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# From Combustion Engines to Electric Vehicles

## A Study of Technological Path Creation and Disruption in Germany

*Tilman Altenburg*

*Joint project with:*

Institute of Development Studies

Tsinghua University
School of Public Policy and Management

Indian Institute of Technology Delhi

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## A study of technological path creation and disruption in Germany

Tilman Altenburg

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# Abstract

Mitigating climate change by reducing carbon emissions is one of the biggest and most complex issues the world has ever faced. Technological innovation plays a major role in taking on this challenge. Old and new industrial powers alike are increasingly reforming their policy frameworks to encourage low-carbon investment and innovation. The research project "Technological trajectories for low-carbon innovation in China, Europe and India" explored to what extent, how and why technological pathways differ across countries. Case studies were conducted in electromobility and wind power technologies.

Evolutionary economics has demonstrated how initial choices of technologies and institutions preclude certain options at later stages; hence, innovations evolve in an incremental and cumulative way, resulting in context-specific technological pathways. *How* industries adapt, *which alternatives emerge*, *how rapidly* they become competitive and eventually substitute the incumbent technologies therefore follow country-specific technological pathways.

This case study deals with electromobility in Germany. Germany adopted a National Electromobility Strategy to make it a lead market and lead provider for electromobility. The lead market target, however, is not likely to be achieved – due to the German industry's and consumers' preference for high-powered cars and due to limited government commitment to accelerate the transition via ambitious emissions targets or subsidies. The target to become a lead provider may be more realistic. While Germany has so far been a latecomer to battery-electric and hybrid powertrain technologies, lagging several years behind Japanese, French, Korean and US manufacturers, series production of battery-electric and plug-in hybrid vehicles appears to have been taking off since 2013/14. This reflects the overall innovative strengths of the German automotive innovation system, rather than particularly conducive home market conditions for electromobility.

The German automotive industry's incremental shift to alternative powertrains displays a number of country-specific characteristics. These include a leading role in hybridisation strategies in the up-market segment where German OEMs offer 'green lifestyle' cars that do not compromise on power, performance and driving pleasure but use high-tech solutions to increase energy efficiency. As another element of competitive specialisation, modularisation and standardisation are consequently used to ensure that customers can choose among a range of powertrain alternatives without compromising on the expected comfort, while at the same time economies of scale can be exploited to keep costs low. Some analysts also expect specific German developments in related services, such as intermodal transport services or smart grid technologies, but these are not yet observable.

# Preface

Mitigating climate change by reducing carbon emissions is one of the biggest and most complex issues the world has ever faced. Technological innovation plays a major role in taking on this challenge. Old and new industrial powers alike are increasingly reforming their policy frameworks to encourage low-carbon investment and innovation.

Evolutionary economics has demonstrated how initial choices of technologies and institutional arrangements preclude certain options at later stages; hence, innovations evolve in an incremental and cumulative way, resulting in context-specific technological pathways. Such path dependency implies that technologies and institutions do not progressively converge toward a unique best practice, as neoclassical equilibrium models might suggest. The historical and social embeddedness of such evolutionary processes instead results in a variety of very different technologies and institutions across countries.

The starting assumption of our research was that low-carbon technologies depend to a high degree on politically negotiated policies, mainly due to the failure of markets to reflect environmental costs. The way national governments and industries deal with the low-carbon challenge varies greatly depending on levels of environmental ambition, technological preferences (such as different attitudes towards nuclear energy, shale gas, carbon capture & storage), the ways markets are structured, and the importance attached to expected co-benefits (such as green jobs or energy security). Consequently, low-carbon technologies are more likely to evolve along diverging pathways than other technologies whose development is more market-driven.

To test this assumption we conducted the international research project "Technological trajectories for low-carbon innovation in China, Europe and India". The project explored to what extent, how and why technological pathways differ across countries. Case studies were conducted in two technological fields, electromobility and wind-power technologies, in China, India and leading European countries. Whether a diversity of pathways emerges or a small number of designs becomes globally dominant has important implications. From an environmental perspective, diversity may help to mobilise a wide range of talents and resources and deliver more context-specific solutions. Convergence, on the other hand, might help to exploit economies of scale and thereby bring about bigger and faster reductions in the cost of new technologies. From an economic perspective, diversity may provide niches for many firms, whereas a globally dominant design is likely to favour concentration in a small number of global firms – which may or may not be the established ones. Comparing European incumbents with Asian newcomers is particularly interesting, because China and India might well become the gamechangers – responsible for most of the increase of $CO_2$ emissions but also leading investors in green technology. In addition, the project explored lessons for international technology cooperation, emphasising ways to navigate the trade-offs between global objectives to mitigate climate change effects and national interests to enhance competitiveness and create green jobs locally.

The project was carried out between 2011 and 2014 as a joint endeavour of four institutions: the German Development Institute / Deutsches Institut für Entwicklungspolitik (DIE), the Institute of Development Studies (IDS) Brighton, the Indian Institute of Technology (IIT) Delhi and the School of Public Policy at Tsinghua University, with additional collaborators from the Universities of Aalborg, London and Frankfurt. The project was truly collaborative, to the extent that international teams jointly conducted interviews in China, India and Europe which helped to build common understanding.

Eight reports have been published in, or are currently being finalised for, the DIE Discussion Paper series:

*(1)* *Altenburg, Tilman* (2014): From combustion engines to electric vehicles: a study of technological path creation and disruption

*(2)* *Bhasin, Shikha* (2014): Enhancing international technology cooperation for climate change mitigation: lessons from an electromobility case study

*(3)* *Chaudhary, Ankur* (2014): Electromobility in India: attempts at leadership by businesses in a scant policy space

*(4)* *Lema, Rasmus / Johan Nordensvärd / Frauke Urban / Wilfried Lütkenhorst* (2014): Innovation paths in wind power: insights from Denmark and Germany

*(5)* *Schamp, Eike W.* (2014): The formation of a new technological trajectory of electric propulsion in the French automobile industry

*(6)* *Ling, Chen / Doris Fischer / Shen Qunhong / Yang Wenhui* (forthcoming): Electric vehicles in China: bridging political and market logics

*(7)* *Dai, Yixin / Yuan Zhou / Di Xia / Mengyu Ding / Lan Xue* (forthcoming): Innovation paths of the Chinese wind power industry

*(8)* *Narain, Ankita / Ankur Chaudhary / Chetan Krishna* (forthcoming): The wind power industry in India.

On the basis of these case studies, the team is currently working on a series of cross-country comparative analyses to be published in academic journals.

The research team is very grateful for generous funding and the very supportive attitude of the Swedish Riksbankens Jubileumsfond under a joint call with the Volkswagen Foundation and Compagnia de San Paolo.

Bonn, October 2014 Tilman Altenburg

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# Abbreviations

| | |
|---|---|
| BEV | Battery-electric vehicle |
| BYD | BYD Company Limited |
| CEM | Clean Energy Ministerial |
| CFRP | Carbon fibre-reinforced polymers |
| CNG | Compressed natural gas |
| $CO_2$ | Carbon dioxide |
| DIE | German Development Institute / Deutsches Institut für Entwicklungspolitik |
| ETS | Emissions Trading System |
| EU | European Union |
| EUR | Euros |
| EV | Electric vehicle |
| EVI | Electric Vehicles Initiative |
| FCEV | Fuel-cell electric vehicle |
| G8 | Group of Eight |
| HEV | Hybrid electric vehicle |
| ICE | Internal combustion engines |
| IEA | International Energy Agency |
| km | Kilometre |
| LPG | Propane |
| MQB | Modular Transversal Toolkit (*Modularer Querbaukasten*) |
| NPE | National Platform Electromobility / Nationale Plattform Elektromobilität (Germany) |
| OECD | Organisation for Economic Co-operation and Development |
| OEM | Original equipment manufacturers |
| PHEV | Plug-in hybrid vehicle |
| R&D | Research and development |
| REEV | Range-extended electric vehicle |
| SUV | Sport utility vehicle |
| TCO | Total cost of ownership |
| US | United States |
| VDA | Verband der Automobilindustrie (German carmakers' association) |

## Summary

Cars powered by internal combustion engines have been the technological solution that dominated the automotive industry and coined the way transport systems have been organised globally. Given the urgent need to decarbonise the world economy, however, alternative powertrain technologies are now gaining competitive advantages, and industries have to adapt. Hybrid and fully electric powertrains attract considerable investments, and so do new mobility concepts and services at the interface of the transport and the energy system. *How* industries adapt, *which alternatives emerge*, *how rapidly* they become competitive and eventually substitute the incumbent technologies, however, depend on country-specific factors, including policy frameworks, the existing industrial structure and specialisation, demand conditions, etc. As a result, the shift to electromobility follows country-specific technological pathways.

This study reviews technological trends in the transition to electromobility in Germany. It is part of a comparative research project exploring differences and similarities between technological pathways in two low-carbon technologies (electromobility and wind turbines) in Europe, China and India. While this report on electromobility in Germany aims to bring out important national technological trends and their underlying determinants, global and European levels are dealt with in order to situate the German case and to allow us to make comparisons with Asian and European competitors at a later stage.

The present study reveals some distinctive features of the shift to electromobility in Germany. To start with, electromobility still plays a subordinate role in the business models of German carmakers and big suppliers. None of the existing hybrid and electric models has a relevant market share so far. Likewise, the manifold new technologies and business models associated with the shift to electromobility – from intermodal mobility services, car-sharing and grid-vehicle communication to inductive charging and new recycling concepts to recuperate scarce natural resources – have not taken off so far.

Germany’s automotive industry, with the Mercedes, BMW, Audi and Porsche brands among others, has a particular strength in the luxury and upper middle-size classes; and even in the smaller car categories, German manufacturers sell in the highest price range. This competitive positioning has so far been very successful, as demand in the premium segments increases at above average rates and competition is not as stiff as in low-cost car production. But high-powered, high-end brands have particular difficulties in meeting the European Union’s (EU) fleet emission standards. While the German automotive industry, seconded by German politics, lobbies strongly against ambitious emissions standards, the trend towards the decarbonisation of powertrain technologies is irreversible.

The German car industry’s high-end specialisation partly explains why Germany is a latecomer to electromobility. While Toyota introduced hybrid electric vehicles (HEV) as early as 1997, none of the German carmakers responded to the challenge. Likewise, series production of plug-in hybrid vehicles (PHEV) and battery-electric vehicles (BEV) is only taking off now, in 2013/14, about two to three years behind Japanese, French, Korean and US manufacturers. This, nonetheless, does not seem to undermine the German automotive industry’s competitiveness. First, the global shift to electromobility is fairly slow and incremental. The technological competences related to internal combustion engines (ICE) powertrains continue to be highly relevant, and many different powertrain technologies will

co-exist for at least the next 2-3 decades. Organisational competences, such as the ability to manage collaborative innovation processes and integrate multi-tiered production systems, are stabilising the German incumbents position in any case. Likewise, change in the supply chain has not so far been radical, and it seems that established suppliers are generally able to adapt their capabilities. Even in battery technology – arguably the weakest element in Germany's automotive innovation system when it comes to electromobility – international progress is slow and Germany seems to be catching up fast.

Germany has a National Electromobility Strategy and created a coordinating body to support the transition to electromobility. The strategy's declared objective is to make Germany a lead market and lead provider for electromobility. The lead market target, however, is not likely to be achieved – due to the German industry's and consumers' preference for (traditional) high-powered cars and due to limited government commitment to accelerate the transition via ambitious emissions targets, a bonus-malus system for emissions, or purchase subsidies for electric vehicles. Having said that, the target to become a lead provider may be more realistic. Very recently, German carmakers have appeared to take off strongly in hybrid and electric powertrain technologies and are expected to catch up with the current market leader Japan within the next 5 years. This reflects the general strength of the German automotive innovation system rather than particularly conducive home market conditions for electromobility.

The German automotive industry's incremental shift to electromobility – or maybe more precisely: toward an increased variety of propulsion technologies – shows a number of country-specific characteristics. These include a leading role in hybridisation strategies in the up-market segment where German OEMs offer 'green lifestyle' cars that do not compromise on power, performance and driving pleasure but use high-tech solutions to increase energy efficiency. As another element of competitive specialisation, modularisation and standardisation are consequently used to ensure that customers can choose among a range of powertrain alternatives without compromising on the expected comfort, while at the same time economies of scale can be exploited to keep costs low. Some analysts also expect specific German developments in related services, such as intermodal transport services or smart grid technologies, but these are not yet observable.

It should be noted, however, that standards for greenhouse gas emissions are likely to become much stricter in the future. The current 95g $CO_2$/km target set by the EU for 2020 can still be achieved without a radical industrial transformation. 10g $CO_2$/km, calculated as the tolerable maximum in 2050 to stay below 2°C global warming, will require a much more radical departure from current technological trajectories.

# 1 Introduction

The automotive industry is gradually shifting from producing traditional cars powered by internal combustion engines (ICE) to less carbon-intensive drive technologies, including fully battery-electric as well as hybrid-electric cars. The latter combine electric engines with smaller combustion engines. This shift implies major changes in the automotive and related industries. New technologies and new capabilities are required, and some old ones will lose their previous importance. Battery-electric vehicles (BEV), for example, need new generations of powerful batteries, electric motors and inverters; and they no longer require some of the core technologies of traditional cars, such as internal combustion engines and gearboxes. New forms of thermo-management need to be developed, as there is no longer a combustion process generating heat which can be used for heating or cooling. Essentially, a major part of the automotive architecture needs to be redesigned. Some radically new designs include motors that are placed in the wheels and auto bodies made from carbon fibre instead of steel. This shift to new technologies and automotive architectures goes along with new capability requirements, opening up opportunities for newcomers, while the substitution of old ones threatens incumbents. This has potentially far-reaching implications for the entire automotive supply chain. Also, the paradigm shift requires new infrastructure solutions. If cars are to be charged from electric grids, a charging infrastructure needs to be put in place; and linking the automotive fleet to the electric grid requires a range of solutions to adapt demand to grid capacity and fluctuating energy supply (especially when electricity from renewable sources is used) and to ensure that access to charging stations is convenient for the customer. Last but not least, the driving range of battery-electric cars is more restricted than that of traditional fuel-powered cars, and thus new business models for mobility need to developed to cope with these restrictions.

The shift from the old transport systems based on fuel-driven cars to electromobility is thus potentially a true techno-institutional paradigm change, as Freyssenet (2009) claims in his book titled “The second automobile revolution”. This paradigm change, however, is just in the making, in Germany as well as in all other industrialised and emerging economies. Predictions about the speed and the depth of the change vary greatly: How rapidly will the combustion engine technology be phased out? How long will it take to overcome the range problem of battery-electric vehicles? Will the bridging technology of hybrid vehicles be a short episode in the history of cars or a long-lasting alternative? Will we mainly see a replacement of internal combustion engine (ICE) cars by electric cars, or will there be more profound changes towards new forms of mobility? And who will be the drivers of change? Will industry incumbents be seriously challenged by newcomers or will the old players gradually adapt and maintain their leadership? How profoundly will supply chains be affected?

