Table of Contents

Go Back

Innovation Process 'Fuel Cell Vehicle': What Strategy Promises To Be Most Successful?

Paper presented to the Twenty-Second International Conference of

the System Dynamics Society

July 2004, Oxford, England

Maik Schneider, Burkhard Schade & Hariolf Grupp

Maik Schneider, Interdisciplinary Institute for Environmental Economics, Ruprecht-Karls-University Heidelberg, 69115 Heidelberg, Germany. Tel. ++49-621-181-1801, E-mail: schneider@eco.uni-heidelberg.de.

Burkhard Schade, Institute for Economic Policy Research, University of Karlsruhe, 76128 Karlsruhe, Germany. Tel. ++49-721-608-7690, E-mail: burkhard.schade@iww.uni-karlsruhe.de.

Hariolf Grupp, Institute for Economic Policy Research, University of Karlsruhe, 76128 Karlsruhe, Germany. Tel. ++49-721-608-7693, E-mail: grupp@iww.uni-karlsruhe.de.

Abstract

Many car manufacturers recognize fuel cell vehicles as future substitutes for conventional cars with internal combustion engine. According to press releases and brochures, different strategic approaches of the automobile companies concerning fuel cell technology can be identified. Those strategies match the market entry strategies known from strategic marketing literature to a high degree. A system dynamics model that reflects the beginning innovation process and the strategic approaches of a pioneer (first to market), an early follower (early to market) and a late follower (late to market) has been build. It examines the future prospects of the car manufacturers' strategies in three different scenarios, which illuminate possible future developments of external influences like politics or fuel infrastructure.

Introduction

Since the early 1990s, it seems that the fuel cell might become the new key technology in the automotive sector leading to a change of paradigm in the next decades. Also in scientific discussion, fuel cells are researched on and described more intensively during the last ten years. The perspective to significantly reduce local emissions as well as to gain independence from crude oil has induced intensive research activities of automobile manufacturers and extensive governmental support. By this effort, the fuel cell has been developed to a possible alternative to the internal combustion engine (ICE). At the moment, governments, oil companies and automobile manufacturers work together in different research and test projects in order to prepare for introduction onto the market. The biggest project with more than 50 fuel cell vehicles (FCEVs) being tested is taking place in California since the beginning of 2000. The so-called California Fuel Cell Partnership comprises more than 25 participating companies, among them e.g. Daimler Chrysler, Ford, General Motors, Volks-wagen, BP, Shell and Ballard Power Systems. Their main goal is to demonstrate vehicle technology by operating and testing under real world conditions, to show the viability of alternative fuel infrastructure technology, explore the path of commercialisation and increase public awareness.[1] Additionally, the US government officially announced the Freedom Cooperative Automotive Research Program at the Detroit Motor Show in January 2002, aiming at a promotion of the development of hydrogen as a primary fuel for cars and trucks in order to reduce America's dependence on foreign oil. Similar cooperations exist in some other countries. For example in Germany, the 'Verkehrswissenschaftliche Energiestrategie (VES)' was founded to develop and implement a strategy for the introduction of an alternative fuel infrastructure within a medium time horizon.

However, launching date and diffusion of fuel cell vehicles not only depend on technological progress, but also on the decisions of the automotive industry. Some car manufacturers are planning to enter the market in 2004 with a production of 1000 vehicles per year, whereas others decide to wait and see, because a tough competition against the internal combustion engine vehicle (ICEV) in a highly saturated market is to be expected. Newspaper reports and brochures of the auto companies indicate different levels of R&D effort and various plans regarding market introduction. Those strategic directions can be compared to the strategic approaches for market entry, known from strategic marketing literature. The goal of this paper is to examine which strategic approach promises to be most successful regarding market share, return on investment and net present value of profits. A System Dynamics Model has been built, reflecting the upcoming innovation process of fuel cell vehicles and the three strategic approaches pioneer, early follower and late follower. Each of the three fictive companies, representing one of the above mentioned strategies, can launch up to four product generations over a simulation time frame of 30 years. The question finally boils down to whether a first-to-market strategy is to be preferred to a later market entrance or in other words whether the classical pioneer advantages of a temporary monopoly and a rapid advance on the experience curve outweigh the follower's lower market education costs and spill-over effects.

This paper is structured as follows. Section one provides a brief overview over fuel cell technology and fuel infrastructure concerns as far as those are relevant to the further investigation. The second section describes the different strategic approaches according to literature and assigns the strategies of the auto-manufacturers to them. Section 3 shows the structure of the System Dynamics Model and its underlying hypotheses. The implementation of the strategies into the simulation model and the definitions of the scenarios are illuminated in sections 4 and 5. Section 6 discusses the results of the simulation in each scenario, followed by final conclusions in section 7.

1 Technological considerations

Four different vehicle concepts are being discussed as possible alternatives for individual mobility in the near future: the vehicle with internal combustion engine, the battery driven electro-car, the hybrid-vehicle, linking ICE and electro-drive, and the fuel cell vehicle. Momentarily, the dominant drive system for cars is the internal combustion engine (Otto and Diesel engine). Research and Development (R & D) over many decades have lead to extensive technological optimisation and high acceptance in the market.[2] The battery driven electro car will probably not be able to succeed in the market, due to its low extension range of about 100 to 140 km and high production costs.[3] The hybrid vehicle avoids low extension ranges by an additional ICE on board. This, however, leads to a complex system and high vehicle weight. It is assumed that the hybrid vehicle will not exceed niche market demand.[4] The fuel cell promises the highest potential for a substitution of the internal combustion engine in the long run. There are still some technical hurdles to overcome and several optimisations to conduct, however, the general realization of the fuel cell vehicle is not questioned, according to car manufacturers.[5]

There are greater uncertainties concerning the fuel module. The central question is, whether a hydrogen infrastructure will already be established in the short term or another kind of fuel will be used in a transition phase, then in connection with a corresponding reformer on board. The reformer is necessary to obtain hydrogen from the fuel alternative. The above-mentioned question comprises technical as well as economic aspects. On the one hand, the engineer prefers the fuel alternative with the highest energy density, to keep tank volumes small and guarantee a wide extension range. On the other hand, simple handling for the customer at the gas station and a fast growing fuel infrastructure are crucial for commercial success. Additionally, fuel price and thus fuel production cost need to be considered. The German ‘Verkehrswissenschaftliche Energiestrategie’ chose three out of ten alternative fuels for further examination focusing on a broad commercial introduction: natural gas, methanol and hydrogen.[6] In the literature, there is no indication of an on-board reforming of natural gas. Natural gas would be burned in the ICE. Focussing on fuel cell vehicles, methanol and hydrogen are the possible fuel alternatives. In the long term, hydrogen represents the most promising fuel regarding efficiency, CO_2 reductions and supply.[7] In the short run, however, methanol seems to be more advantageous. Its energy density is higher,[8] handling at the gas station stays very much the same as with regular gas,[9] the existing fuel infrastructure can be altered without huge expenses[10] and production cost per kWh is lower than that of hydrogen.[11]

Thus it appears most likely that a methanol infrastructure will be build up first, which will be replaced by hydrogen in the medium or long run.[12] Similarly, Grosse and Waidhas as well as the German Ministry for Education and Research are expecting a hydrogen economy only about 30-50 years ahead.[13] According to Grosse and Waidhas, hydrogen has to be obtained by on-board-reforming of well storable, liquid fuels like methanol, ethanol, petrol or diesel.[14] The costs of hydrogen and methanol depend to a great extent on their way of production. For the simulation time frame of thirty years, it is assumed that both alternative fuels are obtained from natural gas. By that time only small amounts of methanol and hydrogen won through renewable sources of energy will be available.[15] This leads to a fixed relation between the price of petrol and the methanol and hydrogen price, since the prices of oil and natural gas are strongly connected. Therefore, a price-driven substitution effect towards alternative fuels is not to be expected in the short term.[16] Only in the long run with the majority of hydrogen being produced by renewable sources of energy an independence from the world market’s oil price can be realized.

Thus, it is assumed in the simulation model, that the three depicted companies equip their first two product generations with a methanol tank and reformer and the following ones with a hydrogen tank. Theoretically, there are three possible types of reformers, which can be used for product generations 1 and 2: the autothermal reformer, the partial oxidation reformer and the heated steam reformer. For the purpose of this simulation, it is argued that the heated steam reformer will be preferred on account of the lowest production costs.[17] Furthermore, petrol price is assumed constant over the simulation time interval[18] and the prices of methanol and hydrogen will be slightly decreasing due to economies of scale with an increasing volume of demand.[19]

2 Timing strategies for market introduction

Fuel Cell technology is based on scientific discoveries which are not new. However, earlier attempts to use it for commercial applications have failed. Generally speaking new technology often runs through two typical phases, one science-driven and one market-led. Several such cases had been observed in the past. In a stylized model of market formation this observation is explained by principles of evolutionary innovation theory, which states a "mutation" and "selection" process.[20]

Literature suggests different classifications to characterize strategies for market entry. A distinction between 'early to market' and 'late to market' seems too vague to derive differentiated statements on the advantages of different launching dates.[21] On the other hand, classifications with many distinctions entail serious definition problems. For the classification of Ansoff/Stewart, which distinguishes between 'First-to-market', 'Follow the leader', 'Application' and 'Me-too-strategy', it is difficult to determine differences between 'Application' and 'Me-too-strategy' with regard to timing-considerations for market-entry, for example.[22] For these reasons, a three-dimensional classification reflecting the pioneer strategy (first to market), the early follower strategy (early to market), and the late follower strategy (late to market) has been chosen.[23]

2.1 Pioneer strategy

The pioneer is the company that at first offers a new technology or an utterly new product at the market. Prerequisite for a pioneer strategy is the possession of a marketable product. This induces high R&D expenses. At the time the pioneer enters the market the firm holds a quasi-monopoly. This offers a big scope in pricing. Usually the pioneer strives for a quick amortization of the R&D expenses by high returns during monopoly. Moreover, the pioneer attempts to establish barriers for market entry. This can be realized for example by marketing an image as the technological leader, introducing a dominant design, gaining cost advantages by progressing on the experience curve and building up a broad customer base.
The disadvantages of the 'first to market' strategy are mainly based on the risk connected with the high uncertainty about the development of the new market in the future. In most cases there is no experience to rely on. Another disadvantage is high market education costs, which are of particular importance if the customer has to be convinced of the advantages of the offered product first. Finally the pioneer has to take the risk of a technological change making his product obsolete.

2.2 Early Follower Strategy

The early follower launches the new product shortly after the pioneer entered the market. The market is still developing; there are no clear market rules, yet. However, the early follower has to consider the strategic actions of the pioneer and must expect further market entrants. The possibility to learn from the experiences of the pioneer is an advantage. The fast follower is able to better estimate the further development of the market. The life cycle stands at its beginning and the early follower still possesses the opportunity to succeed in establishing an own standard in the market. The second firm also benefits from the pioneer's educating the market.

However, high market barriers erected by the pioneer may already exist. Being second in the market, it is necessary to communicate a clear competitive advantage, since newness of the product alone may not be a selling point anymore. Thus, the early follower often aims for the launch of a technologically more advanced product as compared to the pioneer. Moreover a fast reaction to the pioneer's market entry is necessary to not let the first firm move too far ahead on the experience curve and to expand the time interval before other competitors enter the market.[24]

2.3 Late Follower Strategy

The goal of the late follower is to participate on a well-developed growing market. A dominant design has been established already and fundamental knowledge on consumer behaviour is available. In this situation the choice of the exact launching date is of secondary importance. Instead, emphasis must be put on a clear competitive advantage. In this respect, Backhaus distinguishes between a ‘Me-too’-strategy and a niche strategy.[25] A niche strategy is on the look out for market segments that are insufficiently served. This strategy is especially interesting for smaller firms. In this paper, however, the focus will be upon the ‘Me-too’ strategy.

