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# Will the momentum of the electric car last? Testing an hypothesis on disruptive innovation

Prepared for *Technological Forecasting & Social Change*

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## **Abstract**

In this paper we study to what extent electric propulsion is disrupting ‘the order’ in the automotive industry with six extensions to Christensen’s notion of disruptive innovation (1997). For decades the automotive sector has relied on the internal combustion engine (ICE) as the established propulsion technology, but due to environmental regulation and geo-political scarcity problems associated with fossil fuel use, electric propulsion is increasingly applied as sole or additional power source.

We elaborate the Christensen typology, rooted in industrial analysis, with a regime evolution framework based on changes in technology and the institutional context of production and use, with special attention to consumer perspectives and government regulation. We offer a hypothesis for structural conditions for market disruption and test this hypothesis against the development trajectory of full-electric vehicles (FEV).

Drawing on evidence from a range of recent FEV studies, our analysis suggests that the disruptive niche of full-electric mobility is currently insufficient to displace the ICE regime.

**Keywords:** disruptive innovation, transition, product competition, co-evolution, automotive engine technology, incumbents

## Section 1: Introduction

In this paper we study to what extent electric propulsion is disrupting ‘the order’ in the automotive industry with six extensions to Christensen’s (1997) notion of disruptive innovation. For decades the automotive sector has relied on the internal combustion engine (ICE) but with environmental regulation and geo-political scarcity problems associated with fossil fuel use, alternatives to the ICE vehicle have been proposed, including: The battery-electric or full-electric vehicle (FEV), the fuel-cell vehicle (FCV), the hybrid electric vehicle (HEV), and the plug-in hybrid electric vehicle (PHEV).

In this paper we elaborate the Christensen typology of disruptive and sustaining innovation, rooted in industrial analysis, with a regime evolution framework based on changes in technology and the institutional context of production and use, with special attention to consumer product frames of salient product characteristics and government regulation as important determinants of demand. In order to systematize our study, we offer a nested hypothesis for structural conditions for market disruption and compare this hypothesis against the FEV development trajectory. We test the hypothesis by drawing evidence from a range of recent FEV studies, and this analysis suggests that the disruptive niche of full-electric mobility is insufficient to displace the ICE regime. While FEVs have been diffusing rapidly recently thanks to product improvements, supportive government policies and media attention, our analysis identifies that momentum is unlikely to be sustained because FEVs suffer from a web of constraints and weak “innovation motors”<sup>1</sup>. An important constraining factor is the strong competition from more fuel-efficient ICE cars and from PHEVs. Compared to HEV, the PHEV fits better with consumer needs and the current regime of automobility based on individual ownership of cars. Although HEV has some symbiotic effects with PHEV, the negative competition effect dominates.

The method and structure of this paper are as follows. We adopt an explanatory case study approach to contribute to the development of theory of disruptive innovation. Section 2 reviews Christensen’s notion of disruptive innovation and elaborates it for changes in the institutional context of production and use. It offers a hypothesis on when market disruption is likely to be successful. Section 3 tests this hypothesis for the emergence of full-electric vehicles between 1990 and 2015. For this we use secondary data on consumers, firms, policies and technology from a broad range of academic studies, business and policy reports and other documents on the automotive sector. We also use primary data of consumer product frames collected by one of the authors. Our knowledge of the car industry gathered in more than 20 years of research on innovation in car propulsion and company strategies by the authors helps to overcome limitations of

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<sup>1</sup> An early version of this paper was presented at a workshop entitled ‘Electrification of the car: will the momentum last?’ in 2012, and the title of our paper resounds the workshop title (see also Bakker and Farla [2014] introducing a Special Issue on the workshop).

secondary analysis such as lack of familiarity with data and complexity of the data (Bryman, 2001, p. p. 200). A wide range of methods is used within the case study approach, most notably questionnaire surveys, interviews, case studies and discourse analysis. Such a combination of methods can compensate for one-sidedness and prevent partial explanation of a complex phenomenon (Yin, 1994; Kemp and Pontoglio 2011). Objective measures are used for the variables under investigation. The assignment of vehicles trajectories to the four segments of the market evolution scheme has an interpretive element but draws on objective information. Combining methods is usually challenging but found to be quite do-able in our case. We find that synthesizing findings of various methods is a useful and necessary approach to explain a complex phenomenon like the emergence of electric mobility. Section 4 interprets the results of the hypothesis testing (in the context of innovation ‘motors’ and ‘webs of constraints’), whereas Section 5 draws conclusions about the validity of our hypothesis in this sector for the current time period.

## **Section 2: A hypothesis for market disruption**

### **2.1 Disruptive innovation**

Christensen (1997) distinguished between sustaining and disrupting technologies. In later publications (Christensen and Raynor, 2003; Johnson et al., 2008) he replaced the term disruptive technology with disruptive innovation, recognizing that few technologies are intrinsically disruptive or sustaining in character: it is the business model that the technology enables that creates the disruptive impact, not the technology as such. In Christensen’s typology, sustaining innovations foster improved product performance. He argues that most new technologies fall into this category and are mostly are of an incremental nature. What all sustaining innovations have in common is the capacity to improve the performance of established products that mainstream customers have historically valued. An automotive example is the innovation of electronic fuel injection, introduced in the 1980s, which improved the fuel efficiency of internal combustion engines but did not disrupt the market for cars.

Disruptive innovations bring to the market a very different value proposition than had been available previously, and in this have the power ultimately to precipitate the failure of incumbent firms. Initially their performance is usually below that of mainstream products but lower price or unique features compensate it. An example is the photography market after 2000. Early digital cameras suffered from low picture quality and resolution and long shutter lag, but the convenience of small memory cards and portable hard drives that hold thousands of pictures made them attractive for some consumers. Economies of scale and dedicated R&D resulted in cheaper and better products, which helped them to reach a wide consumer base. As a result, non-digital cameras were transformed into a niche product.

Later, Christensen made a distinction between new-market innovations and low-end market innovations. Low-end market innovations are those that do not result in better product performance; they serve users who are attracted by low prices. An example of a low-end innovation is cheap retailing by megastores like Wal-Mart. On the other hand, new market innovations are those serving new users. The personal computer is an example, since new customers had not owned or used the previous generation of products (Johnson et al., 2008).

Christensen does refer to market evolution in various ways, but the analysis and the consequent recommendations are kept at the firm level, since his interest is on how companies (should) behave when confronted with disruptive innovation. Although his analysis addresses the interplay of product performance and firm strategies, he does not assess how the evolution of the market share of the disruptive innovation may or may not lead to a new market regime through a process of niche development and co-evolution.

Disruptive innovation can provide significant competitive advantage to firms. Advantages may stem from being a quick mover or a quick follower. The 'first-moving' firm potentially occupies a whole new market segment. Its position may stem from technological leadership or from the fact that the first entrant can gain control of resources that followers may not be able to match (Lieberman and Montgomery, 1988). First-movers are potentially rewarded with generous profit margins and a monopoly-like status. Being the first also comes with disadvantages: the costs of developing the market and product falls upon one company, which may be too much to bear. The first mover may not be able to capitalize on its advantage, leaving the opportunity to other firms to compete effectively and efficiently versus their earlier entrants. There are "second-mover advantages", in the form of free-rider effects through imitation (and according R&D savings) and lessons from the initial users (successes and failures). Nevertheless, Lieberman and Montgomery suggest that no simple managerial prescriptions apply with regard to first-mover advantages and to the optimal timing of entry.

