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# Time strategies in environmental innovation policy – the case of the mobile fuel cell and hydrogen infrastructure

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**Abstract:**

Although fundamental innovations can make especially important contributions to the environmental soundness of economic progress, they are often impeded by path dependency and lock-in on the part of established technologies. Because the intensity of the latter effect changes in time, it is possible to identify and strategically use *windows of opportunity* – periods in which a successful transition is greatly facilitated.

In the case of the mobile fuel cell, economies of scale, learning and network effects are among the most important techno-economic determinants of such a window. Other more political determinants are political guidance and supra-national agreements. All effects were combined to form a time strategy that allows innovation policy to effectively push the new technology at the lowest possible cost for the economy.

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# 1 Introduction

Political intervention in the development of innovative systems is not a rare phenomenon. It could even be considered the norm in the case of innovations related to environmental protection since, by their very nature, these technologies only allow for a limited internalisation of their benefits by the innovator and therefore need at least temporary support. However, there is frequent complaint that such interventions take place at the wrong time, used inappropriate instruments, and the time horizon employed was inadequate (Klemmer et al. 1999).

One cause of such inadequacy is due to the risk that a technology originally chosen for its environmental advantageousness may later turn out to cause environmental damage on its own. Due to the uncertainty associated with any kind of innovation process, this failure is fundamentally unavoidable. The only way to circumvent the corresponding adverse consequences consists in keeping the technological development flexible such that a new technology can substitute for an existing technology when ever necessary. Sartorius (2006) calls this adaptiveness ‘second-order’ sustainability since it is the necessary condition for transitions towards more sustainable technologies (i.e. first-order sustainability) being achieved at a sufficiently high rate.

This leads to the second kind of problem related to technological change: the difficulty to leave an existing technology path that happens to be predetermined and stabilised by path dependency and lock-in (David 1985). In contrast to uncertainty, the causes of path dependency and lock-in can well be specified and most of them are deterministic by their nature. In addition, they are subject to change in time such that it should be possible to identify and even predict so-called ‘windows of opportunity’ in which the resistance to technological change is lowest and thus political intervention can achieve the optimum effect with regard to cost and benefit (Zundel et al. 2005a). In some cases, the strategic use of those windows may even go so far as to influence their appearance directly – by bringing about the right conditions for an innovative technology path to diffuse or by forcing a technology into existence in the first place. In any case, knowing about the exact nature and intensity of the resistance to change may enable the identification of those measures by means of which the lock-in can be overcome, and the window used, most effectively.

In order to demonstrate the working and operability of the latter approach, the fuel cell as a component of automobile propulsion systems appears to be a very promising case because it is characterised by both significant environmental effects on a global level and pronounced lock-out with respect to the existing technology. The latter point comes to bear especially in the combination of the mobile fuel cell with a hydrogen infrastructure which, depending on the respective political standpoint, is praised for its resource-preserving low specific energy consumption, its climate-protecting lack of greenhouse gas emissions or its abatement of the emission of pollutants that affect health and environment on a local level. Due to its potentially high costs, such an alternative fuel infrastructure can strongly affect the demand for fuel cell vehicles, leading to successful commercialisation of the automobile fuel cell in the best case and to a complete failure in the worst case. Under these circumstances, the development of a time strategy can be decisive because it may represent the only way to keep the installation effort low enough to make the simultaneous implementation of two radically new, interacting technologies – fuel cell and hydrogen – appear economically reasonable and affordable.

In order to develop a time strategy for the effective implementation of the automobile fuel cell, this paper proceeds as follows. After elucidating the theory behind technology stabilisation ('lock-in') and windows of opportunity (in section 2), a set of determinants of such windows (and indicators for their analysis) is presented (in section 3). Before this set is eventually used for the thorough analysis of the fuel cell technology and a complementary hydrogen infrastructure (in section 5), methodological aspects of case study selection and data collection are presented in section 4. Based on the results from section 5, a time strategy for a successful innovation policy with regard to fuel cell-driven cars in a hydrogen infrastructure is developed in section 6. Finally, section 7 concludes.

