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Article

The emergence of electromobility: Comparing technological pathways in France, Germany, China and India

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Abstract

Globally, new forms of electromobility are challenging established transport technologies based on internal combustion engines. We explore how this transition is simultaneously unfolding in four countries, enabling us to shed some light on the dynamics and determinants of technological path creation. Our analysis covers two old industrialized countries (France and Germany) and two newly industrialized countries (China and India) with very different market conditions and policy frameworks. It reveals enormously different choices of technologies and business models and traces them back to four main drivers of divergence: technological capabilities, demand conditions, political priorities and economic governance.

Key words: electromobility; Germany; China; India.

1. Introduction

Globally, road transport technologies are changing. The old technology of combustion engine-driven automobiles is incompatible with the imperative of decarbonizing the world economy. New carbon-efficient transport technologies are required, and electrification is the most prominent alternative option: provided that electricity generation is also decarbonized.

The required change goes far beyond exchanging the cars' engines and transmissions. It implies major changes in the way that cars are constructed and automotive value chains organized. Moreover, electrification of road transport creates new infrastructure and new interfaces between transportation systems and energy systems. It favors new concepts of mobility (e.g. combining mass carriers for long distances with electric vehicles (EVs) for the last mile) and new consumer attitudes towards mobility and car ownership. Anticipating such systemic changes, manifold new alliances between energy utilities, car manufacturers, railway companies and software companies are emerging. Many observers assume that we are at the beginning of a 'paradigm change' (Tagscherer and Frietsch 2014; Donada and Fournier 2014) that reaches out far beyond the automotive industry.

Mitigating climate change is not the only motivation for governments, carmakers and consumers to shift to electromobility. EVs are locally emission-free and therefore a promising solution for polluted (mega)cities. If electric energy is generated on the basis of non-fossil sources, electric cars reduce dependency on imported fuel, which currently causes large foreign trade deficits in many countries. Some countries have bet on electromobility in order to enhance the international competitiveness of their automotive industries. Hence, what motivates governments and industries to pursue the electromobility transformation varies considerably from country to country. Moreover, the initial conditions in terms of technological capabilities, demand conditions, characteristics of the energy system and the like are very different. As a result, car producers and consumers favor different technological options and national policy-makers establish specific policy regimes to support those options.

For these reasons, electromobility provides an interesting laboratory for studying to what extent, how and why technological pathways differ among countries. Anderson and Tushman (1990) describe the early phases after the crisis of a previously dominant technology as 'eras of ferment' characterized by experimentation and open-ended competition among alternative technologies. Much in line with a huge body of literature that deals with path dependence (for an overview see Boschma and Martin 2010) they also describe how at later stages one of the competing options, mainly due to superior network effects and economies of scale, tends to gain the upper hand, suppressing the pursuit of alternative options and thereby evolving into a new 'dominant design' (Utterback and Abernathy 1975). While the literature on evolutionary innovation agrees widely on the existence of successions of path dependence

and highlights the eventual disruption and creation of new paths (Garud and Karnøe 2001), there is very little comparative analysis of path creation, especially during eras of ferment.

This paper seeks to make a contribution by capturing the early stage of experimenting and doing so in a comparative way. We compare two old industrialized economies (France and Germany) and two emerging economies (China and India). All of them launched electromobility policies at roughly the same time, allowing us to observe four simultaneous processes of technological path creation. What makes this comparison particularly interesting is the fact that change is being pursued in countries with entirely different initial conditions. In earlier decades, most innovations originated in the 'Triad' (North America–Europe–Japan), a group of high-income market economies with mature diversified innovation systems, and diffused into developing countries only at later stages. Now we observe a new paradigm being simultaneously pushed by old industrialized countries and emerging economies. Comparing them is particularly interesting, because virtually all of today's technologically leading carmakers have their home bases in old industrialized OECD countries, whereas future demand will mainly come from non-OECD markets,[1] particularly China and India. It will be interesting to see to what extent the 'old' and/or the 'new' markets will shape the new paradigm. The four countries considered in our study also vary greatly regarding the objectives pursued by promoting electromobility as well as in terms of technological capabilities, R&D expenditure, purchasing power, market size, level of electrification, historical liability for carbon emissions, and many other potential determinants of techno-institutional path formation.

Understanding similarities and differences in technological pathways requires taking both national and international determinants into account. The fermentation phase in the European and Asian countries is not shielded from global forces. There is no protection phase for national infants. In both groups of countries, the choice of technology is largely shaped by large firms such as automotive companies which command global production networks. Hence, we may see complex dialectic relationships between carmaker's strategies and country-specific conditions, such that competing technological pathways may be pursued within one country, and the same global carmaker may either impose uniform technologies across countries or experiment with entirely different solutions in different countries.

Many researchers are trying to grasp this complexity. Some have put global value chains at the center of their analyses (Gereffi et al. 2005), others innovations systems which encompass firms and institutions that impact more broadly on innovations. Innovation system approaches necessarily have to define system boundaries, and several research communities have emerged that define the boundaries differently, focusing on geographic spaces at different scales (Moulaert and Sekia 2003), on sectoral (Malerba 2002) or technological boundaries (Bergek et al. 2008). All these analytical perspectives are closely interrelated and they add up to what Murmann and Frenken (2006) have called a multi-level nested hierarchy of overlapping subsystems. Which analytical apparatus is most appropriate depends on the research focus. Here, we consider the country level the most appropriate analytical focus, because most of the major determinants of technological pathways—such as demand conditions and technological capabilities—are essentially shaped by national institutions and their history. But, we do not pretend that national innovation systems are anything like closed systems, and we explicitly recognize driving forces of technological development that may be located outside national boundaries and organized in transnational ways.

The remainder of this paper consists of four sections. Section 2 presents our conceptual foundations of path creation and how they apply to electromobility. We argue that electrifying road transport requires profound systemic change and identify key challenges for countries wanting to promote electromobility. Furthermore, Section 2 also provides a short overview of analytical concepts that may help us to understand the main determinants of technological path formation, at both the country and firm levels.[2] It concludes with some arguments as to why we expect to see a lot of experimentation across the four countries and possibly the emergence of competing technological pathways. In Section 3 we identify important country conditions at the end of the first decade of the present century when the four countries of our sample started to take decisive steps towards electromobility. Section 4 then documents country-specific technological developments in France, Germany, China and India and how those can be related back to specific country conditions. Section 5 highlights comparative observations about the determinants of technological path creation.

2. The establishment of technological pathways in electromobility: Some conceptual and sector-specific background

2.1 The shift to electromobility: Systemic transformation under uncertainty

The automotive industry is gradually shifting from traditional cars powered by internal combustion engines (ICE) to less carbon-intensive drive technologies, including fully battery-electric vehicles (BEV) and hybrid-electric cars. The latter combine electric engines with smaller combustion engines. Different degrees of hybridization exist. 'Mild' hybrid-electric vehicles (HEV) rely on conventional combustion engines as their main source of propulsion but use electric motors and small batteries as a complementary power source. Batteries are charged from the combustion engine and the recuperation of break energy. Plug-in hybrids (PHEV) mainly drive electrically. Their electric engines and batteries are powerful and their combustion engines small. PHEV can be charged from the electric grid. Range-extended electric vehicles (REEV) use a very small conventional engine as a back-up and to increase the driving range. While the public debate is focused on passenger cars, electrification also advances in two- and three-wheelers (particularly relevant in China and India) as well as buses and other means of transport.

