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The emergence of an electric mobility trajectory

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A B S T R A C T

In this paper, we analyse the emergence of a trajectory of electric moblity. We describe developments in electric vehicles before and after 2005. The central thesis of the paper is that electric mobility has crossed a critical threshold and is benefitting from various developments whose influence can be expected to grow in importance: high oil prices, carbon constraints, and rise of organised car sharing and intermodality. We find that the development of vehicle engine technology depends on changes in (fueling) infrastructure, changes in mobility, changes in the global car market, evolution of energy prices, climate policy, and changes in the electricity sector. Special attention is given to interaction of technological alternatives: how these work out for the future of battery electric vehicles, hybrid electric vehicles and hydrogen fuel cell vehicles.

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1. Introduction

In the last five years there has emerged new momentum for (battery) electric vehicles (BEVs), after a period of dissapointment in BEV around the turn of the 21st century. In this paper, we describe developments in electric mobility before and after 2005 and we analyse the emergence of a trajectory of electric moblity. The central thesis of the paper is that electric mobility has crossed a critical threshold and is benefitting from various developments: some technological, both within and outside the automotive sector, and some developments in the social context of car mobility. Special attention is given to interaction effects between the two and how these work out for the future of battery electric vehicles, hybrid electric vehicles and hydrogen fuel cell vehicles.

We adopt a socio-technical transition perspective as an instrument for our analysis, which does not prioritize social and technical elements, but sees these as inexorably linked (Rip and Kemp, 1998; Hoogma et al., 2002; Geels, 2002, 2005; Geels and Schot, 2007). The socio-technical approach is both structuralistic and actor-based, highlighting the close alignment of social and technical elements, including product technology, industry, markets, consumer behavior, policy, infrastructure, spatial arrangements and cultural meaning' (Geels, 2005). Such a view is instrumental for understanding change that is not driven by single factors such as price or technological change, but typically involves co-evolution between multiple developments. The perspective is also actor-based, for it addresses actor perceptions, strategies, actions and interactions between car drivers, car manufacturing firms, policy makers and public opinion. Therefore, it differs from functionalistic approaches that tend to focus on system functions being fulfilled (e.g., in industry sector assessments and comparisons of various technologies) or pure economic approaches (where cost, performance, prices, incentives are the main variables).

The socio-technical transition perspective is instrumental to explain dynamic *stability* and incremental change on the one hand, and radical innovations and system *change* on the other. To explain *change*, it uses concepts such as 'niches', which are protected spaces where potentially radical innovations emerge, and 'socio-technical landscape', which are external developments that can create pressure on existing systems (or better 'regimes'). To explain *stability*, the notion of sociotechnical regime plays an important role, which helps to describe how car mobility is locked into internal combustion engines because the societal context is adapted to their use in terms of expected speed and power, training and knowledge and maintenance networks, regulations (e.g., safety, maximum speed), cultural acceptance, etc. The transition perspective deviates from simple drivers and linear cause-and-effect relationships because it puts emphasis on mutually reinforcing developments and (sometimes unexpected) alignments, co-evolution, circular causality, knock-on effects, and hype-disappointment cycles.

There are various ways in which a possible transition towards electric car mobility could occur, and Geels and Schot (2007) have

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suggested four generic types of 'transition pathways'. In this paper, the term pathway is, however, necessarily broader that the pathways of Geels and Schot, since the automotive sector may not go through transition at all. Therefore we use the term pathway synonymous to scenario, for instance regarding pathways of automobility, referring to possible future developmental path of the car mobility sector (which may involve various technologies). We distinguish the related term trajectory from pathway, and we use trajectory in relation to a specific technology, for instance a trajectory of electric mobility, similar to how various studies on technological trajectories apply the term. In this terminology the future pathway of a sector may thus consist of a range of technological trajectories.

The paper is structured as follows: Section 2 explains the stability of the sector and the lack of momentum of the electric mobility (EM) niche before 2005 by addressing the alignment of social and technical elements, including regulations, pilot projects on the new technology, demand structures and responses in the industry. Section 3 analyses EM developments after 2005, what we termed 'present continuous' to describe how the allignment of social and technical elements is becoming more malleable through certain trends but also through the deliberate practice of a few specific actors. Section 4 examines prospects for the electrification of automobility and, finally, Section 5 summarizes the factors behind EM activity in recent years.

2. The recent past: EM niche developments in the 1990s

After the early appearance and decline in the late 19th and early 20th century, interest in battery electric vehicles (BEVs) re-emerged in the 1960s and 1970s in the USA, mainly due to the negative effects of air pollution and rising oil prices. The 1965 Clean Air Act triggered several research institutes and firms to develop electric cars, but results were poor in terms of both technological performance and price compared to their gasoline counterparts (Mom, 1997). At the end of the 1970s, less than 4000 BEVs had been sold worldwide. After a period of little activity, public interest on BEVs revived once again in the second half of the 1980s and the early 1990s, bringing renewed hopes to environmentalists that BEVs would finally become a mass market reality. This was mainly due to the new regulatory push done by American State of California and, to a lesser extent, to the environmental policies and programs promoted in Europe.

2.1. Regulatory push and bottom-up developments of BEV enthusiasts

Following a tradition of being in the vanguard of emission legislation, in the early 1990s the American State of California led a technology forcing approach for the introduction of zero emissions vehicles (ZEV). The California Air Resources Board (CARB) had the ambition to set strict emission standards to curb health problems in the Los Angeles area provoked by motor vehicles' toxic emissions. Coincidentally, in January of 1990, General Motors presented an BEV concept car (later marketed as the *EV1*) in the Los Angeles Auto Show, which greatly impressed the public and sent signals to CARB that BEVs were ready for mass commercialisation. Though GM did not intend the car to be mass-produced, it encouraged CARB to include BEVs in the Mandate[3] , which was adopted in September of that year (see Hoogma et al. 2002). With the standards, CARB intended to trigger further development and sales of electric vehicles. Since California represented about 4% of the world market for cars and about 12% the US car market at that time, the ZEV Mandate was quite important for automakers (Kemp, 2005). By 1994, four additional states (New York, Massachusetts, Vermont and Maine) had adopted the California ZEV mandate and eight more joined the National Low Emissions Vehicle (NLEV) Program, approving stricter requirements than the federal ones from the Environmental Protection Agency (EPA).

The organisation of the European Union with its system of environmental Directives made it difficult to adopt a regulatory framework similar to the American ZEV mandate. Although national or local authorities could impose a ZEV regulation, there was an apparent consensus among policymakers that the use of incentives, rather than disincentives, was a more desirable and potentially more effective way of promoting cleaner vehicles (Nieuwenhuis and Wells 1997). In Europe, interest in BEV technology had its main origins in engineering schools — Germany, Denmark and Switzerland, in particular. Ecological-conscious students and technicians in small enterprises were able to move from developing solar vehicles to the artisanal manufacturing of lightweight BEVs. After being showcased to the public, coinciding with the developments in California, these vehicles motivated politicians to promote their mass production and commercialization (Hoogma 2000). This led to the support of R&D programmes in several Western European countries, involving the sponsorship of demonstration projects, subsidies, and tax reductions for such vehicles.

