistic about the development of e-mobility. It foresees higher oil prices, accelerated battery cost reduction, stronger government support and a broader product range in the next five to ten years, making EVs a very attractive alternative by 2020. We call this scenario "The future drives electric."

*Downsized mobility* reflects the opinion of those experts who foresee a longer transition period before prices for key components such as batteries come down, subsidies/tax benefits are implemented by authorities and the necessary investments in infrastructure are executed. However, even the more pessimistic experts think that EVs will come in over the longer term. As mentioned earlier, the debate is not about whether it will happen, but when.
"The future drives electric" sees the market for EVs developing much faster, mainly due to governments' carrot and stick approach. In this scenario, EVs and PHEVs achieve a market share of around 20% in Western Europe by 2020, making this region the frontrunner in the field of electric mobility.

**FIGURE 3.4-2: In 2020, Western Europe may be the lead market with annual sales of more than 3 million EVs and PHEVs – followed by China**

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<thead>
<tr>
<th></th>
<th>EU (ICES incl. micro and mild hybrids)</th>
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<tr>
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<tr>
<td></td>
<td>EVs and PHEVs</td>
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**COMMENTS**
- In 2015 both scenarios still show very limited market shares for EVs and PHEVs, reflecting the "frenetic" long lead time for automotive markets to develop.
- In the scenario "The future drives electric" we may see about 8-10 million EVs and PHEVs in global sales by 2020.

1) "Downsized mobility"  
2) "The future drives electric"  
3) Including ultra light duty vehicles

Source: Roland Berger
4. Impact on the mobility value chain and potential new business models

4.1 Introduction

The market success of pure EVs and PHEVs will have a major impact on almost all parts of today’s mobility value chain. The new vehicles will require a number of technically innovative components and systems. This will impact key parts of the component and vehicle creation value chain. In addition, the radically different organization of the fuel and charging side will have a major effect on the downstream side of the mobility value chain, possibly even opening the door for new business models. These changes will mean numerous opportunities for new players to take over certain parts of the value chain – and for incumbents to build on their current position.

Below, we examine the individual sections of the mobility value chain in greater detail. In so doing, we attempt to identify the main areas where change will likely occur, and the risks and opportunities that these changes will bring with them.
4.2 Raw materials

The energy storage systems and electric motors of EVs and PHEVs require specific raw materials. These materials are needed in large volumes for all kinds of electrified powertrains, from mild hybrids to pure EVs.

4.2.1 Materials for Li-Ion batteries

Most battery suppliers currently focus on Li-Ion battery technology. This technology is likely to determine the production ramp-up for the next five to ten years. Although a number of alternative chemical compositions exist for the anode, cathode and electrolyte, all suppliers will need a certain amount of lithium or lithium carbonate as raw material.

Lithium is currently used in a variety of industries, including glass/ceramics, pharmaceuticals, lubricants, synthetic rubber, air-conditioning systems, alloys and batteries. Global reserves are approximately 11 million tons (lithium carbonate equivalent), with around 75% found in Chile and Bolivia, 10% in China and 15% elsewhere. Some 25% of current annual production is used for batteries, mainly for consumer products.2)

Energy cells for EVs and power cells for hybrids will be the main source of future increases in lithium demand. Despite these increases, experts are not expecting a shortage on the supply side of lithium due to the high level of reserves. However, there is a risk of temporary price increases such as have been observed in recent years.

Li-Ion battery cathodes consist mainly of lithium-based composites such as lithium metal phosphates. These are likely to be the key focus of research in the coming years due to their advantages in terms of material costs and safety. The composites need to be produced with a high level of purity and homogeneity, which requires excellent production technology and process expertise. For this reason, although the field is open to new players, it is likely to be dominated by established players from the chemical industry such as Süd-Chemie (Phostec Lithium) in Germany and 3M in the United States.

For battery cell manufacturers, it will be crucial either to control the making of cathode material composites in-house or to establish stable relationships with key players in the field. Patent issues will further increase the complexity of this critical part of the component-making value chain.