The more road transport technologies evolve along the continuum from fuel engines via hybrids towards all-electric driving, the more it is going to change the automotive and related industries. New technologies and new capabilities are required, and some old ones lose their previous importance. BEV, for example, need new generations of powerful batteries, electric motors and inverters. They no longer require some of the core technologies of traditional cars, such as ICE and gearboxes. New forms of thermo-management need to be developed, as there is no longer a combustion process which can be used for heating or cooling. Essentially, a major part of the automotive architecture needs to be redesigned.

This goes along with new capability requirements, opening up opportunities for newcomers and threatening incumbents whose core competencies are no longer required. This is most obvious for specialized suppliers (e.g. those producing gearboxes or parts of combustion engines, such as pistons). But even the large automotive

companies (the so-called original equipment manufacturers (OEMs)) see themselves confronted with new competitors, given that barriers to entry into the car industry are significantly lower when mastering the complex technologies of combustion engines and transmissions is no longer needed. America's Tesla and China's BYD are prominent examples of BEV newcomers. Furthermore, the shift to electromobility requires new infrastructure solutions. If cars are to be charged from electric grids, a charging infrastructure needs to be put in place, whereas demand for fuel filling stations will decrease. Moreover, smart electric grids need to be designed to meet the specific energy needs of car fleets, and the batteries in cars may potentially be used to store energy when supply is abundant and feed it back into the grid when supply is short. Last but not least, electromobility requires new ways of managing transport including well-planned 'intermodal' transport solutions which combine fast train connections for long distances with slow but flexible carriers (such as electric cars and bicycles) for the 'last mile'. What is at stake is thus much more than the introduction of a new technology that displaces an old one: more than that, we see a system transformation in the making.

How fast and how radical this transformation will be is, however, far from clear. First, many technical problems have not yet been solved. Energy storage is the biggest one. Petrol can be stored in tanks, whereas storage of electric energy has yet to find an effective solution. The batteries needed for BEV, REEV and PHEV are heavy, expensive and provide little driving range. Charging takes a relatively long time, and while fast charging is possible, it comes at a high cost in terms of battery lifetime (Nationale Plattform Elektromobilität 2010). Predictions about how rapidly remaining technological problems will be solved and when electric propulsion will become truly competitive diverge enormously.[3]

Second, it is difficult to predict how rapidly alternative technologies will mature relative to battery-electric driving. This concerns fuel cells and methane as alternative pathways, but also the improvement of ICE power trains. In fact, incremental improvements of combustion engines including sophisticated direct injection, turbochargers, compressors, start-stop technology and mild forms of hybridization such as systems to recuperate brake energy are rapidly advancing internationally. This has been called the 'sailing ship effect': the speed of innovation in incumbent technologies sometimes accelerates when being challenged by an emerging new paradigm, just as sailing ship technology received an innovation boost when steam ships appeared (Geels 2002). The success of the old ICE technology in reducing fuel consumption and CO_2 emissions reduces the pressure to shift to EVs.

Third, customers have not (yet) learned how to use EVs in their daily lives. New urban mobility concepts are only just emerging, and people have to become familiar with new options. Cars are more than just functional means of transportation: they symbolize social status, they give driving pleasure, and mobility habits are deeply entrenched in national cultures. While the attitudes of users are slowly changing, especially in some urban environments (Donada and Fournier 2014), little is known about if and when there may be tipping points where users start switching to electric cars and/or new mobility concepts on a massive scale.

Fourth, much depends on the way policy frameworks will be shaped in the future. It is difficult to predict, for example, how rapidly emissions standards will be tightened internationally, to what extent different jurisdictions will tax (or reduce subsidies for) fossil fuels, and if and when effective carbon markets will be established. Similarly, some governments subsidize the purchase of low-carbon vehicles, fund R&D or use public procurement systems to encourage electromobility while others do not (International Council on Clean Transportation 2014; Altenburg et al. 2012). As policies are typically the outcome of complex political negotiations they are inherently difficult to predict.

Hence, all players in the system transformation face enormous uncertainty. Opinions therefore diverge significantly with regard to the pace of transformation and the type of innovations that will eventually emerge (KPMG International 2011: 16). Observers also disagree whether or not the technological discontinuities will require radically new types of competences and thus favor the entry of newcomers, or rather build on and gradually expand the existing competences of incumbent industries.[4] What is certain, however, is that change will come. According to international scenarios,[5] road traffic has to be largely decarbonized by 2050 to keep global warming within manageable limits. This will either be achieved in a structured and sequenced process, or via environmental crises that force societies to take emergency measures.

2.2 What determines the establishment of technological pathways?

Evolutionary economics suggest that innovation advances along specific technological pathways (Dosi 1982).[6] Technological progress is cumulative, building on specific local initial conditions and unfolding from there through incremental changes. Most R&D targets 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 dedicated institutional arrangements (such as regulations, research programs and business networks that evolve in relation to the technologies that were initially chosen) 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, thus giving rise to technological pathways.

Whenever technologies evolve in parallel in different locations and institutional environments, the way one thing leads to another necessarily mirrors local specificities. Thus, technological pathways may diverge considerably across countries, especially when initial conditions are very different. This becomes obvious when we compare the size and design features of cars produced in, say, the USA, Japan, Germany and Italy. 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 most competitive 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 and Abernathy 1975) which, at least temporarily, is not seriously challenged. In the automotive industry, cars powered by ICE have been the dominant design for an entire century, and other societal institutions (such as a transport system based on individual mobility, 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 (Schumpeter 1942). Today's fuel-based transport systems are now being challenged by the pressure to reduce greenhouse gas

emissions and the emergence of several alternative propulsion technologies.

Path dependence is a common concept in evolutionary economics, going back to David (1985) and Arthur (1994). More recently, academic scholars have focused their attention on the determinants of path disruption and the creation of new paths (Garud and Karnøe 2001; Schot and Geels 2008). However, we still know very little about the transition from the early stages of technological life cycles (which are typically characterized by open-ended experimentation) to the stabilization (or 'locking in') of new technological pathways. In particular, it is unclear what the tipping points are where certain designs become dominant and suppress the evolution of alternatives. Against this background, we seek to analyze 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.

2.3 Why we expect divergence in national pathways to electromobility

As the shift to electromobility has only just started to take off we are currently in an 'era of ferment' where old and new market actors experiment with a range of new technologies and business models. To understand whether and to what extent this gives rise to country-specific technological pathways we decided to look at four countries which launched major national electromobility initiatives almost simultaneously around the year 2009, but started from very different initial conditions.