2.2. Pilot and demonstration projects

In the early 1990s, a few small companies outside the (high volume) car industry were dominating BEV-developments. These niche players adopted a different design for the car body, which depended less on economies of scale and allowed them to be profitable by selling only a few hundred vehicles — even though their cars were relatively more expensive than conventional ones. Forced by the Californian ZEV Mandate, high volume car manufacturers showed increasing commitments to the BEV technology and, after presenting prototypes in auto shows, some started to sell a small number of BEVs. Different from the dedicated BEV producers, automakers opted for a low-risk, low-cost strategy of converting existing models into BEVs (the Renault Clio and Peugeot 106 are good examples).

Hoogma et al (2002) studied the European demonstration experiments with electric vehicles in Germany (Rugen Island, 1992–1996), Switzerland (in the town of Mendriso, after 1995), and Norway (via the development of an BEV called *Th!nk*, after 1991), among others. Possibly the most remarkable project was the one led by EDF, the French electric utility, which ordered 2000 BEVs for the experiment in the city of La Rochelle in the West coast of France. The experiment initially seemed a small miracle, since users loved BEVs. Public attention was high and much was learned about user acceptance and the conditions needed to support BEVs. As it turned out, however, only a few consumers were willing to buy the new car outside the experiment. People's willingness to pay for an BEV was not really tested by the experiment.

More positive results were achieved in the large-scale pilot and demonstration project for lightweight electric vehicles (LEVs)

[3] The ZEV Mandate in 1990 required that 2% of all new cars sold in California should be "zero emission" by 1998. In the year 2000 all new cars sold had to be either "low emission", "ultra low emission" or "zero emission". Moreover, by 2003 75 % had to be low emission vehicles (LEV), 15% ultra low emission vehicles (ULEV) and 10 % zero emission vehicles (ZEV). For a more detailed analysis on how this regulation came about, see Kemp (2005).

in the Swiss town of Mendriso between 1995 and 2001. The aim of the project, initiated by the Swiss Federal Office of Energy, was to demonstrate and evaluate the usefulness of LEVs, to identify measures of promotion and to demonstrate the electric mobility concept. By 2001 the project had helped to bring 396 BEVs onto the roads, (174 cars, 20 light duty vehicles, 97 scooters and 96 electric bikes), two-third of the vehicles were owned by individuals and one-third by companies (Hoogma et al, 2002 p. 102). The programme and its follow up heavily relied on subsidies (50 to 60% of the purchase price). When the subsidies ceased, the enthusiasm for BEVs also faded away.

2.3. Doubts and disappointments

The interest in the early 1990s developed rapidly and rose substantially above the public interest registered in previous decades. Nevertheless, around the year 2000 attention shifted to hydrogen fuel cell vehicles (FCVs), indicated by the number of prototypes for BEVs and FCV (Bakker and Van Lente, 2009). BEVs prototypes emerged in the 1990s, fell in the first half of 2000, rising again after 2005. FCV prototypes fell sharply after 2007, which, according to the authors, shows that both types of vehicles are prone to cycles of optimism and pessimism.

All along the entire period, the interest of the car industry remained mostly on internal combustion engine (ICE) technology. The number of patents and new product launches in the period 1990–2005 clearly indicates the focus of European automakers on further developments of ICEs, such as the variable valve timing and direct fuel injection systems. On average, around 80% of the patents were awarded to ICE-related technology, against only about 20% for technologies associated with pure battery EVs and Hybrid EVs (Oltra and Saint Jean, 2009). In Japan, the number of patent applications on electric vehicles began to rise sharply in the early 1990s, stabilized in 1995 and declined rapidly afterwards (Yarime et al., 2008). Overall, most firms did not regard electric propulsion as a profitable strategy, and strong competition on gasoline and diesel engines triggered a great refinement of ICE performance in the 1990s. Although the efforts of regulators to make BEVs a commercial success motivated the formation of design and production networks, the few large-scale demonstration projects in Europe and in the US did not seem to appeal to consumers, discouraging carmakers to scale them up.

An important reason for the disappointment in mass-commercializing BEVs is the limited technological progress achieved during the 1990s, particularly in batteries. In that period, electric vehicles were mainly equipped with lead-acid batteries, resulting in very limited lifetime and range. In the late part of the decade, the focus of R&D shifted to nickel metal-hydrate and lithium-ion batteries, which were expensive at low production volumes. The two-seat BEV of the company Think Nordic is a good example. At €25,000 at that time, it was simply too costly to have a chance to succeed in the marketplace. Even the efforts made by Ford to rump up production, who acquired Think Nordic in 1999, were not sufficient to make the business profitable. Ford sold Think Nordic in 2001. In Japan, several electric vehicles were released to the market in the middle of the 1990s by major automakers (such as the Toyota RAV4 and Honda EV Plus). By the early 2000s, however, commercial production of electric vehicles had almost stopped (Yarime et al., 2008).

Another reason for the failure in scaling up experiments and, broadly, for the commercial failure of BEVs in the 1990s, was consumer preference. Dijk (2011) identified the main attributes consumers were looking for when buying cars, back in 1996. The research was limited to The Netherlands but the results may hold true for other countries as well. Range and price were the most important attributes mentioned by potential consumers of BEVs (75% and 55%, respectively). They were dissatisfied with both functionality and price of BEVs. Environmental impact (35%) was positively appraised, although to a lesser extent than by 1990. By 2000, however, there was only one salient negative attribute: range (71%). Overall, appreciation for BEVs in the 1990s was low. The available vehicle during that period cost twice as much as a conventional car and would take several hours to refuel.

In addition, the lobbying efforts made by the auto industry to loosen up regulations certainly contributed to hold back the commercial success of BEVs. From the early 1990s, car firms voiced their dissatisfaction with California's ZEV regulation and put pressure on US federal and European legislators to limit emission regulations. Although there were electric vehicle associations in Europe, US and Asia (mostly created by BEV enthusiasts), public support for BEVs was not strong enough to counterbalance the industry lobby. As a result, the Mandate was relaxed in 1996 (the requirements for 1998–2002 period were abolished), and again in 1998 (ZEV credits could be earned through partial electric vehicles). With the Mandate watered down, by early 2000s the political support for BEVs in the US had faded away. As a result, between 1995 and 2000 only a few thousands BEVs were sold worldwide, and poor sales records clearly reflected the market failure of BEVs in California and elsewhere, closing another BEV hype-disappointment cycle.

2.4. The only success story: Toyota Prius and hybrid technology

The only major success in the period 1997–2005 was provided by the hybrid technology. In the second half of the 1990s, Toyota and Honda were the first carmakers to move towards the mass commercialization of low-carbon vehicles via alternative powertrain technology. While automakers were relieved by the relaxation of the ZEV mandate in California in 1996, these two Japanese firms saw a business opportunity for the hybrid-electric powertrain technology, independently from regulatory measures. The *Prius I* was launched in 1997 and targeted the green market niche in Japan. In part because acceleration and maximum speed were compromised, the sedan had the lowest consumption in its category (3.6 l/100 km). After capturing the Japanese niche, the *Prius II* was launched California in 2000. The new version had increased acceleration (causing consumption to grow to 5.1 l/100 km) and a more attractive appearance (design). The new version was well received by American consumers, ramping up sales quickly and motivating Toyota to go one step further and launch the third generation of the hybrid technology (*Prius III*) worldwide in 2004. Toyota rolled out the *Prius* vigorously, which appealed to a broad set of consumers, such as the tech-savvy, paving the way for wider applications of hybrid-electric technology in other models. Overall, the car has been a huge success for Toyota, who earned the reputation of the greenest volume carmaker in the world. In the period 1997–2007, Toyota sold more than one million *Prius* worldwide.