These are important questions. How things evolve will have enormous repercussions on decarbonisation pathways globally as well as on the global distribution of technological capabilities and competitive advantages. Moreover, things will evolve differently in different contexts. Today’s techno-institutional developments are always to a certain degree dependent on decisions taken and structures built in the past, which then, through bandwagon and network effects, reinforce the direction of change. Hence the questions asked in the previous paragraph will play out differently in each country, each regional productive cluster, and each automotive value chain.

This report explores the depth, the direction and the potential implications of the shift to electromobility in Germany. It is part of a larger project exploring differences and similarities between technological pathways in two low-carbon technologies (electromobility and wind turbines) in Europe, China and India. While this report on electromobility in Germany aims to bring out important national technological trends and their underlying determinants, global and European levels are dealt with in order to situate the German case and to allow us to make comparisons with Asian and European competitors at a later stage.[1]

This study focuses on passenger vehicles that are *mainly* battery-electric driven. These include BEV, plug-in hybrid vehicles (PHEV) and range-extended electric vehicles (REEV). It *excludes* those hybrid electric vehicles (HEV) that have an electric motor and a small battery used as a complementary power source, but use a conventional combustion engine as the main source of propulsion. It also excludes alternative carbon-efficient drive technologies, such as fuel-cell electric vehicles (FCEV). The following Box 1 briefly explains the main powertrain and car concepts.

**Box 1: Powertrain and car concepts for electromobility**

The term ‘electromobility’ comprises several powertrain and car concepts:

(1) *Hybrid electric vehicles* (HEV), also called parallel hybrids, have a conventional combustion engine supported by an electric motor. The battery capacity is limited and is used as a temporary complementary power source to assist the main engine or replace it at low speed. The batteries are charged by the electricity generated by the engine and brake energy recuperation. Purely electric propulsion is possible, but only for a quite limited range.

(2) *Plug-in hybrid vehicles* (PHEV) are similar to HEV but in addition offer the possibility of plugging them into the power grids. This increases energy storage and driving range. Some PHEV are designed for electric propulsion mainly and therefore use larger batteries.

(3) *Range-extended electric vehicles* (REEV) are equipped with a strong electric motor and a grid chargeable battery. Propulsion is purely electric, but a small combustion engine is installed to recharge the battery in order to extend the driving range.

(4) *Battery-electric vehicles* (BEV) use an electric motor with batteries for electricity storage. The batteries provide energy for all motive and auxiliary power onboard the vehicle. They are recharged from grid electricity and brake energy recuperation, and also potentially from non-grid sources, such as photovoltaic panels at recharging centres.

(5) *Fuel-cell electric vehicles* (FCEV) use an electric motor and a fuel cell for energy supply. The fuel cell converts energy from hydrogen. FCEV also use a battery for brake energy recuperation.

Source: e-mobilBW (2010, 8–9); OECD (2011, 191)

The study consists of five sections. Section 2 briefly introduces the basic notions of technological path dependence and how new pathways are created. It argues that national pathways are likely to diverge strongly in the transition to electromobility, given that (a) resource allocation is driven by public policy to a very high degree and (b) governments have different objectives in mind when supporting electromobility and therefore set incentives differently. Section 3 assesses the depth and main directions of the technological

1 See the respective reports on electromobility in France (Schamp 2014), India (Chaudhary 2014) and China (Chen et al. forthcoming).

shift towards electromobility. It discusses whether we can expect fast and radical or rather slow and incremental change, which parts of automotive value chains are most likely to be affected, and where new business models are emerging in fields related to electromobility. The next sections zoom into the case of Germany. Section 4 presents basic characteristics of the German automotive industry as well as the national (and, where relevant: EU) policy framework that shapes the incentives for electromobility. It concludes with a brief description of recent electric vehicle market development. Section 5 then sets out the main strategies towards electromobility pursued by German companies and discusses to what extent we can observe specific German pathways to electromobility. A few distinct corporate strategies are beginning to show, but in most of the related business segments, firms are still experimenting and it is thus too early to anticipate country-specific trajectories. Section 6 concludes.

# 2 Diversity in the creation of new pathways to electromobility

## 2.1 Technological path dependence and the creation of new pathways

Evolutionary economics suggest that innovation advances along specific technological trajectories (Dosi 1982). Technological progress is cumulative, building on specific local initial conditions and unfolding from there through incremental changes. Most research and development efforts target improvements of the already established technologies rather than testing radically different pathways, thereby reinforcing initial technology choices. Furthermore, the evolution of technologies is underpinned by specific institutional arrangements (such as regulations, research and development (R&D) programmes, and business networks) which are functional for the evolving technologies, but not necessarily for potential alternatives. Hence, technologies and institutions 'co-evolve' (Nelson 1994) in specific, self-reinforcing ways, thereby giving rise to technological 'trajectories' or pathways.

Whenever technologies evolve in parallel in different locations and institutional environments, the way one thing leads to another necessarily mirrors local specificities. Technological pathways may thus diverge considerably across countries, especially when initial conditions – in terms of regulations, consumer habits, purchasing power and the like – are very different. For example, countries with more stringent emissions standards are likely to shift faster to low-emission technologies; high-income countries provide stronger incentives for high-tech solutions than countries with poorer consumers; countries with a diversified set of supporting industries can be expected to innovate faster than others; and large, fast-growing economies have an above-average probability of achieving cost-reduction through economies of scale.

It may well be that pathways diverge strongly at the beginning, as a range of new technologies and mobility concepts are being tested. As technologies mature however, market competition reveals the costs and benefits of existing alternatives and rewards the best options. The beneficiaries may use their growing market shares and rising incomes to reap economies of scale, further enlarging their technological leadership and crowding alternative providers out. This way, their technological offer may become a sort of 'dominant design' (Utterback / Abernathy 1975) which, at least temporarily, is not seriously challenged by anyone. In the automotive industry, cars powered by internal combustion engines have been the dominant design for an entire century, and other societal institutions – such as individualised transport or car ownership as an important source of social prestige – have developed alongside this technology and reinforced its dominance. Still, economic history tells us that no design is dominant forever. In market economies, competitors will sooner or later challenge the incumbents. Today's fuel-based transport systems are now being challenged by the pressure to reduce greenhouse gas emissions, the rise in fuel prices, and the emergence of several alternative propulsion technologies.

Against this background, we seek to understand how the transition from fuel-driven to electric mobility unfolds, how new technological pathways are created, and how and to what extent initial conditions predetermine the selection of emerging technological alternatives and corresponding institutional setups.

## 2.2 Pathways towards electromobility: policy-led and fraught with uncertainty

The automotive industry displays the typical characteristics of path-dependent evolution. Electric cars have been competing with ICE propulsion since the late 19th century. Yet already in the early 20th century, ICE technology became the dominant design, mainly due to limited possibilities of storing electrical energy. For almost a century, electric powertrains were not considered a serious alternative. An automotive industry evolved building up competencies in combustion engines and related technologies, dedicated research centres were formed to improve technologies, and a new infrastructure, from roads to gas filling stations, was developed to support ICE cars.

In the last 5-10 years, electromobility has been receiving much renewed attention and public support, not least because of technological advancements in energy storage technologies, particularly lithium-ion technology, and the need to decarbonise economies. All large automobile-producing countries and almost all carmakers (also called 'original equipment manufacturers', OEMs) are now channelling substantial amounts of money into the development and deployment of hybrid and battery-electric vehicle technology, including R&D programmes, infrastructure investments, establishment of model regions for testing, purchase subsidies, tax incentives and public procurement policies (National Platform Electromobility (NPE) 2012, 59).

Given the nascent state of the new industry, it is not surprising to note that investors and supporting institutions around the world are testing many different techno-institutional options to develop electric or hybrid powertrains as well as mobility concepts. This diversity reflects the enormous uncertainty under which today's actors operate. Uncertainty stems from technology risks, market risks, and policy risks:

1. **Technological uncertainty:** How fast will the remaining technological problems of battery-driven propulsion be overcome, especially with regard to low energy density and high cost of existing battery technologies? How fast will competing technologies (like fuel-cells, methane, or improved fuel combustion) develop in comparison with battery-electric vehicles? And to what extent do carmakers succeed in improving the efficiency of ICE (including sophisticated direct injection, turbochargers and compressors), thereby reducing, or postponing, the incentives for the electrification of

powertrains?[2] Forecasts suggest the co-existence of several powertrain technologies, with BEV, FCEV and PHEV increasing their market shares in the future at the expense of petrol and diesel, and HEV as a bridging technology that expands its market share for about 20 years but then also starts to decline. Predictions about each technology's future market share however are highly speculative.[3]

2. **Market uncertainty:** How rapidly will consumers be willing to change their habits with regard to mobility and car ownership? How will economic incentives evolve, such as the prices of fossil fuels or rare earths (which have a strong impact on the cost of energy storage technologies), and how will consumers react to changing price incentives?

3. **Policy uncertainty:** How decidedly will governments step in to fund R&D, new infrastructure and technology deployment programmes? How strongly will policy intervene to change the energy mix, taxing fuel consumption or carbon emissions? To what extent will environmental regulations be tightened, e. g. with regard to vehicle emissions standards or environmental zoning requirements in cities?

These sources of uncertainty are closely interrelated: Efforts to innovate depend on fuel and carbon prices as well as emissions reduction targets set by governments; an increasing pace of technological progress is likely to result in more ambitious targets; consumer behaviour in turn is influenced by price trends, regulations and increased technological choices. Taken together, these uncertainties increase investment risks; but they also promise extraordinary economic rents for those who make the right bets. As the Organisation for Economic Co-operation and Development (OECD) puts it with regard to electromobility investments, the current high level of uncertainty:

> *shapes a complex strategic game, with newcomers exploring radical alternatives, on the one hand, and, on the other, incumbent firms, with their large accumulated assets, divided between taking a leading exploratory role to rapidly leverage their market power in this emerging sector, and an imitative behaviour to avoid the costs of search-and-try errors and protect their historical brand* (OECD 2011, 193).

Uncertainty is a characteristic feature of paradigm change, and it explains why in the beginning, when the old dominant design is threatened and new pathways loom, market actors bet on alternative options. We argue that national technological trajectories tend to diverge even more in fields of environmental innovation (such as electromobility) than in other technologies because the former are often shaped by *policy* to a particularly high degree (Altenburg / Pegels 2012; Lütkenhorst et al. 2014):

*Firstly,* the readiness of governments to internalise environmental costs, hence the level of ambition of their environmental policies, differs greatly across countries, reflecting the

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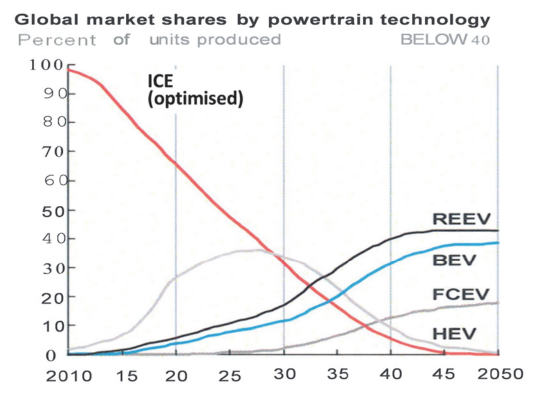
2 Some studies predict major technological advances in reducing the CO2-emissions ICE cars which would significantly reduce the environmental performance gap vis-à-vis HEV and PHEV (The Economist 2011). Innovation scholar have called this the 'sailing ship effect': Rates of innovation incumbent technologies go up when their paradigm is challenged – which was first described for the competition between sailing ships and steam ships (for the car industry: Sushandoyo et al. 2012).

3 http://www.economist.com/news/special-report/21576219-carmakers-are-hedging-their-bets-powering-cars-great-powertrain-race, based on International Energy Agency data

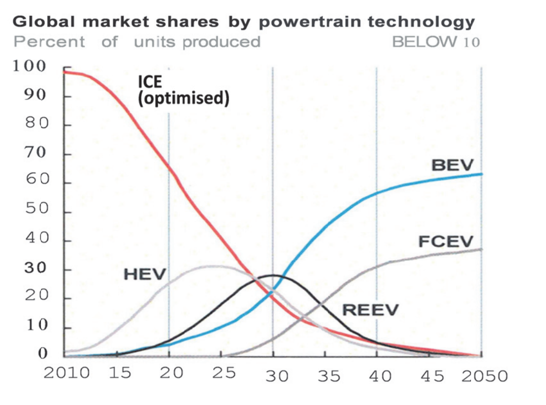
state of the nation's environment, power relations between polluters and environmentalists, as well as peoples' willingness and ability to pay for environmental goods. Also, the ability to enforce environmental regulation differs. Differences in policy framework have a direct effect on the choice of technologies. Figure 1 illustrates how fundamentally technology deployment is affected by changes in the regulatory framework.

**Figure 1: Scenarios of electromobility deployment under different carbon emissions targets**

A) Moderate: Fleet emissions below 40 $gCO_2$/km by 2050




(B) Strict: Fleet emissions below 10 $gCO_2$/km by 2050




Source: McKinsey&Company (2011, 7)

*Secondly,* when promoting environmental technologies, governments (and societies at large) usually link the environmental objectives to certain expected co-benefits, such as energy security or enhanced national competitive advantages and green job creation (Lütkenhorst / Pegels 2014). As the way environmental objectives and co-benefits are balanced depends on political settlements, the resulting policy packages also differ from country to country. In the case of electromobility, four policy objectives are frequently cited for supporting electromobility. The rationale of each of these policy objectives is briefly explained below.

## 2.3 The rationale of supporting electromobility ... and how governments set different priorities

When justifying policy support for electromobility, governments around the world typically bring up four arguments – but they attach quite different priorities to these arguments, which has considerable implications for the way policies are shaped. The four arguments are substantiated as follows:

**1. Climate change mitigation.** To curb greenhouse gas emissions, traffic needs to be decarbonised. Worldwide, the transport sector accounted for approximately 23% of total energy-related $CO_2$ emissions (IPCC 2013, 4). Moreover, no other sector has recently increased its emissions as much as transport.[4] Even in the EU, where the energy efficiency

4 For the EU27, European Commission (2009) shows this growth relative to 1990 levels.

of transport is improving significantly, the gains in efficiency have not been enough to outweigh the increase of transport volume (European Commission 2009, 11). It should be noted that transport activity is increasing even much faster in other world regions, especially those emerging economies with rapidly increasing income levels and growing middle classes (GoldmanSachs 2004). In China alone, car sales skyrocketed from 2.3 million cars in 2001 to 18.5 million cars in 2011.[5] In response to these developments, policymakers in the world's largest economies have recently introduced a series of policies to reduce $CO_2$ emissions from vehicles. While the EU and Japan have adopted the most stringent standards, China, the United States and South Korea also adopted binding reduction targets, and the trend is towards convergence. Much more ambitious goals, however, will be required in the future. In 2009 the EU and Group of Eight (G8) leaders both accepted that, in order to stay within the target of maximum 2°C global warming, $CO_2$ emission needed to be reduced by 80%, which would imply reducing $CO_2$ emissions from road transportation by 95%, given that some other activities cannot be decarbonised as radically (www.roadmap2050.eu).