As will be shown in Section 3, France, Germany, China and India differ enormously in terms of market size and dynamism, technological maturity and business sophistication, purchasing power, consumer habits, relative preferences for growth vs. environmental protection, regulatory frameworks, and several other determinants which strongly impact on the choice of technologies and subsequent co-evolution of technology and institutions. While the two European countries are among the world's earliest movers in the automotive industry, the two Asian countries are newcomers in the industry, but rapidly catching up and expanding their automotive industries.

The shift to electromobility is held back by several market failures. These include the lack of incentives to internalize the environmental costs of greenhouse gas emissions as well as a number of information and coordination failures. These involve a typical 'chicken-and-egg' problem: consumers are unwilling to buy electric cars unless a public charging infrastructure is established, but putting such infrastructure in place does not pay if only few EVs circulate. If and how such problems are solved depends on whether and how public policies intervene in the allocation of resources. Hence, environmentally motivated system transformations, such as the shift to electromobility, need to be strongly policy-led. When national governments understand the role of the public sector in economic governance differently (as the notion of 'varieties of capitalism' suggests (Hall and Soskice 2001)) or when their institutions display different levels of effectiveness, these are additional sources of technological divergence across countries (Altenburg and Pegels 2012).

Moreover, the countries in our sample encourage electromobility for different reasons. Climate change mitigation is not the only reason. In Asian megacities, local air pollution is seen as the most burning issue, suggesting different technical and institutional solutions. Policy-makers, companies and societies at large are also strongly concerned with competitiveness, profits and effects on jobs. Thus, whether a paradigm change in the automotive industry is seen as a threat to a well-established industry or an opportunity to break into new markets greatly influences the way in which policies are designed.

In sum, we can expect considerable divergence in technological experimentation and path creation reflecting differences in supply and demand-side conditions, in political priorities and forms of economic governance.

3. Preconditions for the shift to electromobility: France, Germany, China and India

Four in-depth case studies[7] have been conducted, each based on a thorough literature review and complemented with interviews with key actors in the respective national innovation systems, including leading automotive OEMs, suppliers and related industries as well as researchers and policy-makers. For each of the countries this section briefly describes the conditions of the national automotive industries around the year 2009 (when major national electromobility initiatives were launched in all four countries) as well as other elements of the national policy environments which are especially relevant for understanding the particular ways in which electromobility is currently evolving in each of these countries.

3.1 France

France was among the first automobile-producing nations, starting production immediately after the invention of the automobile in the late 19th century. Over time, France has developed a diversified automobile production system, dominated by two big OEMs: Renault and PSA Peugeot Citroën. The French automobile innovation and production system has strong competences in the volume segment of compact and medium-sized vehicles. This can partly be attributed to specific road conditions and user profiles in France and other Southern European countries where French carmakers have considerable market shares. Roads in French cities tend to be narrow. Also, the average user drives relatively short distances and regards cars as a functional means of transport. Another specific feature is that France is a market for diesel engines and PSA Peugeot Citroën, a European leader in diesel ICE technology, having created some 'new-to-the-world' innovations in this area, such as the diesel particulate filter system.

In recent years the French automobile industry has lost international competitiveness. Ten years ago, France was the fourth largest automobile nation (in terms of produced cars), but has since fallen back to tenth in the ranking.[8] Unit labor costs have significantly increased whereas they remained largely constant in Germany, with the effect that French car production is in decline whereas German production continuously increases. In particular, French carmakers have failed to tap into the highly profitable premium segment of the car market. The industry was further weakened by the 2009 economic crisis which hit France and the Southern European export market of its car industry particularly hard.

In response to declining competitiveness, French companies and the state focused early on EVs as an alternative. Already in 2008, the *Grenelle de l'environnement* law provided a framework for public support. This further increased after the start of the financial crisis, when a fiscal stimulus package was offered to encourage electromobility. Aside from the overall crisis of the national car

industry that forced managers and policy-makers to reconsider the current competitive positioning, three country-specific conditions made electromobility especially appealing. First, there is a national electricity mix with a 75% share of nuclear energy.[9] Whereas in countries with fossil fuel-dependent electricity generation shifting from ICE-driven to electric cars actually increases carbon emissions, the use of the French electricity mix decarbonizes significantly. EDF, the state-owned power company, started promoting EVs early on, offering cheap power on the basis of largely amortized nuclear power stations. Second, France has a particularly interesting record of battery R&D since World War II, partly funded by military research. French battery producers started to produce NiCd and NiMH batteries (suitable for HEV) in series in the mid-1990s and the more powerful lithium-ion and lithium–metal–polymer (LMP) batteries for BEV in the 2000s, which was quite exceptional in the European context. In parallel, the French automotive OEMs and some suppliers have experimented with EVs for decades and came up with innovation such as the e-HDi stop-and-start system. Third, the competitive specialization in small cars also favored the development of BEV.

Against this background, the government started to promote electromobility wholeheartedly. In 2009, it adopted the Low Carbon Vehicle Plan and offered a range of incentives to simultaneously tackle supply- and demand-side constraints. On the R&D side, Ademe, a state agency, fostered cooperative applied research, investments in battery-charging infrastructure were announced, one of the highest subsidies worldwide (€7,000, later reduced to €6,300) was offered for the purchase of a BEV, and several large semi-public companies were nudged to announce the purchase of 100,000 EVs by 2015.

Given these overall favorable preconditions for electromobility, France has been the first European country to launch series production of EVs and also initially became the largest European market for EVs, although since 2012 France has been overtaken by the Netherlands and Norway (Electric Vehicle Initiative and International Energy Agency 2013, 2015).

3.2 Germany

Germany has a very competitive export-oriented automotive innovation and production system. In 2013, automotive industry R&D investment was €18.3 billion, equivalent to one-third of Germany's total R&D expenditure. According to Pavlinek (2012), in 2007 Germany accounted for 67.1% of the EU's automotive R&D (France: 13.3%). This is complemented with a dense and diversified network of dedicated research institutes (including Fraunhofer institutes, technological universities and universities of applied sciences) with a long-established focus on automotive research and education. Germany is the fourth automobile-producing country and the world's largest exporter of automobiles, with competitive advantages particularly in the segment of executive and luxury cars. Leading producers include Daimler, BMW and the Volkswagen Group (which comprises the Audi and Porsche brands). The industry is benefiting from strong demand for up-market cars in Asia and the USA. This allowed German manufacturers to recover much faster from the financial crisis than their French and other European competitors.

Given its competitive specialization in high-powered vehicles, German brands produce higher fleet-average CO_2 emissions than most of their competitors. 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. Also as a country, Germany's average emissions are the highest in the EU (International Council on Clean Transportation 2012). The environmental objective of decarbonizing road traffic thus conflicts with the German OEMs competitive specialization, and it is hardly a coincidence that German OEMs launched HEV, PHEV and BEV models later than most Japanese, French and US competitors. While US, Japanese and French manufacturers launched BEV and PHEV in the period 2008–11, most German manufacturers only followed in 2014 (Altenburg 2014).

