4

Competing technologies and the struggle towards a new dominant design

THE EMERGENCE OF THE HYBRID VEHICLE AT THE EXPENSE OF THE FUEL-CELL VEHICLE?

Marko Hekkert

Utrecht University, The Netherlands

Robert van den Hoed

Delft University of Technology, The Netherlands

Once in a while, a radical breakthrough technology emerges that has a devastating impact on established industries. In comparison to existing technologies, such disruptive innovations deliver a dramatic leap in performance, and incumbent firms tend to respond either by ignoring the new technology or by trying to improve the performance of the established technology (the so-called **sailing ship effect**); as a result, they often perish (Christensen 1997; Utterback 1994). Established industry's reaction to the emergence of possible disruptive technologies is an intensively studied phenomenon in innovation studies (Tushman and Anderson 1986; Henderson and Clark 1990). Due to the unexpected nature of these events, they are often studied *ex post*.

While disruptive and radical technologies are highly imaginative, most technological progress has been made through incremental improvements in the available technology, products and processes (see, for example, Neij 1997). This difference is clearly demonstrated in the recent debates on transitions to more sustainable sociotechnical systems (Geels 2002; Kemp 1994; Schot *et al.* 1994). Although there is consensus over the fact that a transition to a more sustainable system of production and consumption needs to take place, there is no agreement on the role of radical break-through technologies in such a transition. Some consider that breakthrough technologies are necessary in order to reach a desired **final state** (e.g. Kemp 1994) while others stress the difficulties of such a transition and plead for more incremental routes.

Current technological developments in the personal transport system offer an excellent opportunity to compare these two strategies. Where environmental regulations require car-makers increasingly to look for technological alternatives, two major technological routes are currently proposed by the industry. The breakthrough route revolves around the fuel-cell vehicle (FCV), a radically new technology with zero emissions, high efficiency and independence from fossil fuels. The incremental route features the hybrid electrical vehicle (HEV) which is significantly more efficient and has much lower emission levels than conventional internal combustion engine (ICE) vehicles.[1]

Previously positioned as an intermediary staging post on the road to new technologies (such as FCVs), the HEV has always played a modest role in sustainable mobility. However, good environmental performance and recent commercial success are changing people's perspectives of HEV technology, to the extent that the HEV might, in fact, form a competitive threat to FCVs.

In this chapter we focus on the increased competition between these two automotive technology concepts. Based on a comparison of both technologies we will evaluate their chances of becoming the new dominant design. We will conclude by discussing the effect of these potential developments on the life chances of the competing technology.

Theory on competing technologies and transitions

The issues of competing technologies, technology substitution and dominant design are central topics in theories of **technology dynamics** and **technological forecasting**.

Technology dynamics theory frames competing technologies as a variation and selection process (Nelson and Winter 1982). In **variation processes**, many alternatives are developed by the technical community as an alternative to the current dominant design. In **selection processes**, through a series of smaller and larger choices by relevant stakeholders, one technology is selected and this then becomes the dominant design (Anderson and Tushman 1990). Anderson and Tushman (1990) indicate that the process towards a new dominant design can be divided into several stages. After the creation of a technological discontinuity (variation) a **stage of ferment** exists in which the new technology is in competition with the old one. During this period, **competition selection** takes place and the new technology becomes the **dominant design**. Then, an era of incremental change occurs in which the focus is on incremental improvements to the new dominant design. Based on this model, FCV and HEV can be

---

[1] In FCVs, electricity is produced in a fuel cell, preferably fuelled by hydrogen. The HEV has a 'normal' ICE and, additionally, an electric motor: this combination makes the car more efficient.

characterised as **technological discontinuities**.[2] The HEV has already entered the stage of ferment, but the FCV has not yet done so. At this point it is unclear whether the FCV will ever actually enter the stage of ferment.

Both the variation and selection processes take place within a so-called **innovation system**. This is defined as the matrix of economic, social, political, organisational and other factors that influence the development, diffusion and use of innovations (Edquist and Johnson 1997). Innovation systems are often studied by taking a country as a unit of analysis. These studies take as their starting point the assumption that differences in the national system of innovation (NIS) influence the technology choices made by individual firms (Lundvall *et al.* 1992; Nelson and Winter 1982). For our purposes, it is more suitable to use the concept of **technological systems**. Also called **technology-specific innovation systems** (Jacobsson and Johnson 2000), these are systems built around a specific technology or product. The technology-specific nature of this model implies that there are many such systems under development at any one time. Each of these systems is unique in its ability to develop and utilise new technology. Where the focus is on competition between various technologies, this approach is much more suitable than the NIS model (Johnson 2001).

A technological system is formally defined as a 'network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure for the purpose of generating, diffusing and utilising technology' (Carlsson and Stankiewicz 1995: 111).

Determining whether or not a new automotive technology stands a chance of becoming the new dominant design thus requires an analysis of the technological system in which competing technologies, such as ICE, HEV and FCV are developed and selected. Formally, a technological system is made up of organisations and institutions, and the interrelationships between them (Edquist 2001). Organisations can be seen as the players or actors in a system while institutions represent the rules (see Fig. 4.1).