The Me-too strategy strives for a high market share by imitating successful products, which are offered at a lower price. The comparatively low price is achieved by low R&D expenses and investments in modern production facilities. Basing the product on the market’s dominant design, production can be highly standardized. This leads to high output at low costs per piece. The late follower encounters less uncertainty about the future market development and is able to purchase know-how if necessary.

On the other hand, it is harder to get a foothold in the market, since the competitors had enough time to strengthen their positions and erect barriers for entry. Also, the late follower oftentimes has to break existing business connections. This bears the risk of ruinous price-cutting wars. Additionally, the late follower takes on the risk of a bad investment in production facilities. The firm may not be able to amortise high investments in case of a reduction or a change of demand. Another disadvantage is that the late follower strategy mostly involves a negative image.[26]

2.4 Empirical investigations

A lot of empirical investigations indicate that the pioneer mostly succeeds in stabilising a leading market position.[27] However, ex-post analysis often begins with successful launches leaving early failures out of consideration. This suggests a particular successfulness of the pioneer strategy.[28] Golder/Tellis conclude from the results of their investigation, that the success of the pioneer-strategy is being overestimated.[29] According to them, pioneers do not realize an average market share of about 30 – 40%, but around 10%, only. The former market pioneers are in only 11% of the 36 examined product categories today’s market leaders. The average time of pioneers being market leaders is about five years. The ‘loser rate’ amounts to 47%. Also according to Perillieux’s findings, there is no evidence for a dominance of the pioneer strategy.[30]

2.5 Timing strategies of the car manufacturers

According to planned launching dates of fuel cell vehicles and R&D efforts as published in newspaper reports and brochures of the automobile industry, the above discussed strategies can be identified. There are two technologically leading co-operations. This is DaimlerChrysler and the Ford Motor Company, on the one hand, and General Motors and Toyota, on the other. In the year 2000, DaimlerChrysler introduced its fifth generation of the NECAR prototype series. It is a Mercedes A Class, which works on only one stack producing

75 kW with a maximum speed of 175 km/h.[31] Ford's newest model is based on the 'Focus'. DaimlerChrysler and Ford strive for the launch of a small series of 1000 fuel cell vehicles per year in 2004 and expect a production of about 100,000 vehicles per year in 2010. The cooperation between General Motors (GM) and Toyota has similar plans. GM aims for a production-ready fuel cell electric vehicle in 2004 and expects a share of 10% of total sales in 2010 and 25% in 2025. However, a broad market introduction, officials say, is not expected before 2008.[32] The latest publications state that Toyota even plans to introduce a small amount of their FCHV-5 in Japan and the USA by the end of 2002 to test market acceptance.[33] Both co-operations are following a pioneer strategy. Some other Japanese car producers like Honda and Mazda also target a launch of their fuel cell vehicles in 2004. It seems, however, that the state of their research is not as advanced as that of DaimlerChrysler/Ford or GM/Toyota. The Volkswagen AG is expecting a production of 100 fuel cell vehicles per day in 2015. Renault and Peugeot-Citroen (PSA) aim for an initial market entry in 2010. They could be characterized as Early Followers. The state of research of Fiat could indicate a late follower strategy. Its Seicento Elettra possesses a 7 kW fuel cell with an extension range of just 100 – 140 km.

It can be summarized that the pioneer will prospectively launch its fuel cell vehicle between 2004 and 2008, whereas the early follower will probably start commercialisation between 2008 and 2015 and the late follower around 2015 or later.

3 Model structure

The basic structure of this System Dynamics Model is based on the works of Milling, especially on Milling's and Maier's model in 'Invention, Innovation and Imitation'.[34] Opposed to Milling and Maier, however, this simulation model considers marketing aspects as well as external influences like tax politics or infrastructure of complementary goods (here: fuel). Additionally, a more realistic picture of the industry's development has been drawn by differentiating between process- and product-oriented R&D efforts. Therewith, developments according to the industry development model of Abrnathy and Utterback can be simulated,[35] whereas each company strives for technological leadership in Milling's and Maier's model.

Purpose of the model is to depict the innovation process from a company's perspective. The hypothetic companies are producers of fuel cell vehicles that compete against both, the other car producers selling FCEVs and the sellers of regular cars with internal combustion engine. The other vehicle concepts like the battery-driven electro-car or the hybrid vehicle will not be considered, because their market potential seems to be of minor importance. The company can influence its competitiveness by acting in the fields of R&D, marketing and pricing. The actions taken reflect the firm's strategic approach. However, the central strategic decision is the launching date dependent on the company's technical level. Since the market is not an isolated construct but embedded in a frame of external influences, these have to be considered as well. This is of particular importance if the traded good under consideration (fuel cell vehicle) depends on a complementary good (fuel). It is easy to see how crucial a factor for the competitiveness of the fuel cell vehicle the fuel infrastructure will be. Additionally, the model reflects political and societal conditions that the car market reacts upon.

As shown in figure 1, the model can be structured in three areas that show permanent interaction: the market area, the company area and the area of external influences.

The market area is represented by the diffusion sector. Central elements of the diffusion sector are the feedback loops that describe the spread of new products under competitive conditions. Here the demand that each company can serve is determined according to its competitiveness in the market. The company area comprises the sectors R&D, finance and strategic planning.

The R&D sector describes the invention process. It is distinguished between product and process invention. In both cases, the company generates new knowledge in indirect dependence on the R&D budget. This knowledge enhances the product and process technological level of the firm and is then transferred technically into the product. The amount of technological knowledge incorporated in the product represents the technical level of the company and its product generation at the market. Due to necessary standards of mass production, not all the new knowledge, but only small improvements gained in the product invention process can be implemented in the product generation currently sold at the market. The following product generation, however, possesses all the firm's product technological knowledge by the time of its launch. This leads to an innovation that can be exactly determined by the difference of the elements of knowledge incorporated in the product generations under consideration. The process technological knowledge can be transferred to the production process continually, leading to decreasing costs per piece. Additionally, companies with a comparatively low technical level benefit from spillover effects in both, the product invention field and the field of process invention.

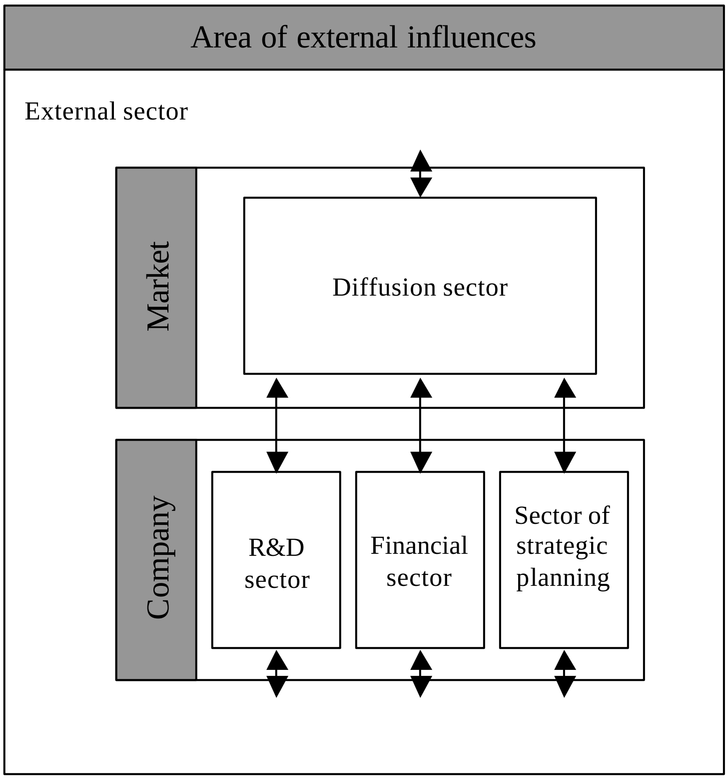

Figure 1: Model structure

The financial sector mainly generates figures to support strategic planning and to assess the company's success. Strategic planning deals with the allocation of financial resources to the R&D and the marketing budget as well as with decisions concerning pricing and launching date.

The previously described sectors are framed by the external sector, which represents external influences that the company cannot or only indirectly act upon. Examples are the development of an infrastructure of alternative fuels or tax burdens on the different car concepts, but also the extent to which the market is educated on the new technology.

3.1 Loop structure

Central elements of System Dynamics are the feedback loops.[36]

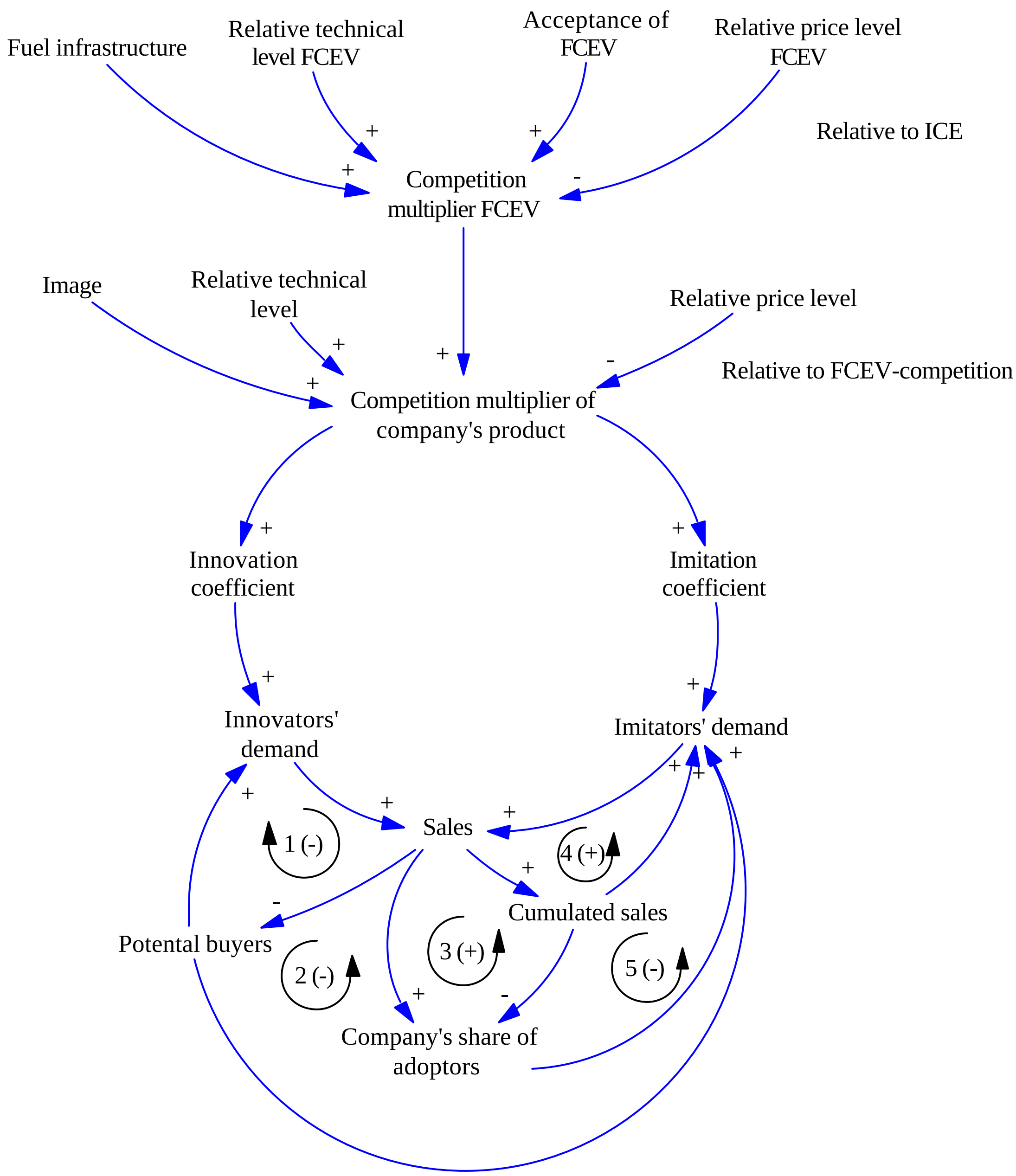

Figure 2: Causal loop diagramm of the diffusion sector

Figure 2 shows the causal loop diagram of the diffusion sector. Positive signs at the arrowhead indicate that the variable at the tail of the arrow causes a change in the same direction for the variable at the arrowhead. In case of a negative sign the variable at the arrowhead is affected to the opposite direction. The signs in the centre of the loops represent the loops' direction. Positive causal loops reinforce behavioural changes. The variables show accelerating growth or accelerating decline. Negative feedback loops tend to keep systems under control by negating or counteracting change.