Moreover, there is one technological weakness in the German innovation system that also hampers the shift to electromobility: German industry and public institutions had largely abandoned battery research in the 1970s when the electrical and optical industries shifted to Asia. German carmakers were also late in recognizing the importance of lithium-ion batteries for energy storage. When small lithium-ion batteries for electronic devices such as computers and mobile phones made unexpected performance leaps, it created a global hype about lithium-ion batteries as a promising option for automotive traction batteries around 2008–11, and Germany was far behind the technological frontier. As the batteries are calculated to make up around 30% of the total value of an electric vehicle (Deutsche Akademie der Technikwissenschaften 2010), the dependence on foreign know-how in this core technology is a strategic weakness. However, as will be shown in Section 4.2, this is beginning to be addressed.

In terms of policy, the strongest wake-up call came from Brussels, when the European Commission announced CO_2 fleet emission targets for passenger cars which were to be phased in between 2012 and 2015. Reaching these targets is particularly challenging for Germany's up-market producers. The German government responded with the launch of the National Electromobility Development Plan in 2009 which set the target of putting:

> . . . one million electric vehicles on the road by 2020, possibly reaching over five million by 2030. (Nationale Plattform Elektromobilität 2012)

One year later, the Nationale Plattform Elektromobilität was formed as a public–private alliance to coordinate technology development.

This political support needs to be seen as part of the broader agenda to bring about the *Energiewende* (i.e. the transition from a coal and nuclear-based to a renewables-based energy system), which ranks high on Germany's political agenda. Germany's National Electromobility Development Plan demands that the additional electric energy that goes into charging EVs should only come from renewable sources. This sets Germany apart from some other large automobile-producing countries, including China (where urban air pollution is the main driving force behind electric mobility and energy supply from coal-fired power plants outside city boundaries is politically accepted) and France (where nuclear energy is regarded as an acceptable option). The electromobility policy also reflects concerns that the German car industry, a backbone of Germany's economy, might miss out on a paradigm change and fall behind international competitors. At the same time, there are strong economic and political alliances willing to defend the interests of German carmakers and their technological focus on high-powered vehicles. In fact, the Federal government and German EU-parliamentarians successfully lobbied to dilute the fleet-average emissions set by the European Commission. Hence, policy-makers

are trying to strike a fine balance between competitiveness and climate policy agendas, and actual policies are sometimes fairly contradictory.

3.3 China

Although China's automobile production goes back to the early years of the People's Republic of China, the industry only took off in the 1990s after being declared strategic for China's economic development. Sales soared when private car ownership was allowed in 1995. By 2012, the number of registered passenger cars in civil use exceeded 89 million (China National Bureau of Statistics 2013), making China the world's largest automobile market.

Car production was seen as a cornerstone of technological development, and national policies aimed to encourage indigenous innovation. Progress in this regard, however, has been slow. Despite automotive research ranking high on China's agenda and foreign investors being obliged to produce in joint ventures with Chinese partners, foreign brands still capture almost 60% of the market. Some success has been achieved in the small car market segments of small cars and two-wheelers, whereas premium cars, which command a large share of the Chinese market, are almost exclusively manufactured with foreign technologies.

The automotive industry is clearly segmented, with some large state-owned enterprises (SOE), many of which are produced in joint ventures with foreign carmakers, and some smaller, often private national car companies that struggle to compete with SOE. Historically, many provincial governments tried to set up their own automotive companies and supply chains, which further contributed to fragmented production structures at the expense of economies of scale. This dual fragmentation—in terms of ownership and jurisdictions—creates disincentives for collaborative research, which is a key asset of advanced automotive production systems. Despite the unprecedented boom in Chinese car manufacturing, knowledge deficits persist in most complex technologies (e.g. engines and power trains) and dependence on licensed technologies and joint venture partners remains high.

Government policy had already started to encourage electromobility in 2001, when a key special project for EVs became part of the national high-tech R&D program. In 2009, the government identified EV production as one of several strategic emerging industries in 2009, creating a range of very attractive incentives and setting the ambitious targets of producing 500,000 BEV/PHEV by 2015 and two million by 2020.

There were two main motivations behind support for electromobility. First, electric driving was seen as an opportunity to upgrade China's disappointing 'indigenous' automotive industry and to enter a growth path based on knowledge and indigenous innovation. This was based on the assumption that the automotive structure of BEV is comparatively simple and an industrial paradigm change would shake up the power structures in the industry. Optimism was further spurred by the fact that China had gained substantial experience in manufacturing lithium-ion batteries for electronic consumer goods and that the country possesses 13% of the world's known lithium reserves as well as substantial deposits of other rare earths.

Urban air pollution is the second important driver of electromobility initiatives. The enormous increase of road traffic in China contributes greatly to air pollution. The concentration of particulate matter in large cities is far beyond what the World Health Organization considers safe, and respiratory health problems are among the main causes of death (Cheng et al. 2013). It should be noted that, with the current Chinese carbon-based electricity mix, shifting from ICE to battery-electric driving actually increases carbon emissions (Wilson 2013). Hence climate change mitigation is not (yet) a core motivation behind the policy.

As a key element of electromobility support, a demonstration project in 13 pilot cities was announced in 2009, to which 12 cities were later added. Later on, especially with the launch of the 'energy saving and new energy vehicles industry development plan (2012–2020)', generous incentives were offered, including purchase subsidies above €6,000 per BEV and tax exemptions for BEV, although with substantial differentiation across provinces. Large dedicated research programs with an emphasis on lithium-ion batteries were initiated. In some megacities, such as Beijing and Shanghai, the rights to buy and drive ICE cars and circulate in the inner cities were restricted. Public procurement triggered the conversion of public bus and taxi fleets to BEV and, to lesser extent, HEV.

3.4 India

India is a latecomer to the global automobile market. Before economic liberalization in the early 1990s, the country only produced small numbers of technologically outdated vehicles. Over the last decades, however, the industry has made enormous progress, benefiting from the acquisition of technological capabilities and the emergence of urban middle-class consumers. With almost 3.3 million cars and over 13 million two-wheelers in 2012, India has become a major automobile manufacturer. Three-wheelers and commercial vehicles also registered impressive growth rates (International Organization of Motor Vehicle Manufacturers (OICA) estimates, ICRA 2012). India has already become the second largest two-wheeler market in the world, closely trailing China. By 2020, India is projected to become the world's third largest automobile market, with a particularly strong growth in the small cars segment (J. D. Power and Associates 2011).While the Indian car industry represented just 1.7% of global car production in 2002, it had grown to a 5.2% global share ten years later (OICA estimates).