2) Source: US Geological Survey
4.2.2 Raw materials for electric motors and other EV components

The rare earth elements needed for permanent magnet electric motors are strongly concentrated in China. According to the Mineral Commodity Summaries published by the US Geological Survey, China controls 93% of rare earth production and its reserves account for 31% of the total worldwide. As demand for this raw material increases, China recently imposed export restrictions on rare earths, resulting in higher prices and stronger dominance of Chinese players.

To avoid higher raw material costs, electric motor producers are likely to promote the development of permanent magnet motors using alternative substances or less rare earth material. They will most likely also focus on developing electric motors featuring induced electro magnetic fields (see Chapter 2). This will open up the field for new players such as Brusa AG in Switzerland.

4.3 Parts and components

With the electrification of the vehicle powertrain, components such as batteries, electric motors, AC/DC and DC/DC converters, power electronics and other auxiliary systems will enjoy much higher growth rates than other areas in the automotive industry. Electrification will also mean that other components such as air-conditioning units, water pumps, brakes and steering systems will have to be adapted to make the overall vehicle system as efficient as possible.

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**FIGURE 4.3-1: The market for electric and electronic powertrain components will soon be worth EUR 20-50 billion a year**

<table>
<thead>
<tr>
<th></th>
<th>High scenario</th>
<th>Low scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-motor (incl. generators)</td>
<td>12.9</td>
<td>25.1</td>
</tr>
<tr>
<td>Power electronics</td>
<td>3.2</td>
<td>5.6</td>
</tr>
<tr>
<td>Battery</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Other components</td>
<td>0.6</td>
<td>1.1</td>
</tr>
</tbody>
</table>

1) Western Europe, US, Japan, China

Source: Roland Berger
This presents opportunities for both established and new players to access new revenue streams and achieve larger profit margins. To this end, OEMs and suppliers need to review their core activities and product portfolios.

### 4.3.1 OEMs’ degree of vertical integration

OEMs traditionally regard the powertrain as a critical part of their in-house development and production base. Indeed, the powertrain is how they differentiate their vehicles from those of their competitors.

With the arrival of new electric technology, OEMs need to redefine their core competences. This is particularly important as electrical components have not traditionally been a focus area for OEMs. Developing and producing new components will be vital for automakers if they want to stay ahead of their competitors in terms of technology.

To some extent this is happening already. Forerunners such as Toyota have built new R&D centers focused purely on electric and hybrid powertrains. Other players such as Daimler are following their example.

In powertrain production, OEMs’ current focus is on core mechanical components, such as the crankcase and cylinder head, as well as final assembly. Here, a complete rethink of the in-house production setup is needed.

In the next five to ten years, OEMs must build up and develop their in-house competence in electric powertrains. Initially, they should concentrate mainly on product and process design. Component manufacturing, integration and assembly can be considered at a later stage, but only if the scale effects justify the efforts.

### 4.3.2 Shake-up of the established supplier base

Established suppliers of current powertrain components must also take a careful look at their product portfolio, technology basis and competitive edge. Failure to do so could result in a loss of future business as the powertrain environment changes and develops.

Toyota and Honda introduced hybrid vehicles in the late 1990s. This has enabled their key component suppliers in Japan to build up a considerable knowledge base. These suppliers are now utilizing this base to further develop their products for use in PHEVs and EVs on a global basis.
At the same time, key European suppliers such as Bosch and Continental are increasing research in this area in an attempt to counterbalance Asian dominance.

Existing players (excepting those in Asia) essentially have to start from scratch when it comes to developing the new electrified components and systems. This makes it much easier for new players to gain a foothold in the market than was previously the case in the highly mature automotive component market.

Indeed, a number of new players such as A123, Litec and Tesla are already offering innovative technologies in specific components, trying to gain a share of the attractive revenues in this section of the value chain. The task facing them is a challenging one for two reasons: strong reactions are expected from incumbents, and heavy up-front investments are required in this field.