Using this model, we will analyse the technological system around automotive technology in terms of the main actors and the common habits, regimes, rules or laws that regulate the relationships within the system. The relations between the actors themselves and between actors and institutions will be included in our analysis. Any consideration of competition between technologies also needs a thorough analysis of the technologies themselves. Therefore, our analysis will focus on:

- **Automotive industry:** to what extent do vested interests and organisational barriers support technological alternatives?
- **Oil industry/infrastructure:** to what extent do technological alternatives fit with the current infrastructure?
- **Institutional environment:** to what extent do regulations support the alternative technologies?

---

[2] Note that the ICE vehicle fuelled by hydrogen or bio-diesel is a variation on the current dominant design. Note also that the electric vehicle is currently no longer considered by the automotive industry due to lack of commercial potential (van den Hoed and Vergragt 2003), which reflects an *ex post* selection process.

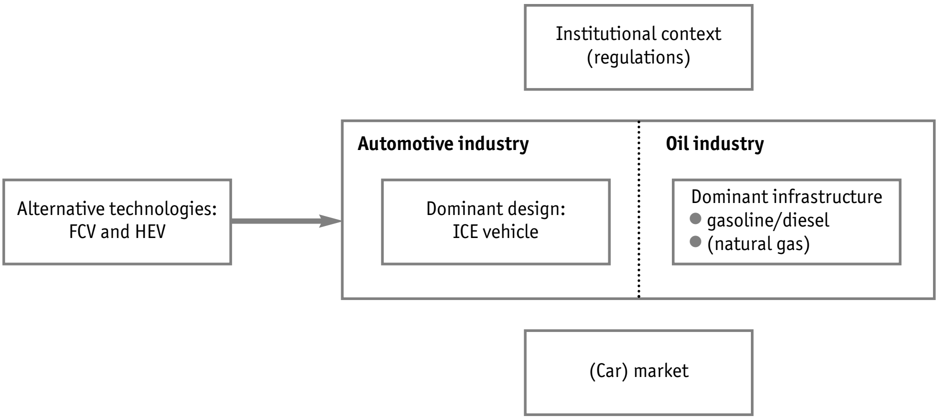

FIGURE 4.1 Technological system around the ICE vehicle and competing alternative technologies

- **Environmental performance:** to what extent do the alternatives compete with the current dominant design?
- **Market performance:** how does the market value the alternative technologies?

In the following sections, FCV and HEV technologies will be analysed in the context of these five factors in order to determine which is the most eligible to become the dominant design, and also to identify the key barriers to the overthrow of the current dominant ICE technology.

HEVs and FCVs in the technical system

In the following sections we will describe how well HEVs and FCVs fit with the actors and regulations in the automotive technological system.

HEVs and FCVs in relation to ICE and the fuel infrastructure

The current technological system for transport is based on the ICE and a gasoline/diesel fuel infrastructure. The introduction of the HEV and the FCV may require changes both at the level of the car and at the level of fuel infrastructure. For both car and infrastructure we discern two dimensions of change associated with the innovation: **technical novelty** and **organisational complexity** (requiring network change). The first dimension is defined as the extent to which the skills and expertise of organisations need to be adjusted to apply the novel technology. An example of such a change is a switch by a manufacturer from producing steel parts to plastic parts. Such a switch either requires hiring new personnel with prior experience or training, or it requires considerable retraining of the existing workforce. The second dimension concerns changes to the structure of the production and implementation network. For example, a shift from combustion-powered vehicles to battery electric vehicles (BEVs) requires changes in fuel supply and repair facilities, in addition to new engine components. Organisations not involved in the existing system will often provide such supporting facilities.

We use several concepts from the literature on innovation to indicate the level of change in these two dimensions: incremental; radical; modular; and system innovations (Henderson and Clark 1990; Tushman and Anderson 1986). Incremental and radical innovations represent the dimension of technical complexity of new innovations (incremental = low complexity; radical = high complexity) while modular and systems innovations represent, respectively, small and large changes in social networks. The two dimensions of change usually combine both technical and network dimensions. This can be seen in Figure 4.2 where technological change is depicted on the incremental–radical dimension and socioeconomic change on the modular–system dimension. The circle sizes indicate carbon emission reduction estimates relative to the gasoline–ICE fuel chain.

The four types of innovations can be placed in the two dimensional space framed by the technological complexity of the innovation and the necessary network change (Goverse *et al.* 2001). Figure 4.2 shows how alternative automotive concepts are placed in relation to conventional ICE vehicles.