Domestic Indian players like Tata Motors, Mahindra & Mahindra, TVS Motors and Bajaj Auto have been able to leverage this high-growth period to move from being importers of foreign technology to being product developers. This has been charted through an extensive learning phase characterized by in-house R&D spending, strategic alliances, joint ventures (Tata Motors with Fiat, Mahindra & Mahindra with Ford and Renault, Bajaj Auto with Kawasaki, and TVS with Suzuki), acquisitions and assets-building efforts in foreign markets (Jaguar Land Rover by Tata Motors, Ssangyong by Mahindra & Mahindra, and KTM by Bajaj Auto). As a result, the technology gaps between Indian and global products in the ICE sector have been continuously decreasing. A significant catch-up has already been achieved (Balcet and Ruet 2011).

Regarding the shift to electromobility, India faces several disincentives. First, electricity is in critically short supply, with a peak electricity shortage of almost 16.6% (in the southern grid) and poor grid resilience despite the fact that a quarter of the population has no electricity. The peak electricity shortage is growing because the increase in demand far outstrips the added generation and because of phenomenally high transmission and distribution losses ($\sim$25%). Thus, encouraging the deployment of electric cars would place additional strains on electricity provision and increase grid instability. Second, the urban consumer's purchasing power is low. Consumers have a strong preference for small vehicle sizes and fuel efficiency,

but few consumers are willing and able to accept the mark-up of EVs. Third, in the current Indian setting, shifting to electromobility would actually increase carbon emissions. With the current electricity mix, the emissions of 370 g CO_2-e/km for BEV far exceed the typical fleet emissions of approx. 140 g CO_2-e/km for the ICE cars (Wilson 2013). This is due to a coal-intensive power sector as well as the high transmission and distribution losses. Fourth, India does not have a significant industry and knowledge base in battery chemistry.

Despite these disincentives, the Indian government launched a subsidy for the purchase of electric two- and three-wheelers in 2010. Following that, the government announced a National Mission for Electric Mobility in early 2011, promising purchase subsidies, duty exemptions, income tax exemption, government fleet procurement, R&D support for EV projects etc.

What drove this policy, as well as the large Indian carmakers' investments, was mainly the wish to maintain a strategic presence in the evolving car industry and to ensure that the successful industry does not miss out on a potentially disruptive global paradigm shift. The scale of such engagement, however, is far lower than that of wealthy car-producing countries and large global OEMs. Also, climate change mitigation is increasingly accepted as a policy objective. The National Mission is actually part of India's low-carbon agenda, even though in the current conditions the electrification of road transport would greatly increase greenhouse gas emissions.

While these considerations have led to a mission-based policy approach announcement, financial considerations have delayed implementation. With the termination of the Alternate Fuel for Surface Transportation Program in 2013, at present there is virtually no policy framework for the EV sector: only limited state-level subsidies are available. In fact, subsidies for car owners are difficult to justify in a country with 400 million poor people.

4. The nascence of technological pathways

Section 3 has shown enormous variance in the preconditions for a technology shift from ICE to electric driving. This section summarizes some of the recent technological developments in the four countries and tries to explain their emergence against the background of specific initial conditions. It shows substantial variation in strategic behavior and technology choice and hints at some elements that may shape country-specific technological pathways, even though it would be premature to predict clear trends given the current state of 'ferment' in the emerging industry.

4.1 France

Favorable conditions for electromobility and determined political support (in terms of purchase subsidies, public procurement of BEV and R&D subsidies) led to an early uptake of EV production following the *Grenelle de l'environnement* law in 2008.

The French OEMs responded quickly to the opportunities, starting to electrify light commercial vehicles, many of which could be sold to the French government and the state-owned postal service. Renault was the first European carmaker to produce BEV at a commercial scale. The first EVs were launched on the basis of a traditional car architecture. PSA launched a licensed version of a Japanese BEV but also immediately invested in new power trains, becoming the first European company to enter serial production of diesel HEV in 2011. While both OEMs chose different product strategies, they focused on their traditional clientele, offering functional and affordable vehicles for low- and middle-income customers and catering to the needs of public fleets. Renault started two experiments to make the expensive lithium-ion batteries affordable. It tested the battery swapping model (which failed) and it was the first European company that leased the battery as a way of dealing with the high purchase price of BEV.

Besides the large OEMs, some small newcomer firms tried to take advantage of the favorable environment for electric cars. The most successful one is the Bolloré Group, an innovative company that developed a special battery technology, the LMP battery which is a technologically very different alternative to the lithium-ion battery which is currently the globally dominant standard. Bolloré developed an electric car, the 'Bluecar', as well as an electric bus with the primary aim of creating a market for and testing its LMP battery. In 2011, Bolloré founded Autolib, a car rental company, for registered customers in Paris which runs a fleet of Bluecars and operates its own network of charging stations, again with the main aim of expanding the market for LMP batteries. The business model is supplemented by a special internet-based information system in the Bluecar vehicles which was developed by another subsidiary of the Bolloré Group. Recently, the car rental was extended to other French cities, to London and Indianapolis (Hildermeier and Villareal 2011; Schamp 2014).

So far, France's early adoption of electromobility does not seem to have translated into any lasting advantage. Despite high subsidies, public procurement programs and government investment in charging infrastructure, the economies of scale that would make EVs profitable have so far not been achieved. On a more positive note, French carmakers have gained considerable experiences with new business models such as EV car rentals and battery leasing.

Purchase subsidies may have convinced some consumers to opt for BEV, but they have not made much difference. This may not be surprising, considering that the large carmakers like Renault and PSA decide on their production strategy with international markets in mind, whereas a national subsidy can only affect domestic sales. Moreover, the subsidy is only temporary and given France's fiscal deficit it is unlikely that high subsidies can be maintained once sales pick up. In the essence, the policy push has not been strong enough to compensate for the French automotive industry's structural lack of competitiveness.

4.2 Germany

The specificities of the German automotive innovation system and political framework conditions have led to particular technological developments. First, German industry with its strength in high-powered ICE is not keen to adopt the new power train technologies. As a result, German OEMs launched HEV and PHEV models as late as 2013–4, two to three years later than France. This latecomer situation is not seen as a matter of concern. German OEMs recognize Toyota's courageous early adoption of hybrid technologies which was a technological and commercial success. Other than that, German OEMs are confident that they can launch PHEV or BEV fast enough once the respective markets develop.

The German carmakers' high average fleet emissions face the risk of alienating environmentally conscious consumers and provoking penalty payments imposed by the European Commission if the required fleet emission standards are not met. Reducing motor power or extra equipments would be incompatible with the target group's expectations. Thus, carbon efficiency is pursued through innovative technical features which, in most cases, are first offered in

up-market segments, a strategy very different from French OEMs focus on simple and affordable EVs. These include improvements of ICE and hybrid technologies, where German competitive strengths in engines, power trains and auto electronics are an asset.

To introduce hybrid and battery-electric technologies in volume production, some German OEMs bet on cost reduction through aggressive modularization and standardization. The idea—most clearly seen in Volkswagen's modular transversal toolkit and Daimler's BlueZero concept—is to develop new automotive concepts in such a way that different power trains (from gasoline and diesel engines to fuel cells, HEV, PHEV, BEV and gas) can be assembled on a common platform and as many parts and components as possible can be standardized for all technological options. This allows economies of scale to be exploited in production while mitigating the risk that comes from not knowing which technology will actually become the dominant design.