Studies of radical innovation have proposed that not incumbents but entrepreneurial new entrants are usually the first-movers regarding disruptive innovation. Incumbents struggle with disruptive technologies for several reasons, as summarized by Bohnsack (2013):

*First, they often fail to recognise demand outside the circle of their well-known key customers. Second, incumbents tend to find disruptive technologies unattractive because of small initial profit margins (Christensen and Bower, 1996). Furthermore, they are restricted by resource allocation processes that are not aligned to the new situation, and a 'familiarity trap' (Ahuja and Lampert, 2001) that favours past routines, prior knowledge and prevailing technologies. Hence, incumbents are often*

*neither motivated nor able to develop disruptive technologies: they lack economic incentives and/or face organisational barriers (Henderson, 1993).*

At the same time, however, Chandy and Tellis (2000), who labeled this complex of factors the “incumbent’s curse”, suggest that this conventional wisdom may not always apply, referring to many cases of (radical) innovative incumbents.

## **2.2 Regime evolution**

Christensen’s analysis is less concerned with changing consumers’ perspectives and government regulation. For our case of electric mobility, however, we think the latter two are especially important, and therefore suggest an elaboration of Christensen’s typology into a regime evolution framework based on changes in both technology and the institutional context of production and use, especially consumer perspectives and government regulation.

Whereas economists and business researchers talk about markets, others have coined the notion of regime (Kemp, 1994; Rip and Kemp, 1998; Geels, 2002): the socio-technical system that has grown between the hardware and user perspectives and practices (reflecting their preferences and endorsed social connotations), producer capabilities, business models and production technologies, regulations, and supporting institutions. Product regimes are socio-technical ensembles that have been aligned and, over time, reproduce the conditions for their own continuation. The prevailing ICE-focused automotive regime is thus an example of a socio-technical system in which dynamic stability is obtained through economies of scale and scope, sunk costs, and social learning. Although alternative regimes can be contemplated, they are not easily realized because they would have to go through a process of emergent realignment during which they must compete against well-developed alternatives.

Dijk et al. (2015) have suggested a regime-based typology of market evolution with four possible quadrants: regime reproduction and regime reorganization (both regime sustaining), and regime-amidst-diversification and regime transition (both regime disruptive), see Figure 1.

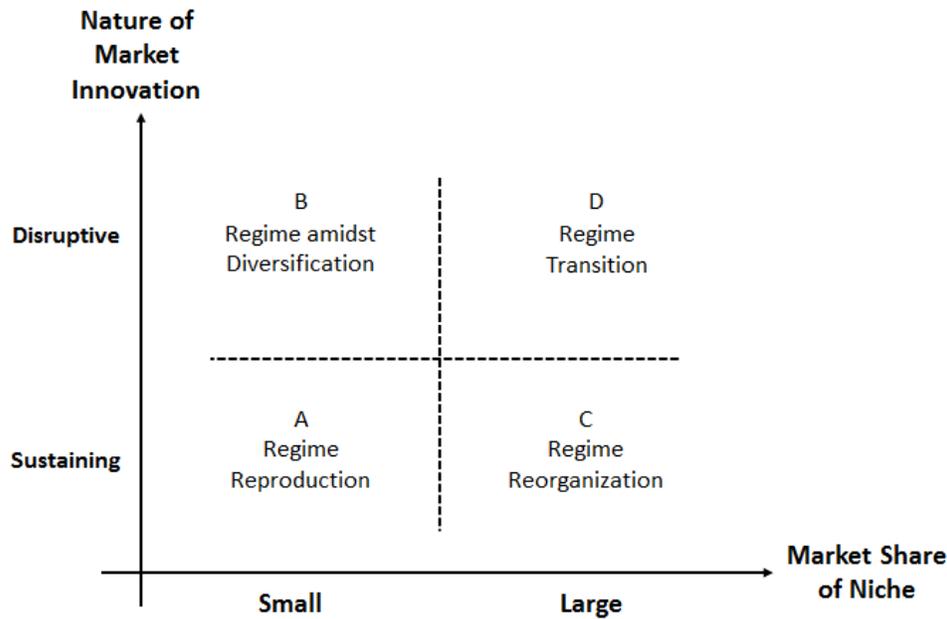


Figure 1: A regime evolution framework (Dijk et al. [2014])

Diffusion of both regime-disruptive and regime-sustaining innovation is governed by endogenous and exogenous structural conditions. Endogenous dynamics may consist of the following six processes (as categorized by Dijk and Kemp [2010]).

- *Increasing returns to scale*: costs per unit fall with economies of scale, allowing firms profitably to sell products at lower prices, further stimulating sales and scale economies
- *Learning about the market*: growing sales lead to better knowledge about the heterogeneity of demand (who prospective buyers are, their willingness to pay for specific features, what is valued and less valued); knowledge which may be used for R&D and new product offerings, resulting in better products and more targeted marketing efforts that will further stimulate sales
- *Learning by users*: Potential users must learn about the new technology - its existence, characteristics and consequences. The information transfer is endogenous to the diffusion process (Rogers, 1983): the more people have adopted it, the better known the solution, and the more it is recognized as a proven, valid solution.
- *Cultural taste formation*: a product may become culturally desirable (fashionable). Cultural dynamics may stimulate sales (in the case of positive stories and connotation) or discourage them (in the case of negative stories and associated meanings)

- *Learning-by-doing*: production experiences lead to improved skills and discovery of cost-efficiencies in production, allowing manufacturers to reduce prices and / or increase profitability.
- *Competition*: results in more supply, wider distribution, greater product variety and lower prices.

These endogenous processes play concurrently between demand and supply in the sector. Endogenous processes interact with exogenous changes such as changes in oil prices, regulation<sup>2</sup> and technological change in other sectors.

The highlighted dynamics suggest that an established regime will tend to a relative advantage in comparison to new market niches, due to scale and learning benefits. Nevertheless, various historic cases show that established technologies have been overthrown, and studies of transformative change have highlighted the importance of:

- *Changing actor perspectives*: the way users, producers, etc. frame the established product may change, and the new niche technology goes through a process of interpretative flexibility (Bijker 1995); products may become more or less desirable because of this. We distinguish:
  - *Reframing of actor perspectives*; when the attention for certain attributes changes. In this respect Windrum and Birchenhall (1998) observe that a viable market niche is often supported by a distinct user group attracted by a new functional attribute offered by the niche technology so their (emergent) framing of the niche technology is more positive compared to the established technology.
  - *Changes in social connotation*; of product technologies (without the attribute structure of consumer frames necessarily changing). Rising positive connotation stimulates sales whereas negative meanings discourage them (Dijk, 2011). Established technology sometimes obtains a negative connotation, giving thrust to alternatives.
- *Policy pressures*: these may go hand-in-hand with the previous factor, but are essentially separate. Regulation can create relative benefits for one technology compared to another (see Ostlund, 1994).
- *Technology spill-over from other sectors*: both market and public sectors, such as the military space programs, universities. These may introduce non-linear learning effects for the niche (or regime) technology.
- *Resource scarcity or other problems*: Key material shortages associated with the established technology may drive up prices (Cowan and Gumby, 1996).

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<sup>2</sup> Regulation is both an exogenous and endogenous factor: some is specifically for the sector, some more general (such as climate change policies that affect many sectors).

Finally it should be noted that the scale and learning effects of established technologies give only an initial disadvantage to the niche vis-à-vis the regime, but later on a disruptive niche can benefit in the same way from them.