Battery cells have a number of different potential chemical compositions. Moreover, safety requirements often conflict with performance requirements. The R&D expenses and production investments involved are also enormous. Only the strongest players will be able to achieve the required economies of scale. This is likely to result in a first supplier concentration process, similar to that found in the semiconductor industry.

Other key components such as electric motors and power electronics also require large up-front investments and rely on companies tapping into economies of scale. Consequently innovative new players are more likely to enter on the software side and in specialized market niches.

4.3.3 Strategic partnerships

OEMs must try to identify strategic partners with the expertise and solid financial backing required to secure access to technological know-how. The joint ventures mentioned below, such as LiTech between Daimler and Evonik in Germany, are good examples of such attempts.
Established suppliers such as Bosch and Continental are also trying to support their in-house development activities with joint ventures with leading independent players. This is particularly the case in the area of batteries, with the newly formed SB LiMotive (a 50-50 joint venture between Bosch and Samsung) being one good example.

Changing technologies for other components, such as air conditioning and cooling, will create additional opportunities for suppliers, while compensating for losses in the traditional components business.

4.4 Vehicles

Another key part of the mobility value chain is the development, manufacture and sale of complete vehicles. Current OEMs are in a natural pole position here with regard to EVs due to the need for comprehensive expertise, established brand names, strong customer relationships and major up-front investment.

Things will not necessarily stay that way, however. New technological requirements, competent suppliers, excellent engineering service providers and hesitation on the part of OEMs are creating opportunities for new players to challenge the status quo in this key section of the value chain.
4.4.1 Financial burden and increased complexity for incumbent OEMs

The current economic crisis is hitting the automotive industry hard. Most OEMs are struggling to keep cashflows positive. This difficult situation is forcing them to look at any opportunity available to make savings on the cost or investment side.

At the same time, OEMs know that they must prepare themselves for the new powertrain era. They need to pursue a number of paths in parallel, improving current ICE technology and investigating different options for the electrification of the powertrain. This involves major investments and substantial risks.

And there's more. OEMs face challenges not only in R&D and manufacturing, but also in sales and distribution. They need to provide their customers with orientation to use established brands, guiding them through the propulsion technologies of the future. Dealer and service networks must also be made ready for the broader product portfolio arriving in the coming years.

Few OEMs have already laid out a clear path for the future. Toyota and the Renault-Nissan Group are two exceptions. Toyota is building on its success with hybrids and developing electrification from this basis step by step – not only in R&D and manufacturing, but also in its brand positioning and other parts of the company. The Renault-Nissan Group is focusing mainly on EVs as the vehicle choice of the future. This leaves a number of areas where new players can enter the mobility value chain by focusing on one of the emerging niches and pushing ahead fast with developments.

4.4.2 Competition from Chinese OEMs

A number of Chinese players see EVs and PHEVs as a way of closing the gap to leading established global automotive players. The Chinese government is strongly supporting their efforts.

Chinese OEMs can challenge established OEMs particularly on the cost side. They enjoy lower raw material costs for Li-Ion batteries and key components for electric motors, such as rare earths for permanent magnets.

They can also keep manufacturing costs down by using domestically produced production equipment and leveraging their lower labor costs. Chinese universities are also placing a strong focus on these topics and postgraduates are increasingly being employed by leading players in the sector.
Chinese companies such as BYD are making the most of their competitive advantages. They are already producing their first high-quality Li-Ion battery cells for automotive use. Chinese PHEV prototypes and pre-production vehicles are not yet of the quality required for global automotive markets, but this is likely to change within the next few years. 3)

**4.4.3 Opportunities for new players**

We foresee two types of new competitors emerging in vehicle manufacturing. On the one hand, there will be companies that are completely new to the business. On the other, there will be companies that are already active in other parts of the value chain and that wish to exploit the opportunity to become OEMs.