In sharp contrast to Toyota and Honda, who launched their hybrids Prius and Insight in 1997 and 1998 respectively, all other carmakers were reluctant to invest in the hybrid technology. Disappointing experiences with fuel-efficient cars (the unsuccessful introduction of Volkswagen's Lupo 3 l in 2000 is a good example) was a factor, as this led them to believe there was no market for more expensive fuel-efficient cars. After 2005, however, there was a shift in perception, with most car manufacturers investing considerable resources in R&D to catch up. Nevertheless, these investments need to be viewed against car manufacturers' strategies and investments to improve ICE. All firms have invested heavily in refining ICEs, and most firms have marketed 'eco' versions of their ICE models, such as Volkswagen's *Bluemotion* line.

3. The present continuous: A new climate for eletric drive

From 2005 onwards, there is a new momentum for electric mobility (EM). This time, climate change concerns rather than urban pollution are driving the efforts towards the electrification of mobility, with *peak oil* also playing a role. The aftermath the Hurricane Katrina in 2005 sensitized public opinion about the negative effects of climate change, and Al Gore's *Inconvenient Truth* documentary (May 2006) raised global awareness. Altogether, such events influenced policymakers to develop regulatory frameworks and market instruments to curb carbon emissions (Orsato 2009). Such instruments, as well the role of entrepreneurs and technological development are described in the following.

3.1. Climate protection policies, targets and programmes

From 2005 onwards, concerns about climate change motivated governments worldwide to demand the car industry to decrease vehicle CO_2 emissions even further. In particular, the emissions targets of the Kyoto protocol gained momentum in this period. Regulatory measurers were introduced after Annex 1 countries realized that they would not meet the Kyoto targets. With the looming threat of having to purchase emission allowances, many countries started regarding EM as a means of reducing CO_2 emissions.

Politicians and policymakers also used climate concerns and policies promoting the diffusion of EM as a means to profile their green credentials, which were high in the public agenda in that period. Green, more fuel-efficient vehicles also featured well in the packages for economic recovery policies after the financial crisis of 2007. In the United States, from the US$16.8 billion provided in the American Reinvestment and Recovery Act for the office of Energy Efficiency and Renewable Energy (EERE), US$2 billion are supposed to be used to build a domestic battery industry. Although green recovery measures certainly represent a boost for EM developments, they also benefitted fuel-efficient ICEs via programs such as *cash for clunker*, which subsidize traditional fuel-efficient ICE cars.

The European Commission has stimulated the development of alternative powertrain technologies through R&D programs (mainly via the 7th Framework), and England, Italy, Germany, and Japan introduced subsidies for the purchase of BEVs. Denmark and Israel championed the incentives for BEVs by exempting them of the taxes paid for ICEs. The EU's 2008 Climate Change Package requests member states to achieve 20% energy efficiency improvements and 20% of the energy supplied by renewables by 2020. Accomplishing the *2020 Commitment* (as it is known) will require the integration of additional wind and solar power into the EU grid system and, as we explore later, large BEV fleets may help electric utilities to optimize power-grid management. In sum, various policies and programs in the largest economies in the world provided signals and incentives for carmakers to invest increasing amounts of money in R&D and acquisitions, in order to build competences in pure and hybrid EV technologies.

3.2. New market enthusiasm for pure batery EVs

After 2005, Nissan became more aggressive in trying to commercialize *pure* EVs. With its French partner Renault (and main shareholder), Nissan became the main supporter of the battery swapping technology, described in more detail in Section 4. Such technology is seen by some as a key solution for the problem of limited range of BEVs (today at around 160 km). Carlos Ghosn, the CEO of Renault–Nissan has been the main supporter of both pure EVs and the battery exchange technology. By 2012 consumers will be able to choose between the four BEV models produced by Renault, and the BEV *Leaf* rolled out by Nissan in late 2010. The partnership between Renault–Nissan and Better Place provided the legitimacy of new approaches and business models for the mass deployment of BEVs. Moreover, it triggered a level of competition around the BEV technology unique in the history of the car industry.

The competition towards the electrification of cars could be seen in the 2009 edition of the Frankfurt Motor Show, with almost every carmaker displaying BEVs prototypes (or *concept cars*, as they are known in the industry). Besides the aggressive marketing campaign around the launch of four models of BEVs by Renault–Nissan, other European volume producers, such as Mercedes and Fiat presented BEV models with clear plans to be launched before 2015. General Motors, following its fall from grace in 2008, put great emphasis in its plug-in hybrid *Chevy Volt* as a potential saviour of its financial problems — even though most analysts think this hope is unfounded[4]. In the Japanese auto industry, Mitsubishi Motors started the mass production of its pure electric vehicle (called *i-MiEV*) in mid-2009 at the scale of 1400 vehicles per year, almost at the same time when Fuji Heavy Industry introduced the plug-in *Stella*. Nissan plans to start commercial production of its BEVs *Leaf*, at the scale of 50,000 per year by early 2011, and to increase its production level to 150,000 per year by 2012. The global production of electric vehicles by the Nissan–Renault alliance will be increared to 500,000 per year by 2015 (Nissan Motor Co., Ltd., 2011). Even the Think Nordic, the Norwegian company, mentioned in Section 2, succeeded to convince new investors that the time for BEVs has finally arrived, avoiding bankruptcy once again[5]. In sum, competition for the development and mass commercialization of BEVs build up in the second half of the 2000s, which stimulated battery development for vehicles and caused one battery developer, the Chinese company Build Your Dream, to enter the car market. Not surprizingly, the race to develop baterry technology followed suit.

3.3. Collaboration for battery ttechnology development

More than with diesel and gasoline innovations, which have been developed only partly by first-tier suppliers (such as Bosch, Denso, Valeo and Delphi), EV research occurred mainly within the supplier network — Japanese ones in particular (Pilkington and Dyerson, 2006). Because battery technology is the key to improving the performance of electric vehicles, automakers started to collaborate closely with battery producers to generate or strengthen competencies. For instance, Toyota and Matsushita (currently Panasonic), Toyota's battery supplier at the time, formed a joint venture for battery development in March 1995, allowing them to share R&D costs and risks associated with battery technology (Magnusson and Berggren, 2001). In 2007 Nissan established a joint venture (called Automotive Energy Supply) to produce lithium-ion batteries, with NEC and NEC Tokin in the electronic industry. In 2009 Honda entered into collaboration for developing batteries through a joint venture (called Blue Energy), with the specialized battery maker GS Yuasa — the same company Mitsubishi Motors created a joint venture (called Lithium Energy Japan) with the particular focus on lithium ion batteries, in December 2007.

While Japanese automakers basically chose to work with battery makers through joint ventures, U.S. auto manufactures preferred to maintain arms-length relationships with battery suppliers (Yarime et al., 2008). Such developments indicate the

[4] Fortune Magazine (April 27, 2009). The Great Electric Car Race. Pages 28–31.

[5] For a broader explanation of the *Think* trajectory, see Orsato et al., 2008.

increasing centrality of battery technology in future of the auto industry. For battery manufacturers, the potential demand for EVs represents a huge growth potential for existing business or new entrants in the industry.