## **2.3 Hypothesis**

By combining findings in earlier studies<sup>3</sup>, we now propose a nested hypothesis for market disruption. The hypothesis is stated in probabilistic terms, to reflect the complexity of interaction effects. It says that market disruption is significantly more probable when:

- Reframing of consumer perspectives takes place: that is when advantageous attributes of the new technology gain more prominence. Various studies (Windrum and Birchenhall, 1998; Shy, 1996; Malerba et al., 1999; Frenken et al. 1999) suggest that a necessary (though not necessarily sufficient) condition for a viable market niche is the support of a distinct user group that is attracted by the functionality offered by the niche technology.
- Social connotation of product technologies changes: when the symbolic-affective value of the niche product is significantly higher than the established technology.
- Firms experience or expect higher financial returns with the new technology compared to the established technology - possibly through new business models.
- Technology spill-over from other sectors compensates the scale and learning gap of the niche with respect to the regime (and accordingly compensates the price/performance gap).
- There is resource scarcity, driving up cost and weakening the price/performance advantage of the established technology (Geels, 2005).
- Regulation provides the niche technology with relative benefits vis-à-vis the established technology. (Yarime, 2009)

Such effects may help to overcome the scale and learning effects enjoyed by ICE cars and tweak the supply side and demand side more towards the use of FEV. In the next sections we test the six hypothesis of this nested hypothesis for market disruption in the ICE-based automobile market.

## **Section 3: Disruption of the car market**

### **3.1 The emergence of alternative engines**

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<sup>3</sup> Not all studies cited below do refer explicitly to disruptive innovation, but also to technological succession (Windrum and Birchenhall 1998) or transition (Geels 2005). We argue that many conditions they find apply to disruptive innovation as well, leaving aside whether this is followed by transition /succession in the sector or not.

The automotive sector has demonstrated increasing attention to alternative propulsion systems in the last 20 years, most notably through FEVs (with market launches in middle of 1990s), HEVs (launched in 1997), PHEVs (launched in 2012) and FCVs (no series production yet), next to the dominant ICE regime. Over time, the technological novelties and their social context can be seen as two unfolding trajectories: one of the established internal combustion engine (ICE) and an emerging trajectory of electric propulsion, in our scheme comprising of both battery electric and fuel-cell vehicles.

There has been significant component-level innovation in the regime trajectory of ICEs between 1990 and 2013, e.g. through the rapid diffusion of direct injection and variable valve systems, but also through turbocharging, the application of multiple valves per cylinder and the use of aluminum (see Dijk and Yarime, 2010). On the other hand, the sale of electric propulsion technologies is only about one percent of global market share for HEVs, while FEVs, PHEVs and FCVs remaining negligible<sup>4</sup>. Electric propulsion requires new capabilities from producers and positive appraisal from consumers. Vehicle manufacturers created capabilities in electric, hybrid-electric, and fuel cell vehicles and ICEs in parallel, offering electric vehicles (in the 1990s some specially designed FEVs such as GM's low-volume EV1, but mostly electric versions of mainstream cars) and new ICEs. Due to the small market, firms were unable to take advantage of scale and learning economies. Vehicle manufacturers were reluctant to invest (much) in new models and capabilities up to 2005, which held back sales. In contrast, new ICE components benefited greatly from scale and learning economies.

Alongside these techno-economic mechanisms (which have been studied relatively well) a social mechanism is found to play a role. Climate concerns enhanced environmental considerations for some consumers<sup>5</sup>. Hybrid vehicles have been proposed as 'the right vehicle for society' (Heffner et al., 2006). The social meanings and images of this new type of engine are not 'instant delivery' phenomena, but unfold over time and with level of use. In the years after 2005, HEVs were increasingly seen as green and trendy (Heffner et al., 2006), notwithstanding the actual merit of the environmental case for such vehicles which is at best complex (Hawkin et al., 2012). Apart from influencing consumers, this social praise for hybrids also reinforced political support for tax discounts on HEVs in countries like The Netherlands. After 2005, actual purchases of HEVs went up considerably; much more than FEVs in the 1990s. This has stimulated car firms to give

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<sup>4</sup> In the most significant car markets worldwide Sierczula et al. (2014) find BEV-shares of less than 0.5% percent (with only 5 exceptions), while HEV shares are about five percent in Japan, about three in the USA and less than one in Europe (Schreurs and De Haan, 2012), and much lower in other areas. This makes us estimate the worldwide share of electric propulsion around one percent worldwide.

<sup>5</sup> In July 2007, an internet survey conducted by The Nielsen Company, reported that 66% of viewers who claimed to have seen *An Inconvenient Truth* said the film had "changed their mind" about global warming and 89% said watching the movie made them more aware of the problem. Three out of four (74%) viewers said they changed some of their habits as a result of seeing the film. Further, a Eurobarometer survey in 2007 found that around 90% of British citizens were concerned about climate change (Eurobarometer, 2007). However, climate change continues to be a low priority issue for most people when contrasted with other societal issues such as the economy, education, or the threat of terrorism (Upham et al., 2009)

more priority to building up necessary electric propulsion capabilities. Nevertheless, up to 2011, these capabilities were mostly used to integrate electric components into ICE and the resulting ‘mild hybrids’ have been more successful in terms of sales than HEV or FEV. Dijk et al. (2015) summarized the market evolution in terms of car propulsion systems with the regime-based typology, see Figure 2. The final phase (five) has a dotted line and a question mark, reflecting our research question: is electric mobility increasingly disrupting the ICE regime? We answer this research question below by testing the proposed hypothesis.

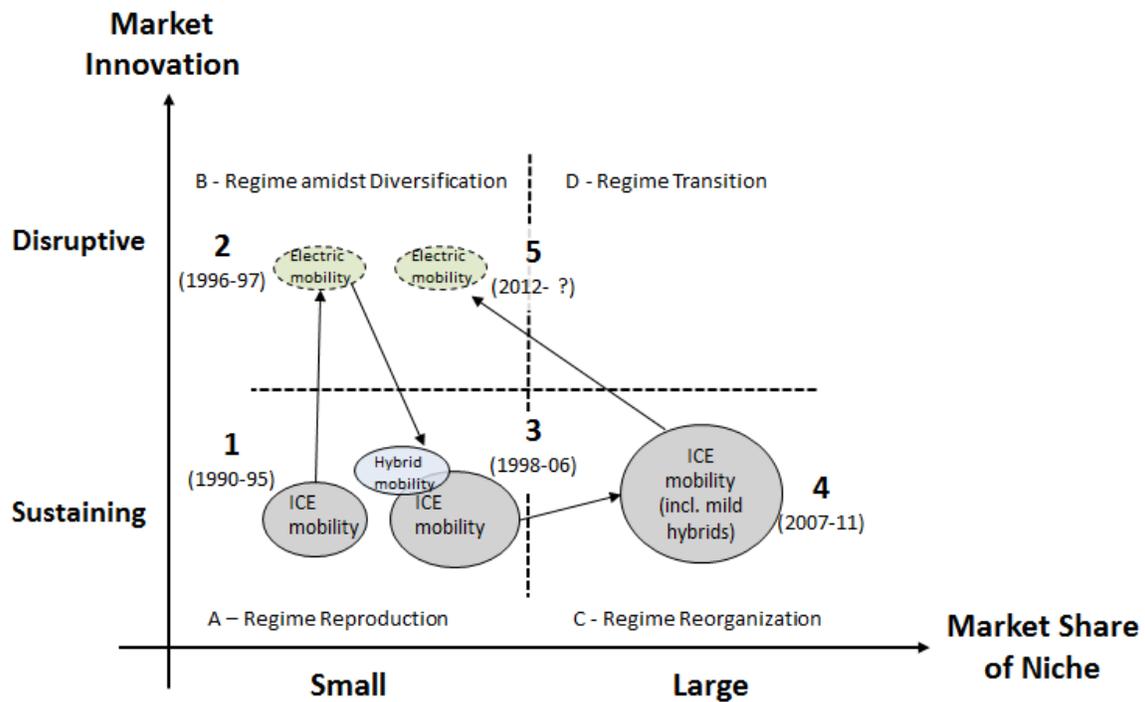


Figure 2: The progression of innovation momentum in the European automobile market (Dijk et al. [2015]). Momentum refers to the socio-technical trajectory with the strongest market share growth.