The dominant ICE technology is situated at the reference case position in Figure 4.2. In the case of HEV, a battery is added to the conventional powertrain to store energy generated by the heat engine and recovered from braking; this allows buffer power to be used for acceleration and allows zero-emission running for brief periods. Its intro-

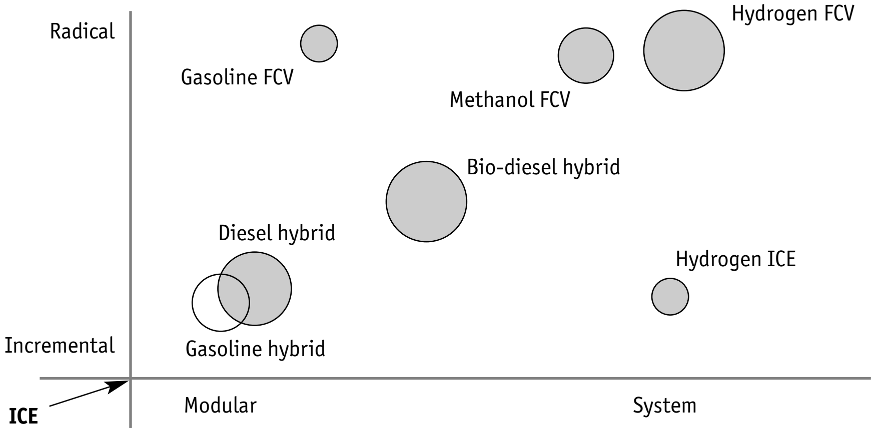

FIGURE 4.2 innovation characteristics of fuel chains

Source: Hekkert *et al.* 2005a

duction does not require changes in fuel supply since regular fuel can be the only energy input. This makes this innovation modular. Technically, this is an incremental innovation since the principles of the mechanical conventional powertrain remain the same in this vehicle, although the propulsion system is extended with an electrical drive.

Overall emissions of HEVs can be further improved by using bio-fuels. Production of bio-fuel requires a well-known, but totally different, fuel production method. The last stages of the fuel chain, distribution and end use, are the same as in the conventional ICE system. Therefore, this innovation is considered to have less systemic features than the other fuel–car systems in which the infrastructure is dramatically different from the current fuel infrastructure.

An alternative, where fuel supply remains unchanged, is the gasoline FCV. Here, the vehicle is the only component that changes. However, the gasoline FCV (in which new technologies are applied to convert gasoline into hydrogen to generate electricity for the electric motor) is technically a radical innovation. This radical innovation also implies that the vehicle's powertrain is fundamentally different, requiring completely new parts and maintenance. Furthermore, consumers will experience differences. Therefore, network changes will especially occur in the area of technology development and consumer information. In terms of network change, this innovation is regarded as being positioned between modular and system innovation.

The hydrogen FCV is placed in the upper-right corner of Figure 4.2, suggesting both technological and socioeconomic environment change. We have already argued that FCV is a radical innovation compared to ICE as the distribution and storage of hydrogen requires significant technical and infrastructure changes. Furthermore, more actors need to be involved in providing the necessary know-how for hydrogen distribution and fuelling.

The alternative option, to use methanol to fuel the FCV, is also situated in the upper-right corner. Although methanol, as a liquid, is easier to handle than hydrogen, a completely new infrastructure would need to be developed requiring huge organisational change. Furthermore, on-board reforming of methanol is necessary to extract hydrogen from it. Creating a small chemical factory within a car is a radical innovation compared to current ICE technology.

Figure 4.2 shows that FCVs with hydrogen fuel are in the upper-right corner and HEVs are in the lower-left corner. The latter is a much better place to be in terms of overcoming implementation barriers. The hybrid vehicle is compatible both with the current ICE system and the existing infrastructure, while the FCV requires changes both in car design and infrastructure. As a result, HEVs will experience far fewer barriers than FCVs.

Oil companies and the development of HEVs and FCVs

The oil companies are expected to play a decisive role in developing the vehicle of the future. As explained above, the relationship between vehicle design and energy infrastructure cannot be overlooked. The power of the oil companies in determining the fuel for FCVs is demonstrated by van den Hoed and Vergragt (2003). They explain that different car manufacturers have different ideas regarding the ideal fuel for FCVs, ranging from methanol and hydrogen to regular gasoline. They argue that DaimlerChrysler had a significant technological advantage in methanol FCV development until 2000–2001, but lost its edge due to an oil industry 'boycott' of 'poisonous' methanol. Exxon has made the boldest statements about methanol not being the fuel of the future, and Shell has also tried to influence DaimlerChrysler to choose a fuel other than methanol (van den Hoed and Vergragt 2003).

The role of the oil companies is hard to predict since they show a strategic behaviour that anticipates different future fuel regimes. Suurs *et al.* (2004) have analysed the preferences of key actors for different fuel regimes. They quote statements from oil companies in which they state that they will sell any future fuel that society asks for (Suurs *et al.* 2004). The same research reveals that the oil companies see hydrogen as the fuel of the future but are more sceptical about its role in the short term. This fits with the variation strategy of Shell which involves the development of business initiatives focusing on both hydrogen and bio-fuels. Shell Hydrogen has been actively developing and installing a number of hydrogen filling stations in different countries.