3.4. Investments in recharging infrastructure

Whereas battery technology and costs are crucial for the market success of EVs, commercial success also depends on the infrastructure for recharging. In a similar attempt to make a transition from diesel engine to compressed natural gas vehicles in Tokyo, it was of critical importance that gas infrastructure providers were involved in cooperation with car makers and users (Yarime, 2009). In the same fashion, mainly after 2005, national and local governments were deeper involved in the market preparation and the provision of infrastructure for EV recharging, and the level of R&D funds is substantially larger than in the 1990s[6]. In the period 2010–2011 there were thousands projects with a much larger budget, compared to a few dozen projects in the 1990s[7]. Moreover, many local governments started providing refuelling infrastructure, even though still in the order of dozens of refuel points, which is too little for a widespread use of EVs.

Electric utilities have been increasingly involved in EV partnerships. Whereas in the 1990s only the French EDF regarded EVs as a business opportunity, the list of utilities engaging in infrastructure developments was much larger in 2010, including the Swiss Energie Ouest Suisse (EOS), Oregon's Portland General Electric, San Diego's Gas and Electric, Ireland's ESB, Tokyo Electric Power Company, among others. These large organizations are important enablers of recharging infrastructure and their involvement in auto mobility seem to be gaining momentum in the early stages of the decade 2010–2020.

3.5. The evolving market demand of fleet operators

Fleet operators are emerging as a key force influencing the directions of EV development and commercialization. In France, for instance, a consortium[8] formed by large fleet operators, is expected to create the demand for at least 100,000 BEVs by 2015. This should not be a surprise. In the early days of the automobile, BEVs were the preferred method for delivery in the postal service and other daily-route sectors, such as dairy delivery. The current average length of routes in France, for instance, is 33 km, well below the 100 km range that is easily achievable with current BEV technologies.

At current electricity and fuel prices, the cost per km is already lower for EVs than for ICEs[9]. Expected increases in gasoline and diesel prices in the coming decades reported by the International Energy Agency (IEA) will help to augment the cost difference. Fleet operators are sensitive to such prospects, more than consumers are. EVs also cost less to operate and maintain and when the cars are parked there is the possibility of using the batteries for reserve power and grid buffering. For forward looking fleet owners such things are important. Although vehicle-to-grid (V2G) entails costs in connecting and controlling batteries for bidirectional flows, fleet operators could profit from both transportation services and battery reserves, when EVs are not in use. EVs also help to reduce carbon emissions. Even when the eventual carbon credits resulting from the move from ICEs to EVs are almost negligible[10], fleet operators can expect to reap up reputational benefits from the decarbonisation strategies (Orsato 2009).

3.6. The emergence of mobility operators

A new type of actor has emerged in the field of transport: mobility providers or operators. Their business is to provide mobility services rather than a vehicle or a ride. Examples of new mobility providers are car sharing organisations (CSO) offering car services in combination with public transport use. Some public transport companies are developing into mobility companies, by adding mobility services to their portfolio. This is a small but significant development for the future of electric mobility (to which we will also retrun in section 4).

Car-sharing should not be confused with car-pooling, in which the vehicle is *simultaneously* shared by a few people. Clients of a CSO use the vehicle sequentially. The car is rented on a per ride basis from an organisation who services and owns the car. Customers can choose among a wide range of vehicles, allowing for customised choices (and therefore providing much potential for BEVs which are attractive for short trips). Between 1998 and 2006, car-sharing has grown at an exponential rate, reaching 350,000 members worldwide in 2006[11]. Car sharing started in Europe but spread to the US where the world's greatest car sharing company is based, ZIPcar, founded in 1999. Following professionalisation, ZIPcar became the global market leader with fleets in San Francisco, Chicago, Vancouver, Toronto, and London, and its membership had soared to some 120,000. Today they serve 325,000 members, using the latest technology such as iPhone applications to arrange car use. The success of Zipcar, stimulated car rental multinational Hertz to enter the market through a subsidiary Connect. Organised car sharing is becoming a highly professionalised business. CSO attract mainly non-car owners but they also encourage people to sell their car (as much as 30% of their members did).

A second type of mobility operator is the Dutch company Mobility Mixx, founded around 2000, and facilitating mobility services in both multimodal and intermodal niches. Initially founded by a public bus company (Connexxion), Mobility Mixx was taken over by Lease Plan (a car leasing company). The services are targeted at business travelers, with intermodal options combining rail, taxis, rental cars, public bikes and parking payment. Total passenger-km of Mobility Mixx members grew from 15 million in 2007 to 45 million in 2009, with 75% of these made on journeys with rail as the main mode and 25% with pool car (provided by Mobility Mixx) as the main mode. Like CSOs, organisations as MobilityMixx provide customers with a choice from a wide range of vehicles, allowing for customised choices.

The rise of mobility operators in the field of car mobility has implications for the choice of car that is being used. Electric vehicles, especially battery electric vehicles, are attractive for mobility operators because of low operating costs, which compensates for the higher purchase prices. One new mobility operator has been founded especially for electric cars: Better Place. The company, founded in 2007 in the US, offers electric mobility services to users. The services consist of the use of an

[6] For instance, Great Brittan reserved 400 million pound for the introduction of electric vehicles, Germany 500 million euro, France 400 million for electric and hybrid vehicles over the next 4 years.

[7] For instance, a 46 million European demonstration project starting in 2010, involving 19 cities, 17 vehicle manufacturers or suppliers and 12 electricity providers, planning to install 14,000 charging points and 9500 vehicles (see www.avere.com).

[8] Press release from the French Ministry of Energy and Environment on 13/04/2010.

[9] Around € 5.00/100 km for EVs, and €8.30/100 km for ICEs (assuming an average of 25 kW h and €1.00/l of gasoline).

[10] For a car that does 40 km a day 350 days a year, emitting an average of 150 g/km, at €30/t of carbon, a shift to EVs would generate €63/year. This does not include transaction costs, which could easily nullify the gain.

[11] Susan Shaheen and Adam Cohen, "Worldwide carsharing growth: an international Comparison" *Transportation Research Record* No. 1992, (2007): 81-89. See also: <www.carsharing.net/library/index.html> (September 2008).

electric car and electric charging services. Through investments in recharging spots and battery exchange stations in major urban areas, the company guarantees that electric power will be available to recharge EVs. Owners of EVs, who sign up for different types of subscription packages, will be able to recharge their vehicles at home or at parking lots and to replace empty batteries by fully-charged ones in locations similar to petrol stations, allowing people to continue their trip on a different battery pack. For users, the electric mobility leasing model of Better Place addresses the problem of upfront costs of batteries (around US$11,000[12]), the uncertainties associated with their lifetime, and the residual value at the end of their lifetime. The company includes the battery in the infrastructure, so the cost of an BEV becomes the cost of the empty car-body. In other words, Better Place will bear both the initial cost of the battery pack and its residual risk value. Better Place, established a partnership with the State of Israel and Renault–Nissan for the mass deployment of BEVs. Israel committed itself to implementing an appropriate tax policy, serving as a test-bed for applications elsewhere. With more than 90% of the population driving less than 70 km/day, and major urban centers being less than 150 km apart, Israel is uniquely suited as a country for electric mobility.