Electromobility *may* contribute significantly to the decarbonisation of road transport. Full electric mobility allows for pollution-free driving. Hybrid drive technologies reduce car emissions to the extent that part of the required energy is electric. Having said that, it should also be noted that net effects on greenhouse gas emissions depend on the source of electricity. If electricity comes from a provider who receives electricity largely from fossil fuel-based power plants, then electromobility only shifts emissions from combustion in cars to combustion in power plants. $CO_2$ emissions of electric cars that use Germany's current electricity mix are similar to those of a conventional ICE car if the emissions generated by the production and distribution of electricity generation and the energy to produce vehicle and battery are accounted for (Pehnt 2010, 7). In China, where more than three-quarters of electricity come from coal-fired power plants, and in the United States (about half from coal), total $CO_2$ emissions of electric vehicles are higher than those of ICE vehicles (Volkwagen AG 2012). If a national government wants to mitigate carbon emissions, then it needs to set incentives for reducing the emissions of the whole production process ('well-to-wheel') and not just the emissions from different internal engines ('tank-to-wheel' resp. 'battery-to-wheel'). Table 1 shows how different these are, depending on the underlying national energy mix. Assuming that cars are charged with 100% electricity from purely renewable sources, emissions would be minimal. Likewise, the French energy mix, with a particularly high share of nuclear energy, produces very low $CO_2$ emissions. It should be noted, however, that this is achieved in exchange for new risks related to radioactive contamination. Finally, the average EU 27 energy mix also reduces well-to-wheel emissions, but not to the extent needed to meet agreed international climate change mitigation targets.

**2. Urban air pollution**. Combustion engines are a major source of air pollution and noise. Emissions of toxic gases and particular matters, especially from diesel engines, cause health problems. With the trend to megacity development and an increasing density of cars, these problems are bound to increase greatly unless emissions per car and kilometer travelled are greatly reduced. By 2050, the OECD (2012) predicts that outdoor air pollution will become the main cause of environmentally related deaths worldwide. The

5 http://www.wautom.com/2012/04/china-car-sales-in-2011-18-5-million/

**Table 1: 'Well-to-wheel' $CO_2$ emissions (g/km) of ICE and electric vehicles (EV) assuming different energy mixes**

| | *Well-to-tank (batteries)* | *Tank (batteries)-to-wheel* | *Total well-to-wheel* |
|---|---|---|---|
| Conventional ICE car | *25-35* | *120-180* | *145-215* |
| EV EU-27 mix 2010 (27% nuclear, 20% renewable, 53% fossil) | *85-105* | *0* | *85-105* |
| EV French mix (75% nuclear, 20% renewable, 5% fossil) | *20-25* | *0* | *20-25* |
| EV 100% renewable (50% photovoltaic, 50% wind) | *8* | *0* | *8* |

Source: ERTRAC (2010)

enormous increase in road traffic, especially in China, contributes greatly to air pollution. In January 2012, *"a Particulate Matter PM 2.5 level of 886 micrograms a cubic meter was recorded in Beijing, nearly 35 times what the World Health Organization considers safe ... (In that month,) Beijing's Jiangong Hospital recorded a 30 percent spike in cases involving respiratory problems"* (CNBC, February 2013). Globally, 3.6 million people will die in 2050 from exposure to particulate matters, the majority in China and India (OECD 2012). Coming to grips with urban air pollution is the most important political driver of electromobility initiatives in China.

**3. Enhancing competitive advantages**. Countries may pursue the aims of building new or enhancing existing competitive advantages. The shift to electric and hybrid drive technologies may on the one hand enhance the competitive edge of established automotive industries if these manage to build upon existing technological capabilities and incorporate new technological demands into their existing innovation systems; but it may also threaten the incumbents if newcomers manage to take advantage of the paradigm change, leapfrog directly into the new generation of technologies without having to care about sunk investments in the old technologies, and thereby take market shares away from the incumbents. Porter and van der Linde (1995) have shown that imposing strict environmental norms may give rise to competitive advantages if later on the respective norms diffuse to other markets. In this case, companies operating in the early regulating country may gain early mover advantages in the respective technology. The desire to create such advantages and reap the related job and income effects is one of the strongest motives for investing in electromobility. A national industry that is well-positioned in the incumbent ICE technologies (such as the German one, see below) can be expected to take a different view on electromobility than one that faces competitive disadvantages in the old technologies and hopes that shifting to electromobililty early would allow it to gain a better foothold in the automotive market.

**4. Fuel saving and energy security**. Decarbonisation would save finite fossil fuels and reduce import dependency for fuel-importing countries. In the European Union, 97% of all transport energy still comes from fossil fuels (European Commission 2009, 11), thereby pushing the import bill up. The prospect of future fossil fuel shortages provides a strong economic incentive for developing alternative energy sources. For some countries, fuel saving and independence from imported fossil fuels are strong motives for supporting electromobility – but this presupposes the expansion of non-fuel sources of electricity in the country.

**In sum,** countries pursue electromobility for a number of reasons. At the same time, each country faces particular challenges and expects particular gains from the pursuit of electromobility strategies, depending on the importance attached to climate change mitigation, the level of urban air pollution, the strength and the type of specialisation of national industries, and the existing energy mix and resource availability, etc. Correspondingly, the policy frameworks which shape a firm's and institution's behaviour are also very diverse, as shown in Altenburg / Fischer / Bhasin (2012). This has important ramifications for the speed and direction of innovation efforts. The following section describes *Germany's* slow shift to electromobility, highlighting how specific industrial characteristics impact on the design of national policies, and how industrial conditions and policy frameworks give rise to new patterns of techno-institutional innovation.

## 3 Assessing the depth and main directions of change

As we have argued in the previous section, there are several motivations to push the automotive industry towards electric drive technologies. While at present electric vehicles are still an unimportant niche technology, accounting for only 0.03% of the total global passenger car stock (IEA 2013), few analysts doubt that electromobility will increasingly challenge the old paradigm of ICE-based mobility, simply because it is technically impossible to increase the efficiency of internal combustion engines to the levels needed to bring greenhouse gas emissions down. According to the International Energy Agency (IEA) scenarios for decarbonisation in line with the 2° C global warming target, *"three-fourths of all vehicle sales by 2050 would need to be plug-in electric of some type"* (CEM / EVI / IEA 2013, 7). Due to the various political and technological uncertainties, however, it is far from clear

- *how fast and how radical* the technological change will be;
- how it will *affect different parts of the automotive value chains*; and
- to what extent *new business models in related service industries* will emerge.

The following sections describe incipient trends, expert perceptions, and initial changes in these regards.

### 3.1 How fast and how radical?

Predictions about the market penetration rate of battery-electric and hybrid-drive technologies diverge considerably.[6] Globally,

6 The consulting firm Roland Berger expects that by 2015 *"2.5 million hybrid vehicles, 300,000 plug-in hybrid vehicles and 500,000 electric vehicles will be produced globally per year"* (Roland Berger

> *figures vary from a long-lasting niche of a few percent and several hundreds of thousands of electric vehicles sold in 2050 to a 50% market share for hybrids and electric vehicles (Accelerated Technology scenario (ACT) by the IEA, 2009) and even 65% for hybrids in industrialised regions* (Greenpeace, 2010; OECD 2011).

It is similarly unclear how radical the related techno-organisational change will be, for instance, whether there will be a fast and deep change of required technological capabilities and industrial structures, or whether change will happen gradually through intermediate technologies, allowing firms and the overall innovation system to adapt step-by-step and therefore leaving the structure of the automotive industry largely intact. A recent global opinion survey conducted among executives from the automotive industry shows that opinions on this issue are divided:

> *Half of those involved in the survey (49 percent) feel that the automotive industry could evolve a completely new business model, where existing interrelationships between OEMs, suppliers and dealers could change radically* (KPMG International 2011, 16).

So far, the shift from an ICE-based paradigm of road transport to electromobility has been incremental and slow. While electric driving is still costly and (due to limited range and long charging intervals) inconvenient, the political incentives to internalise environmental costs and phase ICE engines out are still fairly weak. Vehicle emissions standards are not yet very demanding. The EU and Japan are currently setting the most ambitious standards (the EU targets to bring fleet average emissions down to 95g $CO_2$/km by 2020), but even these are a far cry from the levels of decarbonisation needed to bring emissions in line with the 2°C global warming target, namely, 10g $CO_2$/km by 2050 (Linder 2012). The 95g $CO_2$/km target can be achieved through incremental improvements of combustion engines plus a small number of cleaner cars in the fleet. Also, the regulation allows for a number of exemptions favouring the ICE technology. Fuel prices have increased at a slower rate since the 2007 oil price boom, and carbon prices likewise provide little incentive for greening the industry, especially since the European carbon market has broken down. Last but not least, battery technologies – arguably the most challenging technological barrier for electric mobility – are still far from commercial viability; experts estimate that the problems of high cost and limited driving range will not be solved in the next 10-15 years. Proff et al. (2013, 6) reach the conclusion that *“change is long-term, because vehicles with combustion engine and electric vehicles will be supplied in parallel for at least the next 30 years”* (author’s translation).

But change may accelerate in the future. The systemic interdependencies between the determinants of market development imply that unexpected changes of any one of these determinants may shift the whole system dynamics, thereby making the whole field more unpredictable. Several ‘game changers’ have recently had major impact – some accelerating, others decelerating – on the dynamics of electromobility:

- The Kyoto protocol has triggered investments in technologies for sustainable development more generally.

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2011). A report commissioned by the government of Baden-Württemberg states that *“the share of passenger vehicles that only have an internal combustion engine is expected to decrease from the current level of 98 % to about 67 % in 2020. The share of pure battery-electric vehicles might then have increased to 5%”* (e-mobilBW 2010, 5).

- In 1990, California's Air Resources Board started an initiative to reduce vehicle emissions through the introduction of the Zero Emission Vehicle Programme, prescribing a certain percentage of 'zero emission' vehicles that large manufacturers selling in California had to reach as well as a road map to increase this percentage incrementally to allow carmakers to adapt. This had an effect on carmakers worldwide encouraging them to adapt to such gradual phasing in of emission standards.

- The adoption of mandatory fleet-average emissions standards by the European Commission in 2009 created a policy incentive that further increased electromobility expectations.

- Unexpected performance improvements of lithium-ion batteries used in consumer electronics shifted attention from fuel cells to battery-electric propulsion and triggered an 'e-mobility hype' at the end of the last decade.

- Toyota's impressive commercial success with the Prius HEV model[7] as well as Tesla's success with a high-priced BEV[8] have shown that both technologies are viable commercial options beyond specialist niche markets and established role models for the industry.

- In several OECD countries and China, fiscal stimulus packages to cushion the economic effects of the fiscal crisis gave a boost to electromobility investments.[9]

- Conversely, failure to bring lithium-ion battery costs down as rapidly as predicted provoked a recent reversal of the electromobility hype.[10]

- Successful lobbying of fossil energy and automotive interest groups created confidence among these groups that tightening of standards is likely to proceed much slower than suggested by scenarios that take greenhouse gas effects into account.

As in the case of the market determinants, the accelerators and decelerators of electromobility excitement and uptake are partly triggered by techno-commercial discoveries (or disappointment, when predicted learning curves are flatter than predicted); but it should be noted that the policy environment also adds to uncertainty, as policy road maps are contested and sometimes ambitious environmental targets (for example, for

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7 The Toyota Prius, launched in 1997, was the first mass-produced hybrid vehicle worldwide. Cumulative sales surpassed 3 million in 2013.

8 Tesla is a US company. Tesla is a newcomer in the automotive business, but managed to sell a fully electric sports car and a luxury sedan successfully – the sedan has sold more than 25,000 cars already – and made profits after only ten years of operation.

9 In 2009, many automobile-producing countries introduced subsidies for the purchase of new cars with the dual aim of stimulating internal demand in the financial crisis and replacing old energy-inefficient cars (Mock / Yang 2014).

10 Public and private R&D in several OECD and emerging economies is now shifting back from lithium-ion battery and BEV research to other propulsion systems, including hybrid engines, fuel cells and improved ICE technology and gas (*The Economist*, The great powertrain race, 20 Apr. 2013, http://www.economist.com/news/special-report/21576219-carmakers-are-hedging-their-bets-powering-cars-great-powertrain-race).

carbon market development or fleet emission standards) get diluted by lobbying pressure. Sooner or later, however, climate change mitigation requirements will lead to more ambitious targets. The target derived from climate change scenarios – 10g $CO_2$/km – would require a radical shift of propulsion technologies. Industry and policymakers thus need to prepare for major potential changes in automotive value chains, if there is considerable uncertainty with regard to the speed and depth of the structural change.

## 3.2 Changes in automotive value chains

Depending on the choice of powertrain and automotive architecture, automotive supply chains may change more or less radically. BEV require a range of new components, including electric engines with integrated powertrains, magnets, powerful traction batteries, inverters, charging devices and different power electronics. Suppliers of thermo-management solutions and new materials, such as carbon fibre-reinforced polymers, would also benefit from this change. On the other hand, demand will be reduced for combustion engines and related parts, including pistons and crank shafts, alternators, exhaust systems and fuel tanks. Also, BEV require less complex transmissions, with just one or two gears.

Lithium-ion batteries are by far the most expensive part of any battery-electric car, currently making up around 30% of the total cost of a passenger vehicle (acatech 2010). Batteries for PHEV and REEV can be smaller and less costly, but still constitute a major part of the value added. Producers of battery chemicals (cathode and anode materials) and components (such as separators), battery cell manufacturers and providers of battery management systems will thus capture an increasing part of the value added as the electrification of powertrains advances.

Overall, new components and new technologies will be required on an enormous scale. A recent report commissioned by the State Government of Baden-Württemberg estimates that the components of the electric powertrain (electric engine, power electronics, battery system and charging devices) will account for almost half of global automotive market expansion up to 2020, equivalent to EUR 100 billion (e-mobilBW 2010). In the same vein, McKinsey highlights that:

> *each component will have its own growth trajectory: electric engines and batteries are undoubtedly booming segments. Components that will profit from the increasing complexity (e. g. transmission and turbocharger) will continue growing in revenue through 2020. At that point, however, demand will significantly decline. [...] The increase in vehicle production will temporarily conceal the decline in pure ICE components, but it will be evident in the medium term* (McKinsey&Company 2011, 12).