It is worth noting that the resources devoted by the oil companies to alternative fuels are minuscule in comparison to fossil fuels. The reason for this is simple: even though oil companies anticipate a range of fuel regimes, their vested interests are embedded in gasoline. Any significant change in the fuel infrastructure would require massive investment and this acts as a huge incentive to keep the current fuel infrastructure intact. An example of this strategic behaviour is the development by Shell of an on-board fuel reformer to convert gasoline into hydrogen. The company claims that this option may very well be the ideal transition technology since it provides a means for FCVs to access the current fuel infrastructure. This has led to at least two joint development projects with DaimlerChrysler (Hekkert *et al.* 2005b). However, due to technical problems and the highly complex nature of the technology, Shell has not yet succeeded in convincing vehicle manufacturers that this is the ideal transition technology.

Conclusion

The vested interests of the oil companies are in gasoline, so their focus is on keeping the current infrastructure intact. However, the oil industry is starting to develop a portfolio of knowledge on alternative fuels that might make it more willing to change the infrastructure when there is sufficient pressure to do so. And it is clear that FCVs will also require large organisational changes from car-makers to develop the technology and create the fuel infrastructure.

Environmental performance of different vehicle technologies

Carbon emissions

The reason why FCV technology is considered so promising is hidden in the circles in Figure 4.2. The circles represent the reduction in carbon emissions per kilometre for the different options, based on Hekkert *et al.* (2005a). Thus, the hydrogen FCV shows a large emission reduction potential compared to the hydrogen ICE. However, the figure also clearly shows that HEVs also score well, especially when diesel is used as the fuel. And when diesel is partly replaced by bio-diesel carbon emissions come down even more. In terms of carbon emissions, Hekkert *et al.* (2005a) expect that the bio-diesel HEV very closely approaches the FCV. This is in line with the findings of Weiss *et al.* (2003). Thus, one of the main advantages of FCVs (i.e. their zero emissions) is undermined. Figure 4.2 also shows that adapting the hydrogen FCV to the gasoline FCV in order to overcome infrastructure barriers is not advantageous in terms of carbon emissions. This leaves the hydrogen FCV with just one advantage over HEVs in terms of emissions: it is a zero-emission vehicle (ZEV) under all circumstances while the diesel HEV is zero emission-only when the battery is used for driving.

Other advantages of electric drivetrains

Demand for additional auto features powered by electricity is likely to rise in the future. Examples of these are multimedia in-car entertainment devices, air conditioning to cool the car before the driver gets in and wireless communication with other cars. The FCV has the advantage of being a small power plant and this opens up numerous possibilities for additional features. However, the HEV also does well in terms of these new features since its battery capacity is extremely large compared to current ICE vehicles. Finally, additional small fuel cells can be added to any car exclusively to power these additional features.

Conclusion: environmental performance

The HEV scores better than the FCV in terms of technical and organisational implementation barriers. In terms of efficiency and providing support for additional car functions it can keep up with the FCV. But in terms of emissions the FCV scores much better than the HEV. This seems to be the most important advantage of the FCV. However, this applies only when the FCV is powered by hydrogen. All other FCV fuel combinations cannot compete with the HEV.

Institutional context for HEV and FCV

To what extent are FCVs and HEVs compatible with pressures originating from the institutional context? The following sections will discuss changes in regulatory regimes from 1990 to 2002, with particular focus on ZEV regulation in California.

ZEV regulation in historical perspective

The year 1990 marked an important shift in environmental regulations in the state of California with the passing of the ZEV regulation. In light of growing health problems caused by air pollution, the California Air Resources Board (CARB) decided to mandate sales of ZEVs. Large-volume manufacturers were obliged to bring 2% ZEVs to the market in the period 1998–2000 and 10% by 2003 (see Fig. 4.3). Intermediate-volume manufacturers were obliged to start bringing ZEVs to the market by 2003. The ZEV regulation entailed mandated sales of 60,000 ZEVs between 1998 and 2000 in California, and is expected to achieve 1.1 million ZEVs by 2010.

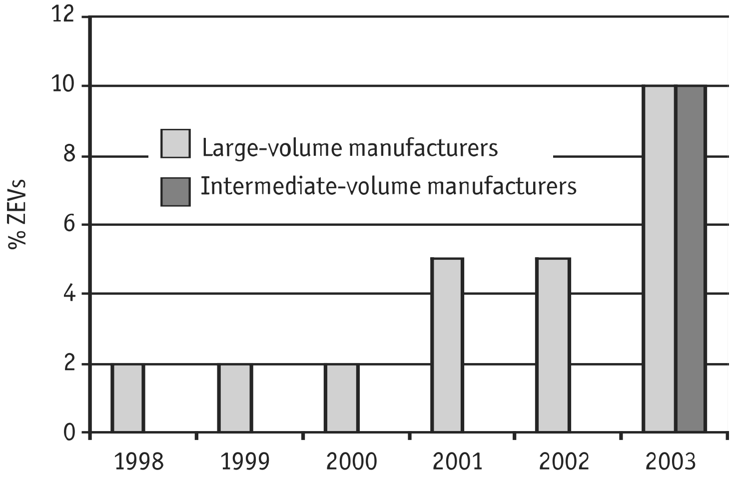

FIGURE 4.3 Original ZEV regulation

The ZEV programme stands out from previous emission controls by challenging the ICE paradigm. Given that, in 1990, battery electric vehicles (BEVs) were seen as the only viable zero-emission technology, the ZEV regulation became a major driver for the development of BEVs and other alternative technologies with zero-emission potential. Failure to comply with the regulation by manufacturers promised penalties of several thousand dollars per ZEV not sold. This proved a great incentive for ZEV development.