Tesla is an example of the first type of new competitor. In the past, OEMs were large, publicly listed companies with an extensive history and tradition behind them. Tesla, by contrast, is a start-up company funded by its founders and venture capital and with a clear vision of the future. Whether this vision will be enough to ensure its survival in the long run remains to be seen.

An example of the second type of new competitor – companies already active in other parts of the value chain – is Pininfarina. Pininfarina is an established contract manufacturer. In 2008 the company unveiled its new City EV. This vehicle builds on the company’s wide experience in automotive design and production, leveraging their brand name, which is well known in the industry. With solid financing behind them, these two players may represent a major challenge to established OEMs.

**4.4.4 Opportunities in EV sales and marketing**

We expect to see a number of new players supplying EVs and PHEVs to the market competing against each other. These companies will need to develop alternative methods of sales (including aftersales) and marketing. This may provide an opportunity to rethink this section of the value chain, currently completely under the control of the established OEMs. New players such as Nicecar in the UK have already entered the market and are currently trying to expand across Europe. 4)

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3) See our recent publication “Powertrain 2020: China’s Ambition to Become Market Leader in E-vehicles.”

4) See our recent publication “Winning the Automotive Powertrain Race: The Frontline Role of Marketing and Sales.”
4.5 Infrastructure and energy provision

Today’s fuel production and the refueling infrastructure (i.e. gas stations) is dominated by a small number of global oil companies, such as Exxon, Shell and BP. With pure EVs and PHEVs used mainly in the electric driving mode, the fuel base will change to electrical energy. Here, production is in the hands of a large number of mostly smaller regional players. They include state-owned companies such as EDF in France, the China National Offshore Oil Corporation (CNOOC) and the State Grid Corporation of China (SGCC), plus independent players such as Southern California Edison in the United States and E.ON in Germany.

The distribution of electrical energy is in the hands of a large number of regional grid operators. Many of these companies are subsidiaries of leading utilities, or are state-owned. However, this does not mean that the last mile to the vehicle customer – i.e. the electrical charging system – will also be controlled by the grid operators. Here, again, the race remains wide open.

If the “charging everywhere” model (see Chapter 3) is realized, with charging stations at home, at work and in parking lots, this business will require a good knowledge of future customers, their mobility needs and driving patterns. Understanding the owners of parking lots and their needs is also essential.
With their expertise in charging technology and grid management, utilities companies are currently well-positioned in this section of the value chain. However, there is much room for new players to move in if they can act quickly, secure strong financial backing and come up with innovative business models that allow local stakeholders to participate in future revenue streams.

The next few years will be crucial for companies hoping to acquire a leading position in this area. To build a solid basis for future business, companies must make significant up-front investments and be prepared to put up with a slow customer growth rate in the initial years. Only the most determined and creative firms will emerge as winners in this tough game.

### 4.6 Mobility service providers

The changes in the industry will create a number of opportunities for innovative companies. This includes companies whose products cover several steps of the new mobility value chain, i.e. mobility service providers.

Customer insecurity about the new technology and ongoing improvements in batteries mean that leasing models for vehicles will be popular. Combined with new ways of "refueling" on an almost daily basis in a number of different locations, this will allow companies to provide end-customer mobility on a monthly payment basis.

The providers of this kind of service can come from a number of different backgrounds. They may be completely new to the business but have a strong understanding of the key business dynamics – companies such as Better Place, for example. Alternatively, they may already be active in one section of the existing mobility value chain, as is the case with OEMs and utility companies.
4.7 Summary

The coming changes in powertrain technology will thoroughly shake up the automotive industry. They will create many opportunities, but also pose serious risks for both established and new players.

The success of individual players will very much depend on how well they understand the market dynamics of their specific section of the value chain. They must formulate a focused business strategy, either defending or expanding on their current position.

In Chapter 5, we provide guidelines for key players on how to evaluate their own position. We also demonstrate how to define existing options and develop a winning business strategy.
5. How to prepare for the change to come

5.1 Introduction

Amid the uncertainties in electric mobility, one thing is sure: the race to find the best, or at least the most promising, business strategy is already underway. For some time now, companies have been trying to position themselves out in front, preparing themselves for a battle that won’t really get going until 2011/12. By doing so, they are laying the groundwork for their future success (or failure) in electric mobility.