The shift to electric powertrains also has implications for the architecture of cars. For example, there are multiple options for the positioning of the electric engine: it can be centrally placed, like a combustion engine, but there may alternatively also be two motors attached to the front and rear axles respectively, or four small motors placed in the wheels (e-mobilBW 2010). Likewise, the large and heavy batteries can be placed as one detachable pack to swap them when they are discharged; or carmakers can choose to build several modules built into various parts of the auto body in order to optimise weight distribution which in turn improves driving performance. Also, there may be modular designs: electric, hybrid and ICE cars can be designed in a similar way in order to exploit economies of scale in production; or radically new purpose-built e-car designs can be chosen, for example using carbon fibre and other lightweight materials instead of a steel-based chassis.

New components and new automotive architectures require new technological capabilities. Demand for capabilities in mechanical engineering and mechatronics in the automotive industries is expected to decrease, whereas capabilities in chemistry, electronics, electrical engineering and new materials will be in high demand (Proff et al. 2013). With changing requirements, the question emerges as to who will occupy these new fields of technological specialisation in the automotive supply chain. Carmakers are reconsidering their make-or-buy decisions, especially in relation to powertrain technologies and batteries. Value added is thus redistributed between car manufacturers and suppliers in different ways (acatech 2010).

Especially in battery technology, due to its high value and the fact that the technology is still at a very incipient stage of development, firms from very different industrial backgrounds have started to invest. Besides the traditional battery companies, such as Bosch, Varta and Johnson Controls, chemical companies, carmakers (often in joint ventures with leading battery producers from Japan and Korea), auto parts manufacturers as well as plant engineering and construction firms are entering at different stages of the battery value chain.[11] But the industrial reshuffle also extends beyond battery production: internationally, battery producers have started manufacturing cars (like BYD in China and Bolloré in France); tyre manufacturers (such as Continental and Michelin) produce entire concept cars; chemical companies (like Evonik) increase their auto parts portfolio; and carmakers and energy utilities venture into new mobility services, such as carsharing.

Besides system integration, the ICE engine has traditionally been a core competency of almost any large carmaker, and its specific design was a crucial determinant of the respective brand identity (Schlick et al. 2011). Battery management systems were designed according to the specific automotive architecture and engine, and therefore also contributed to the uniqueness of each model. With the shift to lithium-ion batteries and electric or hybrid engines, carmakers have to decide whether to develop the respective competencies in-house or to source them from specialist suppliers.

Unless they develop the respective capabilities, the carmaker's share of value added will decrease quite substantially. With regard to batteries, carmakers would have to dominate battery management systems and produce a substantial part of battery cells inhouse in order to maintain their current share in the automotive value chain. At the same time, carmakers may also compensate their loss in value added by moving into new activities. KPMG International (2011) suggests that carmakers engage more strongly in new mobility services which are developing in response to the range restrictions of electric driving: "*automotive companies may have to (...) coordinate the various transport modes, and ensure that their own vehicles are a central part of the offering*" (KPMG International 2011, 11). Fournier et al. (s. a.) show that this is indeed happening, with carmakers such as Daimler and PSA engaging in car-sharing and other mobility services.

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11 Interview with Mr Schulz, Evonik, Berlin, 14 Mar. 2012.

Engines and battery management systems, however, are particularly important because they are major determinants of brand identity. Hence, incentives are strong to build up in-house capabilities, or at least to be closely involved in research and industry partnerships that allow the carmaker to understand the technologies sufficiently so as to define exact product specifications and be able to assess production costs with a command over price negotiations with suppliers.

So far, carmakers are taking various different decisions regarding the desirable depth of value added. Pertaining to batteries, Daimler decided to get more deeply engaged in battery production than any other German automobile company, even producing the battery cells in a joint venture with Evonik. All other German carmakers consider battery cells as a commodity, but engage in joint ventures with battery specialists to build up expertise in battery packaging and battery management. Ford, in contrast, even sources entire batteries externally. With regard to electric motors, Daimler produces electric motors for hybrid vehicles in-house on a large scale, but currently sources electric motors for BEV from a joint venture with Bosch (Schlick et al. 2011, 11). Volkswagen intends to produce the bulk of electric motors in-house. Renault, in contrast, is purchasing electric motors from a large German supplier, Continental. BMW took equity participation in important suppliers for its carbon fibre-based BMWi-series, such as SGL carbon, in order to keep control of a new core technology (Proff et al. 2013).

These strategies reflect a period of experimentation. They may well change once BEV, PHEV and REEV technologies mature and production reach substantial scales. McKinsey also suggests a specific change of value-add depth over time:

> *at the beginning, carmakers do have a strategic interest to dominate the new xEV components to drive system performance, build up (sourcing) competence, and reduce dependency of very few electric Tier-1 suppliers . In the long run, carmakers might profit from leveraging a supplier base (McKinsey&Company 2011, 15).*

Overall, tier-one suppliers in particular seem to take advantage of the paradigm shift:

> *Many of the most sophisticated parts needed for different kinds of advanced powertrains are not made by carmakers but by a select band of high-tech suppliers, including Bosch and Continental of Germany and Denso and Panasonic of Japan. Such suppliers will enjoy growing pricing power, says Philip Watkins of Citigroup, even as suppliers of low-tech parts will continue to be squeezed by the carmakers* (*The Economist*, 20 Apr. 2013).

Continental, for example, traditionally a tyre company, invested heavily in a range of new technologies related to electromobility. It produces electric motors fully integrated in the powertrain as well as hybrid transmissions (in cooperation with another tier-one supplier, ZF Friedrichshafen AG); it also offers lithium-ion batteries and integrated powertrain management systems. Continental even built a concept electric vehicle that incorporates a range of its technologies. French competitor Michelin did the same. A similar case is Evonik, a chemical company, whose Automotive Industry Team developed an electric sports car with a light weight auto body using autoparts on the basis of structural foam and carbon fibres patented by Evonik, a battery using an own-patented ceramic-coated separator, and specific tyres developed by the company.[12]

If the reallocation of value-addition, R&D and patenting activities from OEMs to tier-one suppliers or industrial newcomers continues, it may affect the power relations in the automotive industry. Traditionally, the automotive industry has been organised in so-called producer-driven supply chains (Sturgeon / van Biesebroeck / Gereffi 2008), where OEMs as system integrators set the standards all suppliers have to comply with. The shift to electric mobility may weaken the OEM's competitive advantage and their dominant position in the automotive supply chain. Nevertheless, whether this will actually happen is far from clear. Bergek et al. (2013), for instance, find that so far incumbents seem to be winning the powertrain competition in the car industry. While most newcomers have failed, the established carmakers have shown remarkable success in developing or acquiring and integrating new technologies into their existing knowledge base.

## 3.3 New business models in niche markets and related services

The shift to electromobility requires a range of new services and therefore opens up many business opportunities outside of, but complementary to, the automotive production chain. Some address major bottlenecks of electromobility deployment and are therefore likely to become important drivers of change. As in the automotive production chain, specific technological trajectories may emerge and early movers may be able to build competitive advantages.

Five areas where new business opportunities and models are currently emerging are presented below. In all cases, however, these developments are at very early stages of development. It is therefore not yet possible to assess their growth potential, technological dynamism, or even potential for national trajectories. The following section therefore only describes them briefly.

Innovative business models are currently being tried out

1. to reduce the total cost of ownership (TCO) of electric vehicles;
2. to overcome the range problem;
3. to ensure energy supply and optimise energy usage;
4. for recycling;
5. for new niche market cars.

*(1) Business models to reduce the total cost of ownership.* The high price, stemming mostly from the additional cost of lithium-ion batteries, is one of the main reasons for the slow uptake of electric vehicles. Battery prices currently add more than EUR 10,000 to the purchase price of a BEV, depending on their size. Several German carmakers are

12 http://corporate.evonik.de/de/presse/pressemitteilungen/pages/news-details.aspx?newsid=25088

considering following Renault's example and leasing the battery or renting it at discount rates. Also, analysts predict that business models will shift *"from owning a car to using its mobility"* (Markus / Mikko 2010). Car-sharing is being widely debated as an option for increasing attractiveness, especially for urban users.[13] Especially for energy utilities, the shift to electromobility opens up new business opportunities *"as electricity in cities becomes the primary source of power for moving people"* (KPMG International 2011, 11). Car-sharing may also be a way to accelerate the diffusion of electric vehicles, especially for newcomers who do not have established distribution systems to compete with the large carmakers. The French company Bolloré has developed a BEV ("Bluecar") which can only be rented through a regional car rental in Ile de France which runs more than 2,000 Bluecars in the area. Bolloré is currently expanding into other French cities employing the same business model (Schamp 2014).

*(2) Business models to overcome the range problem.* Limited range and long charging intervals are the second big impediment for BEV deployment. The term 'range anxiety' describes the fear of getting stranded with a discharged battery. Moreover, the inconvenience of having to wait for several hours to fully recharge a battery holds potential customers back from switching to electric driving. Pilot projects concluded that the current charging station model is unlikely to succeed, also because charging stations are expensive as they contain software and need to be designed in a way that they are very resistant, for instance to vandalism. Also, several (Germany: 9) permits are needed to operate a charging station. In addition to improvements in batteries, range extenders and other technological solutions within the car, several systemic solutions are currently being explored to overcome the problems of limited range and inconvenient recharging intervals:

- The battery swapping model is an option to avoid long charging intervals. It implies that discharged batteries are swapped in exchange stations for fully charged batteries. The battery can even by owned by the respective service provider, thereby reducing the capital cost for consumers. This would presuppose a high degree of standardisation of batteries and the way they are mounted in the car. The business model was developed by the company BetterPlace and tested in Denmark and Israel, and it has also been tested by a Chinese consortium in Hangzhou. In Germany, the idea is widely rejected because carmakers design specific batteries suited to the requirements of each model. Batteries are thus a major determinant of brand identity. Also, it is not possible to establish whether the batteries exchanged are of equal quality. In fact, BetterPlace went bankrupt in 2013, and it remains to be seen whether the idea works with less demanding vehicle fleets in China or elsewhere.

- Inductive charging is a technology that uses an electromagnetic field to recharge a vehicle without having to plug into an electric grid. Electric charging can be done in a fixed charging station, e. g. when buses stop for some time at their terminal station; or it can be done when the vehicle is running, provided that an induction coil is built into the road under the surface and power is taken up by vehicles equipped with a second coil which drive on the road. Inductive charging is a way of avoiding the

13 Between 2000 and 2012, global membership of car-sharing pools increased from 0.1 to 1.9 million members: http://thecityfix.com/blog/on-the-move-car-sharing-scales-up-heshuang-zeng/global-growth-car-sharing-embarq/.

inconvenience of long charging periods, but it is still far from commercial maturity due to reasons of safety, energy losses and cost of infrastructure cost.

- Intermodal transport refers to the combination of two or more modes of transport in one journey. By combining a high-speed, high-range mode (such as trains) with lower-speed local transport devices (electric cars, bikes) in a smart way, journeys can become faster and car travel less attractive. This implies business models that provide the local means of transport as well as software solutions to plan, book and pay intermodal journeys. These concepts are likely to develop in diverging country-specific trajectories due to different cultural norms regarding car ownership, status, etc.

*(3) Business models for improved electronic communication* between cars, grids and charging stations to make electromobility more user-friendly and to harmonise the requirements of transport and electric grids. Bosch has acquired two start-ups, INST and Inubit, which develop software that integrates information such as where charging stations are located, whether charging sites are available, other transport means, topography, etc. This is being tested in a field trial in Singapore. Several small start-ups are developing smart charging and billing software which allows car users to pay electricity from their smart phones. Both large carmakers and small start-ups develop cloud services for smart transport systems. Last but not least, energy supply from renewable sources shows substantial fluctuations, thus grid stability is an important issue. If electric cars use energy at times when renewable production is abundant, it can help to stabilise grids. At a later stage, it may even be possible to feed energy back from the battery to the grid. Software is thus needed to make the vehicle grid-friendly, for example, ensuring that grids cannot collapse when too many vehicles charge at the same time. In sum, automotive communication that integrates Global Positioning System (GPS), smart phones, etc. is a growing market, with many applications related to electromobility.

*(4) Business models for recycling.* Recycling may also hold a number of interesting innovations, because of the high cost and scarcity of key materials such as lithium and rare earths which are increasingly needed for energy storage and IT solutions. Also, new lightweight materials require valuable scarce resources. Carbon fibres may replace many steel parts in the future. Production of these fibres is expensive and energy intensive, so concepts to recycle, reuse or develop secondary use options are a major issue. The challenge is to create a closed loop recycling management (NPE 2010).

*(5) Business models for new niche market suppliers of electric cars.* Some new car producers have taken advantages of the paradigm change, producing electric cars in small series for niche markets. International examples – Tesla in the United States, Bolloré in France – show that new electric vehicle concepts may become successful business models. So far, however, most newcomers have gone bankrupt or failed to secure funding for a large-scale roll-out of their car models (e. g. Bergek et al. 2013, 1217).

The following two sections provide evidence from Germany: Section 4 provides background information on characteristics of the automotive industry, the policy framework, and recent electric vehicle market trends. Section 5 then discusses how technological trends, value chain relations, and business models are changing in Germany and to what extent we can identify country-specific technological pathways towards electromobility.

# 4 Germany: industrial characteristics, policy framework and market trends

## 4.1 Key characteristics of the German automotive industry

Germany is the 4th largest automobile-producing country, the largest exporter of automobiles and home to some of the globally leading car manufacturers. In 2011, sales amounted to EUR 351 billion, and the industry employed 720,000 persons in Germany. 6.3 million automobiles (7.8% of global production) were produced in Germany. 77% of all passenger vehicles manufactured in Germany were exported. German carmakers are highly internationalised and produce most cars outside Germany. 14.2 million cars (17.7% of global production) were produced by German firms.[14]

This success is based on a particularly competitive automotive innovation system in Germany. The country hosts several of the globally leading OEMs, including Daimler, BMW and the Volkswagen Group, which owns Audi, Porsche and other high-end brands. In 2011, German carmakers and suppliers jointly invested EUR 22 billion annually in R&D, more than any other industry.[15]

OEMs have a strong tendency to outsource parts and components and to specialise in system integration, branding and marketing. At the same time however, this implies the need for close collaboration in product development (Lange 2010). Germany is home to large automotive suppliers such as Bosch, Continental and ZF Friedrichshafen AG as well as hundreds of medium-sized auto parts producers, all of which make substantial R&D investments. Suppliers account for more than 70% of the value added of a car manufactured in Germany. Germany is characterised by several regional automobile clusters grouped around the major OEM locations which host a multi-tier system of supplier firms, many of whom are global players themselves. Moreover, Germany is known for its dense network of highly specialised research institutions (including the network of Fraunhofer institutes) which have a long tradition of collaborative research with the automotive industry.