Also, German industry and research centers are gradually making up leeway in the previously neglected field of battery technology. A range of different competences are required to produce automotive batteries: spanning from battery chemistry to the production of membranes, production of cell modules, packaging of modules and, finally, battery management systems (BMS), which involve electronics and are decisive for adapting the battery to the specific requirements of each type of automobile. While German carmakers and first-tier suppliers such as Bosch are at the cutting edge of BMS, the upstream activities have not yet been developed for lithium-ion batteries. However, large chemical companies, especially BASF, have now made enormous investments and acquired hi-tech companies in different fields related to battery chemistry and membranes. Daimler and other carmakers have formed a number of strategic alliances with international battery companies and invested in battery packaging facilities. The production of modules is considered to be a relatively low-tech activity that is not critical for driving performance and can thus be outsourced to low-cost locations. Industry analysts are now quite optimistic that German industry will rapidly reduce the technological gap *vis-à-vis* Japan and Korea, the world leaders. This confirms the relevance of 'related variety' (Frenken et al. 2007), a concept that explains how the availability of complementary knowledge assets in a country or region facilitates the creation of new technological capabilities.

Some new business models in electromobility-related services are also underway. One distinct field is intermodal transport. New alliances between carmakers, energy utilities and railway companied are now experimenting with e-carsharing. Some firms are also developing software solutions for efficient driving and charging, electronic payment and billing systems for electricity charging etc. Smart grid technologies capable of dealing with intermittent electricity supply from solar and wind sources also receive a lot of attention. They are particularly relevant for Germany, where a decision was taken to only supply EVs with renewable energy. While such country-specific regulations may encourage the build-up of unique smart grid capabilities in the future, so far the respective service innovations are still at a very early stage and it is impossible to foresee whether any of them has the potential to evolve into a specific field of national technological specialization.

4.3 China

Despite strong policy support and a thriving automobile market, EV sales have not yet taken off in China. While China became the largest car manufacturing hub in the world producing 22.1 million automobiles in 2013, only 0.08% of them were highway-capable new electric cars.[10] The latter have mainly been purchased by bus and taxi companies, whereas individual consumers are still reluctant to buy electric cars. Overall, the Chinese EV industry is still at the stage of experimentation and small batch production. The technological knowledge base is still weak by international standards.

SOE, especially those engaged in joint ventures with international OEMs, and small private companies show a very distinct attitude towards electromobility. Given the former's fairly secure and booming markets in ICE vehicles, they have little incentive to enter the risky field of EVs and only recently started engaging, when the Chinese government offered attractive incentives. This may change in the near future as international joint venture partners are now starting to launch EVs in the country and the government increases pressure on them to share more knowledge locally. So far, however, the large industry players mainly rely on retrofitting existing ICE car models. By the end of 2012, none of the large state-owned car companies had developed a car model optimized for EV technology. Moreover, there is a preference for simple, affordable solutions. China's best-selling EV, the Chery QQ3EV, uses cheap but environmentally harmful lead-acid batteries. A recent market analysis suggests that:

> . . . the 'Chinese EV' may be an electric vehicle equipped with a small ICE whose sole purpose is to recharge the battery on the move. (McKinsey & Company 2012: 10)

This is less demanding in terms of harmonizing battery and ICE technology and does not require an external charging infrastructure.

While SOEs so far remain hesitant to venture into electrification, some newcomer firms in car production became EV pioneers, such as Zotye Auto, initially an automotive part producer. BYD, a battery producer for the electronics industry, first moved into car battery production and then produced the first PHEV in 2008 followed by a BEV in 2010. In 2014, the Daimler–BYD joint venture launched the BEV model Denza, a car co-developed between Daimler and BYD in China and for the German OEM the first car ever developed outside Germany.[11] Several other OEMs, including Toyota and BMW, are currently developing BEV exclusively for the Chinese market.

In addition to highway-capable passenger cars, three specific segments of the electric vehicle market are characteristic of China's emerging trajectory:

- First, the market for electric two-wheelers (bicycles and scooters) is booming. About 140 million electric bicycles circulated in China in 2012, with 24.5 million produced in that very year. To make them affordable for Chinese customers, two-wheelers are generally low-tech and powered by lead-acid batteries.
- Second, hundreds of companies develop technologically simple small low-speed, low-voltage, low-range electric cars. By removing non-essential features ('no frill') and low-cost components, such as lead-acid batteries, these cars can be sold at a price of US$3,000 –8,000, which is affordable for many Chinese households. So far, production has been discouraged by national traffic regulations (e.g. due to their maximum speed of only 50–70 km/h they are not allowed to use urban express highways) and users were not entitled to receive any of the subsidies offered for electric cars. However, some provincial governments do encourage these low-speed EVs, especially Shandong province, where dozens of small carmakers produced 128,000 small-size low-speed EVs in 2012.[12] Whether low-speed cars will survive as a major China-specific alternative to 'hi-tech', high-cost EVs

manufactured by established large carmakers is not clear. While Shandong's EV industry was finally approved by the central government in 2013, many central and local government policies are still contradictory with regard to minimum speed requirements and the phasing out of lead-acid batteries.
- Third, public transport companies are a major driver of electromobility in China. The roll-out of electric buses has been impressive, and buses may potentially become a field of competitive specialization in China. For example, Chongqing Hengtong Bus Power System Co. Ltd. has developed the world's first rapid charging battery-electric public bus.

China-specific technological solutions are also being developed in the field of battery technology. Chinese production of battery modules is technologically close to the international frontier, but the country lags far behind in the more sophisticated fields of battery chemistry, membranes and BMS. Technological mastery of BMS is particularly important to produce premium cars and to differentiate brands: BMS need to be specifically tailored to the energy requirements of each car. Moreover, they are necessary to optimize battery performance and prevent failures. The lack of technological capabilities in this field has led to two China-specific developments:

First, some Chinese companies including BAIC and Zotye have built remote battery monitoring systems which allow them to monitor the status of entire car fleets in real time through wireless networks. Monitoring centers can then send messages to drivers, assisting them to improve battery performance and avoid emergency situations. Compared to mature onboard systems, remote monitoring is clearly a second-best option, but it can substitute for some of the functions of advanced BMS.

Second, Chinese firms are investing in battery swapping whereby cars change their discharged battery for a charged one, rather than recharging their own battery. In principle, this saves time and provides flexibility to the user. The practical problem is that only identical batteries can be swapped. Carmakers, however, design BMS such that they meet the specific requirements of each model, with the effect that swapping stations cannot hold stocks of all battery models. In Hangzhou, EV manufacturers, battery manufacturers and the State Grid Corporation of China set up a city-wide battery swapping experiment whereby the latter owns the batteries. The experiment mainly targets taxis of the Zotye brand and bus fleets, which keeps the number of battery types manageable. Extending the experiment to other car brands, however, will be quite difficult.