Some players have been preparing for years, while others are still debating the possible relevance of electrification for them. Still others are teaming up with partners to face the future challenges. Time is short, at least for companies that hope to lead the way in pure electric vehicles and plug-in hybrids. The success of hybrid vehicles on the market has shown how difficult it is for latecomers to gain an edge in this new field of vehicle technology.

Learning from the past: the Toyota Prius case

In January 1997, Toyota announced the launch of the Toyota Eco Project. The initiative was a response to the long-term environmental challenges facing the globe and the rise in public awareness of environmental issues. The company launched the world’s first mass-produced hybrid car, the Prius, in December 1997 in Japan, to coincide with the Kyoto conference on climate change. Three years later it launched the Prius on other markets, including the United States.

At the time of its release, most OEMs were skeptical about hybrid vehicles. They cast doubt on both their technology and their chances of finding a market. Indeed, hybrid cars have never had it easy. Many experts questioned the wisdom of increasing the cost and weight of vehicles by adding a second, electric powertrain. After all, improving conventional technology would also lead to greater fuel efficiency – at a lower cost.

Yet despite the initial weak sales, Toyota stuck to its guns. In line with its long-term strategy, the company continued improving the technology base, launching the second-generation Prius in 2003. And it paid off: In 2008, more than ten years after its initial market introduction, annual sales were in excess of 280,000 units worldwide. In May 2008, Toyota announced that it had sold its one millionth hybrid car. And Toyota dominates the market for hybrid vehicles, with a market share of more than 70%.
What does the story of the Prius teach us? Toyota had to first invest in the technology and the vehicle. Sales volumes were low, especially relative to the company’s total global sales. What, then, did Toyota gain from its experience with this unexpected winner?

Three things in particular. First, with a market share of more than 70% in the segment, the company is today reaching scale effects in the hybrid technology, allowing Toyota to market it profitably.

Second, Toyota became a "green brand". According to a 2009 Roland Berger customer survey conducted by TNS in Germany, the UK and France, more than 50% of people think that Toyota is the company that makes the most efforts to develop clean drive technology. It is safe to assume that the same would hold true if the survey were conducted on a global scale.

This has influenced the way the company is generally seen in terms of its technological competence. Its leadership in environmentally friendly technologies has also had a knock-on effect on its other products, which are imbued with a particular "moral" value, even where they have no technological edge or green features.
Toyota’s third achievement was the significant technological edge it gained over its competitors. It successfully aligned its entire organization toward powertrain electrification, from its research and development unit to its dealerships and repair shops. The whole company participated in the learning process, developing, producing and marketing hybrid technology. As a result, Toyota is now able to market next-generation (plug-in) hybrid – or even pure electric – vehicles, featuring improved technology. The company is leveraging its early successes to achieve a privileged position in the next phase of technological development, and now has by far the most experienced team in this technology. This includes an experienced and aligned supplier network – a crucial element for successful business development.

The next wave of powertrain electrification – the large-scale introduction of PHEVs and EVs – brings with it new challenges. There are some striking similarities with the situation over a decade ago when the Prius was first launched, though the challenges are probably even bigger:

- A huge technological step that may require a complete new vehicle layout
- Even more dependence on competent and capable suppliers
- The necessary new business model requires new partnerships
- Without government support, the market launch will be even tougher
- Advanced battery technology is a crucial enabler
But, in addition to all that, the necessary infrastructure setup with all of its related system complexities adds a new dimension. This represents the biggest single difference to the introduction of the hybrid, which was not burdened with infrastructure issues.

Therefore, entering an emerging, technology-driven market early on, as in 1997, again requires a bold strategic decision. Introducing a new technology while it is still relatively immature (at least in terms of established requirements on the vehicle side) is definitely a risk. The challenge is to deal with the uncertainties, while bearing in mind that the outcome will very likely have a huge impact on the overall industry.