The feedback loops 1 through 5 in figure 2 reflect the equations of the Bass model. Innovators' demand depends on the market potential in terms of potential buyers as well as on the innovation coefficient. With increasing innovators' demand, sales increase. This in turn leads to a decreasing number of potential buyers, involving a negative effect on sales. Feedback loop 1 is negative. The imitation effect of the Bass model is defined by the loops 2 through 5. With an enhanced share of buyers adopting the new product, the company builds up imitation pressure on the remaining potential buyers. This leads to higher sales. So do an increased imitation coefficient and an increased number of potential buyers. Here again, decreasing market potential with increasing sales restricts the growth process. For a better understanding of the model structure, the effects of the competition multipliers on demand are shown in figure 2 as well. The competition multiplier of the fuel cell vehicle reflects the competitiveness of the FCEV as compared to the substitute ICEV. It influences the competition multiplier of the company's product, which represents the attractiveness of the company's FCEV relative to its competition within the market of fuel cell vehicles. High competition multipliers show positive effects on sales by way of increasing the innovation and imitation coefficient.

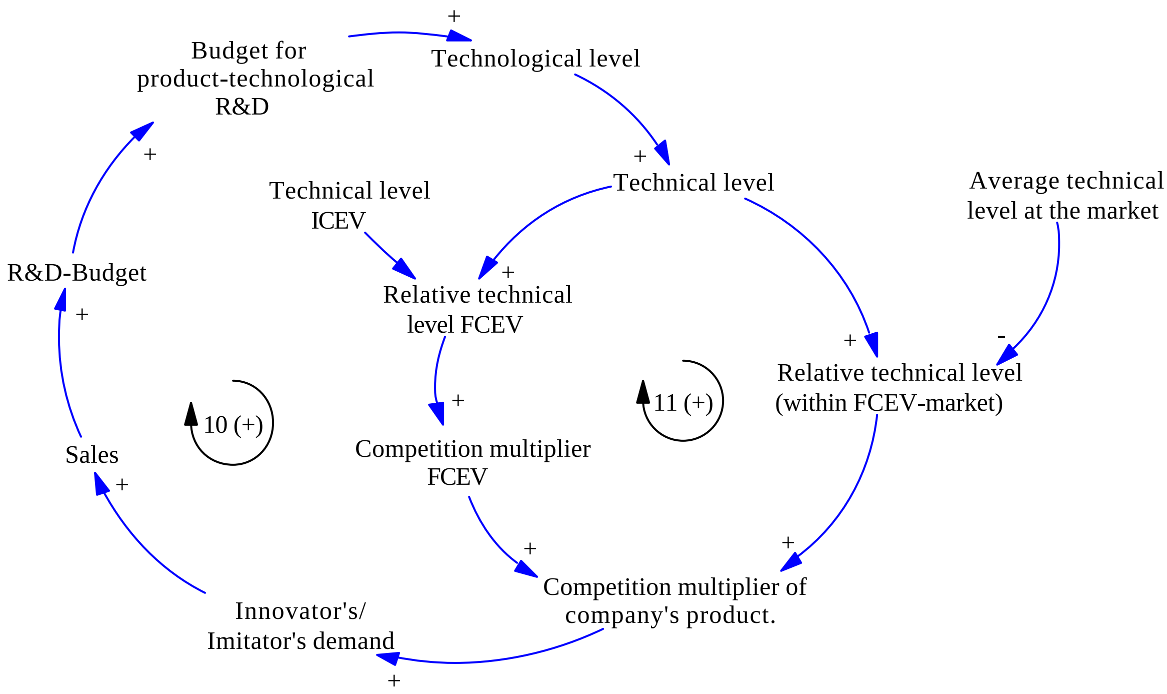

Figure 3: Technical level and sales

As shown in figure 3 the technical level of the company's FCEV affects the relative position of the company within the market for FCEVs as well as the competitiveness of the FCEV relative to the ICEV. A higher technical level, thus, leads to a higher competition multiplier of the company's product involving a higher amount of sales. The increased revenue allows for a higher R&D budget, which again influences the technical level positively. Similar feedback loops show the effects of price or marketing efforts on sales: Low price leads to high sales. High sales volumes involve high production volumes, which allow for a fast advance on the experience curve. Low costs then enable the company to set a low price. In addition, marketing efforts increase the company's image, which involves higher sales. This positively affects the height of the marketing budget, giving the company the opportunity to enlarge spending on advertising. In total the model consists of 17 feedback loops, of which 12 are of positive and 5 of negative direction.[37] This might lead to the assumption that the entire system will show accelerating growth. However, this process is limited by two factors: market potential and willingness to invest, which restricts spending in case the company accumulates a strong loss.

3.2 Diffusion sector

As stated above, the diffusion sector represents the spread of the fuel cell vehicles in the market. The diffusion process is modelled by Bass's diffusion model, which combines the pure innovative model of Fourt/Woodlock[38] and the pure imitative model of Fisher/Pry-Mansfield-Blackman.[39] Although repeat purchases have to be considered in this investigation, the Bass model was preferred to the repeat-purchase models on account of its dynamic depiction of the development of sales over time. In order to adapt the model to the problem examined, some modifications have been made. According to the Bass model, potential buyers are influenced by innovative or imitative means of marketing communication and as a consequence become adopters of a new technology. The remaining market potential is decreasing by the number of adopters. In this simulation model, the adopters become potential buyers again after the average time of usage. Moreover, it is assumed, that the maximum market potential is as high as the entire market for automobiles, since every car could be driven by a fuel cell. However, the car producers will just launch one model as fuel cell vehicle and only gradually extend fuel cell technology to the entire product line. Assumptions for the model are, that most companies initially launch a lower middle-class vehicle. With product generation 2 the middle-class and upper-middle-class segments are served as well. Finally all models of the firm's product line will be available with a fuel cell system from the introduction of the third product generation on. According to that, the variable 'market potential' increases with the launch of a new product generation by the potential customers of the additional market segments.

Furthermore, the innovation and imitation coefficients of the Bass model are modified by so-called 'competition multipliers', which reflect the competitiveness of the company's product generation.[40] There are two competition multipliers. The first indicates the competitiveness of the fuel cell vehicle in comparison to the conventional car with internal combustion engine. It calculates from the four external influence factors and, thus, represents the link to the external sector of the model. The relative average price, the relative average technical level, the density of the alternative fuel infrastructure and the acceptance by the potential customers are multiplied to the 'competition multiplier of the fuel cell vehicle'. A multiplicative connection has been chosen to reflect a logical AND, since, if one factor were zero, there would be no sales at all. The 'competition multiplier of the fuel cell vehicle' then influences the second multiplier called 'competition multiplier of the company's product'. This multiplier additionally considers the competitive position of the company's product generation within the market for fuel cell vehicles, which adds up the weighted 'relative technical level' and 'relative price level', both compared to the respective sales weighted averages in the fuel cell market, and 'relative image' of the firm, which can be enhanced by marketing efforts. Here, an addition has been preferred, to show the compensative nature of these factors in the buying process. For example, a low price could make up for a low technical level or a bad image and vice versa. This sum is then multiplied by the competition multiplier of the fuel cell, the result of which being the competition multiplier of the company's product. The calculation of the competition multipliers reflects a decision process of the potential buyer that is divided into two phases. In a first step the potential customer decides whether to buy a fuel cell vehicle or a car with internal combustion engine. In case he/she decides to buy a fuel cell vehicle, he/she is going to choose a supplier within the market for fuel cells in the next phase.

3.3 Sector of external influences

The external sector depicts external influences on the market of fuel cell vehicles. Those factors cannot be directly controlled by the car manufacturers and via the ‘competition multiplier of the fuel cell vehicle’ which constitute a measure for the attractiveness of the alternative drive concept for the customer. This model sector is divided into four subsections, each of which describing one of the four influence factors considered.

Fuel infrastructure plays a crucial part for the diffusion of fuel cell vehicles. According to the technical considerations at the beginning of this paper, assumptions are that a methanol infrastructure is going to be established first, which will later be replaced by hydrogen filling stations. The factor ‘normal yearly increase’ and the willingness to invest of the oil companies determine the number of filling stations carrying alternative fuels. The oil companies are especially interested in an investment when a high market share of fuel cell vehicles promises high sales volumes. The development of the fuel infrastructure has been modelled in an S-shaped curve, assuming exponential growth at the beginning that weakens with increasing saturation.[41] The density of the fuel infrastructure under consideration is the quotient of the amount of the alternative filling stations and the number of regular filling stations. This rate is then taken into the calculation of the ‘competition multiplier of the FCEV’.

In the model, the factor ‘acceptance of the fuel cell vehicle’ depends on the knowledge of the potential customers about the new technology as well as on the prevailing consciousness for the environment. Especially with goods that induce a high involvement buying process, the potential buyer needs to be informed about the new technology. This need for information causes education costs for the company. In the simulation model the companies are able to communicate with the customers via commercials on TV. According to data on advertising in Germany from 1998, an average 22 second spot on TV costs 2228.92€.[42] It is assumed that with one commercial, an average of 250 000 potential customers can be reached. Morgenzstern claims, that a 20 second spot is later remembered by 15% of the audience.[43] In this case 15% make up for 37,500 potential buyers. With a total market potential in Germany of 50 Mio. people,[44] this would lead to an increase of 0.075 % of informed customers. However, the share of uninformed customers reached is decreasing with an increasing spread of knowledge: the commercials are not as efficient, anymore. Additionally, it is assumed that the potential customer has to be exposed to the commercial ten times to really know the technology. The company has to spent major parts of its marketing budget for education purposes, first. If the market is educated, the company switches to commercials to enhance its image. The effects of advertising the company’s image are modelled the same way as previously described for market education. Instead of an increase in the knowledge of the technology, the firm’s image increases.

The factor ‘consciousnesses for the environment’ is influenced, on the one hand, by the perceived pollution and, on the other hand, by a so-called marketing for ecology. A marketing-for-ecology effort aims at enhancing awareness for the environment.[45] A company can decide to spend a part of its marketing budget for marketing for ecology, thereby increasing acceptance of ecological innovations like fuel cell vehicles. It has been modelled to give the companies the possibility to react on special marketing problems of ecological innovations. Most of the cases ecological innovations are more expensive and bear collective benefits rather than individual ones. For example the fuel cell vehicle avoids toxic emissions and noise pollution, however, is supposed to stand back behind the internal combustion engine vehicle in terms of power and extension range. Moreover it is assumed to be more expensive. Thus there is a need to promote the ecological advantages by a marketing-for-ecology effort.