Public companies may also become mobility companies. An example is the Dutch railway company NS. It offers public bicycles at a low cost to train travellers and issued a mobility card with integrated billing services for business people. The system of public bikes (OV fiets) proved popular: in 2009 alone the number of train travellers using a public bicycle grew by 31%, with the typical user making 10 annual trips, half of them for business. NS expects a further increase from 0.67 to 1 million trips in 2011 (Parkhurst et al., 2012). Public bike systems also prove to be popular in countries without a bike culture such as France. In the city of Paris, the Velib public bike system was an instant success, with 25 million users in the first year. For the Velib users, using a public bike is not an extravagant behavior of urban hippies but just another way of moving around the city. The success with bikes motivated public administrators of the city of Paris to extend the system to electric vehicles. The City of Paris is currently in the process of developing a similar system for 2000 Electric cars called 'Autolib' (FR3 7 October, 2008). Overall, mobility operators are a new actor in the field of mobility, for whom electric cars and bikes are attractive and part of their product offerings.

In sum, the developments described in this section indicate a positive tendency towards electric mobility (EM) Starting with government incentives and developments in battery storage technology, the new EM momentum is also powered by the enthusiasm of investors in cleantech, new market entrants such as BYD and Better Place, as well as the new powertrain diversification strategies of some large automakers. Overall, the innovation trajectory of electric powertrain technologies centers around a few distinctive electric drives, not just battery electric vehicles (BEVs), but also HEVs, and electrified ICEs, and the interactions between these trajectories and what this implies for a possible transition is explored in the next section.

4. The future of e-mobility: Critical factors and interaction effects

The retropective of BEV developments in the last 40 years showed that BEVs have gone through cycles of hype and disillusionment, and were unable to break out their small niche. Neither traditional cars converted to BEVs (produced by regular manufacturers) nor especially dedicated BEVs manufactured by market entrants were able to compete with vehicles with internal combustion engine. BEVs have mostly been sold in unconventional markets: demonstration projects, fleet users committed to green issues, with the help of subsidies.

The disappointing experiences of BEVs are in sharp contrast with the sales of the Toyota *Prius*, a hybrid electric vehicle (HEV), of which more than 3 million verhicles were sold globally from December 1997 to March 2011 in total (Toyota Motor Corporation, 2011). In this section, we examine relevant developments and interaction effects that will determine the future of electric mobility. The effects of relevant developments are examined for three configurations of electric vehicles: battery electric vehicles hybrid electric vehicles (including HEV that can recharge their batteries as conventional BEV, so called *plug-in* HEVs), and fuel cell vehicles[13] . The reasons for looking at different configurations is that they compete with each other and reinforce each other in certain ways, since the electric drive technology is common to them all. Advances in electric drive will help them to compete against more fuel-efficient ICEV.

4.1. Important developments for E-mobility

The future of E-mobility depends on developments in (1) infrastructure, (2) developments in mobility, (3) developments in the global car manufacturing regime, (4) developments in energy prices, and (5) developments in the electricity sector. Each of these developments is connected with (6) policy, in ways described below.

4.1.1. Fuelling infrastructure and road infrastructure

EVs require investments in new *refuelling infrastructure*, charging points in the case of BEV and HEV and hydrogen outlets in the case of FCV. Investment in fuelling infrastructure is a necessary conditions for FCV. For BEV two types of infrastructure solutions are possible: a battery swapping system and recharge points. Plug-in HEV also require recharging points but the battery can also be recharged by a spinning wheel connected to a ICE. According to Köhler et al. (2010), a fast build-up of a network of at least 500 filling stations (in urban areas and at highways) is very important for the market acceptance of hydrogen vehicles. The costs are considered to be quite affordable, a fraction of the costs for subsidies for vehicles and fuel. In Europe, approximnately 200 million Euros are necessary for a hydrogen infrastructure build-up in urban areas, for highways an additional support is needed of approximately 100 million Euros (Köhler et al., 2010). For electric charging there have been commitment from various governments. The UK government committed itself of installing up to 8500 charging points across the UK by 2013, as part of their new carbon plan. The costs of this are estimated at £30 million[14]. Besides national government, local government and electriciy companies (such as EDF in France) are involved in the creation of (quick) recharging points. In Israel, Better Place has committed itself to put in place 500,000 charge spots and 100 battery-swapping stations by 2015. They are also active in other countries, such as Denmark, a country with similarly short driving ranges and densely populated urban areas[15]. When the operations in these countries turn out to be succesful they will certainly

[12] Deutsche Bank Estimates that Lithium Ion batteries, depending on which type, will cost around US$500-600/kWh which comes to US$11,000 for a full EV 22kWh. Deutsche Bank, Electric Cars: Plugged In-Batteries must be included, 9 June, 2008.

[13] In order words, we refer to electric mobility ('e-mobility') as mobility employing one of these three configurations.

[14] http://www.telegraph.co.uk/earth/greenpolitics/8367096/Thousands-of-charging-points-to-be-installed-across-UK-over-next-two-years-Government-to-say.html

[15] For details about Better Place, see Chapter 7 of Orsato (2009). See also www.betterplace.com.

spread to other countries. The diffusion of E-mobility configurations will depend on infrastructure investments. ICEV obviously have an refuelling infrastructure advantage. A second infrastructure issue is the capacity of roads. Growing infrastructure costs may encourage policy makers to introduce car restraining policies in urban areas (e.g., zero emission zones) from which electric cars may benefit indirectly.

4.1.2. Developments in mobility

E-mobility depends on changes in mobility patterns. Two relevant developments here are: the emergence of moblity operators and systems of intermodality. It can be expected that the considerable rise of Car-sharing Organizations (CSO) will continue in the future, with positive effects for electric mobility. High purchase price has been a burden for electric vehicles, whereas car-sharing membership eliminates the purchase price of cars and reduces the costs associated with car ownership, such as insurance, maintenance and depreciation, while giving the customers the possibility of owning several cars.

In times of credit difficulties such as the one following the financial crisis of 2008, the elimination of the purchase costs is certainly appealing to a large segment of consumers that rely on credit for the purchase of cars. A further growth of CSO will likely benefit battery electric vehicles relatively more than the other types of vehicles, because they encourage using the type of car 'fit for the trip'. From Monday to Friday, for instance, a BEV to go and return from work may be just right (entailing the lowest in operation cost), while a hybrid SUV may be the best choice for the family trip in the weekend. Connect already offers BEVs in New York City and London, with San Francisco and Washington D.C. following later in 2011. Multiple car ownership can also stimulate e-mobility, when one of the cars is an electric car. When families have multiple cars, the restricted range of a BEV is less of a problem, as the battery electric car can be used for shorter trips only.

The creation of better systems of intermodality also can be expected to affect car mobility and e-mobility. Instead of using a car for the entire trip, it may be used for part of the trip, in combination with other transport modes. This, requires convenient transfer points, technically known as *park-and-ride* (P+R). Within transport policy, in many western countries, more and more attention is given to intermodality, to reduce the reliance on the car, especially for those trips that lack a single alternative to the car. For example, the number of P+R sites in the UK rose from about 20 by 1990 to more than 120 by 2006. P+R is a service provided to motorist to park at (usually) the periphery of an urban area, where public transport operate to and from the city centre. These sites are increasingly accompanied by car restricting policies in the city centre and this may continue in the future. Better modality systems and problems of congestion encourage that cars are used in combination with other modes of transport (traditional public transport, fast trains and electric bikes and scooters). In many cities public transportation has been extended with public bicycle schemes or even public (electric) scooter schemes, and such programs increase the quality of intermodal trips (by opening the opportunity of car-bicycle or car-scooter trips). Car-restraining policies can be expected to stimulate intermodality and organised car sharing. Silent urban cars are favoured in mobility policy. E-mobility thus depends on wider changes in mobility which in turn depend on wider socio-economic developments.