### 3.2 Testing the disruption hypothesis

We evaluate each hypothesis of our nested hypothesis for the situation after about 2012:

*Are consumer perspectives changing?* Is the consumer segment that is attracted by FEVs growing?

Dijk (2011) found some evidence for sub-frames among private consumers. Supported by an analysis of actual sales in the Netherlands, but probably valid for more markets in Western Europe, three sub-groups were distinguished in the total population of

consumers of new cars: for the first group (in size about 35%) price is the most salient attribute. They are satisfied with the functionality of the smallest or least powerful engine. The second group (about 60%) is willing to pay more for a stronger engine, one that accelerates the vehicle faster, achieves a higher top speed, etc. For both these two groups, the environmental impact of the engines is a neglected attribute; only indirectly, via the fuel economy and operational cost, and possibly via tax benefits for 'cleaner' engines, does it play a role. Finally a small third group is willing to pay more for a cleaner engine, one with lower emissions. This group is not larger than 2 or 3% and there is little evidence that it is growing.

It should be noted that identifying changing consumer perspectives can be problematic. Anable (2005) demonstrates that with regard to alternative vehicles and the behavior of consumers the same behavior can occur for different reasons, and that different behavior may result from the same reasons, effectively meaning that the a priori identification of consumer segments is difficult. For instance, the growth in sales of many 'eco' sub-brands that most vehicle manufacturers does not necessarily mean a growth of 'eco-drivers', but may be because members of the first sub-group of low-cost drivers start opting for these relatively cheap, eco-versions.

Frames of the established technology, conventional diesel and gasoline engines, tend to be more obdurate than those of an unconventional engine (Dijk, 2011) as consensus emerged among different relevant social groups about the dominant meaning of the artifact (Bijker, 1995). Hybrid-electric and electric technologies are new for the market, and therefore their framing is still fairly fluid. Vehicle manufacturers have almost universally sought to introduce products with 'green' sub-branding that to some extent may have negated the allure of more radical alternatives, particularly in Europe. Hence Mercedes has its 'Blue Efficiency' sub-brand; Renault its ECO2 sub-brand; and BMW its 'Efficient Dynamics' concept as examples. Toyota has used the 'Hybrid Synergy Drive' label on its hybrid models, with the notion that each model in the range should have at least one hybrid version in time. These sub-brands and concepts, however, are embedded within product ranges that extend also to traditional 'high performance' models and variants, albeit within the general framework of reducing CO<sub>2</sub> emissions across the entire range to meet regulatory pressures.

Overall, there is little evidence that consumer perspectives are reframing in such a way that a disruptive market niche is emerging. Studies conducted specifically with regard to FEVs or PHEVs suggest that consumer interest is negligible, and confined to those with a strong interest in environmental issues or concerns over the geo-politics of petroleum supply (Sangkapichai and Saphores, 2009; Carley et al., 2013). However, Tran et al. (2012) argue that analysis of FEV prospects has been overly technical and concerned with energy or climate change impacts, whereas the behavior, values and motivation of consumers has been rather neglected. Similar comments apply to historical studies of

FEVs prior to 1914 (Ivory and Genus, 2010). Recent studies of FEV users appear to indicate rather conservative framing of the technology, in terms that equate to traditional ICE vehicles (Skippon and Garwood, 2011). This is borne out in surveys conducted in the ENEVATE Programme (2011-13) in which 214 respondents using FEVs were asked to express their purchasing priorities. Of these it is pertinent to note that 61% ranked (low) purchase cost as their priority on a likert scale, whereas only 35% ranked (low) running cost as a priority. Although total cost of ownership may be lower with lower running costs, and is a strength of the FEV product proposition, traditional purchase price concerns dominate. In contrast, only 14% of respondents ranked environmental factors a priority. Unsurprisingly then the vast majority of respondents were strongly in favor of purchase incentives or tax waivers, compared with measures such as dedicated parking bays or road lanes for FEVs.

*Is the social connotation of FEVs more positive than for ICEs?*

Although for car engines social connotation is not the most important attribute for consumers, rather prices and functional performance, it does play a role (Dijk, 2011). Apart from influencing consumers, social connotation affects policy discussions about political support for tax measures. The same study mapped the development of social connotation of diesel engines and electric engines through the analysis of stories in newspaper articles. In a significant share of the accounts social connotative attributes are attached to the diesel engine (45% in 2000, 28% in 2005), which is stable and positive, varying from 'super-diesel' to 'delicious'. Highest appraisal occurred around 2000; by 2005 the enthusiasm had slightly tempered.

The development of social connotation of electric and especially hybrid-electric vehicles shows some remarkable dynamics. In the mid-1990s social connotation was found to be underdeveloped; stories about the engine were quite neutral statements, summing up technical characteristics. Around 2000 attention for FEVs collapsed. Meanwhile, attention for HEVs grew considerably, up to 22 accounts by 2000. Social connotative attributes already appeared in one third of the accounts. They were mostly positive with adjectives such as 'high-tech', 'environmental friendly', 'modern', some were neutral, and one was negative. By 2005 attention had mounted up to 41 accounts, even more than direct injection diesels in that year. Reference to social connotation appeared in about a third of the accounts, and its mainly positive appraisal had caught up with direct injected diesel.

Therefore social connotation plays a role in the development of new car engines, but (new) diesel engines are appraised broadly as equally positive as hybrid-vehicles. This means that social connotation is not bringing a competitive edge to the disruptive technology. Presently then, the electric car may even be characterised as a form of conspicuous minimalism as much as it is the sort of technology-hungry early adoption

much loved by marketing theorists, though the phenomenon of elite sustainable consumption is somewhat under-researched (Wolfgramm and Conroy, 2011). Studies in California, one of the most developed FEV markets, suggest that using FEVs can actually contribute to households adopting wider sustainability values (Axsen and Kurani, 2013). It is also interesting that consumers contemplating alternative-fueled vehicles do appear to consider wider environmental and even geo-political issues (Li et al., 2013). Furthermore, non-FEV drivers who encountered FEV drivers have been shown to be willing at least to reappraise their values with regard to FEVs more positively (Burgess et al., 2013), suggesting that the social connotation of FEVs is both fluid and amenable to positive change. Such 'neighbor effects' are of course more likely as the penetration of FEVs into the market increases (Mau et al., 2008). This is perhaps fortunate for the FEV industry, as Graham-Rowe et al. (2012) showed that non-FEV drivers had doubts over the social desirability of the vehicles. Axsen and Kurani (2012) propose that changes to the social connotation of PHEVs can occur when specific conditions are met: that the drivers understand the technology; that they are in the midst of wider lifestyle changes; and that their wider social network exhibits sustainability values. Participation in socio-technical FEV experiments does appear to be a powerful tool for changing the social connotation of the vehicles: In the ENEVATE survey noted above some 79% of those responding claimed their FEV experience was a positive one. A typical comment from this survey was:

'They've got a short battery life but apart from that I really like them. I like doing my bit for the planet and I like to convey the image of an eco-conscious social worker!'

#### *Do firms experience higher increasing returns in producing FEVs?*

The question of whether there are increasing returns to participants in FEVs is confused by the requirement for innovative business models that variously combine the elements of what has been termed the electric vehicle ecosystem (Ernst and Young, 2011), in which participants new to the sector are seeking to capture some of the anticipated new mobility market. Unsurprisingly then, it would appear that the position of the mainstream vehicle manufacturers is at best ambivalent: participating in multiple socio-technical experiments while simultaneously expanding the global market for traditional ICE vehicles.