The purchase decision of the customer is greatly influenced by technical level and pricing of the FCEV in comparison to the ICEV. The relative technical level of the fuel cell is defined as the quotient of the average amount of knowledge incorporated in the FCEVs offered at the market and an assumed number of knowledge elements of the ICEV. Presuming that a standard at the market for fuel cell vehicles can only be established if the technical level is at least as high as that of its substitutes, the amount of knowledge incorporated in the ICEV has been set equal to that of the dominant design in the FCEV market.

Similar to the relative technical level, the relative price level of the fuel cell vehicle is calculated. This variable compares the total prices of the vehicle alternatives, which comprise purchase price and the discounted running expenses over the average time of utilization. Purchase price of the FCEV is represented by the sales-weighted average price at the market. Connected to the progress on the experience curve, average price is successively sinking. Running expenses can be divided into fuel costs and tax burdens, both depending heavily on political decisions.[46]

3.4 Research and Development sector

The R&D sector reflects the company's invention processes. It is distinguished between product and process technological research efforts, which are coordinated by the allocation of the R&D budget. This differentiation enables a projection of Abernathy/Utterback's industry development model.[47] Furthermore the companies are given the possibility to pursue a low price strategy supported by process technological progress.

The invention process is modelled according to an evolutionary approach. In nature, random mutations occur in the transfer of genetic information. Via the resulting physical appearance, those are selected that fit the prevailing environmental conditions best. They build the basis for further development. By analogy, technological solutions suggested by researchers can be interpreted as mutations, of which those are selected that improve the product.[48] According to Rechenberg or Reichert, the knowledge incorporated into the product could be interpreted as a matrix consisting of knowledge elements that can take on the values 0 and 1.[49] The number of elements in the matrix represents the amount of knowledge that a basic invention like the fuel cell involves. 0 means that the knowledge element is not yet researched on to the extent that it could be transferred into the product. On the opposite, 1 means that this knowledge element has been discovered and could theoretically be incorporated into the product. According to these considerations, the R&D department tries to change 0s into 1s in the knowledge system of the product. The sum of 1s represents the technological level.

There are two driving forces involved in the research process. On the one hand, more knowledge discovered leads to an acceleration of research. On the other hand, it is getting harder to improve the product with a growing technological level. This leads to a development of the amount of discovered elements in the knowledge system showing an S-shaped curve as suggested by the technology development models. To emphasize the aspect of coincidence in the invention process and to avoid a direct dependence between money spent and inventions generated, a normal distribution has been applied to the selection process. Therewith a realistic projection has been achieved, reflecting the characteristics of the R&D process like randomness of mutation and certain observable patterns like the S-curve.

It is difficult, however, to define the number of elements of a knowledge system. This model makes the following assumptions to solve the problem. Supposing that within the cooperation between DaimlerChrysler and Ballard Power Inc. the development of fuel cell vehicles lies utterly on Ballard's side, it can be seen in Ballard's annual report that the company generated 1525 inventions from 1996 to 2000, some of which were patented, however, all have been applied for patent. In 1996, DaimlerChrysler launched its second generation of the FCEV-prototype series NECAR, which is a Mercedes V class with a hydrogen tank under its cover on top of the roof, a maximum speed of 110 km/h and an extension range of about 250 km. On November 7, 2000, NECAR 5 has been introduced to the public. It is a Mercedes A class with only one fuel cell stack producing 75 kW and a maximum speed of 175 km/h. For the first time the entire interior could be used by passengers. It is seen as an important step towards market introduction. Defining the technical level of a market-ready fuel cell vehicle at 30% discovered knowledge elements, NECAR 5 is assigned a technical level of 0.2. NECAR 2 shows significant deficits in terms of extension range, maximum speed and weight and, hence, is given a technical value of 0.1. From NECAR 2 to NECAR 5 exists a relative technical progress of 0.1. According to its annual report, Ballard generated 500 inventions in 2000.[50] Since NECAR 5 has been launched in November, assumptions are that half of the technical problem solutions were integrated into this prototype. This means that NECAR 5 contains 1275 discovered knowledge elements more than NECAR 2. A relative technological progress of 0.1 consists of 1275 inventions. This leads to a technological limit of 12,750 knowledge elements. Ballard spent 54.315 million Can$ for R&D in 2000 resulting in 500 inventions. According to the assumption that the probability to find a problem solution depends on the technological level of the company, the expectation value of mutations conducted in 2000 by Ballard would be 500/0.2 = 2500. Thus, one mutation makes up for an average of 21,726 Can$ in costs, which is about 15,404 € at an exchange rate of 0.709 € per Can$. For simplification purposes the same numbers are used in the process invention field.

Spillover effects occur, in case a company possesses a lower technological level as the technical level of the products offered at the market. The difference between the technological level available at the market and the technological level of the company modified by a transfer factor enhances the technologically less developed firm's knowledge system. The technological level of the company is increased by own research efforts and by spillover effects. The knowledge elements of the firm's knowledge system are then with an implementation time lag transferred into the product. However, due to standardization constraints, not all the new knowledge elements gained can be incorporated into the product currently offered at the market. This leads to an innovation step with the launch of the succeeding product generation. Identical to the product technological field, process technological gains also result from own research and spillover effects. However, all the new knowledge elements in this area can be continually implemented into the production process after a certain time of implementation. The process technical level can be enhanced continually leading to lower production costs by a faster forthcoming on the experience curve. The weight that is given to the different research areas is determined by the company's budget allocation. According to the industry development model of Abernathy/Utterback (op. cit.), product technological R&D efforts are dominating before a dominant design has been found. Only then process invention efforts can be taken to a greater extent.

3.5 Sector of strategic planning

The company's strategic decisions reflecting its chosen market strategy are depicted in the sector of strategic planning. The sector is divided into three parts representing the three strategic fields of action: budgeting, launching date and pricing.

3.5.1 Budgeting

The company determines the extent of marketing and R&D efforts via budget allocation. Both, the marketing budget and the R&D budget consist of a turnover-dependent and an extraordinary part. The launch of the pioneer's and the early follower's first product generation is supported by market education efforts. Since there are almost no sales at the beginning, this marketing engagement has to be financed independent from turnover. By the time the need for information on the new technology is satisfied, the company switches to a solely turnover-dependent marketing budget. The late follower is expected to save market education costs due to his late launching date. However, this firm has to fight image deficits, which force it to supplement the turnover-dependent marketing budget by extraordinary marketing expenses until the image value reaches its initial height. The marketing budget is smoothed over two years to avoid unrealistic abrupt budget cuts. The desired share of turnover for marketing purposes is set to 1.5 %.

As stated above, the R&D budget is structured similar to the marketing budget. There is a need for extraordinary R&D expenses until a market-ready technical level allows for product launch. Then the budget amounts to 4% of turnover, which is about the share big car manufacturers spent for R&D the last years, according to annual reports.[51] Again, the height of the R&D budget is smoothed over seven years to avoid influences from short-term fluctuations in sales. However, company spending is limited by a critical loss. In case losses exceed this critical amount, the company's willingness to invest will decrease successively, involving budget cuts in the R&D and marketing area.

3.5.2 Launching date

The companies introduce their fuel cell vehicles onto the market dependent on their technological level. The variable 'desired technological level' indicates at what relative technological level the companies are planning to launch each product generation. The relative technological level of a market-ready fuel cell vehicle is defined at 30% discovered knowledge elements in the knowledge system. It is assumed that the second product generation, which shows a relative technical level of 0.5, establishes a dominant design in the market. For market introduction, the following product generations require 70% and 80% of discovered knowledge elements, respectively. If the desired technical level has been reached, the market entry variable of the corresponding product generation switches to 1: the product is launched. Simultaneously, the company draws the previous product generation off the market. The only exemption is the transition from product generation 2 to product generation 3, which marks the transition from methanol to hydrogen-driven fuel cells. Since it is unrealistic that a company withdraws from the market with a successful product replacing it by a not as competitive one, the company pulls back its methanol-driven fuel cell vehicle only when the hydrogen driven product generation 3 possesses the same competitiveness in the market, which is indicated by the 'competition multiplier of the FCEV'.

3.5.3 Pricing

One of the most important marketing decisions is pricing. In this simulation model, every company can offer its product at a skimming price, a penetration price or a full cost price. Full cost price adds up production costs, marketing and R&D expenses and a mark up of 10%. According to the literature, the dynamic pricing strategies penetration pricing and skimming pricing are based on the optimum price.

In an oligopoly the optimum price is obtained from the Amoroso-Robinson Relation, as shown below.[52]

$$p^{opt} = [(\varepsilon + \rho * \varepsilon_{ij}) / (1 + \varepsilon + \rho * \varepsilon_{ij})] * K' \qquad (01)$$

with:

ε = direct price elasticity of sales of i

ε_{ij} = cross price elasticity of brand i with regard to the average price of competition p_j

ρ = reaction elasticity of the average price of competition p_j with regard to the price of brand i

K' = variable costs per piece

The direct price elasticity is assumed to be negative: sinking price leads to increasing sales. Cross price elasticity takes on the higher a numerical value the better substitutes the considered products are. FCEVs and ICEVs are almost perfect substitutes, suggesting a high cross price elasticity. Since reaction elasticity is assumed positive, the mathematical expression in brackets results to < 1. This means that the optimum price is lower than variable costs. Thus, as a basis for price calculation, the variable cost per piece is taken as a good approximate value. The penetration enetration price is derived from the optimum price plus a 'mark-up-modifier', which starts out at 20% and falls gradually with increasing market saturation. The penetration price equals the optimum price minus the 'mark-up-modifier'.[53]

3.6 Financial sector

The financial sector generates figures that serve as decision support for strategic planning and also as a basis for the assessment of the company's strategy. Profits, net present value of profits and return on investment are obtained from data on turnover, costs and interest rate. The company's costs comprise marketing and R&D expenses as well as production costs, which are affected by experience curve effects. With regard to production cost calculations, it is distinguished between the fuel cell power train and the vehicle without power train consisting of steering wheel, tires, body, seats etc. Experience curve effects only apply to the drive system, since the other parts have been produced in high quantities, thus, offering only minor cost reduction potential. Cumulative production volume and the experience exponent mainly determine progress on the experience curve. To avoid the unrealistic scenario that after years the follower's first fuel cell vehicle produced involves the same amount of cost as the pioneer's first vehicle, spillover effects have been considered. A certain amount of cumulative production volume determined by the transfer factor increases the cumulative production volume of the followers so long as they were not producing themselves. This reflects a progress in production technology that the followers benefit from. Besides cumulative production volume, the experience curve effect can be accelerated by process technological research. In the simulation model, the process technological level of the firm influences the value of the experience coefficient. Starting out at 0.32, representing an 80% experience curve, the experience coefficient can be increased up to 0.52, which leads to a 70% experience curve.[54]

3.7 Validation aspects

The validity of the system dynamics model must be shown on three levels: model structure, model parameter and model behaviour.[55] Validation of model structure and of model parameters takes place in the model-building phase. With respect to this model, most hypotheses relate to commercial facts and economic theories like the experience curve, Bass's diffusion model etc. They find empirical evidence or are of high plausibility. Similarly, the model parameters are largely based on empirical values, obtained from literature analysis.
The validation of model behaviour comprises the plausibility test, the consistency test and the forecast test. These tests are supposed to check whether the assumptions taken in the model conform to reality. Plausibility tests aim at avoidance of unequivocal unreasonable model behaviour like negative sales volumes. This can be ensured for this model within the considered simulation time frame. Via consistency tests, the model is supposed to show its ability to duplicate observed real behaviour with sufficient accuracy. With regard to the fact that the model reflects an innovation process showing several particularities, it is difficult to rely on empirical data for validation purposes. On the one hand there is no data available on serial production of fuel cells. On the other hand, most empirical investigations on product diffusion at the market can not be taken into account due to peculiarities in the diffusion process of fuel cell vehicles like dependence on an alternative fuel infrastructure or the fact of a saturated market that the fuel cell vehicle is launched to without offering extensive additional value for the individual. It can be shown, however, that this model reproduces well the commercial facts and economic theories incorporated. One of the most demanding tests to the model is the forecast test. It checks whether model behaviour matches reality with regard to future events. The verification of the forecasting abilities of the model can only take place after the forecast period. Thus this test is omitted in the scope of this investigation.[56] The model meets the essential validation requirements, but still the degree of validity is rather low.