4.1.3. The global car manufacturing regime

The global car manufacturing regime is changing, both in terms of market sizes and in terms of technological focus. While it is unlikely to expect much growth in the traditional automotive markets in Europe, Japan, and the United States, the emerging countries, including BRICS (Brazile, Russia, India, China, and South Africa) and the Next 11 (Iran, Indonesia, Egypt, South Korea, Turkey, Nigeria, Bangladesh, Pakistan, the Philippines, Vietnam, and Mexico), are showing a significant growth in the sales of automobiles (Zhou, 2011). The emerging countries accounted for only 24% of the sales of automobiles in the world largest ten markets in 2006, whereas they increased their share to 37% in 2008. In particular, China's market is of growing importance. The number of the automobiles sold in the Chinese market reached to 18 millions in 2010, surpassing the largest sales of 17.4 million automobiles recorded in the U.S. market in 2000 (Zhou, 2011). Although established firms currently benefit from this market very much, Chinese competitors are also entering the market. So far these are producing largely for the home market but this may change. The Chinese automotive industry has started to develop relatively recently, much later than the counterpart in the U.S., Europe, or Japan. Since ICE vehicles have been already developed to a considerable extent by the companies in these industrialized countries, the electrification of vehicles has been explicitly encouraged in China through close collaboration between industry, academia, and government (Zhou, 2011). The Chinese government has set an ambitious target of introducing 10 million electric vehicles by 2010 through various types of financial support and other types of assistance to assemblying makers as well as suppliers of parts such as batteries and motors (Shimizu 2010). Influenced strongly by government policies for promoting electric vehicles, the Chinese industry has focused on the latest types of electric vehicles and associated batteries for its knowledge development activities. The attention given to electric propulsion stimulates attention to (light-weight) plastic bodies; as lower weight increase the electric range of BEVs vehicles. This is important as the all-steel body is a cornerstone to the foundations of the mass production car industry (Nieuwenhuis and Wells, 2007).

The conventional mass-market vehicles with ICEs are typically developed and manufactured in a production system characterised by modular design (Christensen, 2011). As the automitive industry is showing a sign of gradual shift towards electrification, the importance of modular design is increasingly highlighted. While the number of parts necessary for making an ICE-based car is said to be in the range of 20 to 30 thousands, an electric vehicle needs new parts such as a motor and battery, but does not require other parts such as an engine and exhausted gas system, which would reduce the number of parts to a range of a few hundreds to ten thousands (Zhou, 2011). That would lower the barrier for emerging local companies to enter the automotive market in China, without requiring the same level of coordination and collaboration between parts makers and assemblers as in the case of ICE vehicles. That is illusrated with the case of the growth and transformation of the domestic company BYD from a producer of batteries into one of the major manufacturers of battery electric vehicles in China.

A final development in the global car manufacturing regime of importance here is,the continuous improvement of the conventional ICE vehicles, which have achieved a significant reduction in energy consumption through a deliberate strategy of established, especially European, manufacturers after the successful introduction of Toyota's Prius (see end of Section 2). Apart from surging sales of 'eco-tech' ICE vehicles in Europe, these models are selling well in China, being cheaper then hybrid vehciles and where companies like VW and BMW benefit from a good brand image among Chinese consumers, (Fujimoto, 2011).

4.1.4. Developments in energy prices

Oil prices are expected to rise in the coming decades, because of higher costs involved in the exploitation of non-conventional oil (oil sands and oil shale), growing demand for oil in China and India, with regular price hikes because of supply shortfalls. The price of electricity may increase too but is generally expected to increase less than the price of oil. Carbon policies will add a further cost to carbon-based fuels. The overall effect of energy price changes is that it will stimulate E-mobility as well as fuel–efficient vehicles.

4.1.5. *Changes in the electricity sector*

In the electricity sector two important developments will affect E-mobility: the growth in renewable energy technologies and the emergence of smart grid systems. The intermittent nature of most renewables requires electricity storage, for which batteries in vehicles may be used. With the help of smartgrid-based systems of electricity management, batteries can be used to store energy and serve as a reserve of power during the time BEVs are idle. For electricity suppliers, the electrification of mobility offers off-peak demand and supply, which will reduce the burden on the grid system during peak hours. Electric vehicles may become the link between the energy and the transportation sectors (which together represent 75% of CO_2 emissions). Besides creating demand and sales, BEVs can help utilities to reduce system inefficiencies and fluctuations embedded in today's grid. For electric utilities, there is a synergetic relationship between the smartgrid and BEVs. Furthermore, when electric vehicles are increasingly integrated into smart grids, large amounts of data and information will be accessible to those who deal with the infrastructure and communication systems. That would create new opportunities for companies in these sectors to enter the automotive industry, influencing the competitive positions and business strategies of the existing automakers.

4.1.6. *Climate policies and public opinion*

Climate policies stimulate renewable energy generation and E-mobility. In Europe, regulations will require the average CO_2 emissions of vehicles to be reduced to 130 g/km by 2012, while plans to lower to 95 g/km by 2020 are underway. Climate concerns are likely to become an important landscape factor through the use of CO_2 regulations, climate cities aiming to become climate neutral and cultural criticism of gasoline cars. The availablity of electric vehicles may contribute to cultural criticism of gasoline cars, as people can now choose a climate-friendly car. Fuel-efficient gasoline cars may suffer from a bad cultural image as they still rely on fossil fuels.

In Fig. 1 we have plotted how different developments in infrastructure, policy, demand and congestion may affect and be affected by electric mobility. The plus (+) and minus (−) signs that accompany the arrows in the Figure indicate influences that promote (+) or detracting (−) the development of different powertrain technologies. It does not include every possible effect, but focusses on what we consider to be the most important relations. As the figure suggests, compared to ICEV, the electric configurations are expected to benefit from the following developments: higher oil prices, better recharging systems, new business propositions such as mobility leasing with battery swapping, urban policies to restrain car traffic and promote clean and silent cars, better systems of intermodality and the cultural acceptance of electric mobility and organised car sharing. Some of the developments feed each other: car restraining policies can be expected to stimulate intermodality which feeds on car sharing and electric mobility. There are also balancing developments: the availability of cleaner ICE vehicles will slow down the diffusion of electric vehicles. Car restraining policies and motorised two-wheeler will reduce congestion and public and private investment in intermodality.