In simple terms, the sale of FEVs has been considerably below expectations, and consequently it is unlikely that many of those involved are enjoying profitability of any degree, let alone above the prevailing (and generally poor) profitability of the mainstream automotive sector. The position is complicated by the vehicle manufacturers having to pursue multiple alternative fuel vehicles without knowing which will succeed (Sierzchula et al., 2012a; 2012b). At the start of 2012, reporting on the first full year of sales of the FEV Nissan Leaf and PHEV Chevrolet Volt, Reed and Simon (2012) commented that

‘The latest electric vehicles are off to a halting start, their progress slowed by high prices and supply bottlenecks.’ At the time both Nissan and GM anticipated stronger sales for 2012, but again the outcomes have been well below expectations. Reporting on the UK market one year later, Vaughan (2013) was able to identify that sales of FEVs had ‘rapidly picked up speed’ over 2012, but from an incredibly low base: 1,419 FEVs were registered compared with 1.9 million conventional vehicles in the UK in 2012. As a consequence, it would appear that some vehicle manufacturers are reducing their interest in FEVs. Renault-Nissan, the leading global producer of FEVs reported sales of 43,829 units in 2012, compared with total group sales of all vehicles of over 8 million units. Most notably Toyota in late 2012 was reported to be scrapping plans for widespread sales of its new FEV (the eQ city car) because the company ‘...had misread the market and the ability of still-emerging battery technology to meet consumer demands’ (Kubota, 2012). In addition, sales of the PHEV version of the Prius were only 20% of expectations in 2012. In a similar vein, by late 2012 Woodall et al. (2012) reported that the Chevrolet Volt was costing GM up to US\$49,000 per vehicle sold. While GM denied this figure, Woodall et al. argued that a combination of over-engineering and low volumes meant unit costs of between US\$76,000 and US\$89,000, well over the US\$39,995 base price; full year sales of around 15,000 units in 2012 were well below planned output of 40,000 units and resulted in the manufacturing plant being shut down twice in 2012.

Equally, others in the FEV ‘ecosystem’ have found profitability elusive. For the electricity generation and distribution providers the extra sales are minute compared with the rest of their business, and if the market for FEVs does increase significantly it will create problems with load balancing requiring new investments. The recharger manufacturers equally have not gained enough sales and rechargers are already a ‘commodity’ product with low margins. According to Pike Research, annual revenues from recharger equipment sales will grow from US\$355 million in 2012 to more than US\$3.8 billion in 2020, but there are too many companies seeking a share of this market even if it does materialize (BusinessWire, 2013). The infrastructure network managers are also failing to generate sufficient revenues either by subscription or by sale of premium priced electricity, and to date all deployments of such networks have required public subsidy. The more innovative experiments such as those of Better Place are also reportedly struggling to create and capture sufficient revenues. In March 2012, Better Place reportedly had a cumulative loss since foundation of US\$360 million (Koblenz, 2012). By October 2012, five years after foundation, those losses had grown to US\$490 million and its charismatic Chairman Shai Agassi was effectively removed from control (Woody, 2012). By May 2013 Better Place had used over US\$800m in capital and was declared bankrupt (Reed, 2013), eventually the assets were bought for about US\$12m.

*Are there recent technology breakthroughs in FEVs?*

Performance of vehicle batteries, especially Li-ion, has benefitted from the boom in consumer electronics. For example, from 1991 to 2005 the energy capacity per price of lithium ion batteries improved more than ten-fold, from 0.3Wh per dollar to over 3Wh per dollar (Smith 2015). Nevertheless, the scope for a dramatic technology breakthrough appears limited for FEVs. Typically about half the cost of a battery pack is attributable to the battery cells, with the rest accounted for by the wider system (Element Energy, 2012). There is an expectation that the cost per kWh will reduce with time, but this expectation is dependent upon increased production (and sales) volumes (Ramsey, 2012). Ironically, in the period 2009 to 2013 battery pack prices for automotive applications fell from an estimated US\$1,000 per kWh to US\$689 per kWh by early 2012 according to a Bloomberg New Energy Finance report cited by Chestney (2012), but with much of that fall attributed to over-supply as installed capacity greatly exceeded consumer demand. The industry hopes to achieve perhaps US\$150 per kWh by around 2030; put another way there is a hope that compared with the typical US\$21,000 and 300 kg battery pack of 2011, by 2030 there will be a cost reduction of 70% and a weight reduction of 45% (Element Energy, 2012). Equally, there are no major breakthroughs in recharging batteries that could sufficiently compete with the matter of minutes that is needed to refill the tank of an ICE car.

Tesla has been a key driver of expectations and their battery ‘Gigafactory’ under construction in Nevada is illustrative. Tesla originally purchased a 1,000 acre site, with a further 1,863 acres added in July 2015 (Ramsey, 2015), and should be in production by the end of 2016 following a US\$5 billion investment along with partners including Panasonic. The plant should have a capacity of 50 gigawatt-hours of battery packs annually, and is claimed by Elon Musk (founder of Tesla) to offer batter pack cost reductions of 30% and be key to building 500,000 electric cars per annum by 2020 (and to diverting 25% of output to non-automotive uses). However, external observers have been more critical. Schmitt (2014) noted that total global annual sales of battery electric cars (all brands) in 2014 would only account for 10% of the capacity at the Gigafactory. Moreover, in 2013 Nissan was by far the world leader in battery electric vehicle sales (with the Leaf) with a cumulative total of 150,000 units; but Nissan could build 310,000 battery packs annually. Telsa has been extremely successful in garnering publicity on the basis of very modest sales, which could perhaps be interpreted as being in the early phases of the Garner hype-disillusionment cycle. The company has yet to make a profit. Factories that are not running near to capacity are likely to have unsupportable capital costs rather than contributing to lower prices to consumers.

According to the study by Element Energy (2012) there are two pathways that have potential to improve energy density in lithium-ion batteries: developing electrode materials with higher capacity (mAh/g); or developing cells using higher voltage

chemistry. Alternatives to lithium-ion are many and varied, but lithium-air technologies offer the most likely improvement route with market applications unlikely before 2030.

#### *Is scarcity driving up cost?*

The period prior to the 2008-9 world financial crisis did see a considerable escalation in fuel and other commodity prices, reflecting strong economic growth around the world and in particular in several key emergent economies. In such periods of strong growth the expansion of supply capacity usually proceeds more slowly, resulting in higher prices and stimulating further investment in the scarce products or materials. The automotive industry was clearly subject to some of these pressures.

More pertinently perhaps, the question of geo-political scarcity in the wake of the US 'war on terror' stimulated several nations to explore strategies of energy diversification and conservation in pursuit of security. These landscape developments thus provided some pressure on the prevailing automotive ICE regime and to that extent also provided some scope for niche technology to emerge.

In the 'post-crisis' era however some of these landscape pressures have changed, and not necessarily to the advantage of FEVs. Such disadvantaging changes include the rapid exploitation of shale oil and gas via 'fracking' in the US, the shut-down of nuclear reactors in Japan and Germany following the catastrophe at Fukushima, the decline of spot crude petroleum prices as demand weakened alongside related declines in other commodities, and the growth of concerns over the supply of Lithium.

#### *Do policies favor FEVs?*

One study found that in Europe in the last 20 years policy instruments at a European level were mostly applied in a way that they favored technical fixes and incremental innovation (Dijk and Kemp, 2012). It discussed four types of instruments: emission requirements, voluntary agreements, direct R&D support, and consumer tax exemption schemes. It found that policymakers have played an important role in facilitating sustaining innovation, mainly through emissions requirements and tax benefit regulations that were set in such a way that they could be met by internal combustion engine solutions, given in to industry pressures.