4 Strategy implementation into the model

Each of the three fictive companies depicted in the simulation represents one of the strategies pioneer, early follower and late follower. The strategic approaches are defined by decisions on marketing and R&D expenses, pricing and launching date. The pioneer attempts to enter the market first. As soon as a marketable technical level is reached, the pioneer will launch the new product. Hence, the firm is pushing R&D with high investments. It also faces high marketing expenditures to educate the market. With regard to pricing the pioneer possesses a big scope of action due to its monopoly until the early follower's market entry. Here it is supposed that the pioneer pursues a pure skimming strategy. The early follower tries to avoid high market education costs and follows the pioneer. Since newness of the product may not be a selling point anymore, this product is initially offered with a slightly higher technical level than that of the pioneer. The early follower tries to challenge the pioneer's leading market position with a penetration price. However, the penetration price will not cover variable costs, according to the considerations in paragraph 3.4.3. Therefore, the early follower switches to full cost pricing with the launch of the second product generation to avoid financial problems. The following firms stick with the full cost price for product generations 3 and 4. Only by the time a standard is established in the market offering the possibility of fast cost reductions, the late follower launches an own fuel cell vehicle. The aim is to benefit from spillover effects and to push process technological R&D to support a low price strategy. Thus the late follower shows the lowest extraordinary R&D budget, but sticks with it until a desired process technological level is reached. This firm also enters the market with a penetration-priced FCEV to gain market share, which helps to move fast along the experience curve. The next product generations offered are full-cost-priced, due to financial considerations. The late follower's initial launch is accompanied by marketing efforts to enhance the low image.

The precise strategic parameters are as follows. The pioneer invests an extraordinary R&D budget of 80 Mio. € per year until the technological level is reached that allows for market entry. After a transition period, R&D expenses make up 4% of turnover. The early follower pursues the same R&D strategy, but spends only a yearly 60 Mio. € for extraordinary R&D effort. The late follower possesses an extraordinary R&D budget of 40 Mio. € per year and keeps it until a relative process technological level of 0.5 is achieved, then switching to a turnover dependent R&D budget. The pioneer and the early follower spend 10 Mio. € per year as extraordinary marketing expenses and drop it if the need for information on the new technology is satisfied. The late follower commits to extraordinary marketing expenses of 10 Mio. € until the assumed image deficits are compensated. At the earliest possible date the pioneer launches the next product generations. This means, according to the definitions taken, with a relative technical level of 0.3, 0.5, 0.7 and 0.8, respectively. The early follower attempts to enter the market with a slightly higher technical level at the beginning, thus launching product generations with a 0.31, 0.51, 0.71 and 0.8 share of discovered knowledge elements. Since the late follower aims at fast cost reductions through standardized production, this firm only enters the market with a product that possesses the technical level of the dominant design. It is not launching a product with a technical level corresponding to the first product generations of its competitors. The desired relative technical levels for market introduction are 0.5, 0.7, and 0.8 in this case, resp. The pricing strategies of the modelled companies have been illustrated above with the pioneer pursuing a pure skimming strategy and the competitors offering their first product generations at a penetration price and switching to a full cost price for their following product generations.

5 Scenario development

There is a great number of factors that influence the diffusion of FCEVs on the market. The most important ones have been considered in the model. These are: fuel infrastructure, cost of the fuel alternatives, knowledge of the potential customers, consciousness for the environment and tax politics. They represent the exogenous frame of the company's actions. Due to uncertainties of the external influence factors' future development, scenarios have been built. Assigning each of the five external influence factors a positive, negative and neutral direction of future development, 243 possible scenarios would result. However, the factors are not independent. For example, low price of methanol or hydrogen probably results from low taxes on it or a wide spread of alternative filling stations causing economies of scale. Exemplary three scenarios are illuminated in this investigation: the reference scenario, the scenario 'politics and ecology' and the negative scenario. The reference scenario represents the most probable development from today's perspective. Special political support of ecological innovations and favourable societal conditions are reflected in the scenario 'politics and ecology'. The negative scenario sketches a kind of worst case for the diffusion of fuel cell vehicles.

The assumptions that constitute the scenarios are depicted in table 1.

External influence factor	Model parameter		Scenario		
			Reference	Politics and ecology	Negative
Fuel infrastructure	incraltFS		0.45	0.55	0.35
Fuel cost	fcostdev	petrol	1	1	1
		MeOH, H2	1	1	+50%
Tax	vehtaxdev	petrol	1	+20%	1
		MeOH, H2	1	0	no tax exemptions
	fueltaxdev	petrol	1	+100%	1
		MeOH	1	1	Same as petrol
		H2	1	1	Half the amount of petrol
Market education	initknowpotcust		0.01	0.2	0.01
Consciousness for the environment	initecology		1	1.3	0.5
	pollution		1	+100%	-25%

Table 1: Scenarios

The 'normal' increase of the number of filling stations with methanol or hydrogen is determined by the model parameter 'incraltFS'. It has been chosen according to estimations of Grahl.[57] In the scenario 'politics and ecology', 'incraltFS' is about 25% higher due to political support, for example in Germany via the VES. However, it is clearly lower in the negative scenario. The price of petrol stays at its current level in all the scenarios during the simulation period. A scarcity of oil is not expected until 2050. And even if the oil price rose, methanol and hydrogen prices would also be affected due to conventional production.[58] In the reference scenario and the scenario 'politics and ecology', alternative fuels realize the full cost reduction potential arising from economies of scale. The conventional production process itself does not bear any cost reduction potential anymore.[59] The negative scenario assumes that those estimations were too optimistic and only 50% of the projected cost reductions can be achieved. Tax considerations are based on the German tax system. The reference scenario shows a continuation of the current system over the simulation period. The fuel cell friendly scenario 'politics and ecology' expects a gradual increase in motor vehicle tax for regular cars of 20% and a drop of all motor vehicle tax burdens for fuel cell vehicles. Additionally, fuel tax on petrol is successively doubled until 2030. In contrast, no motor-vehicle tax increase for regular cars, but a cancellation of the five-year tax exemption for fuel cell vehicles is projected in the negative scenario. Also tax on petrol stays the same over the simulation period, whereas tax burdens on the considered fuel alternatives increase for methanol to the same amount as for petrol and to half of this amount for hydrogen. This represents an increase of 100% as compared to the reference scenario. With regard to the societal factors, the scenario 'politics and ecology' assumes a much higher knowledge of the potential customers about fuel cell technology than the reference scenario and the negative scenario does. The latter estimate a share of 1 % of the potential buyers being well informed. In the scenario ‘politics and ecology’ the informed persons amount to a share of 20%. Also, a 30% higher initial consciousness for environmental concerns is stated in the scenario ‘politics and ecology’. Additionally, perceived pollution increases until 2030 by 100 %. The negative scenario assumes only half the consciousness for environmental concerns and less pollution perceived by society. The figures of the reference scenario concerning ecological issues do not influence the results of the model, because their values of 1 are neutral in the multiplicative connection calculating the acceptance value that is used to determine the competitiveness of the fuel cell vehicle.

6 Simulation results

6.1 Reference scenario

In the reference scenario, the pioneer reaches a market-ready technical level in 2007, then launching his fuel cell vehicle. The early follower enters the market in 2009 and the late follower in 2014. This corresponds to the expected real launching dates. According to the simulation results, the pioneer is able to introduce the second product generation four years after the first, already. With the launch of product generation 3 in 2017, the firm prepares for the transition from methanol to hydrogen driven fuel cell vehicles. Finally the pioneer enters the market with product generation 4 in 2027. As compared to the pioneer, the early follower seems to lose ground in the sequel of the simulation. The interval between the pioneer’s and the early follower’s launch of the first product generation being two years, it increases to three years for the second and even to six years for the third product generation. Due to growing turnover-dependent R&D expenses, the early follower catches up on the pioneer again, launching the fourth product generation in 2029, right before the end of the simulation. Only with a technical level corresponding to the second product generation, the late follower initially enters the market in 2014. The aim is to quickly move along the experience curve supported by process technological progress. As a consequence, the launch of product generation 3 is only in 2026. The late follower is not able to introduce a fourth product generation on the market within the simulation time frame.

As stated earlier, the companies take their products off the market with the launch of the succeeding product generation. An exemption is the transition from methanol to hydrogen-driven fuel cell vehicles. The methanol-driven product generation 2 will only be pulled out of the market when the hydrogen-driven product generation 3 possesses the same competitiveness, expressed by the ‘competition multiplier of the fuel cell vehicle’. In the reference scenario, this will probably be the case in 2025 as shown in figure 4.

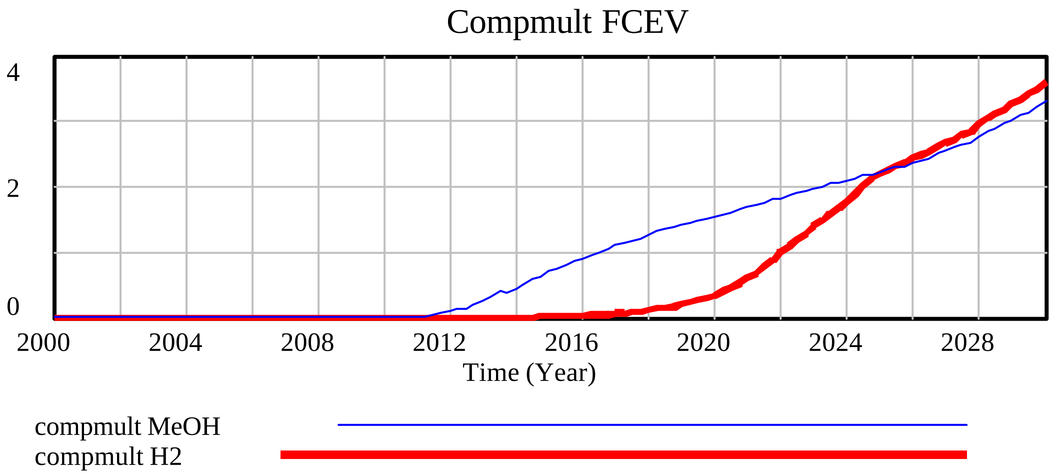

Figure 4: Competition multiplier of the fuel cell vehicle

Being first to the market, the pioneer can realize the entire innovators' demand and, thus, build up imitation pressure for succeeding products. The early follower tries to challenge the dominant position of the pioneer with penetration pricing. This firm does not succeed in taking over the leading market position, however, realizes a market share of about 45 %. In 2011, the pioneer introduces the second product generation, therewith conquering back lost market share. Additionally, the early follower changes to a full cost pricing with the launch of the second product generation in 2014. By this time the full cost price is comparatively high due to little progress on the experience curve. This causes a poor 'price multiplier', which is one determinant of the 'competition multiplier of the company's product'. This leads to further losses of market share for the early follower. In contrast, the late follower enters the market with high gains of market share. This firm is the cheapest seller, due to penetration pricing. It also benefits from a higher competitiveness of the fuel cell vehicle by the time of initial launch. Temporarily the late follower even outstrips the early follower in terms of market share. Due to the fact that the methanol-driven product generation is only taken off the market when the competitiveness of the hydrogen-driven fuel cell vehicle reaches the same height, the pioneer offers two products simultaneously from 2017 on. With a strongly increasing competition multiplier of the hydrogen-driven fuel cell from 2021 on, the pioneer gains market share again. The early follower stops the negative trend with the launch of product generation 3, therewith enhancing the product's competition multiplier. Those gains of market share go to the debit of the late follower, which is forced into a comparatively weaker position. The company is able to stabilize the market share by launching a third product generation in 2026 (see figure 5).