In sum, given the lack of critical technological capabilities and the booming demand of consumer groups who can afford a cheap family vehicle for the first time, most Chinese EV innovations can be classified as low-cost, low-tech, 'no-frills' innovations. Whether these will only be temporary experiments that will be outperformed by higher-tech (currently in most cases non-Chinese) alternatives or whether they will stabilize their sales in low-income markets remains to be seen.

It should be noted, however, that foreign carmakers are also developing China-specific innovations. Some are co-developed with Chinese partners (as the Daimler–BYD Denza), others rely almost exclusively on foreign technology. So carmakers develop models that fit Chinese market conditions and in some cases are exclusively produced for this market. This development further complicates the basic idea of country-specific technological pathways.

4.4 India

Given the lack of some core technological capabilities, the deficits in electricity supply, the large infrastructural investments required and the low levels of purchasing power, a large-scale deployment of BEVs is very unlikely in this decade. In fact, neither Tata Motors, the Indian market leader, nor any of the major global OEMs are planning BEV launches for the Indian market anytime soon. The only attempts to develop BEV relate to niche markets (intra-city vehicles, delivery vehicles, premises-bound mobility vehicles etc.). Also from a climate policy perspective, the electrification of road transport with the current energy mix would do more harm than good.

Long before the present wave of interest in EVs, India had an electric car available domestically. The REVA compact electric car, launched in 2001 with design and development assistance from a California-based firm, however, never became a commercial success. By 2012, when the company ceased production of the REVAi, it had sold less than 5,000 units. The company was then acquired by Mahindra & Mahindra, one of India's large carmakers. The new company launched the updated REVA E2O, targeting wealthy urban families interested in a second family car with limited range requirements, but so far with little success.

A more promising technological specialization can be observed in mild hybridization. Major Indian automobile industry players (including Tata, Mahindra & Mahindra, TVS and first-tier suppliers such as Bharat Forge) have undertaken activities to develop hybrid technologies for two reasons. First, technologies such as regenerative braking, stop-start as well as systems that intelligently modulate the power flowing between the ICE and electric power train promise to achieve higher efficiencies—a good sales argument in India's price-sensitive market. Second, India's booming automotive industry wants to keep up with technological developments that may potentially revolutionize the global car industry. Through prototypes and concept vehicles, Indian OEMs such as Tata have demonstrated development capabilities, but the additional costs of drivetrain hybridization are widely seen as being too high for Indian market conditions.

Two recent low-cost developments are particularly promising, both still at an experimental stage but basically ready for a commercial launch. First, KPIT Cummins, India's largest automobile technology services company, has developed a plug-in hybrid conversion kit, called Revolo, which can be retrofitted in new or existing petrol or diesel cars. It consists of an electric motor, an electronic motor controller, a battery pack, battery management system and software which controls battery and motor performance, recognizing driving patterns and self-adjusting for better efficiencies. The control system ensures that the ICE engine works in its most efficient running cycles. Independent tests have proved efficiency improvements of over 35%. The vehicle can be plugged into the electricity grid. Similar retrofitting kits exist in the US market, but Revolo will sell at a much lower price (US$1,200–2,800 depending on engine size) compared to US$20,000 in the USA.[13] Moreover, the producer intends to offer batteries on lease to make the product even more affordable.

Second, low-cost plug-in hybrid scooters have been developed with significantly improved hybrid mode efficiency. India is a large two-wheeler market, with annual sales of motorbikes and scooters exceeding 13 million. The first electric two-wheelers were imported kits from China. Due to their poor performance and lack of service infrastructure, however, consumers turned away from Chinese two-wheelers. At the same time, Indian firms have built up strong R&D and development capabilities. Given the undersupply of electric power, some players such as TVS have moved away from purely battery-electric two-wheelers and concentrated their efforts on hybrids. Developed in the period 2009–12, the TVS Qube became the first

hybrid two-wheeler in the world expected to retail at only a US$100 price premium over a similar ICE powered vehicle. A small (0.25–1 KWh) lithium-ion battery provides a short pure electric range (~10 km) and thereafter uses the battery to support the hybrid mode (with stop-start, regenerative braking etc.). The market potential for such low-cost innovations is enormous, not just in India, but also in many other countries.

5. Conclusions

With this paper we set out to analyze to what extent, how and why technological pathways differ between countries. We placed special emphasis on the question of how patterns of technological specialization evolve out of phases of experimentation at the beginning of a paradigm shift. We analyzed the shift from road transport based on ICE to electromobility, comparing four countries (France, Germany, China and India) which initiated change almost simultaneously but started from different positions.

The comparison shows that very different technological experiments are undertaken in each of the countries, despite the fact that automobile production is a highly globalized industry in which powerful corporations organize production networks spanning all major markets worldwide. But production networks for alternatives to the old ICE technology have not yet been established on a global scale. As long as this is not the case, the specificity of initial country conditions favors technological plurality. In the case of China, the automotive industry's global players themselves contribute to the establishment of a country-specific pathway, as they develop, together with local partners, distinct technologies for that market.

Paradigm change is often associated with changing actor constellations and power relations. The rise of electromobility as an alternative has indeed triggered the entry of newcomers trying to challenge the dominating firms of the old paradigm. BYD in China and Bolloré in France are some remarkable examples. Overall, however, our observations confirm the results of Bergek et al. (2013), who found that incumbents persevere with the ICE but add new features by combining new and existing knowledge bases.

The same holds for country-level competition. While China, India and even France, given the declining competitiveness of its automotive industry, hoped to exploit the paradigm change to close the competitiveness gap *vis-à-vis* Japan, Germany or Korea, so far their hopes have been unfounded. The new technologies require many of the capabilities which global OEMs and automotive clusters have developed over time, in narrowly technical (e.g. mechatronics, software and new materials) as well as in organizational terms (such as organizing collaborative research and multi-tiered production systems). Transferring such capabilities from traditional to electric car manufacturing seems to be easier than building them in the first place. Seen through this lens, Germany's highly competitive automotive innovation system seems best prepared to meet the challenges of the electromobility transition.

Our analysis revealed four main drivers of divergence which can unfold unhampered as long as globalization and scale effects are not bending innovation towards convergence. These drivers lead to very different technologies and business models being developed in the four countries.

First, there are the different technological capabilities of national automotive and related industries. Despite China's and India' enormous progress in car manufacturing, the challenge of developing new power trains and new energy storage technologies and combining them into commercially viable new products have so far overstrained their technological capabilities. In the field of electromobility, low-tech solutions characterize the emerging technological pathways, such as retrofitted ICE vehicles and the use of lead-acid batteries. In contrast, France and Germany, with their century-old automotive innovation systems, are among those countries that compete for technological leadership in the emerging industry, bringing out new-to-the-world innovations (e.g. in lightweight car architecture, in diesel hybrid technology, new batteries and new business models). Interestingly, Germany's innovation capabilities not only in the auto and auto parts industries but also in related industries seems to enable the local industry to quickly overcome its latecomer status in hybrid and fully EVs including its backlog in the battery industry.