BEV, (P)HEV, and FCV are all benefitting from advances in electric drive technology (batteries, electric engines and control systems etc.) as well as from government support policies for electric mobility, plug-in infrastructure, stricter fuel economy standards, higher oil prices and consumer acceptance of electric drives. They therefore complement each other in the promise and thrive for near-zero emission vehicles. Although there are certainly competitive elements too, the configurations can be expected to serve different markets, with BEVs better suited for urban fleets (taxis, postal delivery, city distribution, organised car sharing) and PHEV & FCV more used by individual consumers and car rental companies, for

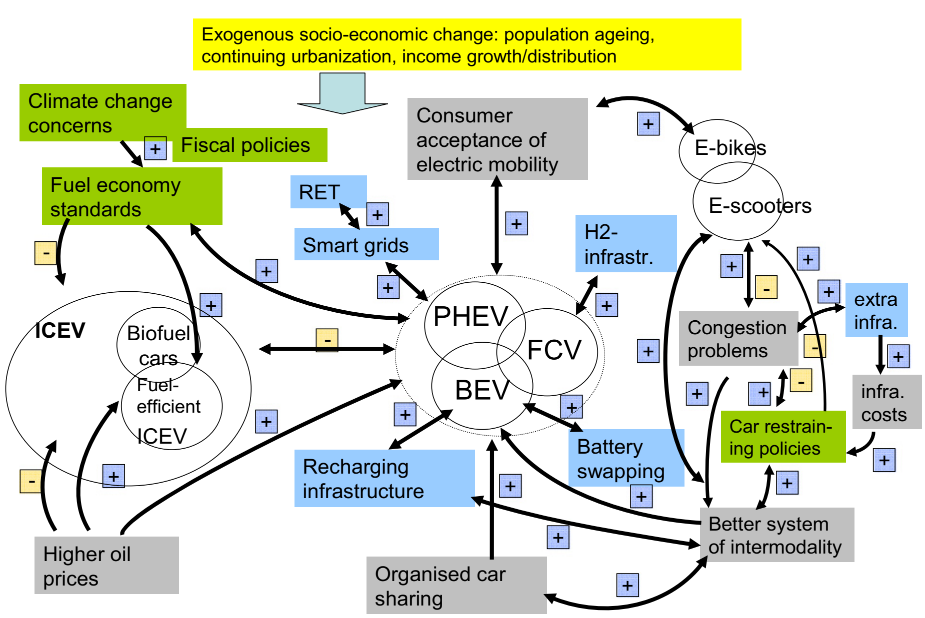

Fig. 1. Factors promoting (+) or detracting (−) the adoption of different powertrain technologies and vehicles.

instance. These spill-over effects strengthen the trajectory of electrification[16]. An interesting, unexpected spill-over effect is the electrification of bicycles and scooters. The significant rise of e-bikes and e-scooters, especially in China, boosts the battery industry. Production of electric two-wheelers grew from 7 million in 2004 to 24 million in 2010. Improvements in two-wheeler batteries may trigger advancements of electric vehicle batteries, whereas the use of electric two-wheelers may enhance consumer acceptance of electric mobility in general and improve systems of intermodality.

4.2. Three configurations

As we noted we consider three configurations of electric vehicles. Hybrid electric vehicles have an auxilliary electric engine, fuelled by batteries that are charged by the internal combustion engine or through infrastructure-based charging points. Better batteries and power management (involving, e.g., the use of fly weel and supercapacitor-based energy storage) may extend the electric range of HEVs. For users the main benefits, compared to pure ICE, are: electric drive in urban centres and better fuel economy. Plug-in versions allow people to charge their vehicle at home or at special locations (potentially at work). Fuel cell vehicles (FCV) are more suitable for long-term drive, because their range is much longer than PHEV or BEV, but they require a special infrastructure. Their diffusion will critically depend on the costs of fossil fuel (oil), advancements of fuel effient ICEVs and CO_2 regulations. Battery electric vehicles (BEV) also require a special infrastructure. Fast recharging technologies have been developed, to compensate for the problem of slow charging at home. Small, efficient ICE may be used in BEV as range extenders. Range problems may also be dealt with through the use of quick recharging technologies and battery swapping at special stations.

Prospective users of the three configurations, like their functionality, may also be different. Prospective users for FCV and HEV would be high-mobility people driving long distances. Prospective users of BEV would be fleet companies and urban users. It is important to note that different *socio-technical* configurations of the powertrains are possible: a vehicle may have different propulsion systems, a family may own and use different cars, vehicles and batteries may be rented instead of owned and vehicles may be used in combination with other modes of transport. BEVs, for instance, are currently more attractive as an urban vehicle, which is hired rather than owned. For people wanting to own a car for reasons of immediate access and status, the high cost of batteries is a big barrier, but this problem can be dealt with through leasing of the batteries, being the business proposition of Better Place, in which people would own the car but not the batteries. We now turn to explore the future pathways of these configurations more systematically.

4.3. Future pathways

The discussion of relevant developments around electric mobility above highlighted the key interaction between vehicle engine technology and the car use context. In Fig. 2 we have mapped the electric configurations onto a fit-stretch scheme of technology and user context. The first dimension (horizontal axis) is the *fit* regime or *stretch* of an innovation in terms of *technical form and design*; the second dimension (vertical axis) represents the fit or stretch in terms of *user context and functionality*. The more an innovation is similar to the established practice, the higher the fit, and the smaller the stretch. The combination of the two dimensions allows us to place pure electric or HEVs relative to each other. Earlier studies suggest that new technologies are successful only when the technological and behavioral discontinuity – between the old and the new – is not too significant and that during a transition, the niche stretches in both form and function (Geels, 2005). Our fit-stretch scheme shows that we find two stylized pathways in which electric propulsion plays a dinstinct role: one pathway in which alternative fuel vehicles are simply another car in a sustained social context, much like a technical subsitution process (not a transition) and, second, a pathway in which alternative fuel vehicles are, to a high extent, used in combination with other transport modes, much like a reconfiguration pathway (in the terminology of Geels and Schot (2007)[17]).

The key difference between both pathways is the degree of change in mobility patterns and travel behavior on the demand side. In the upper path, user preferences and mobility patterns remain more or less unchanged. People buy a 'greener' car but do not really change their travel behavior (although high penetration of ICT in cars and infrastructures may change car-based travel experience). The second pathway assumes more change in mobility behavior, especially more active travel planning, mixed use of multiple transport modes, perhaps less private car ownership and so forth. This second path also assumes technological change of supporting products (e.g., new ICT devices), investments in modal transfer and parking spaces that allow the linking of transport modes and policy change (e.g., new taxes, subsidies, visions and experimentation programs), but the main change concerns consumer behavior.

In both pathways the trajectories of the alternative electric configurations have their own dynamics, they partly compete with each other but there are also synergetic relationships: all electric vehicles use batteries and benefit from advances in battery technology, they all contribute to cultural acceptance of electric mobility and help to build a constituency for electric mobility which is necessary for government support policies for electric mobility. The actual pathway that the sector will take, will inlude elements of the two stylized pathways and is shaped by reinforcing and balancing effects between the vehicle engine technology and the mobility user context.

A strong surge of the reconfiguration pathway and corresponding dominance of BEVs will coincide with, and thus critically depend on: (1) an extensive recharging infrastructure, (2) a significant shift in mobility patterns towards shared ownership and intermodality, (3) the emergence of a significant and profitable BEV market segment, (4) a strong increase of the oil price, (5) ambitious climate policies and (6) a significant change of the electricity system towards variable loading by solar and wind energy in combination with smartgrids. Fig. 3 plots this hypothesized growth of electric mobility in combination with the growing links between car mobility and non-car mobility. The share of electric drive is hypothetical but the overall evolution is fairly certain.

If the six trends turn out to be different, other configurations will accordingly become more dominant, and we summarized this for the respective configurations in Table 1.

In areas with a poor recharging infrastructure and only some shift to intermodality, PHEV is more likely than BEV. Regarding the continued use of ICE in PHEV (at least partly), this would

[16] By 2015 the market value of car batteries is expected to reach €15 Billion, rising to 30 Billion in 2030 (Deutsche Bank. Electric Cars: Plugged In. 9 June 2008). There is some divergence about the decrease rate batteries prices, but it is certain that prices will reduce over time.