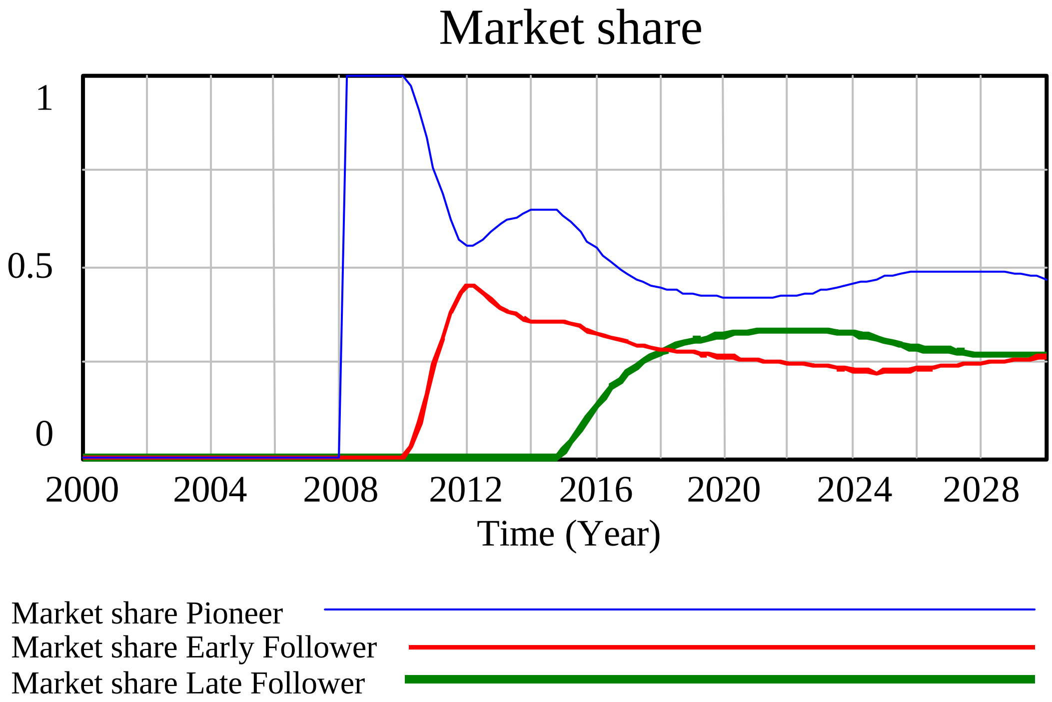

Figure 5: Market share in the reference scenario

Due to market education costs and low sales shortly after initial launch, the pioneer shows negative profits. The entrepreneur realizes positive numbers with the successively sinking extraordinary R&D expenses and after dropping the extraordinary marketing budget. The early follower must engage in market education as well, however, the firm's losses are mainly caused by its penetration pricing strategy of product generation 1. Due to full cost priced product generation 2, it succeeds in realizing the highest return on investment as well as the highest profits. The strong increase of return on investment as compared to profits is caused by less marketing and R&D expenses due to no extraordinary expenses, anymore. Around 2022, the early follower's return on investment decreases as a consequence of comparatively high pricing and therewith sinking market share. The pioneer outperforms the early follower. Further progress on the experience curve, a well-established alternative fuel infrastructure by the end of the second decade, high acceptance of fuel cell technology and a higher technical level compared to the ICEV lead to significant increases of sales volumes. Around the beginning of the third decade, the fuel cell vehicle seems to be established in the automobile market. However, the returns on investment of the pioneer and the early follower are not increasing as fast as profits. The reason is that the considerably growing turnover-dependent marketing and R&D expenses cannot be employed as effective, anymore, due to the achieved high technological level and high image values. The marketing and R&D expenses do not translate as easy into sales anymore. The more unfavourable development of the pioneer's return on investment and profits as compared to the early follower's ones at the end of the simulation, finds its reason, on the one hand, in the change from product generation 3 to 4 and, on the other hand, in a decreasing 'mark-up modifier' with increasing market saturation. Both effects do not apply to the early follower by that time. Concerning profits, the late follower pays tribute to the own penetration strategy. However, with full cost priced third product generation the company realizes first profits, too. Benefiting from spillover effects at the beginning, high process-technological R&D efforts and a high cumulative production volume gained through penetration pricing, the late follower succeeds in producing at the lowest cost. However, the difference is too small to challenge the pioneer on this basis. Within the simulation, the late entrepreneur is not able to catch up with the pioneer or early follower in terms of profitability. Additionally the late follower has to fight financial problems from 2026 on. The firm exceeds the critical loss of 2 Bill. € and as a consequence must engage in cutting marketing and R&D expenses. The situation only eases off with the first profits from the full cost priced third product generation.

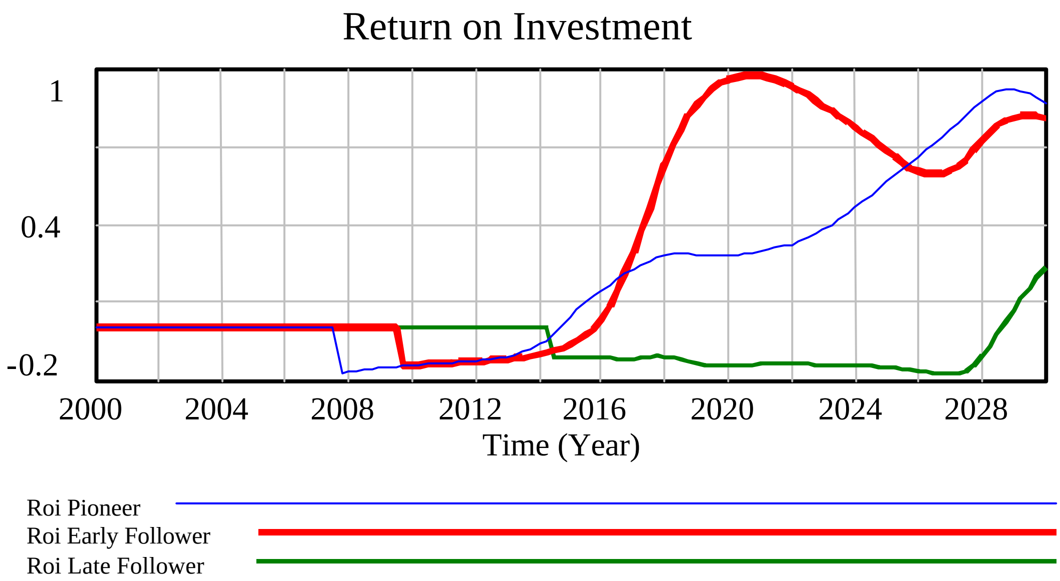

Figure 6: Return on investment in the reference scenario

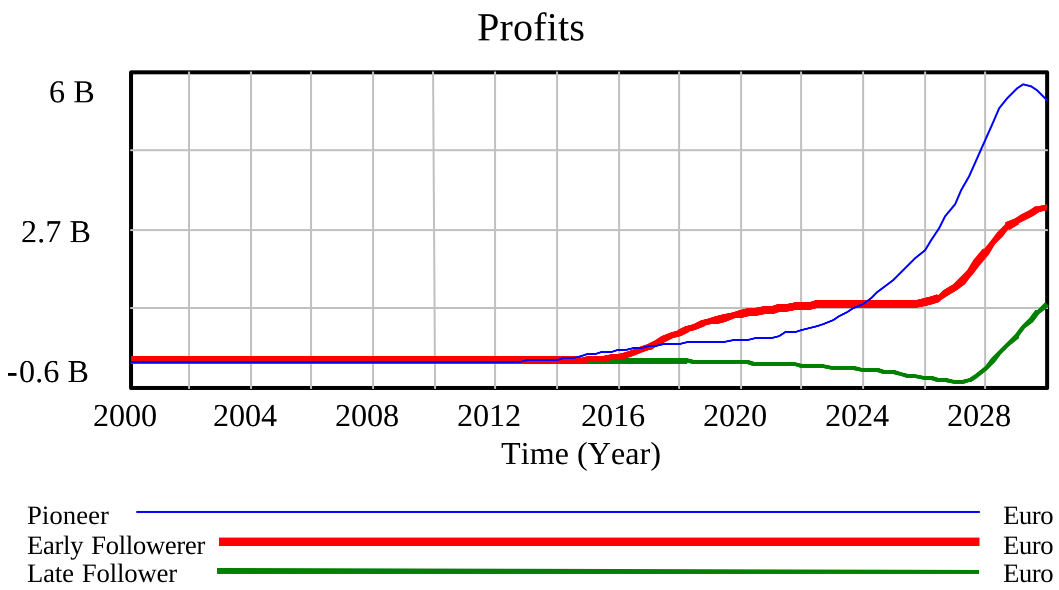

Figure 7: Profits in the reference scenario

As can be seen from figure 5, the pioneer realizes the highest profits from 2024 on. However, the early follower shows the highest net present value of profits until 2029. On the one hand, this results from the early follower's lower market education and R&D expenses at the beginning of the simulation, on the other hand, from the temporarily high profits of product generation 2. At the end of the simulation, the pioneer shows a slightly higher net present value of profits than the early follower. However, both of them realize an average return of more than the desired 8%. Within the time interval of the simulation, the late follower pays a high price for gains in the market share and cannot justify the losses with the effects resulting from the lowest production costs.

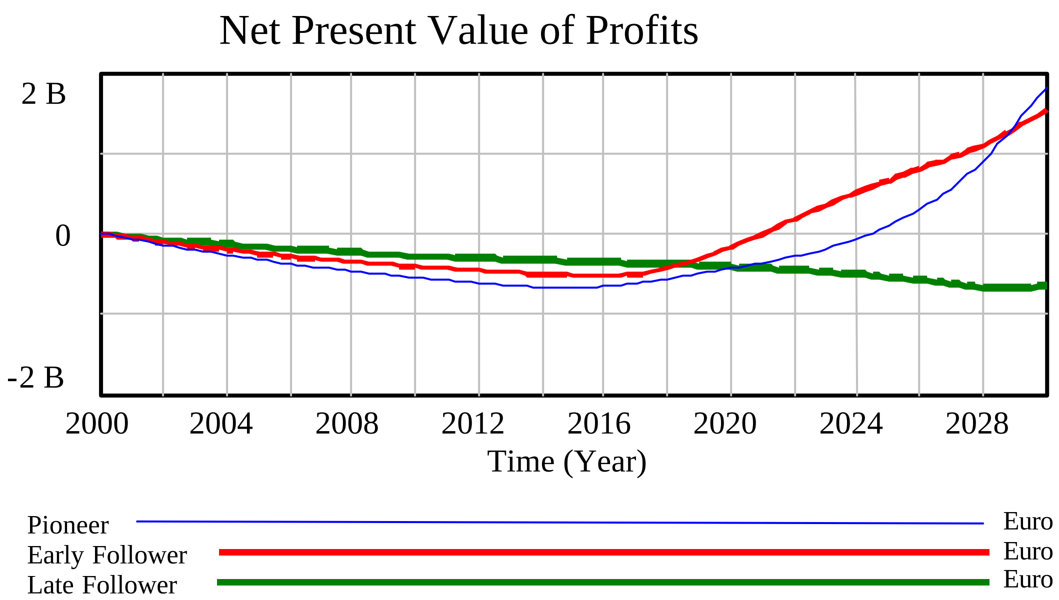

Figure 8: Net present value of profits in the reference scenario

6.2 Scenario 'politics and ecology'

The scenario 'politics and ecology' represents particularly favourable political and societal conditions for the diffusion of fuel cell vehicles. These are reflected in considerably faster growing competition multipliers of the fuel cell vehicle, leading to higher market saturation over time. Market share figures show that the pioneer is able to establish a stronger position in the market as in the reference scenario. A higher sales volume during monopoly is realized, initiating greater pressure for imitation towards the innovative brand. Additionally, the entrepreneur moves along the experience curve faster. As a consequence, the price advantage of the early follower's penetration priced product generation 1 is smaller. In the scenario 'politics and ecology', the early follower does not reach a 45% market share shortly after initial market entry. During the entire simulation market share of the early follower is slightly lower than in the reference scenario. The late follower in contrast has to suffer from considerable losses in market share. Realizing higher sales volumes with their early product generations, the early market entrants are able to strengthen their market positions, making it harder for the late follower to gain a foothold.