The German car industry’s competitive edge is particularly in high-priced and highly-powered vehicles. In value terms, the share of German manufacturers in the global automotive market is therefore even larger than in terms of automobiles produced. Table 2 compares the average price of some German and international car brands. It shows that German brands BMW, Mercedes and Audi cost about twice as much as the main Japanese, French, Korean and Italian brands. It should also be noted that other high-end brands, including Porsche, Bentley, Bugatti (Volkswagen Group) and Rolls-Royce (BMW) are also owned by German manufacturers. German carmakers are clearly overrepresented in the luxury and upper middle-size classes. These (and Sport Utility Vehicles (SUV)) are also the segments with the largest increase in production in Germany.[16] Also in the smaller car categories, German manufacturers dominate the so-called premium segment, that is, they sell in the highest price range.[17]

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14 http://www.vda.de/de/zahlen/jahreszahlen/automobilproduktion/index.html

15 http://www.vda.de/de/meldungen/news/20130102-2.html

16 ibid.

17 http://www.autovalue.de/files/120125_automotive_keynote_ihs_neujahrsprognose_2012_auszug.pdf

**Table 2: Average price (2012) of new cars sold in Germany (catalogue price): German* versus select international brands**

| Brand | Average price (EUR) |
|---|---|
| Mercedes* | 40,170 |
| BMW* | 40,039 |
| Audi* | 37,168 |
| Volvo | 34,921 |
| Volkswagen* | 23,740 |
| Mini* | 23,179 |
| Ford | 21,819 |
| Nissan | 20,922 |
| Peugeot | 20,660 |
| Toyota | 18,173 |
| Renault | 17,914 |
| Hyundai | 17,173 |
| Fiat | 14,651 |

Source: http://www.wiwo.de/unternehmen/auto/neuwagenpreise-so-teuer-sind-unsere-autos-wirklich/8342956.html

Due to this specific profile of the German automotive industry, $CO_2$ fleet emissions of German manufacturers are clearly above the EU average. The Mercedes Benz fleet has the highest emissions among all major brands in Europe, and BMW and Audi are also clearly above the European average (ICCT 2012). Also as a country, Germany has the highest average emissions in the EU (147g $CO_2$/km compared to an EU27 average of 136g (ICCT 2012)). Achieving the EU's 2015 target (of 130g $CO_2$/km) is therefore particularly challenging for the German industry. The threat is further aggravated by the fact that German manufacturers largely missed out on two low-carbon technology developments:

- Germany (both the private sector and publicly funded science) almost fully abandoned R&D on battery technologies when the consumer electronics and optical industries shifted to Asia in the 1970s.[18] Supported by major publicly funded R&D programmes, Germany's industry had pursued alternative technologies, including fuel cells. At the end of the last decade, lithium-ion batteries used for electronic goods (such as laptops and mobile phones) improved their performance radically and emerged as a promising option for traction batteries in electric cars. This greatly raised the expectations regarding battery-electric cars, which was perceived as a major competitive threat by the German automotive industry: if electric cars were to become a viable alternative to ICE cars, lithium-ion batteries would make up an enormous part of the value added of a car, and in this technology Germany had fallen far behind Asian competitors.

18 Interview with Dr Randolf Schließer, VDI/VDE, Berlin, 9 Nov. 2011.

- Japan (and Toyota in particular) had invested in hybrid car technologies early on. Toyota launched the HEV Prius model in Japan as early as 1997. Germany had largely missed out on this development also.

Thus, Germany's automotive industry has to strike a difficult balance between exploiting its competitive edge in high-end markets and achieving emissions targets.

## 4.2 Germany's policy environment for electromobility

In Germany, electromobility policies mainly reflect two objectives: climate change mitigation, and more specifically the transition to a renewable energy-based energy system ('*Energiewende'*); and the strengthening of the German automotive industry, a traditional backbone of the German economy. The competitive strength of this industry is in high-powered cars for high-end markets, which are above-average carbon emitters. Protecting and supporting this industry thus often conflicts with mitigation targets. German policymakers hence have to strike a fine balance between these objectives – and concrete policies are sometimes fairly contradictory.

- While *climate change mitigation* (and specifically the shift to a renewable energy-based energy system) is high on the political agenda, car traffic is one of the main sources of emissions, accounting for 14% of $CO_2$ emissions in Germany (Bundesregierung 2009, 8). With the decision to phase out nuclear energy and accelerate the shift to renewables, Germany has become a trendsetter in energy policies. The *Energiewende* is the most ambitious objective of the current government. This also has ramifications for electromobility. As argued earlier, shifting to electric driving only makes sense from a climate change mitigation perspective when electricity comes from low-carbon sources. This sets Germany apart from some other large automobile-producing countries, including China (where reducing urban air pollution is the main driving force for electromobility and an energy supply from coal-fired power plants outside city boundaries is politically accepted); and, having decided to phase out nuclear energy, Germany's focus on renewable energy as the only acceptable source of energy for electric driving calls for a policy agenda that is also different from that of countries like France which regard nuclear energy as an acceptable option. The environmental agenda is also strongly backed by the European Commission which requires all European manufacturers to bring fleet-average $CO_2$ emissions down to 130 g/km by 2015 and 95 g/km by 2021. The European Commission also adopted an obligatory target of 10% renewable energy sources in transport fuel by 2020.

- At the same time, there are huge concerns about maintaining or even enhancing Germany's *competitiveness in the automotive industry*. Germany is the 4th largest automobile producing country and the world's largest exporter of automobiles. Being ahead of the competitors and making sure that the latter do not take advantage of the paradigm change to break into markets traditionally served by the German industry is therefore a central concern shared by industry and government. The competitive threat is particularly relevant given the German car industry's strength in producing executive and luxury cars with above-average $CO_2$ emissions.

Maintaining this competitive edge and protecting this industry's interests without undermining Germany's credibility as a global champion in the climate change mitigation debate is a difficult challenge. In fact, policy signals are strongly contradictory. On the one hand, the German car industry successfully lobbied the national government to push for less ambitious European $CO_2$ emission targets for new passenger cars.[19] As Box 2 shows, a number of exceptions and additional incentives have been attached to the programme to reduce the mitigation pressure on manufacturers of high-emission cars. Likewise, Germany's conservative political majority supported the decision of the European Parliament not to rescue the European carbon market after carbon prices had fallen, due to oversupply of quota, from EUR 30/t $CO_2$ in 2008 to about EUR 5 in 2013. As a result, the EU Emissions Trading System (ETS), formerly a declared cornerstone of the EU's environmental policy, has now, according to analysts, become *"irrelevant as an emissions reduction tool for many years to come."*[20]

**Box 2: $CO_2$ emission targets for new passenger cars**

The European Commission adopted $CO_2$ emission targets for passenger cars on 23 April 2009. The regulation established a fleet-average $CO_2$ emission target of 130g/km to be reached by 2015. The regulation also defines a long-term target of 95g $CO_2$/km to be reached by 2021. The regulation is phased-in over the period from 2012 to 2015. Manufacturers must meet their average $CO_2$ emission targets in 65% of their fleets in 2012, 75% in 2013, 80% in 2014, and 100% from 2015.

However, some exceptions and additional incentives apply, such as:

- The above targets are applicable to vehicles of an average mass, while lighter cars have lower $CO_2$ targets and heavier vehicles have higher $CO_2$ targets.
- Vehicles of $CO_2$ emissions below 50 g/km receive super-credits. Each such vehicle is counted as 3.5 cars in 2012 and 2013, as 2.5 cars in 2014, 1.5 cars in 2015, and as 1 car from 2016 onwards.
- $CO_2$ emissions of vehicles capable of running on a mixture of gasoline with 85% ethanol (E85) are reduced by 5% until the end of 2015.
- Several manufacturers may form a pool to jointly meet their $CO_2$ emission targets.

Source: Adapted from http://www.dieselnet.com/standards/eu/ghg.php

On the other hand, the German government initiated a coordinated policy initiative to accelerate the search for new electromobility solutions. This coordinated electromobility policy took shape between 2008 and 2010. In 2008, a National Strategy Conference on Electromobility was held. In 2009, the National Electromobility Development Plan (Bundesregierung 2009) was approved and the fiscal stimulus package to mitigate the financial and economic crisis, an EUR 500 million R&D programme, was launched. The National Plan recognised the need to set up a body for stakeholder consultation and to appoint working groups for dealing with specific open questions. This was done in 2010

19 In late 2013, the Quandt/von Klatten family, principal shareholders of BMW, donated EUR 690,000 to the Christian Democratic Party (CDU) a few days before the CDU-led government blocked the adoption of more stringent emissions standards at a meeting of EU Ministers of Environment in Luxemburg. http://www.spiegel.de/wirtschaft/soziales/was-die-deutschen-autolobbyisten-in-bruessel-erreichen-a-844098.html.

20 See *Financial Times* 13 Apr. 2003: http://www.ft.com/cms/s/0/4557f206-a5ea-11e2-9b77-00144feabdc0.html#axzz2Qjmh5XAd.

when the National Platform Electromobility (NPE) was created. Four ministries formed a steering committee and established a joint secretariat.

The objective was formulated to make Germany a lead market (*Leitmarkt*) and market leader (*Leitanbieter*) for electromobility (NPE 2012). Also, a (non-binding) target was set to put *“one million electric vehicles on the road by 2020, possibly reaching over five million by 2030. By 2050, most urban traffic will be able to do without fossil fuels”* (ibid., 17). For the period 2011–2020, three development phases were specified: market preparation until 2014; market establishment until 2017; and starting mass manufacturing after that date.

The lead market idea suggests that Germany become

> *a market that serves future demand trends at an early stage – it performs a leadership function by translating innovative concepts earlier than elsewhere into marketable products and services (which are accepted by customers). This enables the branches of industry involved to gain competitive advantages, particularly on international or global markets* (ibid., 47).

To develop the lead market, incentives were announced to improve electricity supply and grid interfaces, homogenise technical standards, develop infrastructure facilities und user privileges for e-cars, and to adapt public procurement guidelines. Market leadership would thus follow from lead market conditions and would further be promoted through stakeholder coordination and regional pilot projects as well as targeted supply-side support for R&D and vocational training.

The NPE plays a core role as a strategic coordinator and facilitator. The platform has 147 members including all the main industrial players – carmakers, parts and component manufacturers, the chemical industry, energy utilities and others – as well as ministries, research institutes, industry associations, unions, environmental NGOs, the German automobile club, and others. It established seven thematic working groups:

- Powertrain technology and systems integration
- Battery technology
- Charging infrastructure and grid integration
- Norming, standardisation, certification
- Materials and recycling
- Training and qualification
- Framework conditions.

All these groups are largely private-sector driven. Each consists of some 20 expert members, mainly top managers from the relevant industries, some leading researchers and one or two representatives of civil society organisations. Each group prepares annual reports which take stock of the industrial situation and identify research and policy gaps.

All stakeholders interviewed have assessed the role of the NPE positively. Interviewees highlighted the insights gained from strategic discussions across different fields of technology and mentioned a range of practical instances of cooperation, from joint applications for research projects to longer-term strategic partnerships among firms from different industries, resulting from the coordination process.[21] Also, the wide range of stakeholders has so far avoided specific interest groups imposing their views and lobbying for preferential treatment.[22] Also, cooperation among the four ministries seems to work fairly well.

There are strong statements in the policy documents that Germany will pursue a technology-open, industry- and research-driven experimental policy. Interviewees reported a broad consensus within the NPE to support R&D and pilot projects rather than employing funds for purchasing subsidies or big public procurement projects, which play a large role in France and China, for instance. The carmakers' association VDA (Verband der Automobilindustrie) pushes for such subsidies, but analysts doubt that national subsidies would have a significant influence on German carmakers' investments, as they increasingly manufacture 'world cars' for global markets. Home market conditions, including the level of domestic subsidies, are therefore becoming less and less decisive for their R&D and production strategies.[23]

One major element of the Federal Government's National Electromobility Development Plan is decentralised experimentation. Three decentralised policies are being supported:

*(1) Showcases* (*Schaufenster*): Already under the fiscal stimulus package for the German economy, EUR 130 million had been allocated for trials in eight regions throughout Germany whose main aim is to sensitise the population and test business models and outreach. They are testing charging infrastructure, consumer behaviour, logistics solutions for company fleets, inter-modal traffic concepts linking public and private mobility services, and so on and are typically implemented by alliances involving energy utilities, carmakers, and city governments. In October 2011, a tender was published whereby regions were called to submit *showcase* proposals. In April 2012, four regions were then chosen for support (Baden-Württemberg, Bavaria/Saxony, Berlin/Brandenburg, and Lower Saxony) and a total of EUR 180 million earmarked for these regions (NPE 2012). In addition to learning from experimentation, their main function is to enhance the visibility of electromobility and offer consumers the opportunity to test vehicles. So far, the regional experiments have shown, for example, that fleets are promising entry options for electric cars because of limited range and circulation from a home base where vehicles can be recharged overnight, etc. Given that about 10% of Germany's cars belong to company fleets[24], this market should not be underestimated. Also, car-sharing and intermodal traffic solutions have emerged as promising entry points to e-mobility in Germany.

*(2) Leading edge clusters (Spitzencluster):* As part of its national High-Tech Strategy, the German government launched a 'Leading-Edge Cluster Competition offering EUR 40 million of funding for each region for a five-year period. Three competitions were held

21 Mr Schulz, Evonik, Berlin, 14 Mar. 2012

22 Ms Ott, Bureau of the National Platform Electromobility, Berlin, 9 Nov. 2011

23 Dr Andreas Gutsch, Karlsruhe Institute of Technology, Karlsruhe, 16 May 2012

24 Professor Martin Wietschel, Fraunhofer ISI, Karlsruhe, 11 May 2012

between 2007 and 2012 recognising a total of 15 regions as ‘leading edge clusters’. In the latest round in 2012, two clusters in the field of electromobility won this competition: The “Electromobility South-West” cluster and and the “M.A.I. Carbon” cluster in the Munich-Augsburg-Ingolstadt. The former comprises some 80 companies and research institutes in Germany’s main automotive region, hosting Daimler, Bosch and Porsche and many suppliers. The latter aims to develop carbon fibre-reinforced polymers (CFRP) which offer lightweight solutions replacing steel and aluminium. Here, 70 important players are involved, including Audi, BMW, SGL Carbon and some aerospace companies. Cluster activities include research alliances, local implementation of pilot schemes, facilitation of international network, etc.

*(3) Technological beacons (Leuchttürme):* The NPE’s second summary report defined six beacon projects for R&D funding (batteries; powertrain technology; ICT & infrastructure; vehicle integration; light materials; and recycling) and industry-science consortia were encouraged to apply for projects. The scope for financial support decreased however because funding depended on tax income from emissions certificate trading, which largely broke down in Europe.