Second, there are specific demand conditions. Many of China's and India's emerging specializations relate to 'no-frills' innovations aimed at consumers with little purchasing power, such as two-wheelers and low-speed cars. India's frequent power shortages gave rise to specific competences in low-cost hybrid solutions. The French innovation efforts target affordable, functional electric cars: those that French consumers demand. The availability of cheap low-carbon electricity from its nuclear power stations also led to an early emphasis on BEV, whereas in the field of hybrids, France has become a leader in diesel hybrids reflecting the national preference for diesel. Germany is entering the new industries from the high-end, focusing on technologically sophisticated cars and ensuring that electrification does not sacrifice driving pleasure and performance. The early adopters of innovation also differ. In the European countries, early EV adopters tend to be environmentally conscious consumers as well as technology 'aficionados'. In China, these segments are less likely to adopt EV. Here, the most important early adopters are public fleets (McKinsey & Company 2012). Also, urban consumers in Europe are developing new business models including e-carsharing and intermodal travelling, which are not yet gaining traction among Chinese and Indian consumers.

Third, there are different perceptions of the problem and political priorities of governments and societies. In the EU, a policy directive to reduce CO_2 emissions provided the main impetus for reform. Thus, electromobility was linked to low-carbon sources of electricity. In France, where nuclear energy is in abundant supply, fully electric BEV received strong policy support. In Germany, where nuclear energy is being phased out, supply must come from renewable sources, which forces German innovators to develop smart grids capable of handling fluctuating supply. In China, urban air pollution is seen as the most pressing environmental problem, and electromobility is therefore encouraged even if cars obtain their electricity from coal-fired power plant, as long as the emissions are kept away from the cities. For all countries, increasing or retaining competitiveness in the auto industry is a key motivation. This means that Germany needs to find solutions for its high-emission car brands whereas all other countries hope that a changing paradigm provides opportunities for closing the existing competitiveness gap.

Fourth, there are different notions of economic governance. The transition from systems based on fuel and internal combustion to electricity-based transport systems is held back by manifold market failures and requires subsidies and concerted action. What governments are willing to subsidize and how they intend to overcome coordination failure, however, is very different. China and France both provide very high purchase subsidies to start the market and persuade SOEs and parastatals to help achieving their policy objectives. Germany subsidizes research rather than consumer uptake and

leaves coordination to private-sector led initiatives. India has announced, but so far failed to implement, a credible and coherent electromobility policy. How decisively governments intervene in markets and how they allocate subsidies or taxes to different technologies gives rises to country-specific processes of cumulative causation. The French support for BEV and Germany's lobbying to allow higher emissions for heavy cars are cases in point.

While our country studies have shed some light on the technological experimentation during the 'era of ferment' at the beginning of a paradigm change, four major research gaps have become evident:

The first one relates to the emergence of new dominant designs. As Anderson and Tushman (1990) argue, experimentation is typical during regime transitions, but certain designs sooner or later become dominant, crowding out less viable alternatives. In fact, our analysis showed the risks and uncertainties surrounding many of the ongoing experiments, suggesting that many of them may be short-lived. How much of the current variety will remain, and at what point in time converging forces kick in, can only be shown in future research.

Second, more research is needed to fully understand the dialectic relationships between global value chains and geographically embedded innovation systems. Our case studies revealed how large carmakers which are anchored in the same national innovation system (such as Renault and Peugeot) nevertheless pursue very different strategies; and how others (e.g. Daimler and BMW) pursue specific technological pathways for the Chinese and for their traditional markets. Hence, path formation results from different combinations of country conditions and firm strategies. The more global value chains cut across territorially defined innovation systems and the more technological interfaces appear between previously well-defined subsystems such as the automobile industry, the energy system and the public transport system, the more difficult it becomes to identify clearly defined technological pathways. This calls for going beyond narrowly defined research frameworks and accepting the challenge of analyzing nested and overlapping subsystems.

A third research gap relates to the future of, and policy frameworks for, low-tech, 'no-frills' innovations. We have shown that most innovations in China and India are in this field, although (with the notable exception of Shandong province) they are not encouraged by policy-makers. While it is advisable to discourage low-tech options that are harmful to the environment (like lead-acid batteries) or compromise on safety (low-speed cars), there may be low-tech solutions (hybrid motorbikes) without such undesirable features. 'No-frills' or 'frugal' innovations from emerging economies have recently received considerable attention in the literature (Tiwari and Herstatt 2012), but more research is needed to assess their market potential and better understand the type of regulatory and innovation policies to support those that are socially desirable.

Fourth, our analysis suggests that powerful incumbents from the old high-carbon economy continue to dominate technology even during the transition. At first glance, this seems to be bad news for climate change mitigation, and may partly explain why the pace of decarbonization is slow. It may, however, also be a good thing if large corporations, with all their accumulated expertise in organizing technological progress, find a way of shifting smoothly towards new low-carbon paradigms rather than being destroyed by disruptive change. The question thus arises: under which conditions can high-carbon incumbents be persuaded (or forced) to support low-carbon transitions rather than block them?

Notes

1. While in 2000, non-OECD countries accounted for only 46% of global passenger mobility (person km), their share is projected to increase to 78% in 2050 (OECD and International Transport Forum 2011).
2. A more comprehensive review is undertaken by Schmitz and Altenburg (2015, this issue).
3. See <http://www.idtechex.com/research/articles/big-disagreement-on-where-lithium-ion-batteries-are-headed-00004598.asp> accessed 9 Nov 2014.
4. For a discussion of competence-enhancing vs. competence-destroying technological discontinuities see Anderson and Tushman (1986).
5. See for instance Intergovernmental Panel on Climate Change (2014).
6. Dosi (1982) uses the synonymous term 'technological trajectory'.
7. For detailed country studies and further references see Schamp (2014) for France, Altenburg (2014) for Germany, Chaudhary (2014) for India and Chen et al. (forthcoming) for China. Sections 3 and 4 are mainly based on these four publications.
8. See <http://www.faz.net/aktuell/wirtschaft/renault-und-peugeot-schleichender-niedergang-der-franzoesischen-autoindustrie-11831432.html> accessed 10 Nov 2014.
9. See <http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/France/> accessed 23 Nov 2014.
10. Present authors' calculation based on <http://en.wikipedia.org/wiki/Electric_car_use_by_country#China> accessed 11 Jan 2015 and Chinese car production statistics.
11. For an analysis of Chinese firm strategies see Shen et al. (2015, this issue).
12. See <https://www.techinasia.com/china-shandong-becomes-hub-for-electric-vehicles/> accessed 22 Nov 2014.
13. See 'PHEV conversions slow to catch on in U.S. But could be big elsewhere' <Edmunds.com> accessed 13 Sep 2010.

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