The EU-level voluntary agreement on CO<sub>2</sub> reduction launched in 1998 is illustrative in this context. In June 2007 the EU decided to change the agreement because of lack of success, to a compulsory requirement for 2010: a CO<sub>2</sub> emission of 130 g/km, which was later postponed to 2012. Lobbying from various sides has prevented the target being adopted but did again push it back to 2015. Fines will be levied for manufacturers failing to achieve their targets increasing sharply from €5 per gram per car sold for the first gram

to €95 for the fourth gram and beyond. Clearly, the EU as legislative institution is subject to significant external influence here. This was shown again in 2013 when the German government, often a proponent of climate policy, used its power for protecting the German automotive industry (especially BMW and Mercedes with primarily larger vehicles) to block EU voting on stricter vehicle CO<sub>2</sub> emissions requirements at an advanced stage of negotiations. This has made the moment of enforcement still uncertain.

National and local policies with respect to FEVs are often a complex amalgam of industrial, transport and environmental goals that may be more or less incompatible and in competition with other locations (Andersen et al., 2009; Wells, 2012). Policies are often presented as a ‘now or never’ opportunity to participants in an emergent wealth-creating sector (Accenture, 2011; Matthies et al., 2010). Predominately the policy framework logic is that nurturing the nascent electric mobility market at a local or national level will also attract and retain the attendant industrial base in vehicles and infrastructure supply. These initiatives to secure some of the wealth-generation benefits of the electric vehicle industry range from major automotive industry nations such as America (USDOE, 2010) to those with a hitherto minor presence such as the Irish Republic (DTTAS, 2009). The position articulated in America is illustrative. As part of a broader national recovery plan, America allocated US\$4 billion for electric vehicle industry support.

*‘This combination of private and public investments in advanced vehicles is stimulating economic growth, creating jobs in both the short- and long term, and increasing the country’s global competitiveness. These jobs represent a shift—the shift of important industries moving jobs back to American shores and the growth of a domestic battery industry. The Recovery Act is laying the groundwork for long-term, sustainable recovery by ensuring that the industries of the future are American industries.’ (USDOE, 2010:4)*

In the EU the patchwork of initiatives at national and local levels is constantly changing (Charue-Duboc et al., 2011). Eurelectric (which represents the European electricity industry) list over 50 electric car and smart-grid schemes in Europe on their interactive map (see <http://www2.eurelectric.org/Content/Default.asp?PageID=1092>). Countries such as the Netherlands, Denmark, Germany, France, the UK, Ireland, Portugal and others all have their own distinct initiatives in place, as to many city authorities (Christensen et al., 2012; GFG, 2009; DTTAS, 2011; GLA, 2009; MacNeill and Bailey 2010; OLEV, 2011; Pinto, 2011; PPA Automotive, 2006; Proctor, 2011; Williams, 2011). Norway offers a combination of purchase tax exemption and local user benefits (toll road and parking), which resulted in the highest global market share (14% in 2014). Critics estimated the cost at 13.500 USD/tCO<sub>2</sub> (Holtmark and Skonhøft 2015)<sup>6</sup>, and do not

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<sup>6</sup> This study considers a Nissan Leaf owner, previously owning a Prius, living 10km from Oslo and commuting daily to city center Oslo. It assumes forgone toll road charges of 1400 USD a year, forgone

recommend the policy to other countries. There are also already multiple low emissions zones across Europe, notably in Italy, Germany and Scandinavia (see <http://www.lowemissionzones.eu/>) to provide a context within which FEVs could operate. According to ACEA (that represents the automotive industry in the EU), in 2010 there were 16 Member State countries offering some form of tax and / or purchase incentive for electric cars (ACEA, 2011), though in detail the schemes vary widely in terms of how they are structured and their overall value (Reiner et al., 2010). The European Commission has sought to consolidate and focus this complex policy environment with for example the Green eMotion scheme (Green eMotion, 2011) that has a four-year timeframe and €41.8 million funding to coalesce the myriad schemes in Europe.

It is possible that the variety, complexity and volatility of this policy environment is somewhat counter-productive, as it is confusing and risky for those seeking to supply FEVs and equally daunting for those contemplating buying or using them. Moreover, others have questioned the contribution of electric vehicle policy to the wider aim of sustainable mobility (Driscoll et al., 2012).

All in all, our analysis of the six hypotheses suggests that the proposed nested hypothesis for market disruption cannot be rejected for the case of the car market in view of the marginal sales of FEVs in combination with a practical absence of the six conditions for market disruption. Therefore the analysis increases confidence in the hypothesis as such, although more distinctive tests of it are necessary, especially for cases where the disruptive niche is actually growing<sup>7</sup>.

## **Section 4: Web of constraints acting against ‘motors’**

Although the six conditions were presented and evaluated as a list of single factors, our discussion actually highlighted the interplay of factors. Each factor can become a potential starting point of a chain reaction for growth of a disruptive niche. For example, when policies in the Netherlands required the use of energy labels on new cars and connected tax reductions to the label (in 2006), energy use (and/or the corresponding price drop) became a more significant attribute for consumers in that market. Producers

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parking fees of 5000 USD a year, road tax 400 USD a year, and (converted) purchase tax exemption of 1300 USD a year. All these assumptions reflect the upper limit of the cost per ton CO<sub>2</sub>, not the average level.

<sup>7</sup> It's interesting in this respect to compare the current situation with the period of 1995 -1997, when regulation in a few American states triggered temporal diversification through an EV niche. Here we found that whilst the other four factors were lacking, regulatory pressure was effective in providing a temporal effect. Nevertheless, it was not more than a temporal effect (and the regulation was not able to affect the other four factors, at least not in the time frame it was applied), and therefore we find the hypothesis still not rejected there too.

reacted by expanding their product range of suitable cars and making those products more attractive to consumers thereby stimulating use. In other words<sup>8</sup>, each factor can be the trigger in a cause-and-effect mechanism creating a positive inducement of the disruptive niche when the factors start feeding each other.

In the social psychology literature on innovation and in techno-economic studies of adoption it is common to talk about ‘drivers’ and ‘barriers’. Examples of such studies are drivers of environmental behaviour (Steg and Vlek, 2009) or drivers of energy efficiency in the building sector (Nassen and Holmberg, 2005). In the two types of literature, drivers and barriers of innovation are seen as a concrete ‘things’ that can be put in place or removed (such as a political rule, subsidy, lack of information, absence of certain social norms). Weber (1997) identifies four groups of barriers: institutional (i.e. barriers caused by state government or local authorities), market, organizational, and behavioural<sup>9</sup>. He distinguishes three features of a barrier: (1) the objective obstacle; (2) the subject hindered; and (3) the action hindered. Overcoming barriers typically involves a specific action that needs to be done, but often barriers of different kinds (such as market and behavioural barriers) interact. There is often an a priori assumption of the subject being ‘hindered’ from adopting the innovation, but for the stakeholder this may not be the case at all. He does not feel hindered, simply uninterested in the product offering (for reasons to be uncovered). Subsequently, the social context tends to be treated in a somewhat mechanistic way (identify obstacle, delete obstacle, subject will adopt innovation), which overlooks the multiplicity of concerns.

We suggest to go beyond the idea of barriers and drivers as concrete ‘things’ to the notions of ‘motors’ and ‘webs of constraints’, that occur in the context of the endogenous processes (discussed in section 2.2) and that constitute or govern regime-disruptive or regime-sustaining innovation, including the shaping of practices, mind-sets, regulation, and unequal development of technologies. Motors refer to processes of feedback; the webs of constraints to the intertwined factors working against the development and diffusion of FEVs<sup>10</sup>. Alleviating one constraint (for example the range of batteries) is insufficient for widespread use given the presence of other constraints (costs of producing the batteries, short lifetime of the batteries, the need for a network of recharging stations, and low cost-advantages compared with ICEVs).