By international comparison, Germany’s support package is not particularly voluminous. Targeted R&D subsidies for electromobility are lower than those offered in the United States, China, France and Japan; there are no government subsidies for the purchase of e-vehicles; and the government has little influence on the procurement strategies of large state-owned or private enterprises. This contrasts with France and China, where big purchase subsidies are offered[25] and corporations nudged to purchase large fleets of electric vehicles (Altenburg / Fischer / Bhasin 2012).

## 4.3 Electric vehicle market development

Deployment of electric vehicles in the German market is slow by international comparison. In early 2014, only 0.02% of German passenger car stocks were BEV, and all hybrid cars together accounted for just 0.19 % of the market.[26] 10,500 BEV and PHEV were sold between 2010 and 2013, compared to 28,500 in France. The United States are by far the largest and most dynamic market for electric cars, with a stock of 260,000 in early 2014.[27] Given this slow uptake, the German government’s original target of one million electric vehicles by 2020 has been revised downward to 600,000 (Proff et al. 2013).

So far, the German automotive markets as well as the German OEMs have been late adopters of electric and hybrid powertrain technologies. Plötz et al. (2013) have calculated the market expansion for electric vehicles, assuming total cost of ownership as the main determinant of consumer choice, and creating several scenarios with different assumptions about electricity, fuel and battery prices. Their predictions for 2020 vary between 150,000-200,000 electric vehicles sold in Germany and more than one million. This enormous

25 In France, purchase subsidies amount to EUR 6,300 per BEV (Schamp 2014).

26 http://www.kba.de/DE/Presse/Pressemitteilungen/2014/Fahrzeugbestand/pm10_fz_bestand_pm_komplett.html?nn=716842

27 http://en.wikipedia.org/wiki/Electric_car_use_by_country#Germany

range shows to what extent uptake of electric vehicles depends on the evolution of relative market prices of energy inputs. Predicting their evolution over the next two or three decades is thus not easy, but this may quickly change.

Furthermore, the uptake of electromobility innovations may quickly accelerate in response to any of the potential game changers discussed earlier. Progress in battery performance and price as well as the tightening of fleet emission standards are most likely to accelerate electric vehicle technology diffusion. In fact, the latest developments suggest that German industry will now seriously engage in electric vehicles. Many new HEV, PHEV and BEV models have been launched in 2013 and 2014, and McKinsey's Electric Vehicle Index of April 2014 sees Germany emerging as a global lead provider for electric vehicles. Based on 5-year production forecasts, the launch of new models and R&D expenditure, the report expects Germany to produce 460,000 units per annum by 2019, overtaking the current leader Japan (McKinsey&Company 2014). How realistic these forecasts are depends, of course, on the game changers.

# 5 Emerging patterns of specialisation in the German automotive and related industries

Having reviewed Germany's industrial specialisation and policy framework, we can now come back to the initial questions of how, and to what extent, country-specific initial conditions predetermine the selection of technological alternatives, thereby giving rise to national technological pathways towards electromobility. Before we try to extract key elements of Germany's emerging pattern of competitive specialisation, we will briefly touch upon the question of to what extent *national* technological pathways still play a role in an increasingly globalised industry (5.1). Following this, we will – based on firm-level sources and expert interviews – assess whether being latecomers to electromobility is likely to harm German carmaker's competitive ambitions (5.2), before we sketch out two key aspects of German OEM's competitive electromobility strategies: a unique product strategy with a main focus on upmarket hybrids (5.3), which we exemplify using the example of BMW's i-series (5.4); and efforts to achieve cost advantages via aggressive modularisation and standardisation (5.5). The final subsection captures some emerging service activities related to electromobility (5.6).

## 5.1 Putting 'national technological pathways' into perspective

Before we delve into the exercise of identifying nation-specific technological trends, two important caveats are pertinent:

- First, given the very recent trend towards electric powertrains, the emerging patterns of specialisation described in this section are just starting to take shape. Both globally and in Germany, a lot of experimentation is going on with a range of competing technologies and business models. Furthermore, as argued in Section 4, there is still enormous uncertainty, not only about technological trends, but also about political and economic framework conditions. Thus, one cannot make reliable predictions, at this stage, of which of those will actually emerge as the dominant characteristics of the German pathway to electromobility.

- Second, the notion of *national* pathways has its limitations. While technological choices are shaped by country-specific regulations and consumer preferences, established local industry clusters or national traditions of how the research system interacts with the private sector, these national characteristics are overlaid with international dynamics. The German automotive industry is highly globalised in every aspect: German-owned OEMs produce more cars outside Germany than within; most of the cars produced in Germany are sold to foreign customers; German carmakers own many traditionally foreign brands; and they are engaged in a multitude of joint ventures all over the world. The same applies to the German-owned supplier industry. Last but not least, cars are increasingly conceptualised for global markets, using the same platforms and components in all markets. Thus, while home market conditions still have some influence on carmakers strategies, the complex interactions between national innovation systems and globalised production networks need to be taken into account. Furthermore, the strategies of German-owned carmakers are far from homogeneous.

With these caveats in mind, however, our international research project on technological trajectories for low-carbon innovation (see Introduction) unambiguously reveals distinctive national patterns. In all the four countries studied (China, Germany, France, India) the shift to electromobility follows quite dissimilar technological trajectories reflecting differences in home-market demand conditions, levels of technological capabilities and political preferences. Some of the national trends identified are already clearly reflected in production or patenting trends. For example, there is a clear difference between Germany's trend to introduce hybrid powertrains in highly-priced models, whereas French producers are launching a range of simple, functional and affordable BEV and have a competitive edge in diesel hybrids (Schamp 2014). China offers a market for unsophisticated low cost range-extended vehicles, electric two-wheelers powered by lead batteries, and low speed/low voltage cars for low income consumers. Also, battery swapping is being tested as a serious option in China (Chen et al., forthcoming), but is disapproved of almost unanimously by all stakeholders in Germany. India is also developing innovative electromobility solutions mainly in the low-cost segment, including hybrid two-wheelers (reflecting the frequent power blackouts that make pure electric driving unattractive) and plug-in hybrid conversion kits which add a small electric motor to an existing ICE car as well as electronic control systems to optimise the operation of electric and ICE power. Indian carmakers also offer a simple intra-city car, intended as the second car for a family, which can mainly be charged at home (Chaudhary 2014). We may thus summarise that, even when production networks are increasingly global, country-specific initial conditions strongly influence the way the transition to electric drive technologies evolves.

Germany's automotive industry, and the innovation system in which it is embedded, display a number of special characteristics:

- A very long history of automotive innovations (the automobile was invented in Germany), and a long tradition of customers demanding innovations.

- A high-performing, R&D-intensive and collaborative automotive innovation system.

- A high degree of internationalisation, both in terms of foreign direct investment and exports.
- Very successful competitive specialisation in high-powered vehicles for high-end markets.
- Above-average fleet-emissions and therefore special pressure to increase carbon efficiency without sacrificing the competitive advantage in high-end markets.
- A latecomer situation with respect to hybrid and battery-electric cars.
- A gap in the innovation system regarding (lithium-ion) battery technology.
- A peculiar role of national politics, which on the one hand encourages nuclear phase-out and supports renewable energy (also as the source of electricity for cars) and other low-carbon technologies more than most other OECD countries, but on the other hand lobbies against EU low-carbon legislation in order to protect the interests of certain domestic high-carbon companies (not least the automotive industry).

Not all of these characteristics are unique. For example, the Japanese and Korean automotive industries share some of the strengths of the German system; other European car-producing countries are also latecomers to electromobility, etc. The strong competitive specialisation in high-end markets, in contrast, is something that sets Germany apart from all other car-producing countries. Most importantly, the *combination* of these characteristics is what makes the German automotive innovation system unique.

## 5.2 German carmakers: from late adopters to market leaders?

Germany's automotive industry has been a very late adopter of HEV technology and is not among the early movers in PHEV and BEV either. Yet most large carmakers – in Germany as elsewhere – have been working on concept cars for quite some time. BMW was the first German manufacturer that produced more than 500 electric cars (the Mini E) as demonstration cars to be used in international fleet trials, but these were simple adaptations of the traditional Mini Cooper and not purpose-built electric cars. For example, the heavy battery was just stored in a traditionally designed car rather than changing the entire architecture of the car so as to optimise weight distribution and roadholding. International competitors were about two years earlier than German carmakers in launching commercial serial production of electric cars. With BEV, Mitsubishi, Nissan, Peugeot, Citroen, and the Chinese BYD all launched series production in 2011. The Smart ForTwo Electric Drive was the first German-built follower, launched in 2012. Volkswagen and BMW only launched their first BEV in 2013.

Toyota, which had pioneered HEV development, is also the first producer of a mass-manufactured PHEV starting in 2012. In Germany, Opel (which belongs to General Motors) launched a REEV vehicle, the Ampera, in 2011. Some hybrid cars are already offered in the premium segment, including by BMW, Porsche, Daimler and Audi. A Volkswagen Golf PHEV is announced for 2014 which is expected to become the first serious competitor for Toyota in this segment (see Table 3).

German carmakers including Mercedes, Volkswagen, Audi and Opel, but also international competitors like Toyota, have recently revised their electric vehicle targets down, particularly in the segment of BEV. Several BEV projects were stopped shortly before the

**Table 3: Market introduction of PHEV and BEV by German OEM compared to early movers (year of first commercial series)**

| | **Early movers** | **German manufacturers** |
|---|---|---|
| PHEV (Plug-in hybrids) | Toyota Prius Plug-in (2012) | Daimler S500 Plug-In (2014),<br>BMW i8 (2014),<br>Golf PHEV (2014) |
| REEV (Serial hybrid) | Chevrolet Volt (2010) | Opel Ampera (2011),<br>BMWi3 (2014),<br>Audi A3 e-tron (2014) |
| BEV (Battery-electric) | Tesla Roadster (2008),<br>Mitsubishi i-MiEV (2009)<br>Nissan Leaf (2010),<br>BYD e6 (2010),<br>Renault Fluence Z.E. (2011) | Smart ForTwo ED (2012),<br>VW E-Golf (2014),<br>VW EUp (2012) |

Source: emobilBW 2010 (press reports)

planned serial production, including Opel's small e-car Adam and Audi's R8 e-tron sports vehicle and its A2.[28] This happened for economic rather than technical reasons. Lithium-ion battery costs did not decrease as expected, and battery life time – and thus guarantee risks – can hardly be anticipated. At the current price of production, electric cars are not saleable in considerable volumes. Nonetheless R&D efforts continue, indicating that carmakers do believe in BEV and PHEV as important powertrain technologies of the future – firstly, because battery performance is expected to improve considerably, even if progress has been slow; and secondly because emissions standards will be tightened over time. According to the NPE, German industry is investing up to EUR 17 billion in electromobility during the market preparation phase (2011–2014) alone.

> *German carmakers alone invest 10–12 billion € in the development of new powertrains, of which 80% go into electromobility. [... ] More than 15 new electric car models from German manufacturers will be on sale during the market preparation phase. Each model corresponds to several hundred million € investments throughout the entire automotive industry* (NPE 2012).

German carmakers are not afraid that their late entry into BEV and PHEV manufacturing may turn out to be a competitive disadvantage. Toyota's early mover advantage in hybrid technology is generally acknowledged, but the two-year head start of other manufacturers in BEV and PHEV s not seen as a problem. The sales of all early movers are fairly low, and uptake is slower than expected. None of the pioneering models has sold sufficiently well so far as to recover development costs. Developing a new automotive architecture specifically designed for BEV or PHEV costs in the range of EUR 200–300 million, and enormous

28 http://www.wiwo.de/technologie/auto/serienproduktion-gestoppt-warum-audi-beim-a2-und-r8-den-stecker-zog/7396966.html; accessed 28 Apr. 2013.

economies of scale are needed to amortise these investments.[29] An OECD study underlines the enormous importance of economies of scale, arguing that

> *for example, with Deloitte's medium forecast (i. e. total sales of 465,000 electric vehicles in the United States in 2020), with five main competitors on the market and two electric models offered by each, this means production per model of only 46,000, a volume far too small to effectively trigger scale economies and to recoup development and manufacturing investment* (OECD 2011, 194).

Given these enormous costs, one Volkswagen manager argued that it was a deliberate company decision *not* to be an early mover. Volkswagen's strategy is instead to enter when the demand conditions allow for economies of scale and the technology is sufficiently mature to ensure the same driving comfort as an ICE car. Market leadership will then be pursued by reducing production costs through modularisation and standardisation.[30]

It remains to be seen to what extent early movers benefit from their opportunity to learn from having the first generation of electric cars on the streets. VW has about 140 electric Golf vehicles in fleet trials, and BMW provided 500 Mini E for pilot projects in several countries. The German carmakers are confident that this provides enough insights about user profiles and technological challenges to catch up with the first movers. McKinsey's Electric Vehicle Index reflects this optimism, suggesting that German carmakers will take the lead within the next five years.

## 5.3 Competitive electromobility strategies of German carmakers

The competitive edge of most German carmakers lies in large, powerful and sportive hi-tech cars that offer driving pleasure to better-off customers. Germany's producers of premium cars can therefore hardly be expected to push for decarbonisation proactively. The need to reduce fleet emission standards, however, is a reality they have to face. Also, as German producers depend on overseas exports, they closely observe international trends towards stricter emissions standards or inner-city restrictions and congestion charges imposed on ICE vehicles in megacities.[31] The challenge for Germany's up-market automotive industry is thus to strike a fine balance: To comply with fleet-average emission standards, keep up with new technological developments, and offer zero-emissions megacity vehicles to new customer groups while at the same time *"securing the social acceptance of large/high performance vehicles"*, as a BMW manager puts it (Kell 2010), and protecting their up-market brand images.

29 Dr Lars Hofmann, Volkswagen AG, E-Traction Unit, 23 Oct. 2012

30 ibid.

31 For example, limiting access to city centres to low-emission cars or restricting the number of licenses for cars that are allowed to circulate in megacities and assigning them on the basis of CO2 emissions (KPMG International 2011).

The response of Daimler, BMW and the Volkswagen Group (which includes Audi and Porsche, among others) to the electromobility challenge is a fairly similar product strategy resting on four pillars:[32]

1. In the short run, the main emphasis is on optimisation of ICE technology through improved gears and aerodynamics, reducing driving resistance, recuperation of breaking energy, better thermo management, etc. In the case of BMW, such incremental innovation allowed fleet $CO_2$ emissions to be reduced by more than 25% between 1995 and 2008 (Kell 2010).

2. All big manufacturers also pursue the development of hydrogen and fuel-cell technology as a medium to long-term alternative.