Over the years, ZEV standards have been postponed and watered down. In 1996, the pre-2003 ZEV obligations were skipped, although the 2003 requirement of 10% remained. An important argument in favour of omitting the early ZEV requirements related to the conclusions drawn by the Battery Panel—which was set up by the state of California to investigate the future potential of battery technology—that lead-acid batteries were not yet competitive while more promising technologies, such as nickel-metal-hydride (NiMH) batteries, required more development work.

By 1998, the 10% ZEV requirement had been watered down to 4% after fierce lobbying by vehicle manufacturers who argued that market opportunities for BEVs were low. A new category was proposed for the remaining 6%, the partial ZEV category (PZEV) (CARB 1998). Cars eligible for PZEV were required to reach the so-called SULEV (super-ultra-low-emission vehicle) standards, equivalent to what the emissions utilities produce for generating electricity for BEVs. The new category can be achieved by the most efficient HEVs.

In 2001, the ZEV regulation was changed again (CARB 2003), with the 4% ZEV requirement for 2003 reduced to 2%. For the remaining 2% another new category was introduced, the ZEV–AT (alternative technology). CARB's rationale for introducing a new category was to allow for the stimulation of new technologies which, although not necessarily achieving zero emissions, nevertheless offered strong advantages over ICE. The technologies eligible for the ZEV–AT category include HEVs, FCVs (methanol or gasoline) or natural gas vehicles. Thus, HEV and FCV technologies were further stimulated by CARB.

The last alteration made to the ZEV regulation occurred in 2003 (CARB 2004). The proposed amendments delayed the start of the ZEV requirements from the 2003 model year to the 2005 model year. An important element was a new mechanism allowing large-volume vehicle manufacturers to choose between the following two compliance paths in 2005 and subsequent model years:

1. A manufacturer is permitted to satisfy its ZEV obligations by meeting requirements similar to those in the ZEV regulation as amended in 2001 (2% 'gold' ZEV vehicles plus 2% 'silver' ZEV–AT and 6% 'bronze' PZEVs)
2. The manufacturer also has the option of electing a new alternative ZEV compliance path, by selling a number of FCVs by model year 2008 (the number is sales-dependent, but averages around 250 per vehicle manufacturer). This option relieves any ZEV obligations, but still requires the car-maker to sell a mix of 4% AT PZEVs and 6% PZEVs

Thus, by adding the second compliance path, the 2003 amendments provided further motivation for developing FCVs. Similarly, the HEV option remains an important route for achieving the ZEV obligations.

Carbon dioxide, energy efficiency, alternative fuels

Low- and zero-emission controls were the most demanding environmental requirements for the car industry in the 1990s. In recent years, however, issues around carbon dioxide emissions and energy efficiency have risen up the political agenda.

The 1992 Kyoto Protocol provided a key starting point, requiring governments to develop measures to curb greenhouse gas emissions at national level. In the EU this led, in 1995, to a collective voluntary agreement between the European, Korean and Japanese car industry to reduce carbon dioxide emissions by 25% in 2005 (in comparison to 1995 levels).[3] The standards are a major driver for car-makers to increase efficiency and develop new technologies. As a result, optimisation technologies for ICE vehicles have been developed (e.g. direct injection, common rail). HEV technology has also progressed, with the Toyota Prius accredited as the most efficient vehicle in its segment in 2001.

Furthermore, the 9/11 attack on the World Trade Center and the turmoil in the Middle East and Iraq has highlighted the dependence of the West (particularly the US) on oil and given the search for alternative fuels a new urgency. The quest for alternatives (for instance, natural gas- or ethanol-fuelled vehicles) was stimulated in the 1990s.

---

[3] See europa.eu.int/comm/environment/co2/co2_home.htm.

However, in recent years, the **hydrogen vision** has generated so much momentum that the governments of Japan and the US, and those in Europe, have set up large hydrogen stimulation programmes. Indicative is the US$1.2 billion project set up by the Bush administration in 2002 under the significant name of FreedomCar. The programme entails a considerable push for hydrogen technology in transportation purposes. Unlike carbon dioxide emissions and energy efficiency, the unidirectional push to hydrogen is a strong supporting driver for FCV development; it does not, however, favour HEVs.