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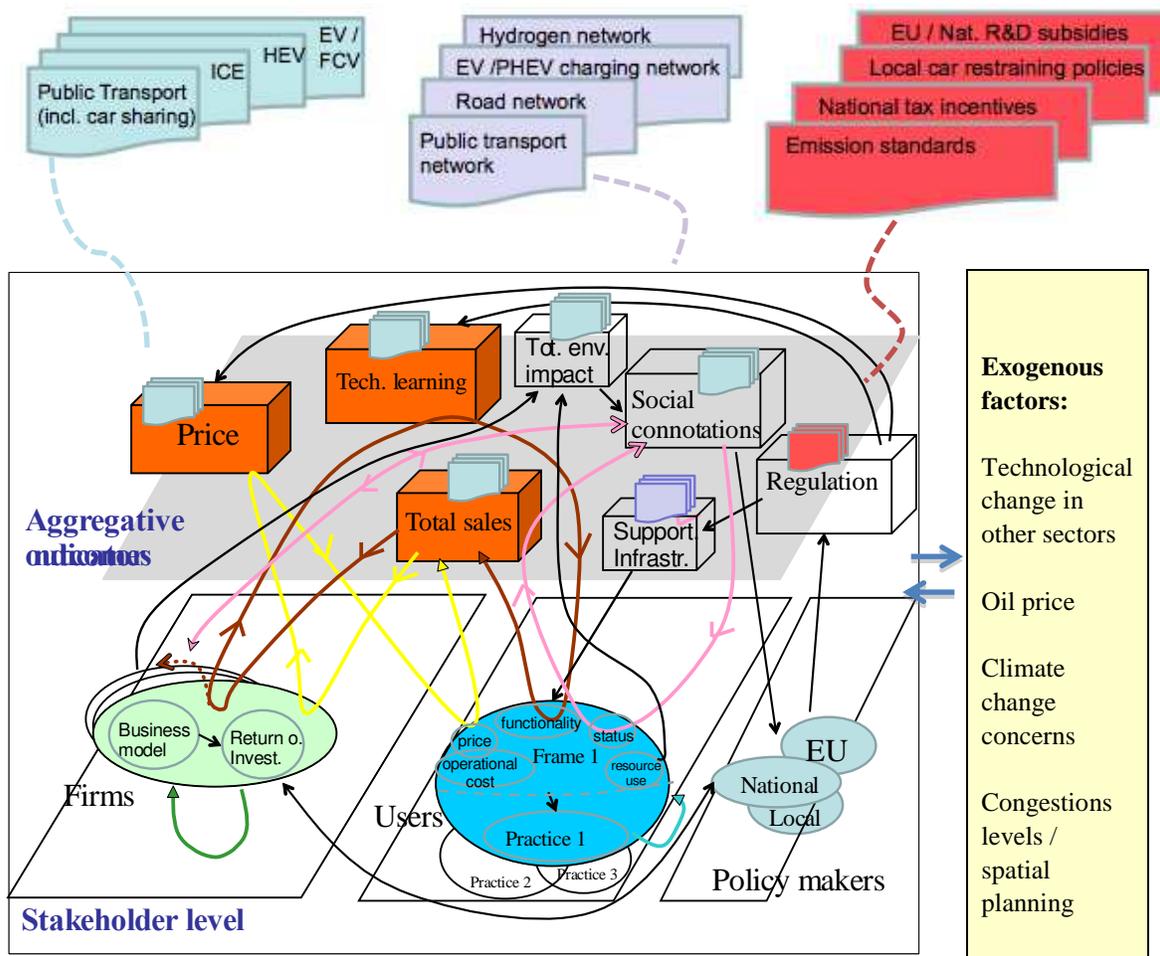
<sup>8</sup> We like to give an example from the automotive sector here and, by lack of disruptive examples, we need to bring up an example of sustaining innovation, but the point of ‘interplay of factors’ still holds.

<sup>9</sup> Another example is Montalvo (2008) who distinguishes seven groups of drivers and barriers to innovation: public policy, economics, markets, social pressures, attitudes, technological opportunities and capabilities, and organizational capabilities.

<sup>10</sup> The notion of motor is coined by Roald Suurs in his work on technology innovation systems (2009). He differentiates four motors: The Science and Technology Push Motor, The Entrepreneurial Motor, The System Building Motor and The Market Motor. We deviate from Suurs’ work by not viewing motors as interactions of innovation ‘functions’, but interactions of micro-characteristics and aggregative variables.

Reflecting on our discussion of the six conditions we are convinced that instead of six independent factors, the items are more like a chain of cause-and effect relations: if one factor changes, it starts effecting the others, and due to the inter-connectedness of factors, change can go non-linearly fast.

In an attempt to make the inter-connectedness of the conditions explicit, we provide a complex but still illustrative scheme (see Figure 3a) that reflects the endogenous processes of Section 2.2. We distinguish a micro level where the innovation is described via social actors (consumer and supplier perspectives and practices), and a macro level with more objectified (aggregative) variables of the innovation (such as prices, sales levels, functional performances, regulation etc.). Together, the scheme provides the context for the ‘motors’ and ‘webs of constraints’ and these can be highlighted for specific cases.



**Figure 3a:** Cause & effect relationships for car mobility and alternatives, incl. six feedback-loops: increasing returns-to-scale (yellow), learning-by-doing (green), learning by users (blue), learning-from-

the-market (brown), and cultural taste formation (pink), and competition between products. Further there are environmental externalities and regulation (black).

Figure 3b sketches how different developments in infrastructure, regulation, demand, and business models affect the emergence of a specific example case of electric mobility: Autolib in Paris. The plus (+) and minus (-) signs that accompany the arrows in the Figure indicate influences that promote (+) or detract (-) the factors around the development of different mobility alternatives. It does not include every possible effect, but focusses on what the authors consider to be the most important relations (with the relations directly affecting Autolib in bold).

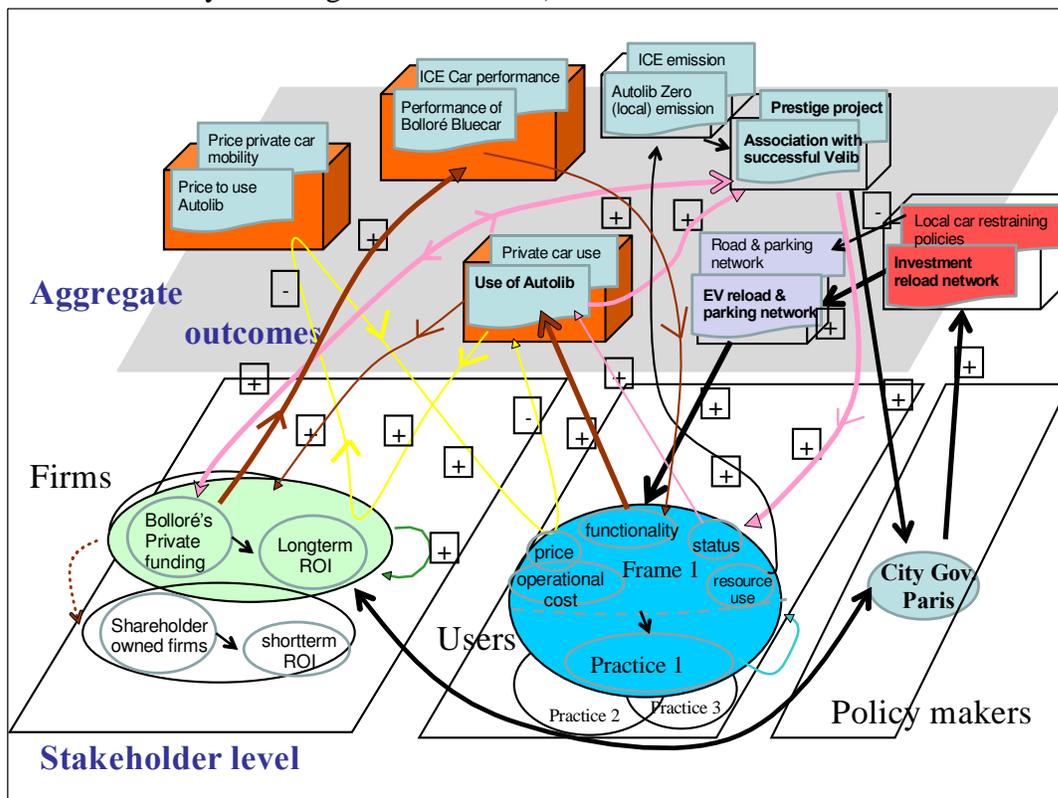


Figure 3b: An example of specific factors Promoting (+) or Detracting (-) Autolib in Paris.