With regard to return on investment, the higher absolute sales volumes of the scenario 'politics and ecology' amplify the developments as observed in the reference scenario. Higher cumulative production volumes leading to sinking costs per piece and lower market education efforts induce a strong increase in profits for the pioneer. Similar developments apply to the early follower strategy. As a consequence of higher turnover–dependent R&D expenses the companies launch their hydrogen-driven product generations earlier. The pioneer introduces a fourth product generation already in 2025, instead of 2028 in the reference scenario. The early follower succeeds in cutting development time by one year for the third product generation and by two years for product generation 4. The late follower in contrast launches a third product generation only half a year earlier. However, the enhanced marketing and R&D expenses lift the companies' technical level. Due to penetration pricing of product generation 2 and increased marketing and R&D expenses, the late follower encounters stronger financial problems as it was already the case in the reference scenario. The willingness to invest decreases to almost 0. As stated earlier, the full cost pricing of product generation 3 solves the problems.

As opposed to the net present values of the reference scenario, the pioneer now clearly outperforms the early follower. Besides market share, the early follows scenario ‘politics and ecology’. The company realizes a considerably lower net present value than the pioneer, but from an absolute perspective the present value of fuel cell vehicle investment is significantly higher than in the reference scenario. For the late follower, the fuel-cell-friendly external frame turns out to be more unfavourable as the reference scenario. It has to be mentioned, however, that the late follower also realizes higher profits with product generation 3, due to the generally higher sales volumes in the market. In relation to its competitors the firm finds itself in a conceivably bad situation. It produces at lower costs than the early follower from the first quarter of 2019 on, but, in spite of high process-technological efforts, does not succeed to underbid the pioneer, which benefits from high cumulative production volume. It can be concluded that in the scenario ‘politics and ecology’ an early launch is to be preferred.

6.3 Negative scenario

A slow construction of an alternative fuel infrastructure, a reduced acceptance caused by low environmental concern in society and higher tax burdens on fuel cell vehicles cause a considerably lower competitiveness of the fuel cell vehicle in the negative scenario. As a curiosum, the competition multiplier of the hydrogen-driven fuel cell vehicle stays below that of the methanol driven alternative over the entire simulation. The reason is mainly an only slowly increasing hydrogen infrastructure. Consequently, the companies do not take their product generations 2 off the market. The negative scenario involves considerably lower market saturation as compared to the reference scenario. The simulation results in the reference scenario suggest a market share of fuel cell vehicles in the car market of about 25% by 2030, whereas political support and favourable societal conditions (scenario ‘politics and ecology’) could double this share. However, only about 6% of all cars will be fuel cell vehicles by 2030 in the negative scenario. Against the background of low competitiveness of the fuel cell vehicle, the pioneer is not able to benefit from classical first-mover advantages to the same extent as in the reference scenario. The leading market position is more vulnerable, enabling the early follower to realize a slightly higher market share as in the reference scenario. The late follower, in contrast, outperforms the early follower and temporarily even stands eye to eye with the pioneer in terms of market share.

Generally speaking, profits of the companies are lower in the negative scenario, except the late follower’s one’s: In this case the losses are not as high due to lower production costs as well as reduced turnover-dependent marketing and R&D expenses. All companies allow only lower R&D budgets, which lead to later launching dates of their product generations. The pioneer is not able to introduce the fourth product generation on the market within the simulation time frame. Neither is the early follower. Those time shifts also influence profits and return on investment. As compared to the reference scenario the developments are lower and delayed. This particularly affects the pioneer strategy, but also the early follower shows lower profits. However, the relative position towards the pioneer is strengthened.

The late follower, on the one hand, benefits from the lower sales volumes while pursuing a penetration price strategy. Additionally, this firm is the lowest cost producer from 2021 on, already. On the other hand, it does not reach the profit zone with product generation 3 within the simulation interval. Obviously, the unfavourable political and societal conditions lead to weaker losses, but also to lower profits. Due to reduced losses, the late follower does not encounter major financial problems. As compared to the reference scenario, the late follower is the only one to show a slightly higher net present value. The losses saved with product generation 2 outweigh the considerably lower profits at the end of the simulation. Absolutely speaking, however, the late follower still shows the lowest net present value at the end of the simulation. Opposed to the pioneer and the late follower, the early follower realizes a positive net present value in the negative scenario. The pioneer achieves positive cumulative profits, but does not succeed in realizing an average return of 8% on investments. As a conclusion, it can be said that the unfavourable political and societal conditions strengthen the relative market position of the late market entrants.

7 Final conclusions

In this paper, the development of the external influence factors have been estimated cautiously as far as they could not be based on secure empirical data. Thus, a slow spread of fuel cell technology in the automobile market is to be expected according to simulation results. Sales volumes of more than 100,000 FCEVs per year are realized only from 2015 on. One of the major reasons is the alternative fuel infrastructure, which will reach a density similar to the existing one in the middle of the second decade; another is the price level of the FCEV relative to the conventional ICEV that probably will not be competitive before the beginning of the upcoming decade, either.

Nevertheless, the pioneer maintains a leading position with the biggest market share over the simulation interval. Through high R&D expenditures, the entrepreneurial firm positions itself as the technological leader. The pioneer realizes image advantages and moves ahead on the experience curve during monopoly. It skims the entire innovators' demand and builds up imitation pressure for its products. Due to high investments, the firm temporarily stands back behind the early follower with regard to return on investment and net present value of profits. But still, the pioneer holds a very good position within the market for fuel cell vehicles. Independent from external influences, the firm possesses the highest market share, the highest technical level and competitive production costs. This suggests a positive business development beyond 2030. According to the simulation, the pioneer strategy shows the greatest fluctuations on net present value. Strong positive results are realized in the reference scenario and the scenario 'politics and ecology', but a slightly negative net present value of profits in the negative scenario. With the results of the reference scenario being most probable, the pioneer can expect an average profitability of more than 8% during the simulation interval.

The early follower challenges the leading position of the pioneer with a penetration pricing strategy for the first product generation. This firm achieves high gains in market share, but is not able to overtake the pioneer's leading position. With low prices, the early follower establishes high imitation pressure, which is 'consumed' with a relatively high priced product generation 2. It shows increasing profits and decreasing market share. However, turnover is hardly higher than the pioneer's, so that the early follower is not able to challenge the pioneer's leading technological position without additional R&D investments. Nevertheless, the early follower strategy proves very successful with regard to financial figures. For a long period of the simulation, this company realizes the highest profits and return on investment. It also shows a positive net present value in all scenarios. The early follower's net present value is sensitive to the external influences, too, but to a smaller extent than the pioneer's. With respect to relative market position, the future economic development of the early follower seems uncertain. The firm produces at the highest costs and most probably possesses the lowest market share. Only its technical level is clearly higher than that of the late follower. After 2030 the early follower will probably not be able to challenge the pioneer, instead it has to defend its position against the late follower.

Benefiting from the high price of the early follower's product generation 2, the late follower realizes fast gains in market share. This company launches its first product generation only after a standard has been established in the market, aiming at the use of standardization potentials in production. It does not offer a product with a technical level of the competition's first product generations. The technical level of the late follower's first launch contains an amount of knowledge elements corresponding to that of the competitors' second product generations.

Due to the late follower's losses with the penetration-priced first product generation, the firm encounters financial problems at high sales volumes such as in the scenario 'politics and ecology'. Its losses fall below the critical amount, involving cuts in the marketing and R&D budget. The situation only eases off with the introduction of the full cost priced third product generation. According to the simulation results, it is most probable that the late follower succeeds in producing at the lowest costs. However, only in case of the negative scenario, the cost advantage seems high enough to gain a competitive advantage. Most probably, the pioneer cannot be underbid to the desired extent, due to the high cumulative production volume and low cost reduction potentials at the end of the simulation.

Regarding the strategies with special emphasis on the scenarios, it can be said that special political support and enhanced societal concern for environmental issues induce higher sales volumes, leading to higher profits, altogether. The late follower constitutes an exemption: This firm has to take higher losses due to its penetration strategy. Supported by a favourable external frame, however, it realizes fast profits with the full cost priced product generation 3. In the reverse case, the profits of the companies decrease with unfavourable developments of the external influence factors. Here again the late follower is an exemption: The firm does not lose as much money with product generation 2, but is not able to move into profit with product generation 3. Relatively speaking, an early launching date is more advantageous in case of favourable external influences. In contrast, unfavourable political and societal conditions strengthen the relative positions of the later market entrants, since the classical first mover advantages cannot be realized to the full extent.

With regard to the innovation process from the ICEV to the FCEV, a hard market introduction phase for the FCEV is to be expected. This is mainly due to an alternative fuel infrastructure not yet established and strong competition of a technically mature product that the customer is used to. This fact would strengthen the relative position of the followers. On the other hand, the fuel cell power train offers high cost reduction potential, which allows the early market entrants to move along the experience curve and therewith erect market entry barriers. In spite of spillover effects, the follower has to reach the cost level of the pioneer first, which in the most unfavourable case for the follower, does not allow for extensive further reductions anymore. As stated above, an early launch implies the possibility to build up first customer contacts and establish oneself as technological leader by engaging in R&D efforts. According to the simulation results, these advantages endow the pioneer with the best competitive position in the long run: the initial investments seem to pay over time. In case the fuel cell vehicle flops, a follower strategy would be favourable, enabling the company to withdraw from the market with smaller losses.

Notes and References

[1] Government Procurement, ‘Fuel Cell Partnership Sets 2003 Vehicle Goal’, Vol. 9, Issue 5, Oct. 9th, 2001.

[2] D. Oertel, *Fuel Cell Technology: Hope for Climate Protection: Technical, Economical and Ecological Aspects of its Use in the Traffic and Energy Sector* (Brennstoffzellen-Technologie: Hoffnungsträger für den Klimaschutz: technische, ökonomische und ökologische Aspekte ihres Einsatzes in Verkehr und Energiewirtschaft), (Berlin, Erich Schmidt, 2001), p. 86.

[3] L. Jörissen & J. Garche, ‘Fuel Cell Powertrain’ (Brennstoffzellen für den Fahrzeugantrieb), in: FhG-ISI, IWW + wbk TU Karlsruhe, ZEW Manheim & ZSW Ulm (Eds), *Innovation process from the internal combustion engine towards the fuel cell* (Innovationsprozess vom Verbrennungsmotor zur Brennstoffzelle), (Karlsruhe, FhG-ISI, 2000), p. 44.

[4] D. Oertel, *op. cit.*, Ref. 2, p. 89.

[5] M. K. Grahl, *Economical Analysis of the Drive System of Passenger Cars with Polymer-Electrolyte-Fuel Cells Utilizing New Fuels* (Oekonomische Systemanalyse zum Antrieb von Personenwagen mit Polymer-Elektrolyt-Brennstoffzellen unter Verwendung neuer Kraftstoffe), (Berlin, dissertation.de, 2000), p. 16.