Conclusion: institutional context

Since 1990, the regulatory context, particularly in California, has stimulated the development of alternatives to the ICE vehicle. The emphasis has long been on zero emissions, providing a push for BEVs and FCVs, and limiting the potential for HEVs. Nevertheless, a shift can be discerned. The postponement and watering-down of zero-emission standards on the one hand, and the increased importance of energy efficiency and carbon dioxide emission reduction on the other, forms an increasingly favourable context for HEVs to co-exist alongside FCVs.

Market factors with respect to FCVs and HEVs

The costs of FCV technology are still hard to estimate given the limited data. Several studies have attempted to estimate costs, based on different assumptions leading to strongly varying results (van Dijkum 2003). This section looks at several studies on FCV stacks/systems costs.

Arthur D. Little (2000), under contract to the US Department of Energy (DOE), estimates that fuel-cell system costs are US$324/kW, assuming production volumes of 500,000 per annum for a 50 kW stack (total stack costs would thus be US$16,200). Similar values of US$195–325/kW (also assuming production volume of 500,000 units per annum) were found by Carlson *et al.* (2002). The Arthur D. Little research indicates that total fuel-cell system costs are dominated by stack costs, platinum loading and the material costs of the membrane electrode assembly (MEA). Costs for complementary components for cooling and pressurising the systems were minor. The study also estimates the cost of a reformer as around US$80/kW.

Another much cited study is that of Morisot (2002). This used real-time data of current fuel-cell costs (whereas the studies mentioned above used figures of projected material costs), but took volume production into account. The study concludes that total fuel-cell system costs can currently be estimated at around €8,100/kW, more than a factor of 20 higher than earlier studies: the fuel-cell stack being largely responsible for these costs (€5,320/kW) due to platinum and electrodes costs. Morisot (2002) makes a projection to 2005 and 2010 under assumptions concerning cost reductions of membranes (with Nafion assumed to be replaced by a different membrane altogether), electrodes and bipolar plates. Furthermore, a tenfold reduction in platinum loading in 2010 is assumed. As a result, cost estimates for a total fuel-cell system in 2010 is expected to be around €1,710/kW, still considerably higher than the other studies mentioned. Surprisingly, Morisot expects proton exchange membrane (PEM) fuel cell stacks to be €200/kW in 2010, but sees fewer opportunities to reduce costs for balance of plant, reformers and additional components (in total €1,510/kW). Also, Kalhammer *et al.* (1998) predict that balance of plant issues are underemphasised in current research and form big challenges for the FCV.

These figures give an indication of the costs of fuel-cell systems, being several hundreds of dollars per kW. In comparison, the current cost for an ICE system is US$25–35/kW: thus, fuel-cell technology faces enormous competitive challenges. An illustration of the costliness of FCV technology is demonstrated by the FCV prototypes delivered by Honda to the Japanese government in November 2002 and estimated at around US$1 million each. Nonetheless, FCVs have come a long way, with enormous cost reductions in the last decade, and further significant reductions expected in the future.

In contrast, the HEV has a relatively small price premium of 10–15% (based on sales prices). Although industry experts suspect that Toyota sold its HEV Prius at a loss in 1997–2000, in 2002 Toyota announced that it now made a modest profit.

With regard to drivability, the expectation is that the FCV will compete with ICE vehicles in the mid to long term (Kalhammer *et al.* 1998). Currently, the stacks are heavy, less energy-dense and the dynamic behaviour of the FCV still requires development (Hoogers 2003). Acceleration is a relatively strong asset due to a maximum torque available from 0 rpm. However, this comes at the price of a heavier motor. FCVs still require significant improvements to be competitive in performance, and it remains to be seen if they will succeed. HEVs, on the other hand, already compete on drivability with conventional cars.

Conclusions: market factors

Although difficult to predict the market value of the FCV, from a consumer point of view, the first signs do not seem favourable, particularly in terms of costs. HEVs, on the other hand, show considerable market success and are proving an increasingly robust competitor to ICE vehicles.

Overview of technological system indicators

Table 4.1 summarises the findings presented above. It shows that in terms of necessary technical change the FCV scores poorly. It can be considered as a radical technological change that needs much more development work to be competitive on the market. By contrast, the HEV has developed much further; it represents a less radical technological change and is already sold commercially. In terms of infrastructure change, the hydrogen FCV again scores very poorly. Building the hydrogen infrastructure will require massive effort and capital. The other FCV types (gasoline and methanol) are much more compatible with the current infrastructure but cannot be considered an alternative due to their poor emissions performance. The HEV is completely compatible with the current fuel infrastructure.

	Technical changes	Infrastructure changes	Regulation	Environmental performance	Market potential
FCV	– –	– – (hydrogen) + (gasoline) – (methanol)	+ + → +	+ + → + – → – – → –	? ? → –
HEV	+ / + +	+ +	– → +	– → +/–	– → +

TABLE 4.1 Overview of factors influencing the viability of FCV and HEV over time

The ZEV regulation in California was a strong push for both HEV and FCV development. However, due to a postponement and relaxation of zero-emission targets, the influence of the regulatory environment on FCV development seems to be declining. The HEV, on the other hand, is likely to profit from this trend. Other types of regulation-based efficiency standards do not discriminate between FCV and HEV and therefore indirectly favour HEV due to its positive scores on the previous two criteria.