In the following sections, we take a look at the necessary steps toward developing such a successful business strategy for incumbent OEMs, suppliers and new players in this field. We also attempt to shed some light on the different approaches and their validity for the individual players in the market.

5.2 Key steps toward developing a successful electric mobility business strategy

Electric mobility raises a number of very critical questions for any market participant, and the answers to these questions – i.e. the individual business strategy – will differ from company to company. However, the basic approach to developing such a strategy is common to most players and is described below.

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**FIGURE 5.2-1: Key steps to developing a successful, tailored electric mobility business strategy**

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Evaluate strategic importance of the topic for yourself</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; What is the significance of electric mobility for my organization?</td>
<td></td>
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<tr>
<td>&gt; How aggressive do I need to be to enter this field?</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Step 2</th>
<th>Assess and (re-)allocate resources</th>
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</thead>
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<tr>
<td>&gt; How much can I afford to put into this new market?</td>
<td></td>
</tr>
<tr>
<td>&gt; What are my capabilities?</td>
<td></td>
</tr>
<tr>
<td>&gt; What knowledge do I have/need?</td>
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<table>
<thead>
<tr>
<th>Step 3</th>
<th>Define your position in the new electric mobility value chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; Where should the future focus of my business be?</td>
<td></td>
</tr>
<tr>
<td>&gt; Are there opportunities to create additional value?</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 4</th>
<th>Adapt your current business</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; Where do I have to build up new resources or adapt existing resources?</td>
<td></td>
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<tr>
<td>&gt; What can I cut back without damaging the top line?</td>
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</table>

Source: Roland Berger
Step 1: Evaluate the strategic importance of the topic for yourself – How aggressive do I need to be to enter this field?

The necessity of entering this new market and technology field depends very much on the current position of the individual player, i.e. product portfolio, current brand image and overall market position. The potential losses from doing nothing need to be carefully weighed against potential gains from entering this new field early on and with an aggressive approach. This detailed analysis will yield valuable input for defining both the strategic importance of the topic and your vision.

What does this mean for OEMs, suppliers and niche players? OEMs may have to go beyond pure vehicle selling and expand their product portfolio, market reach and service offer. Suppliers may have to completely redesign their long-term product portfolio, with new partners and relationships. And new or niche players can take center stage – or in some cases, maybe just slightly adjust their current business setup. Developing a sound vision very much depends on a profound understanding of key market trends and a company’s own capabilities – combined with a creative and comprehensive development process.

Message: The more you stand to gain from entering the market – or lose from doing nothing – the more important it is to hone your business approach and target the market aggressively.

Step 2: Assess your resources – How much can I afford to put into this new market?

What determines the additional R&D and business development efforts that can be put into this new market and technology? First, it depends on how much companies already dedicate to this area. Second, the company’s financial power is an important factor. Finally, the appropriate resources need to be available. A detailed analysis of the necessary development areas and resource requirements for achieving the company’s vision, developed in step 1, will provide valuable input for focusing and prioritizing the activities. As electric mobility is a new market, we believe that new partnerships will evolve, not only among the players in the industry, but especially between industries. Government support will play an important role here in giving longer-term direction and providing short-term financial support.

Message: Tailor your approach to your individual resource constraints and consider partnerships to realize your vision. Utilize government support to stabilize, expand and accelerate your strategic activities.
Synthesis: Define your general strategic roadmap – Where is my technology focus and what is my implementation plan?

The results from the first two analytical steps will lead to one of four very different strategic approaches to electric mobility. This approach will then serve as the fundamental basis/roadmap for the overall business strategy.

Companies’ chances for survival in the coming years very much depend on how carefully they evaluate their electric mobility strategies. Bad timing and inappropriate resource allocation can have dramatic effects. Taking the uncertainty in this field into account (especially as regards timing), developing a Plan B should be an integral part of the evaluation.