## 2 Radical innovations, lock-in and ‘windows of opportunity’

According to Dosi (1982, 1988), technological progress typically proceeds in either one of two different ways. The majority of innovations are brought about by the systematic or accidental change of a small number of parameters *within* a given technological *paradigm*, that is, within a specific technical ‘pattern’ for the solution of a given techno-economic problem that is usually based on a narrow set of scientific principles and, thus, on a small number of basic innovations (Dosi 1988: 224). Such change *along* a technological *trajectory* is *gradual* and, although its outcome is not predictable in the strict sense, the corresponding rate of progress closely correlates (in the short run) with the invested R&D effort. It is essentially this relation to which the New Growth Theory refers when assuming that investment into human capital leads to economic growth going beyond what is possible by the mere variation of capital and labour inputs in traditional production theory. Although this kind of progress is essential for the possibility to exploit economies of scale and learning effects, it cannot explain progress in the long run as the marginal return on investment into human capital diminishes within any single paradigm and so do the incentives for entrepreneurs to invest in the first place.

This dilemma is resolved by the second kind of technological progress: the *transition between* different paradigms. Starting point for such a transition is a new basic, that is, a *radical* innovation that allows a given problem to be solved in a (economically) more efficient way, or the emergence of a new demand that can effectively be satisfied only within a new paradigm. The latter point is particularly relevant for environmental or sustainability problems which can often be solved in a new technological paradigm more easily (i.e. less costly) than within the established paradigm in which they arose in the first place. Contrary to gradual innovations, radical innovations also allow for the realisation of scale economies and learning effects that are much larger at the beginning of the trajectory than at its end. However, as this offers an attractive prospect for radical innovations in the long run, it is this (and other) factors that give rise to a barrier to market entry in the short run. For *realised* economies of scale and learning effects (like all other kinds of increasing returns to adoption) constitute significant competitive advantages for the established technology which lead to a lack of competitiveness for the new technology, if they are not offset by a genuine advantage of at least the same size. David (1985) calls this lack of contestability of the established technology by even superior competitors a ‘*lock-in*’ and considers it as the major reason why decisive aspects of many technologies can be influenced at the very beginning of their trajectories but not later when they become established. At the same time, this severely restricts the possibility to change from any given trajectory to any other – a phenomenon for which he coined the term ‘*path dependency*’.

The way in which the rigidity of a technological paradigm is discussed by David (1985) and modelled by Arthur (1988) could imply that such states of stability are omnipresent and, once they turn up, tend to persist for prolonged periods of time. Not surprisingly, many economists (e.g. Liebowitz and Margolis 1994) are convinced that the latter position grossly overstates the relevance of (in this case) network externalities, as this would allow them to become the cause of almost ubiquitous market failure. In the latter debate, an intermediate position is adopted by Witt (1997) who, while principally acknowledging the relevance of network effects, limits their general importance for the function of the market to certain limited periods of time. So, periods of stability tend to alternate with periods of instability where new networks can be formed. Since in the latter case, the direction of technological progress is flexible, the corresponding periods are referred to as ‘windows of opportunity’ (David 1987, Erdmann 1993, Witt 1997). Disregarding these windows can severely hamper, if not completely inhibit, many useful innovations. And even when, in the pursuit of sustainability, a new (sustainable) technology is to be pushed successfully by governmental regulation with no regard at the specific circumstances, the difference between stable and unstable phases can be worth a lot of money.

In order to minimise not the least the financial effort of such an innovation policy towards sustainability, it makes perfect sense to analyse the relation between the innovative technology and its conventional counterpart with regard to the possible existence and causes of windows of opportunity and to develop a *time strategy* in which the combined effects that could amount to a barrier to entry for the new technology are screened over time and action is focused on times when the combined required effort is lowest. In view of this, it will be the main objective of the following section to identify the most important determinants of windows of opportunity and accordingly derive a set of indicators that allow political and other decision makers to make a well-founded judgement as to whether and when a window of opportunity exists.

# 3 Determinants of windows of opportunity

Although, in section 2, windows of opportunity were mainly discussed from the economic perspective, their existence is not limited to the *techno-economic* sphere. Due to the fact that many sustainable or environmentally sound technologies fail to take advantage of their reduced cost externalisation, the government and its regulatory activities typically play a crucial role in overcoming initial or persistent barriers to competitiveness in the relevant markets. If, in this context, the technological transition could only be brought about after a major change in the *political system*, then, in analogy to the techno-economic window, the period of instability facilitating this change is now called a political 'window of opportunity'.[1]