[17] When radical innovations are initially developed in niches, but subsequently trigger further adjustments in the basic architecture of the regime, Geels and Schot (2007) speak of a reconfiguration transition pathway. On our second pathway this is the case, as explained in Fig. 2, when electric propulsion triggers further changes in the car use and ownership context.

entail only some adjustment of the electricity grid, and medium adaptation of car manufacturers' practice of building steel-bodied cars.

FCV critically depends on a H_2 infrastructure, but can operate well in an individual-based car system with few intermodal trips. They will be more prominent when energy prices rise while transformation of the electricity grid and the shift in mobility patterns stalls.

If all factors turn out to be weak, ICEV have the chance to remain in place as practically the only propulsion system. In contrast to the last 90 years, we should say this is quite unlikely for the next 20 years. Especially in urban areas there are various trends reinforcing each other, such as clean air policies, car restricting policies, more real-time travel data, the rise of CSO, development of plug-in infrastructure and support of zero-emission vehicles. In contrast to the past, car companies over the world are investing now heavily in electric propulsion, battery suppliers are focusing on the automotive industry and governments who were originally fearful of promoting electric technologies have become strong supporters of it, in part for reasons of industrial policy. All this suggests that electric mobility development has passed a critical threshold. Even when special policy support for electric vehicles will wane, other developments will continue to support electric mobility. Different from the past, electric mobility is able to benefit from self-reinforcing co-dynamics.

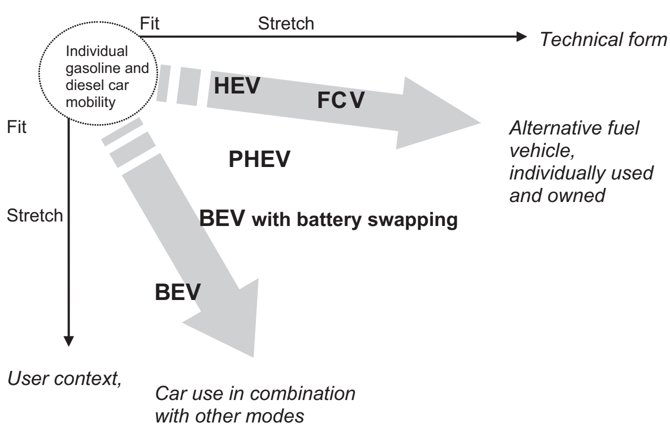

Fig. 2. Fit-stretch pattern for powertrain technologies (based on Hoogma 2000 and Geels (2005).

5. Looking back and forward

The regime around the internal combustion engine (ICE) car has reigned for more than 100 years. One source of lock-in comes from the production side: it has not been economically attractive to invest in a new technology that has been considered non-competitive in terms of costs. Competition has indeed been fierce in the past decades with many large car manufactures struggling to survive. For these companies, it has been both more attractive and safer to invest in innovation in the existing ICE technology than in technological options that carry the risk of low consumer acceptance. This yields a pattern in which car manufacturers continuously refine the dominant design in order to improve environmental performance of ICEs (see also Dijk and Yarime 2010). In this respect, the development of hybrid technology can also be seen as an attempt by car assemblers to innovate without having to move away from their core competencies.

In the last five years (2005–2010), however, there has been a spell of activity in electric mobility (EM), which has to do with the following developments:

1. Climate protection policies and targets that included electric propulsion as a source of reduction of CO_2;
2. FCVs and (erspecially after 2005) BEVs becoming an icon for zero-carbon vehicles;
3. The peak oil expectation and the unpredictability of future prices which brought attention to vehicles that do not depend on oil;
4. The success of the Toyota HEV Prius in the past decade, showcasing electric drive;
5. Progress in battery technology spurred by consumer electronic sector, helping to lower the costs of EVs;
6. New offers of EVs based on battery leasing and mobility packages such as the one of Better Place, which aroused consumer curiosity and widened consumer choice;

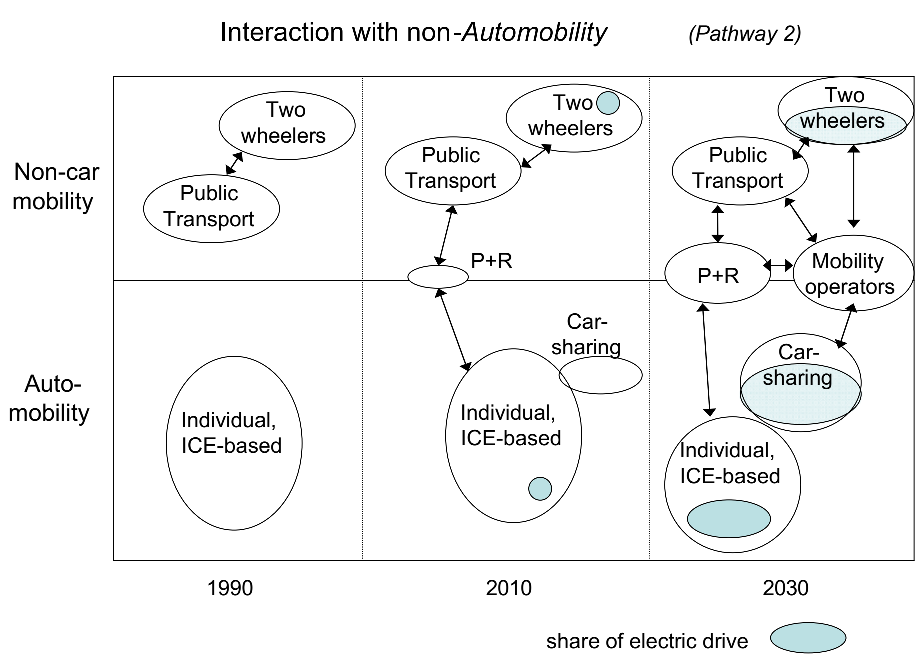

Fig. 3. The diffusion of electric drive in different mobility segments.

Table 1
Configurations and critical developments.

Dominant configuration	Extensiveness of recharging infrastructure	Shift in car ownership and intermodality	Market for electric propulsion	Energy prices	Climate Policy	Transfor-mation of electricity grid
BEV	High	High	High	High	Strong	High
PHEV	Medium	Medium	Medium	High	Medium	Medium
FCV	High	Low	High-medium	High	Strong	Low
ICEV	Low	Low	Low	Medium	Weak	Low

7. The realization by fleet operators and, to a certain extent, by individual consumers that EVs may have lower overall driving costs than ICEs.
8. The economic recovery programmes in the US and Europe which favoured clean technologies, including EVs;
9. Car manufacturers adopting a diversification strategy, including hybrid and pure EVs in their portfolio.

On the other hand, there are also factors working against electric mobility, including:

1. The still large investments by many auto manufacturers in continuing development of pure internal combustion engine (ICE) vehicles;
2. Increasing sales and preference for cheaper ICE cars in emerging markets such as China, as compared to more expense hybrid vehicles;
3. The current dominance of cultural attachment to owning rather than leasing vehicles;
4. Doubts that (hydrogen) fuel-cell technology will be ready for commercial use any time soon.

Altogether, these developments suggest that a pathway of electrification of cars is underway, led mainly by progress in batteries, carbon reduction policies, new value propositions by business, as well as an increasing positive image of electric drive amongst consumers and policy makers. It remains to be seen, however, whether these developments will lead to a transformation of the established regime, with a more prominent place for hybrids (HEV and PHEV), although still individually used and owned, or whether it will entail a transition to a new regime in which a majority of pure electric cars are used in close combination with other transport modes.

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