For OEMs, this positioning is of utmost importance, and the choice of strategy is highly dependent on the current market position:

> To market advanced technology to their customers, premium OEMs must develop a tighter technology focus and target the market more aggressively. They will therefore likely benefit from a generalist or specialized front runner strategy. Having electric or plug-in hybrid vehicles in the portfolio is necessary for keeping and increasing the technological edge, market share and price premium.
> Volume OEMs from the triad markets have more choices. Any of the four strategies is suitable, depending on the current market position and resource availability. Some volume OEMs, such as Renault and General Motors, are first movers that aggressively approach the market with new technologies and innovative business models. Motivated by declining sales volumes of ICE vehicles and lacking brand awareness in traditional segments, they are taking high risks, but the potential rewards are attractive. A good share of first customers are likely to be former Mercedes, BMW and Audi drivers. Other volume OEMs position themselves with low-profile or risk-averse strategies, carefully observing the market dynamics and developing technologies, but avoiding high up-front investments. Their first products will likely be more advanced than those of first movers, but the range of options for uniquely positioning products and brands will definitely be narrowed down.

> OEMs on emerging markets tend to gravitate toward specialized front runner strategies, to allow for the possibility of international expansion. They often cannot catch up in ICE technology, but some providers, such as Hong Kong-based BYD, have superior capabilities in certain key EV/PHEV technologies. This can become a possible gateway to penetrating the European and North American markets.

For powertrain component suppliers, betting on the wrong technology or holding on too long to the current product portfolio will have a dramatic impact over the next ten years. EVs and PHEVs will start to replace ICE models, and market volumes for mechanical components for traditional gasoline and diesel powertrains will decline. Therefore, it is not a question of "if", but rather of "how and when" to strengthen or build up competencies for electrified powertrains and battery technologies.

All other suppliers, in particular those with energy-consuming components such as brakes, steering and HVAC systems, will also see significant changes to their product portfolio, although not as radical and as soon as their peers. EVs and PHEVs will require new product designs and new components with different packaging, performance and energy consumption characteristics. Early involvement in developing these components will be the key to successfully participating in that future market.
Step 3: Define your position in the new electric mobility value chain – Where should the future focus of my business be? Are there opportunities for creating additional value?

As described in chapter 4, the significant technological changes bring with them both risks and opportunities in several areas of the new mobility value chain. Players need to analyze all potential opportunities (and risks) based on current brand and market perception, technological capabilities and partnering options. The results will provide the necessary basis for defining the company’s long-term value chain (re)positioning.

For OEMs, newly designed EVs and PHEVs, with their large batteries and a new type of fuel, raise the question of the final OEM product for the end customer. The options range from selling the vehicle without the battery – i.e. giving up some of the traditional added value – to a full package: selling the whole vehicle including the necessary electricity plus access to an appropriate charging infrastructure plus services.

![FIGURE 5.2-3: OEMs need to decide which product to market – from the vehicle without the battery to a full mobility package](image)

Product options and their pros & cons for OEMs

- **Vehicle without battery**
  - Option considered by some leading OEMs
  - Battery would be supplied to the customer through a preferred partner
  - Battery risk not borne by the OEM

- **Vehicle with battery**
  - Vehicle and battery supplied by OEM
  - Battery can be rented or leased – in case of leasing, the OEM owns the battery
  - More value captured

- **Full package**
  - Customer pays a monthly fee that includes full maintenance service, electricity (in some countries) and insurance
  - Battery owned by OEM
  - Most value captured – mobility provider
  - More touch points with customer through periodic bills
  - Battery risks borne in full
  - Highly complex business model
  - Business framework along the lines of a virtual mobile operator is essential

1) But image risks in case of battery failure

Source: Roland Berger
The traditional approach to selling vehicles can and will be used for electric mobility as well. OEMs will offer the EVs and PHEVs including the battery, and one or several partners will offer access to infrastructure, electricity and services. Customers will create their own package, and benefit from competition at every step along the value chain.