[6] German Ministry for Traffic and Housing, *Scientific Energy Strategy in the Traffic Sector* (Verkehrswissenschaftliche Energiestrategie), 2001.

[7] Ibid.

[8] L. Jörissen & J. Garche, *op. cit*., Ref. 3, p. 29.

[9] R. A. Lewis, ‘Methanol Fuel Cell Vehicles: Fuel and Refueling Infrastructure, Issues and Solutions’, in: L. Blomen (Eds), *Fuel Cell 2000, Proceedings of the International Conference with Exhibition, July 10.-14., 2000* (Lucern, CH, Oberrohrdorf, CH, European Fuel Cell Forum, 2000), p. 350.

[10] G. Hackenjos, ‘Fuel Infrastructure: State and Perspectives’ (Betankungsinfrastruktur, Stand und Perspektiven) in: FhG-ISI, IWW + wbk TU Karlsruhe, ZEW Manheim & ZSW Ulm (Eds), *Innovation process from the internal combustion engine towards the fuel cell* (Innovationsprozess vom Verbrennungsmotor zur Brennstoffzelle), (Karlsruhe, FhG-ISI, 2000), p. 89.

[11] T. E. Lipman, & M.A. DeLucci,, ‘Hydrogen-fuelled vehicles’, *International Journal of Vehicle Design*, 17, No.s 5/6 (Special Issue), 1996, p.562-587.

[12] D. Oertel, *op. cit.*, Ref. 2, p. 113.

[13] J. Große & M. Waidhas, ‘Progress in the Development of PEM-Fuel Cells’ (Fortschritte bei der PEM-Brennstoffzellenentwicklung), in: VDI-Reports 1378: *Battery, Fuel Cell and Hybrid Vehicles, Conference in Dresden, Germany, February 17th and 18th*, 1998, (Düsseldorf, VDI Verlag, 1998).

[14] Ibid.

[15] German Agency for Environmental Concerns (Umweltbundesamt), *Prospects for the Environment* (Chance für die Umwelt), 1999, p. 3., also available on the internet: http://www.umweltbundesamt.de/uba-info-daten/daten/brennstoffzelle.htm; see also: G. Erdmann, ‘How soon and how cheap: How economical will the fuel cell become’ (Wie bald und wie billig: Wie wirtschaftlich wird die Brennstoffzelle, *Working paper, TU Berlin*, 2000, p. 3; also available on the internet: http://www.tu-berlin.de/fbb/ifet/ensys/publicationen/download/erd_bzelle_00:pdf.

[16] G. Erdmann, *op. cit*., Ref. 15, p. 3.

[17] For production costs of the different types of reformers see: M. K. Grahl, *op. cit*., Ref. 5, p. 102.

[18] E. Schirrmeister, W. Mannsbart & F. Marscheider-Weidemann, ‘Influence Factors and Scenarios of Diffusion’ (Einflussfaktoren und Szenarien der Diffusion) in: FhG-ISI, IWW + wbk TU Karlsruhe, ZEW Manheim & ZSW Ulm (Eds.), *Innovation process from the internal combustion engine towards the fuel cell* (Innovationsprozess vom Verbrennungsmotor zur Brennstoffzelle), (Karlsruhe, FhG-ISI, 2000), p. 59.

[19] M. K. Grahl, *op. cit*., Ref. 5, Appendix II, INFRACEST, p. 12ff

[20] Compare H. Grupp, *Foundations of the Economics of Innovation*, Teldenham, Edward Elge Publishers,1998, Section 1.4.

[21] A distinction in early and late follower is suggested by: W. Beuttel, ‘Market Strategies in fast growing Markets’ (Marktstrategien in schnell wachsenden Märkten), in: N. Wieslhuber & A. Töpfer (Eds), *Handbook of Strategic Marketing*, Landsberg a. L., 1985, pp. 308-318. G. Specht & W. W. Zörgiebel, ‘Technology oriented Market Strategies’ (Technologieorientierte Wettbewerbsstrategien), *Marketing ZfB*, 7, 1985, p. 161-172.

[22] H. I. Ansoff & J. M. Steward, ‘Strategies for a Technology-based Business’, *Harvard Business Review*, 45, 1967, p. 71-83.

[23] A three divisional classification has been suggested by: W. T. Robinson & C. Fornell,, *Market Pioneering and Sustainable Market Share Advatage*, *The PIMSLETTER on Business Strategy*, 39, Strategic Planning Institute, Cambridge, MA., 1986; S. P. Schnaars, ‘When Entering Growth Markets, Are Pioneers Better Than Poachers?’, in: *Business Horizons*, March-April, 1986, p. 27-36; and K. Backhaus, *Marketing Industrial Goods* (Industriegütermarketing), Munich, Vahlen, 1990.

[24] See S. P. Schnaars, *Managing imitation strategies: how later entrants seize markets from pioneers*, New York, The Free Press, 1994.

[25] K. Backhaus, *op. cit*., Ref. 23.

[26] Ibid.

[27] For example: W. T. Robinson & C. Fornell, 'Sources of Market Pioneer Advantages in Consumer Goods Industries', *Journal of Marketing Research*, 8, 1985, p. 305-317; G. L. Urban, 'Market Share Rewards to Pioneering Brands: An Empirical Analysis and Strategic Implications', *Management Science*, 6, 1986, p. 645-659; G. S. Carpenter & K. Nakamoto, Consumer Preference Formation and Pioneer Advantage, Journal of Marketing Research, 8, 1989, p. 285-298.

[28] S. P. Schnaars, 'When Entering Growth Markets, Are Pioneers Better Than Poachers?', *Business Horizons*, March-April, 1986, p. 30.

[29] Golder, G.J., Tellis, G.J. Pioneer, Advantage: Marketing Logic or Marketing Legend? in: *Journal of Marketing Research*, 30 (1993), S. 158-170.

[30] R. Perillieux, *The Timing Factor in Strategic Technology Management: Early or Late Launch of Technical Innovations* (Der Zeitfaktor im strategischen Technologie-Management: früher oder später Einstieg bei technischen Produktinnovationen), Berlin, Erich Schmidt, 1987.

[31] DaimlerChrysler, Fuel Cell Vehicles, 2002. Also available on the internet: http://www.mercedes-benz.com/innovation/fmobil/fuelcell

[32] www.hyweb.de, www.forum-brennstoffzelle.de.

[33] Frankfurter Allgemeine Zeitung, Tuesday, 2. Juli 2002, Nr. 150, p. 16.

[34] P. Milling, & F. Maier, *Invention, Innovation and Imitation*, (Berlin, Duncker & Humblot, 1996).

[35] W.J. Abernathy & J.H. Utterback, ‚Paterns of Industrial Innovation', *Technology Review*, 80 (7), 1978, p. 40-47

[36] J. W. Forrester, *Principles of systems*, (Cambridge, MA, Wright-Allen, 1972).

[37] All feedback-loops of the model can be found in: M. Schneider, *An Explorative Study on the Market Introduction of Fuel Cell Vehicles* (Explorative Studie zur Markteinführung von Brennstoffzellenfahrzeugen), (Karlsruhe: IWW, 2002).

[38] L.A. Fourt & J.W. Woodlock, 'Early Prediction of Market Success for New Grocery Products', *Journal of Marketing*, 24, 1960, p. 34-38

[39] E. Mansfield, 'Technical Change and the role of Imitation', *Econometrica*, 29, 1961, p. 741-765, see also: G. L. Lilien & P. Kotler, *Marketing Decision Making: A Model Building Approach*, (New York: Harper & Row), p.706 f.; F. M. Bass, 'A New Growth Model for Consumer Durables', *Management Science*, 15, 1969, p. 215-227.

[40] P. Milling, & F. Maier, *op. cit.*, Ref. 34.

[41] The factor determining exponential growth has been chosen according to the forecasts of Grahl, expecting 1300 methanol filling stations in 2010.His estimations also suggest an initial value of 18 filling stations at the beginning of the simulation being the year 2000. M. K. Grahl, *op. cit.*, Ref. 5, Appendix II, INFRACEST, p. 13.

[42] German Advertising Association (Zentralverband der deutschen Werbewirtschaft), *Advertising* (Werbung), (Bonn, Zentralverband der deutschen Werbewirtschaft, 1999), p. 261 ff.

[43] H. Steffenhagen, *Impacts of Advertising, Concepts – Explanations – Findings* (Wirkungen der Werbung, Konzepte – Erklärungen – Befunde), (Aachen, Verlag der Augustinus Buchhandlung, 1996), p. 157, with reference to Morgenzstern.

[44] W. Diez expects the saturation point of the automobile market in Germany at 50 Mio. cars. See W. Diez, *Automobile-Marketing*, (Landsberg a. L., Verlag Moderne Industrie, 2001); Similarly, in a traffic forecast of the German Ministry for Traffic and Housing, all considered scenarios suppose, that 49.8 Mio. automobiles will be on German streets by 2015. German Aerospace Center (DLR), Fuel Consumption 2002 (Flottenverbrauch 2002), not yet published.

[45] H. Meffert, *Marketing*, 9th Ed., (Wiesbaden, Gabler, 2000), p. 1297.

[46] In this simulation model the actual German tax system has been implemented. The average time of utilization is 12 years according to the Association of the German Automotive Industry, *Annual Report 2001*. Technical data concerning fuel consumption and average driving distance per year have been taken from the estimations of M. K. Grahl, *op. cit.*, Ref. 5.

[47] W. J. Abernathy & J. H. Utterback, *op. cit*., Ref. 35.

[48] J. Ziman, 'Evolutionary Models for Technological Change', in: J. Ziman (Ed), *Technological Innovation as an Evolutionary Process*, (Cambridge, UK, Cambridge University Press, 2000), p. 15.

[49] L. Reichert, *Evolution and Innovation, Prolegomenon of an Interdisciplinary Theory of Business Innovations* (Evolution und Innovation: Prolegomenon einer interdisziplinären Theorie betriebswirtschaftlicher Innovationen), (Berlin, Duncker & Humblot, 1994), p. 250ff.; I. Rechenberg, *Evolution Strategy* (Evolutionsstrategie), (Stuttgart, Friedrich Frommann, 1973), p. 78 ff.

[50] Ballard Power Inc., *Annual Report 2000*, (Burnaby, Canada, Ballard Power Inc., 2001), p 31.

[51] See V. Trommsdorf, *Case Studies of Innovation Marketing* (Fallstudien zum Innovationsmarketing), Munich, Vahlen, 1995, p. 40; Volkswagen AG, *Annual Report 2001*, (Wolfsburg, Volkswagen AG, 2002); BMW Group, *Annual Report 2001*, (Munich, BMW Group, 2002).

[52] F. M. Bass, *The Relationship between Diffusion Rates, Experience Curves and Demand Elasticities for Consumer Durable Technological Innovations*, Paper no. 660, (West Lafayette, Ind., Institute for Research in the Behavioral, Economic and Management Sciences, Kramert Graduate School of Management, Purdue University, 1978).

[53] P. Milling, & F. Maier, *op. cit.*, Ref. 34, p. 165.

[54] For the program listing of the simulation model see M. Schneider, *op. cit.*, Ref. 37.

[55] P. Milling, Technical Progress in the Production Process (Der technische Fortschritt beim Produktionsprozess), (Wiesbaden, Gabler, 1974), p. 208.

[56] Milling and Maier also omit the forecast test for their model in P. Milling, & F. Maier, *op. cit.*, Ref. 34.

[57] M. K. Grahl, *op. cit.*, Ref. 5, Appendix II, INFRACEST, p. 13.

[58] See the technical considerations at the beginning of this paper.

[59] See T. E. Lipman, & M.A. DeLucci, *op. cit*., Ref. 11, p. 563.

Back to the Top