In terms of environmental performance, FCV has been seen as the best option for the future. However, recent studies have shown that in terms of efficiency and carbon emissions the FCV will have trouble competing with the HEV. The absence of non-carbon emissions is a very strong asset for the FCV. So the overall score on emissions is in favour of the FCV.

In terms of the market, expectations for the FCV are uncertain due to unknowable future costs. However, different car manufacturers claim that the costs are likely to stay very high for a long time. For HEVs, the market potential has improved considerably due to significant cost reductions and increases in profitability.

Industry activities in FCVs and HEVs

The above analysis, in which HEV is increasingly favoured over FCV, can also be observed in industrial activities. Based on patent analysis by automotive firms between 1990 and 2002, van den Hoed and Vergragt (see Chapter 5) came to the following conclusions. First, there was a rise and fall in BEV patents between 1990 and 2002, with a peak in 1996. Most BEVs were launched between 1996 and 1997, but the anticipation of a weak market led to a decline in patent activity and low R&D activity from 1996 on. Second, the data suggests a shift in research focus from BEV to both HEV and FCV after 1996. Patent activities of HEV and FCV accelerate around 1996–97 and, by 1998–99, they are acquiring more patents than BEVs. Third, HEVs receive increasingly more patents than FCVs, indicating their higher priority for car-makers. By 2000, nearly 50% of all alternative-fuel vehicle (AFV) patents were HEV-related, followed by approximately 35% for FCVs. Only 15% of all AFV patents were BEV-related.

The patent study illustrates how vehicle manufacturers have shifted attention from BEVs to HEVs and FCVs, and how HEVs and FCVs are competing for R&D funds at automotive research centres. By 2003, nearly all the major vehicle manufacturers had extensive FCV and HEV programmes. Where around 100 concept FCVs have been tested worldwide, HEVs are on sale and sell well. Initiated by Toyota and Honda, the market for HEVs exceeds 50,000 units and is rising rapidly, forming a formidable niche market. While large-scale commercial FCVs sales are not expected before 2008, HEVs have become a popular commercial alternative for achieving lower emissions and higher efficiency.

More importantly, a majority of vehicle manufacturers is currently involved in HEV development, thereby increasing the industry consensus that HEV has a future—possibly, even, as a dominant design rather than an intermediary step.

Conclusions

To understand the implications for the life chances of the FCV we fall back to lessons learned from innovation studies. We will discuss these implications in the context of **technological relative advantages** (Rogers 1984) and **technological trajectories** (Dosi 1982).

Rogers (1984) introduced the concept of relative advantages of one technology over the other as one of the factors that determine the chance of adoption. In other words: if a technology has large advantages over another, a customer is more likely to buy it. If the HEV becomes the new dominant design after ICE, the relative advantages (in terms of efficiency and emissions) of the FCV will be lower compared to the HEV than to ICE. This is likely to reduce the justification for large investments in technology development of the FCV.

Another important issue is the concept of technological trajectories. We have learned that a major transition from one technological system to another often takes place via so-called transition (or intermediate) technologies. These technologies form a bridge between the old regime and the new one. Some see the HEV as such a transition technology. However, this is questionable since HEV technology offers no experience of producing fuel cells or developing an alternative fuel infrastructure. A more logical transition technology is the gasoline FCV; this fits well with the current regime both in terms of fuel and technology. It is more efficient than current ICE cars and it offers an opportunity to create a mass market in fuel cells, thereby strongly reducing costs. When the FCV has outperformed ICE vehicles, the 'only' thing left is adaptation of the energy infrastructure. With HEV as the dominant design, there will be far fewer advantages to the gasoline FCV since HEVs are more efficient than gasoline FCVs. So now the argumentation will be that, due to better-performing reference technology, the opportunities for FCVs are drastically reduced.

Thus, when the HEV has become the dominant design, the step to the hydrogen FCV will have to be made directly. This will require a simultaneous effort to change both the infrastructure and engine technology. This is likely only under a very strict regulatory system focusing on non-carbon emissions, which is in opposition to the current trend.

References

Arthur D. Little (2000) *Cost Analysis of Fuel Cell System for Transportation, Base Line System Cost Estimate* (New York: Arthur D. Little).

Anderson, P., and M.L. Tushman (1990) 'Technological discontinuities and dominant designs: a cyclical model of technological change', *Administrative Science Quarterly* 35.4: 604-33.

CARB (California Air Resources Board) (1998) *Proposed Amendments to California Exhaust, Evaporative and Refuelling Emissions Standards and Test: Procedures for Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles-LEVII* (Sacramento, CA: CARB).

—— (2003) *Staff Report. Initial Statement of Reasons: 2003 Proposed Amendments to the California Zero Emission Vehicle Programme Regulations* (Sacramento, CA: CARB).

—— (2004) California Air Resources Board, Resolution 03-4, 24 April 2003, www.arb.ca.gov/regact/zev2003/res0304.pdf.