There is definitely also a possibility that the OEMs will reduce their added value by offering the electric vehicle without the battery, and partners will provide the battery, electricity and services to the customer. New players, such as Better Place, target this new business model and position themselves as partners for the OEMs. This approach has the following advantages:

> The purchase price of the vehicle can be reduced significantly – the battery is the major additional cost element in comparison to ICE vehicles

> The cost of the battery is covered in monthly payments together with electricity, infrastructure access and services

> Partners could be better positioned to utilize the battery throughout its whole lifetime, including possible reusage in stationary applications

> OEMs do not carry the battery risk, associated with its (so far) unexplored real-world lifetime and performance

As a third option, OEMs could also act as “virtual operators” by selling mobility to their customers and offering targeted products and services around the EV/PHEV. This is the option incumbent OEMs need to carefully consider, as it increases the added value for OEMs and could contribute to higher customer loyalty. However, the investments and associated risks of this business model will be higher.

Taking a look at the production value chain, the vertical integration of each system should be defined dynamically, meaning it should evolve over time in response to changes in the competitive environment.
In early phases, automakers are likely to become deeply involved in many of the processes in order to get a better understanding of the fundamentals within critical systems. OEMs will also need this involvement to make decisions about required in-house competencies, which is so critical for sustainable product differentiation.

Later on, as the market matures and competitive landscapes become clearer, automakers might think about scaling back their involvement, reducing it to their core areas.

These considerations apply in particular to the battery. Most OEMs, such as Toyota, VW and Daimler, have entered into strategic alliances with battery producers, either through long-term agreements or even joint ventures (as described in chapter 4). BYD, for example, is one manufacturer deeply involved in battery production, and is actually a leading supplier of Li-Ion batteries for cell phones. The company develops and produces LiFePO4 batteries in-house. It covers most of the value chain down to raw materials production.

Message: If you don’t grab a share of the additional profit pool, others will get their hands on it.
Step 4: Adapt your current business – What can be cut back without hurting the top line?

Before the financial crisis, a lot of players followed a strategy of dedicating resources to many of the new technologies while changing nothing in their current core business. Dramatic revenue losses are now forcing most of the players to reduce investments and fixed costs. Together with the need to keep future investments, this situation requires bold moves in the existing business as well. Companies must figure out how to reduce in-house resources without hurting their current business and the top line too much as they develop new business strategies.

The combined challenge of technological change and eroding current business should provide enough motivation to look at the current business from a different perspective – and ask for new solutions. Ultimately, it’s about reallocating sufficient resources to the new business field that can enable your organization to join the race.

As established in previous chapters, this race is global. However, the necessary organizational change process and implementation actions should reflect the regional and even local differences and characteristics.

Message: Join the race, but with a real team (reallocate resources now).

5.3 Summary

Now that you have gone through the above described steps and answered the key questions for your company, your optimal business strategy will have three main parts:

Strategic roadmap: Develop a vision and a strategic roadmap for your company in 2020. Base it on the assumption that electric mobility will be a major element of personal transportation by then. Your strategy should cover your product definition/value chain positioning, in-house focus, product portfolio/mix, brand image, etc. Everyone should have a clear understanding of what the world and your company may look like in the next 10 years.
Implementation and timing: Define your timeline with key milestones and turning points between now and 2020, when your new company vision should be fully established. This way, everyone has a clear understanding of what needs to be achieved by when to reach the long-term target. Always keep in mind that within the next 2-3 years, key lessons learned and unexpected changes in the technology and competitive landscape may still require certain adaptations to the overall strategy.

Organizational change: Develop a detailed transition plan with regard to product portfolio development, resource allocation, skill build-up, partnering network and financial implications.

Start this process now; there's no better time for radical thinking and change management than today. If you don't, the changes around you might force you to adapt anyway in the coming years, but it will be even more painful then.

Ultimately, the move toward electric mobility comes down to two things: viewing and doing. Viewing the future potential in the area, and "doing" by starting clearly defined projects to build up know-how and gain hands-on experience.
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