3. A range of hybrid models – HEV, PHEV and REEV – is offered in most, or even all, vehicle classes. In the medium- and luxury class, the focus is on hybrid models. The strategy here is to add hi-tech solutions and enhance driving pleasure rather than reducing motor power, energy-intensive functions or otherwise compromising on performance. BMW for example promotes its futuristic BMWi8 sportscar as a 'green lifestyle car' that offers fun and extravagance for well-off urban consumers, not primarily as a low-carbon solution for typical ecology-minded consumers (see below).

4. A small number of pure BEV in the segment of small and compact cars which are seen as a way of completing the product portfolio, testing the emerging BEV market and earning 'supercredits' which help to reduce the calculated fleet-average emissions – remember that carmakers are allowed to count electric vehicles and hybrid vehicles as low-emission vehicles several times. Also, a market for BEV is seen in the medium-sized segment for commercial fleets that serve regular short distance deliveries (Plötz et al. 2013).

Only the third and fourth pillars relate to electromobility and will therefore be analysed in detail here.

Germany's carmakers are torn between two strategic targets: *On the one hand,* they are highly specialised in luxury and upper-middle class cars (see Sub-section 5.1 above). This is particularly the case with Daimler, BMW, Audi and Porsche. What is more, these are the markets where German exports are growing fastest,[33] benefitting from the rapidly increasing number of wealthy consumers in emerging markets. Also, the up-market segment is likely to deliver innovation rents in the longer term because few international competitors have the capabilities to compete at this level, whereas price competition is very stiff in the lower product categories. Reducing motor power or extra equipment would be incompatible with the target group's expectations. Thus, carbon efficiency is pursued through innovative technical features. As a Volkswagen manager states, *"... we're launching a Touareg hybrid in 2011, which is still a powerful car. Most customers*

32 See, for instance, Ulrich Kranz, head of project i at BMW: http://verantwortungzukunft.fazinstitut.de/sites/verantwortungzukunft.de/files/images/VZ_E_Paper_297x210_Ausgabe_2_2012_RGB_BMW_Interview.pdf.

33 http://www.vda.de/de/zahlen/jahreszahlen/automobilproduktion/index.html

*want to be environmentally friendly but don't want to compromise on performance."*[34] Often, PHEV are first offered in up-market segments. The first PHEV of the whole Volkswagen group was launched by Porsche: the Porsche 918 Spyder PHEV, at a price of USD 845,000, with technical innovations such as the flywheel energy storage, which had been developed for racing cars. In the BEV segment, Porsche offers the Boxter E. Audi offers its first hybrid models in the expensive Q5, A6 and A8 series. Daimler launched its first PHEV in the S-Class in 2014, powered by a 325 kW engine and priced above EUR 100,000. Here, customers expect some technological innovation and do not care too much about the related price markup. Later, the technological innovations are introduced in medium-priced models.

*On the other hand*, this specialisation goes along with above-average emissions, which bears the risks of alienating environmentally conscious consumers as well as penalty payments if the required fleet emission standards set by the European Commission are not met. For these reasons, all OEMs complement their focus on upmarket, sportive and high-performance cars with a product line of small and compact BEV, such as the Mini-E, Volkswagen e-up and Smart ForTwo electric drive (Kleinert 2012).[35] These cars target urban consumers for whom the range limitations of BEV are acceptable. While international competitors in the *upmarket hybrid segment* are still relatively few, the segment of *small and compact BEV* is much more contested and German OEMs have to compete with early movers including Nissan (BEV model "Leaf"), Mitsubishi ("i-MiEV"), Citröen ("C-Zero") and many others. Nevertheless, having some low-emissions cars in their portfolio is of strategic importance for German OEMs: first, producers of high-powered cars need BEV in their fleet to offset above-limit emissions of their large ICE cars (taking advantage of the 'supercredits' incentive that allows them to count low-carbon vehicles several times when calculating average fleet emissions); second, they can 'green' their image; and third, they need to ensure that they keep up with technological innovations that may become relevant in a low-carbon future.

## 5.4 BMW's i-series: low-carbon innovation without compromising on comfort and performance

BMW's i series is a particularly interesting example of a high-price strategy for demanding customers. The company developed its new "BMW i" sub-brand with two models in a radically new architecture and design. BMW i3 is a 4-seated battery-electric compact car and BMW i8 is a plug-in hybrid sports car. The new sub-brand was developed through a long-term Megacity Vehicle Project in alliance with a non-traditional partner, SGL Carbon. Here, BMW targets a group of wealthy global megacity consumers who are willing to accept a high price for very unique and fancy cars. The target group is the 'i-phone

34 Bernd Pichler, Managing Director (Commercial) Volkswagen (China) Import Co. Ltd, cited in KPMG International (2011)

35 Audi developed the A1 e-tron in this segment, but then decided to postpone serial production of this REEV until battery performance was improved; production plans for the sportive up-market BEV Audi R8 e-tron were also cancelled. http://www.zeit.de/auto/2013-05/audi-elektroauto-hybrid.

generation" that likes to have new gadgets.[36] Both cars have been on sale since November 2013.

The main innovation is the lightweight auto body, which consists of two modules, called 'Drive' und 'Life': the Drive module is made from aluminium. The lithium-ion battery is installed here, powering the electric engine which drives the rear axle. The powertrain is much more compact than a comparable ICE powertrain, thus it can be mounted above the rear axle, leaving room for a spacious passenger compartment. The passenger compartment is called the Life module and is made out of CFRP, which is 50% lighter than steel, but similarly resistant and safe for passengers. This compensates for the extra weight of 250–300 kg added by the battery. The whole i3 weighs 1250 kg, compared to the 1567 kg weight of the BEV market leader, Nissan Leaf.[37] Mass-producing an entire passenger compartment from CFRP is a radical and new-to-the-world innovation. At EUR 40,000, the i3 is quite highly priced. BMW's factory in Leipzig is preparing to produce 30,000 units per annum.

The i3 has a range of 130-160 km. Drivers can chose among various driving modes, from comfortable to very energy efficient for maximum range. Also, BMW offers an i3 REEV version which adds a small two-cylinder motorbike engine and fuel tank, adding a 130 km additional range and costing an additional EUR 3,000.[38]

The i3 has a range of innovative features, including a single pedal that acts as an accelerator and a brake: when it is released, kinetic energy is recuperated and charges the battery, which slows the car down.[39] Also, the i3 has an innovative energy-saving heating and cooling system; LED lamps; a navigation system that identifies the most energy-efficient route, as well as available charging stations; smartphone apps for remote control of energy charging; crash absorbers in the front and rear, and front-hinged front doors and rear-hinged rear doors.

The i8 version is a much more expensive PHEV sports car. It has a similar LifeDrive architecture and uses a similar electric powertrain as the i3 for the front axle, but adds a powerful 164 kW combustion engine driving the rear axle.

The new BMWi sub-brand tests a new high-end market segment for BEV and PHEV. With its 125 kW engine, even the small i3 compact car is quite sportive. Also, its interior has a stylish design for demanding urban consumers, using recyclable materials such as leather, wood from certified sustainable plantations, and natural fibres to enhance its image as a'green lifestyle car'. While BMW managers are aware that BEV so far have not been commercially successful, the assumption behind the i-series is that enough young wealthy urban consumers will be willing to buy a car that combines sportiveness, technological innovation, and a unique and appealing design with an image of environmental sustainability.

There are doubts, however, about the net $CO_2$ effects of the lightweight construction. While the cars consume fairly little energy when driving, the production of CFRP is very energy-

36 Telephone interview with Mr Robert Diab, BMW, 22 Oct. 2012.

37 http://www.myelectriccarforums.com/bmw-i3-electric-car-test-rides/

38 ibid.

39 http://green.wikia.com/wiki/BMW_i3

intensive. Assuming the EU average energy mix, producing the CFRP passenger compartment will cause more carbon emission than the lightweight construction saves during the lifetime of the car. To improve the energy balance, BMW produces the carbon fibres in a US plant that gets its electricity from a hydroelectric (emissions-free) power plant. This, though, raises questions about fungibility: Given the limited availability of hydropower resources, any increase in its consumption augments demand for power from other sources. The CFRP technology may thus not make real net contributions to climate change mitigation. From BMW's business perspective, however, it may become a commercial success and in any case helps the company to achieve its fleet emission standards; thus it charts a pathway for German high-tech carmakers for coping with $CO_2$ regulations.

## 5.5 Cost reduction through aggressive modularisation and standardisation

As we have shown in Section 3, there will be a range of competing propulsion technologies in the future, and carmakers have to deal with high uncertainty, and thus investment risks, with regard to how future markets will be divided among different technologies and who will eventually win *"the great powertrain race"* (*The Economist,* 20 Apr. 2013). What is clear is that the diversity will come at higher production costs and market risks. To keep those costs and risks under control, German carmakers pursue modularisation and standardisation more aggressively than in the past. The idea is to develop new automotive concepts in such a way that different powertrains can be assembled on a common platform.

One of the early movers was the Daimler AG with its modular BlueZero concept. In the late 1990s, Mercedes-Benz introduced a so-called sandwich-floor architecture, mainly with the aim of increasing passenger safety. The new concept raised the height of the passenger compartment and mounted the engine in a slightly tilted position; with the effect that in the case of a strong frontal collision, the motor and gearbox slide under the passenger compartment where a special space is left to accommodate it. The BlueZero concept, first presented in 2009, is built on this architecture. It allows for mounting the relevant powertrain components of three different propulsion systems – a BEV, REEV and a FCEV version – to be accommodated under the passenger compartment. This particular solution makes the BlueZERO models *"very different from conventionally-built electricity-powered vehicles, which had to accommodate heavy, bulky storage batteries in the boot or in the rear seat area."*[40] At the same time, the rest of the vehicle architecture is left unchanged, allowing for economies of scale in the production of parts and vehicle asssembly. BlueZero however has so far not gone into serial production.

A more radical modularisation approach is pursued by Volkswagen AG. Volkswagen has started a new production concept in 2012, called Modular Transversal Toolkit (or MQB, an acronym for the German term *Modularer Querbaukasten*).[41] MQB uses standardised modules across a wide variety of platforms. Volkswagen plans to use it for 40 out of

40 http://media.daimler.com/dcmedia/0-921-657488-1-1417069-1-0-0-0-0-1-11702-614318-0-1-0-0-0-0-0.html

41 Interview with Mr Lars Hofmann, Volkswagen AG, Wolfsburg, 23 Oct. 2012 and http://www.handelsblatt.com/auto/test-technik/modularer-querbaukasten-vws-erfolgsrezept-fuer-die-kompaktwagen-zukunft/7040736.html?slp=false&p=9&a=false#image.

currently 200 models offered by the Volkswagen Group, including the high volume models Golf, Polo, Passat and Audi A3 as well as the family vans. According to Volkswagen's strategy, more than 3.5 million vehicles per annum will be based on the common platform – more than the total annual production of BMW and Daimler (ibid.). It will be possible to mount seven different propulsion systems – conventional gasoline and diesel ICEs; BEV and PHEV; as well as three types of bioenergy driven engines (compressed natural gas (CNG), propane (LPG) and ethanol). All engines will be mounted in an identical position, leaving the remaining architecture intact. Such standardisation makes it possible to assemble all these models at the same plant. In principle, it will even be possible to use the same assembly lines for the company's various brands.[42] Modular production with standardised parts and assembly procedures is expected to reduce unit costs by 20% while increasing the flexibility in the design of new models.[43] It allows carmakers to abate the costs and risks involved in a confusing situation of competing technological design and, at the same time, benefits the large globalised OEMs due to their economies of scale.

## 5.6 New business models

In addition to changes in the established automotive and autoparts industry, expectations are high with regard to the emergence of new business models (e. g. Founier et al. s. a.). These mainly include new services related to electromobility, but also some notable endeavours of newcomer firms to break into the domain of traditional carmakers and manufacture newly designed BEV. Sub-section 3.3 summarised major *international* developments in this regard. Our interest in this section is to see to what extent such new services offers are emerging *in Germany*, and whether those display country-specific characteristics that may contribute to forming a specific national technological pathway.

Our research identified a number of interesting experiments, driven by large incumbents as well as start-up companies – but so far, almost none of them has reached a commercial scale. Most of the experiments are related to mobility services and software solutions to connect cars with electricity grids:

- Many of Germany's regional 'showcases' and clusters are testing the consumers' readiness to accept electric driving in cities. The idea underlying the intermodal transport serviced idea is to link long-distance transport carriers, such as intercity trains, to electric cars or bicycles for the last mile – where the range limitations of electric driving do not matter. Car-to-go in Stuttgart, for example, runs 500 small electric cars; it offers an IT system and a smart card for intermodal transport. Interesting new business coalitions are emerging in this field, including alliances between Deutsche Bahn Car Sharing and Peugeot to set up charging stations. The retail chain REWE cooperates with the energy utility Vattenfall to provide electricity from renewable sources on the parking lots of supermarkets supposedly a 'win-win' opportunity as charging time can be used during shopping times, and charging

42 http://en.wikipedia.org/wiki/Volkswagen_Group_MQB_platform

43 http://www.handelsblatt.com/auto/test-technik/modularer-querbaukasten-vws-erfolgsrezept-fuer-die-kompaktwagen-zukunft/7040736.html?slp=false&p=9&a=false#image

stations would attract additional consumers (Pehnt 2010). All these initiatives, however, are still at experimental stages and have not yet evolved into widely accepted and profitable business cases.

- BMW Group, Bosch, Daimler, EnBW, RWE and Siemens have created *hubject GmbH* as a joint company to advance an open IT platform for roaming and clearing to ensure that compatible IT standards develop for charging, billing and planning of charging services. The company is still not fully operational, but inter-industry talks are taking place to harmonise standards. Also in this field, there are no commercially successful business cases so far, not least because the German electricity law does not provide for demand-side management. This needs to be changed first, if Germany wants to exploit early mover advantages in this field.

- The Berlin-based start-up *ubitricity* experiments with simple plugs in traffic-light posts to reduce the costs of a charging infrastructure. The model implies that the necessary hard- and software is placed in the car rather than the charging stations.

- Several German firms, including SEW EuroDrive and Wampfler Conductix, are developing inductive charging technologies and testing them with bus fleets and small trucks.

There are also some endeavours underway to develop newly designed electric cars for niche markets, although on a fairly small scale – compared for example with the successful launch of Tesla in the United States. German niche market producers of electric cars are small independent companies, including Karabag, e-Wolf and German e-cars. Furthermore, some large companies are also experimenting with electric prototype cars, including Continental in Germany. None of them currently seems to be growing out of existing small niche markets, not least because the costs of homologation – the technical approval for road transportation – constitute a serious entry barrier.

Overall, although the multitude of new business models related to electromobility has received considerable interest in the public debate, empirical evidence suggests that actual change is quite small. This may be due to the early stage of electromobility deployment, and more dynamic developments may take place when electric vehicle deployment picks up. Nevertheless, even then, current trends suggest that many production and service opportunities may be developed by established large incumbents – carmakers, large supplier industries, energy utilities, Deutsch Bahn etc. – rather than newcomers.