Carlson, E.J., J.H. Thijssen, S. Lasher, S. Sriramulu and G.C. Stevens (2002) 'Cost modelling of PEM fuel cell systems for automobiles', paper presented at the *SAE Future Car Congress*, Arlington, VA, 3–5 June 2002.

Carlsson, B., and R. Stankiewicz (1995) 'On the nature, function and composition of technological systems', in B. Carlsson (ed.), *Technological Systems and Economic Performance: The Case of Factory Automation* (Boston/Dordrecht/London: Kluwer Academic Publishers).

Christensen, C.M. (1997) *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston, MA: Harvard Business School Press).

Dosi, G. (1982) 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and direction of technical change', *Research Policy* 11.3: 147-62

Edquist, C. (2001) 'Innovation systems and innovation policy: the state of the art', paper presented at *DRUID's Nelson–Winter Conference*, Aalborg, Denmark, 12–15 June 2001.

—— and B. Johnson (1997) 'Institutions and organisations in systems of innovation', in C. Edquist (ed.), *Systems of Innovation* (London/Washington, DC: Pinter): 41-60.

Geels, F.W. (2002) 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study', *Research Policy* 31.8–9: 1,257-74.

Goverse, T., M.P. Hekkert, P. Groenewegen, E. Worrell and R.E.H.M. Smits (2001) 'Wood in the residential construction sector: opportunities and constraints', *Resources, Conservation and Recycling* 34.1: 54-73.

Hekkert, M.P., F. Hendriks, A.P.C. Faaij and M. Neelis (2005a) 'Natural gas as an alternative to crude oil in automotive fuel chains: well-to-wheel analysis and transition strategy development', *Energy Policy* 33.5: 579-94.

——, J. F. van Giessel, M. Ros, M. Wietschel and M. Meeus (2005b) 'The evolution of hydrogen research: is Germany heading for an early lock-in?', *International Journal of Hydrogen Energy* 30.10: 1,045-52.

Henderson, R.M., and K.B. Clark (1990) 'Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms', *Administrative Science Quarterly* 35.1: 9-30.

Hoogers, G. (2003) *Fuel Cell Technology Handbook* (Boca Raton, FL: CRC Press).

Jacobsson, S., and A. Johnson (2000) 'The diffusion of renewable energy technology: an analytical framework and key issues for research', *Energy Policy* 28.9: 625-40.

Johnson, A. (2001) 'Functions in innovation system approaches', paper presented at *DRUID's Nelson–Winter Conference*, Aalborg, Denmark, 12–15 June 2001.

Kalhammer, F.R., P.R. Prokopius, V.P. Roan and G.E. Voecks (1998) 'Status and prospects of fuel cells as automobile engines: a report of the fuel cell technical advisory panel, Sacramento, CA', prepared for the State of California Air Resources Board.

Kemp, R. (1994) 'Technology and the transition to environmental sustainability: the problem of technological regime shifts', *Futures* 26.10: 1,023-46.

Lundvall, B., A.B. Johnson, E.S. Andersen and B. Dalum (2002) 'National systems of production, innovation and competence building', *Research Policy* 31.2: 213-31.

Morisot, O. (2002) 'EasyPac: technical and economical assessment of stationary PEM fuel cell systems', *European Fuel Cell News* 9.3: 12-19.

Neij, L. (1997) 'Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology', *Energy Policy* 25.13: 1,099-07.

Nelson, R.R., and S.G. Winter (1982) *An Evolutionary Theory of Economic Change* (Cambridge, MA: Harvard University Press).

Rogers, E.M. (1984) *Diffusion of Innovations* (New York: Free Press, 4th edn 1995).

Schot, J., R. Hoogma and B. Elzen (1994) 'Strategies for shifting technological systems: the case of the automobile system', *Futures* 26.10: 1,060-76.

Suurs, R., M.P. Hekkert, M.T.H. Meeus and E. Nieuwlaar (2004) 'Assessing transition trajectories towards a sustainable energy system: a case study on the Dutch transition to climate neutral transport fuels', *Innovation: Management, Policy and Practice* 6.2: 269-85.

Tushman, M.L., and A. Anderson (1986) 'Technological discontinuities and organisational environments', *Administrative Science Quarterly* 31.3: 429-65.

Utterback, J.M. (1994) *Mastering the Dynamics of Innovation* (Boston, MA: Harvard Business School Press).

Van den Hoed, R., and P.J. Vergragt (2003) 'Technological shifts and industry reaction: shifts in fuel preference for the fuel cell vehicle in the automotive industry', paper presented at *Knowledge and Economic and Social Change: New Challenges to Innovation Studies' Conference*, Manchester, UK, 7–9 April 2003.

Van Dijkum, P.H. (2003) 'The path to handy, cost-effective fuel cells', *European Fuel Cell News* 9.4: 7-11.

Weiss, M.A., J.B. Heywood, A. Schafer and V.K. Natarajan (2003) *Comparative Assessment of Fuel Cell Cars* (Cambridge, MA: MIT Press).