Autolib is Paris' electric car-sharing service (a new 'supporting infrastructure' in the scheme) introduced in late 2011, which attracted 70,000 users by April 2013. As the Figure depicts, many local travellers are familiar with the successful bicycle sharing service Velib, making car sharing a relatively small step for those tired of the parking pressure in Paris. By late 2014 with over 1,800 vehicles (all Bolloré Bluecars), Autolib is bigger than similar schemes in the German cities of Berlin and Stuttgart, mainly because of two local drivers. First, the project has become a shop window for the French billionaire Vincent Bolloré, who invested €2bn in electric vehicle technology without shareholder pressure. Secondly, the scheme is also a prestige project of the Socialists,

Paris' largest political party. The city of Paris has invested €35m in the charging points. Nevertheless, it is a majority privately-funded scheme, with Bolloré spending €50m a year to run Autolib – which in 2014 broke even four years ahead of schedule.

Compared to private ICE mobility, FEV car sharing in Paris benefits from the expanding FEV infrastructure, and a positive cultural image of car sharing, which affect users and also policymakers and an entrepreneur. These factors can reinforce each other further. More indirectly or exogenously there are supporting factors such as car restraining policies and higher oil prices. But concurrently there are also developments that promote alternatives or weaken Autolib: the development of cleaner ICE vehicles will decrease the relative environmental attractiveness of electric vehicles, the local political climate may shift and Autolib cease being a prestige project, the single operator thwarts the speed of learning of Autolib and some green travellers may shift to public transportation (left out in the diagram) when the system grows in size. It is notable that Autolib has expanded to other French cities and potentially Indianapolis and London.

The scheme helps to see in a structured way that innovations (such as new business initiatives, their early successes or new policies) take place amidst an existing web of relationships that include 'motors' and 'web of constraints'. This web greatly affects the further progression of the innovation and the scheme helps to put a single development in its socio-technical context. We find that the disruptive niche trajectory of electric mobility is not driven by single factors such as price or technological change, but involves a complex web of social, business, environmental, regulatory etc. drivers and constraints. Our 'descriptive' analysis of conditions (in Section 3) is useful but less suitable for highlighting interaction effects, and we sense simulation models with dynamic capabilities should augment our type of analysis here, for a more encompassing test of our hypothesis.

## **Section 5: Conclusion**

In this paper we elaborate the theory of disruptive innovation for changes in the institutional context of production and use. Our integrative approach of disruptive innovation proposed and tested six hypotheses on when market disruption is likely to be successful; three that address changes in the key framing the innovation, three others to key drivers of innovation dynamics. Table 1 summarizes the findings. The findings suggest that the proposed nested hypothesis for market disruption cannot be rejected for the case of the car market in view of the marginal sales of FEVs in combination with a practical absence of the six conditions for market disruption. Therefore the analysis increases confidence in the hypothesis as such, although more distinctive tests of it are necessary, especially for cases where the disruptive niche is growing more significantly.

**Table 1:** Summary of test of nested hypothesis

Hypothesis	Our findings
<i>Probabilistically, market disruption is significantly more probable when:</i>	
Reframing of consumer perspectives takes place	There is no radical change in consumer perspectives about HEV
Social connotation of product technologies changes	Social connotation is not giving a competitive edge to the disruptive technology.
Firms experience or expect higher financial returns	HEV producing firms are not enjoying profitability above the mainstream automotive sector. HEV is not a money maker
Technology spills over from other sectors	Despite benefits of battery advancements in consumer electronics, the scope for dramatic technology breakthrough is limited
There is resource scarcity	Geo-political scarcity in the wake of the US ‘war on terror’ stimulated energy diversification in pursuit of security providing some pressure on the prevailing automotive ICE regime
Regulation provides the niche technology with relative benefits	Policy support schemes in various countries are driving FEV sales, but these seem financially unsustainable

In our scheme, for a disruptive business proposition to succeed the motors for change should be strong enough to overcome the web of constraints that acts against it. In the case of cars, consumer preferences play an important role. In the words of Windrum and Birchenhall (2005): *The probability of disruption depends on there being at least some positive differential between the distributions of consumer receptiveness for the new technology goods opposed to the receptiveness for old technology goods.* For suppliers there should be a profit in producing the product and offering it to consumers. Thus far, FEV have been loss-making products for the suppliers, they were driven by positive expectations and active support policies from business and government. The momentum for FEV has become lower, because, in our metaphor, the motors shifted to lower gears and webs of constraints remained important.

Throughout this overview of 20-year history of the automotive industry we are struck by the stability of the established regime. Vehicle manufacturers have tried to avoid costly and risky radical technological innovation, which emerges at industry level as a tendency to avoid regime disruption, and an inclination to regime reproduction or reorganization, partly by incorporating elements of disruptive niches into the regime. This pattern has been observed earlier in the shift from sailing ships to steamships (and therefore it has been referred to as “the sailing ship effect” (Ward, 1967)). The pattern results, primarily, from defensive strategies of incumbent firms, who find FEVs too risky. The contemporary structures of automobility thus appear to be likely to remain intact (Cohen, 2012).

We found that policymakers have played an important role in facilitating hybridizations, mainly through emissions requirements and tax benefit regulations that were set in such a way that they could be met by internal combustion engine solutions, with industry being the source of information on that.

Our analysis suggests that the few FEV successes are local, often connected to distinctive policy support. The case of Autolib is an example with local government strongly supportive of FEVs and Norway with both national and local support. Start-ups such as Tesla, too, have been successful in targeting a limited, luxury niche market and found customers who are willing to pay a premium for an electric sports car. Firms targeting a broader consumer base, such as Better Place in Israel, have not been successful. Certainly, a niche can have knock-on effects, evolve and accumulate (Geels, 2005), but at the moment we did not find evidence for this.

Like Bohnsack (2013) we find confirmation of the proposition for FEVs that not incumbents but entrepreneurial new entrants are usually the first-movers regarding disruptive innovation. Autolib' introduced a novel FEV car sharing system. Better Place, by introducing a mobile phone payment method for electric cars, aimed to provide a solution for the range and recharging challenges. The new entrants predominantly followed a novelty-based approach (Zott & Amit, 2007; Bohnsack, 2013). That is, rather than competing with incumbents head-on, the new entrants designed new transaction mechanisms –e.g. in the form of leasing the battery separately—that targeted customers in distinctive ways and that involved collaboration with incumbents. Incumbents have introduced FEV innovations of lower disruption level (still 'selling vehicles') and also at relatively slow pace, with only two of them offering production models by 2011 (Nissan-Renault, Mitsubishi) and one plug-in hybrid (GM), although more followed later.

The market disruption hypothesis will benefit from being tested in cases where the disruptive niche is actually growing, and we recommend further research to address well-documented (historic) cases in industries that experienced disruptive innovation. We have already hinted at the value of methods that augment our 'descriptive' analysis, such as simulation models with capabilities to simulate dynamic effects better. These would be more favorable to highlight various cause-and-effect mechanisms, and a combination of the two approaches would probably provide the most encompassing test of the nested hypothesis.

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