## 6 Conclusions

Cars powered by internal combustion engines have been the technological solution that dominated the automotive industry and coined the way that transport systems have been organised globally. Given the urgent need to decarbonise the world economy, however, alternative powertrain technologies are now gaining competitive advantages, and industries have to adapt. Hybrid and fully electric powertrains attract considerable investments, and so do new mobility concepts and services at the interface of the transport and the energy system. *How* industries adapt, *which alternatives emerge*, *how rapidly* they become competitive and eventually substitute the incumbent technologies, however, depend on country-specific factors, including policy frameworks, the existing industrial structure and specialisation, demand conditions, etc. As a result, the shift to electromobility follows country-specific technological pathways.

This study reviewed technological trends in the transition to electromobility in Germany. It revealed some distinctive features:

To date, electromobility plays a subordinate role in the business models of German carmakers and big suppliers. None of the existing hybrid and electric models has a relevant market share so far. Likewise, the manifold new technologies and business models associated with the shift to electromobility – from intermodal mobility services, car-sharing and grid-vehicle communication to inductive charging and new recycling concepts to recuperate scarce natural resources – have not really taken off so far.

Germany's automotive industry, with Mercedes, BMW, Audi and Porsche brands among others, has a particular strength in the luxury and upper middle-size classes; and even in the smaller car categories, German manufacturers sell in the highest price range. This competitive positioning has so far been very successful, as demand in the premium segments increases at above average rates and competition is not as stiff as in low-cost car production. But high-powered, high-end brands experience particular difficulties in meeting the EU's fleet emission standards. While the German automotive industry, seconded by German politics, lobbies strongly against ambitious emissions standards, the trend towards the decarbonisation of powertrain technologies is irreversible.

The German car industry's high-end specialisation partly explains why Germany is a latecomer to electromobility. While Toyota introduced HEV as early as 1997, none of the German carmakers responded to the challenge. Likewise, series production of PHEV and BEV is only taking off now, in 2013/14, about two to three years behind Japanese, French, Korean and US manufacturers. Be that as it may, this does not seem to undermine the German automotive industry's competitiveness. First, the global shift to electromobility is fairly slow and incremental. The technological competences related to ICE powertrains continue to be highly relevant, and many different powertrain technologies will co-exist for at least the next 2-3 decades. In any case, organisational competences, such as the ability to manage collaborative innovation processes and integrate multi-tiered production systems, are stabilising the German incumbents position. Likewise, change in the supply chain has not been radical so far, and it seems that established suppliers are generally able to adapt their capabilities. Even in battery technology – arguably the weakest element in Germany's automotive innovation system when it comes to electromobility – international progress is slow and Germany seems to catch up fast.

Germany has a National Electromobility Strategy and created a coordinating body to support the transition to electromobility. The strategy's declared objective is to make Germany a lead market and lead provider for electromobility. The lead market target, however, is not likely to be achieved – due to the German industry's and consumers' preference for (traditional) high-powered cars and due to limited government commitment to accelerate the transition via ambitious emissions targets, a bonus-malus system for emissions, or purchase subsidies for electric vehicles. The target to become a lead provider may however be more realistic. Very recently, German carmakers seem to be taking off strongly in hybrid and electric powertrain technologies and are expected to catch up with the current market leader, Japan, within the next 5 years. This reflects the general strength of the German automotive innovation system rather than particularly conducive home-market conditions for electromobility.

The German automotive industry's incremental shift to electromobility – or maybe more precisely: toward an increased variety of propulsion technologies – shows a number of country-specific characteristics. These include a leading role in hybridisation strategies in the up-market segment where German OEMs offer 'green lifestyle' cars that do not compromise on power, performance and driving pleasure but use high-tech solutions to increase energy efficiency. As another element of competitive specialisation, modularisation and standardisation are consequently used to ensure that customers can choose among a range of powertrain alternatives without compromising on the expected comfort, while at the same time economies of scale can be exploited to keep costs low. Some analysts also expect specific German developments in related services, such as intermodal transport services or smart grid technologies, but these are not yet observable.

It should be noted, however, that standards for greenhouse gas emissions are likely to become much stricter in the future. The current 95g $CO_2$/km target set by the EU for 2020 can still be achieved without a radical industrial transformation. 10g $CO_2$/km – calculated as the tolerable maximum in 2050 to stay below 2°C global warming – will require a much radical departure from current technological trajectories.

## Bibliography

*acatech (Deutsche Akademie der Technikwissenschaften)* (2010): Wie Deutschland zum Leitanbieter für Elektromobilität werden kann, Heidelberg: Springer Verlag (acatech bezieht Position 6)

*Altenburg, T. / D. Fischer / S. Bhasin* (2012): Sustainability-oriented innovation in the auto industry : advancing electromobility in China, France, Germany and India, in: *Innovation and Development* 2 (1), 67–85

*– / A. Pegels* (2012): Sustainability-oriented innovation systems – managing the green transformation, in: *Innovation and Development* 2 (1), 5–22

*Bergek, A. et al.* (2013): Technological discontinuities and the challenge for incumbent firms : destruction, disruption or creative accumulation? in: *Research Policy* 42 (2013), 1210–1224

*Bundesregierung* (2009): German Federal Government's national electromobility development plan; online: https://www.bmwi.de/English/Redaktion/Pdf/national-electromobility-development-plan,property=pdf,bereich=bmwi,sprache=en,rwb=true.pdf (accessed 3 Sep. 2014)

*CEM (Clean Energy Ministerial) / EVI (Electric Vehicle Initiative) / IEA (International Energy Agency)* (2013): Global EV outlook : understanding the electric vehicle landscape to 2020, Paris

*Chaudhary, A.* (2014): Electromobility in India : attempts at leadership by businesses in a scant policy space, Bonn: DIE (Discussion Paper 15/2014)

*Chen, L. et al.* (forthcoming): Electric vehicles in China : bridging political and market logics, Bonn: DIE (Discussion Paper)

*Dosi, G.* (1982): Technological paradigms and technological trajectories : a suggested interpretation of the determinants and directions of technical change, in: *Research Policy* 11 (3), 147–162

*e-mobilBW* (2010): Strukturstudie BWe mobil − Baden-Württemberg auf dem Weg in die Elektromobilität. Studie, Stuttgart

*ERTRAC (European Road Transport Research Advisory Council) et al.* (2010): European roadmap : electrification of road transport, version 2.0; online: ftp://ftp.cordis.europa.eu/pub/technology-platforms/docs/roadmap-electrification-nov2010_en.pdf (accessed 3 Sep. 2014)

*European Commission* (2009): A sustainable future for transport : towards an integrated, technology-led and user-friendly system, Luxembourg

*Fournier, G. et al.* (s. a.): Der Weg zur emissionsfreien Mobilität : Strategien der Hersteller im internationalen Vergleich, mimeo

*Freyssenet, M.* (ed., 2009): The second automobile revolution. Trajectories of the world carmakers in the 21st century, Basingstoke and New York: Palgrave Macmillan

*Goldman-Sachs* (2004): The BRICs and global markets : crude, cars and capital (Global Economics Paper No. 118)

*ICCT (International Council on Clean Transportation Europe)* (2012): European vehicle market statistics : pocketbook 2012, Berlin

*IEA (International Energy Agency)* (2013): Global EV outlook : understanding the electric vehicle landscape to 2020, Paris

*IPCC (Intergovernmental Panel on Climate Change)* (2007): Climate change 2007: synthesis report, Geneva online: URL: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm (accessed 3 Sep. 2014)

– (2013): Working Group III. Mitigation of Climate Change, Chapter 8: Transport, Geneva.*Johnstone, N. / I. Haščič* (2010): Innovation in electric and hybrid vehicle technologies : the role of prices, standards and R&D, paper presented at the joint IEA/ GHG-TransPoRD workshop "Reducing greenhousegas emissions of transport beyond 2020 : linking R&D, transport policies and reduction targets", Paris, 17–18 Jun. 2010

*Kell, T.* (2010): Elektromobilität ein Teil der Strategie Efficient Dynamics : Powerpoint presentation, Dresden, 24 Feb. 2010

*Kleinert, I.* (2012): Ready for change? : electric vehicle technologies challenge the German automotive innovation system, paper presented at the 20th Gerpisa International Colloquium, Krakov

*KPMG International* (2011): KPMG's global automotive executive survey 2011; online: https://www.kpmg.com/FR/fr/IssuesAndInsights/ArticlesPublications/Documents/Automotive-Survey-2011.pdf (accessed 3 Sep. 2014)

*Lange, K.* (2010): Kooperationen in der Automobilindustrie – Analyse und Systematisierung (Arbeitspapiere des Instituts für Genossenschaftswesen der Westfälischen Wilhelms-Universität Münster 94); online: http://www.wiwi.uni-muenster.de/06/forschen/veroeffentlichungen/2010/material/ap_94_lange.pdf (accessed 3 Sep. 2014)

*Linder, M.* (2012): The potential of fuel cell electric vehicles in a portfolio of powertrains and industry initiatives for commercialisation in Europe, presentation held at the International Hydrogen Forum, Fukuoka, 1 Feb. 2012, McKinsey&Company

*Lütkenhorst, W. et al.* (2014): Green industrial policy : managing transformation under uncertainty, Bonn: DIE (Discussion Paper 28/2014)

*– / A. Pegels* (2014): Germany's green industrial policy : stable policies – turbulent markets : the costs and benefits of promoting solar PV and wind energy, Geneva: The International Institute for Sustainable Development

*Markus, T. / K. Mikko* (2010): Electric vehicles : Powerpoint presentation, FINPRO

*McKinsey & Company* (2011): Boost! Transforming the powertrain value chain : a portfolio challenge; online: http://actions-incitatives.ifsttar.fr/fileadmin/uploads/recherches/geri/PFI_VE/pdf/McKinsey_boost.pdf (accessed 3 Sep. 2014)

– (2014): Electric vehicle index (EVI); online: http://www.mckinsey.de/elektromobilitaet (accessed 3 Sep. 2014)

*Mock, P. / Z. Yang* (2014): Driving electrification : global comparison of fiscal incentive policy for electric vehicles. ICCT White paper May 2014, Beijing et al.: International Council on Clean Transportation

*Nelson, R. R.* (1994): The co-evolution of technology, industrial structure, and supporting institutions, in: *Industrial and Corporate Change*, 3 (1), 47–63

*NPE (Nationale Plattform Elektromobilität)* (2010): Zwischenbericht der Arbeitsgruppe 5, Materialien und Recycling, Berlin

– (2012): Progress report of the German National Platform for electric mobility (third report), Berlin

*OECD (Organisation for Economic Co-operation and Development)* (2011): Better policies to support eco-innovation (OECD Studies on Environmental Innovation); online: http://dx.doi.org/10.1787/9789264096684-en

– (2012): OECD environmental outlook to 2050 : the consequences of inaction, Paris: OECD Publishing

*Pehnt, M.* (2010): Elektromobilität und erneuerbare Energien, in: T. Müller (ed.), 20 Jahre Recht der Erneuerbaren Energien, Würzburg: Nomos

*Plötz, P. et al.* (2013): Markthochlaufszenarien für Elektrofahrzeuge – Langfassung, report comissioned by acatech (Deutsche Akademie der Technikwissenschaften) and Nationale Plattform Elektromobilität, Karlsruhe: Fraunhofer ISI

*Porter, M. E.* (1990): The competitive advantage of nations, New York: Free Press

– / C. van der Linde (1995): Toward a new conception of the environment-competitiveness relationship, in: *Journal of Economic Perspectives* 9 (4), 97–118

*Proff, H. et al.* (2013): Aufbruch in die Elektromobilität. Märkte – Geschäftsmodelle – Qualifikationen – Bewertung, Duisburg: Universität Duiburg-Essen/Kienbaum

*Roland Berger* (2011): Global study on the development of the automotive Li-ion battery market, Munich: Roland Berger Strategy Consultants

*Schamp, E. W.* (2014): The formation of a new technological trajectory of electric propulsion in the French automobile industry. Bonn: DIE (Discussion Paper 12/2014)

*Schlick, T. et al.* (2011): Zukunftsfeld Elektromobilität – Chancen und Herausforderungen für den deutschen Maschinen- und Anlagenbau, Amsterdam: Roland Berger Strategy Consultants

*Sperling, D. / D. Gordon* (2009): Two billion cars : driving toward sustainability, Oxford: Oxford University Press

*Sturgeon, T. / J. van Biesebroeck / G. Gereffi* (2008): Value chains, networks and clusters: reframing the global automotive industry, in: *Journal of Economic Geography* 8 (3), 297–321

*Sushandoyo, D. et al.* (2012): 'Sailing ship effects' in the global automotive industry? : competition between 'new' and 'old' technologies in the race for sustainable solutions, in: G. Calabrese (ed.), The greening of the automotive industry, Basingstoke: Palgrave Macmillan, 103–123

*The Economist* (2011): Revenge of the petrolheads : fossil-fuel cars are getting much cleaner, making life hard for green ones, 10 Dec. 2011; online: http://www.economist.com/node/21541443

*Utterback, J. M. / W. J. Abernathy* (1975): A dynamic model of product and process innovation, in: *Omega* 3 (6), 639–656

*Volkswagen AG* (2012): Die e-Mission : Elektromobilität und Umwelt, Wolfsburg

## Interviews

1. German Federation of Engineers (VDE/VDI), Dr Randolph Schliesser, Berlin, 9.11.2011
2. BMUB (German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety), Mr Samson, Berlin, 14.3.2012
3. BMUB (German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety), Dr Markus Becker, Berlin, 31.5.2012
4. BMWi (German Federal Ministry for Economic Affairs and Energy), Mr Arnold, Dr Spelten, Berlin, 14.3.2012
5. Evonik, Mr Schulz, Berlin, 14.3.2012
6. Verband der Automobilindustrie (VDA), Dr Josefine Meusinger, Berlin, 15.3.2012
7. Bureau of the National Platform Electromobility, Ms Ingrid Ott, Berlin, 9.11.2011
8. Bosch, Dr Sascha Henke, Dr Richard Aumayer, Berlin, 25.4.2012
9. SBLiMotive, Dr Joachim Fetzer, Stuttgart, 9.5.2012
10. emobil BW, Dr Stefan Büchele, Stuttgart, 10.5.2012
11. Ministry of Finance and Economy, Baden-Württemberg, Dr Markus Decker, Stuttgart, 10.5.2012
12. Fraunhofer IAO, Mr Alanus von Radecki, Stuttgart, 10.5.2012
13. Fraunhofer ISI, Professor Martin Wietschel, Dr Axel Thielmann, Karlsruhe, 11.5.2012
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