Particularly in the case of environmental innovations with their short-run costs often exceeding their short-run benefits, a government or policy makers in general typically respond to promoting forces from other parts of the society rather than act out of their own initiative. With regard to the fact that such forces are often due to major changes in public attitude or perception, it appears to be justified to additionally include a *socio-cultural* window of opportunity in our considerations.[2]

In the following, a variety of determinants of windows of opportunity from all three, the techno-economic, the political and socio-cultural sphere is presented. Their selections occurred on the basis of *a priori* theoretical plausibility considerations and *ex post* after the screening of relevant case studies (see Sartorius and Zundel 2005). Due to their large number, it is not possible to present them here at length; for a more detailed discussion, the reader is therefore referred to Zundel et al. (2005).

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1 If, by contrast, a change in the political system was not necessary because it was ready to support the transition towards the more sustainable technology from the beginning, the system is called 'open' (without showing a window) (cf. Zundel et al. 2005b).

2 With his distinction between the problem, politics, and policy streams, Kingdon (1995) employs a three-fold distinction of social sub-systems similar to the one used in this paper. However, his perspective differs strongly with regard to the role of the policy maker. While in this paper, windows are considered as a structural condition that needs to be taken into account, but can be influenced only to a limited extent, Kingdon adopts a strategic-actor approach in which policy makers can pursue certain objectives through the synchronisation of the corresponding streams. Although it would be a long-term goal to include the strategic actor also in our approach, it is the purpose of this paper to identify and render operable the structural conditions in the first place.

## 3.1 Techno-economic determinants

Three of the most prominent factors potentially stabilising an established technology were already mentioned in preceding parts of this paper. *Economies of scale* and *learning by doing* refer to the advantage manufacturers can draw from specialisation, either by producing large numbers of the same good or by accumulating know-how in the course of the production process. By contrast, *network effects* refer to the use of a good, notably positive externalities exerted by every additional user of the same good (e.g. tele-communication or operating systems of computers). Another stabilising factor are *economies of scope*, that is, the synergy effects resulting from the joint production of different goods (e.g. in the chemical industry). *Sunk cost* can also stabilise a given technology in a hardly contestable market where the willingness to invest into a new technology is low as long as the old technology is not depreciated. *Market structure* influences the potential of new technologies quite generally as monopolistic and oligopolistic supplier markets tend to invest more into the maintenance of the existing market barriers than in innovative activities. Whether or not an entrepreneur is willing to invest into a new (more sustainable) production or product technology will finally depend on the innovation rent he can reasonably expect to realise, that is, on the new technology's *potential and risk*. In this context, it is often quite advantageous for a new technology, if it can draw advantage from *extra-demand* (e.g. in pioneer or *niche markets*) that cannot be met by the established technology. In actual cases, not all techno-economic determinants will apply jointly, but none of these factors relies on another one to become effective. So, there mode of aggregation is *additive*.

## 3.2 Socio-cultural determinants

The socio-cultural system essentially distinguishes two main window determinants. Those leading to the *discovery* of the environmental or sustainability problem (and its potential solution) in the first place and those translating this discovery (or a major accident or disaster) into *public concern* and a willingness to accept possible solutions even though they may cause substantial costs or require significant changes in the accustomed lifestyle. With regard to their joint effects, these factors depend on each other for being effective; their combined effect is yielded by *multiplying* the constituents' effects.

## 3.3 Political determinants

In the political system, two kinds of determinants are distinguished. The first group comprises *structural* features of a political system such as *institutional background*, *interest groups* (or, in a wider sense, *coalitions of actors*), *election cycles*, *legislative majorities* and *knowledge asymmetries*. The second group contains *procedural* aspects such as the potential for *legislative initiatives*, the relation between laws that have to pass legislation and ordinances enacted by the administration, *resubmission* and *reassessment cycles*, *corporate structures*, *participation* and integration into *supranational structures*. While structural and procedural factors in general appear to complement each other in a multiplicative way, the specific structural (or procedural) factors tend to work in parallel. Table 1 summarises the determinants of windows of opportunity in all three systems together with the ways in which these determinants may be assessed empirically.

Table 1: Factors determining the stability or instability in each of the three subsystems and the indicators used for their operationalisation

| | Effect | Indicators | Operationalisation |
|---|---|---|---|
| Techno-economic subsystem | Economies of scale | | Cost (or price) development as a function of actual output |
| | Sunk costs | Average capitalisation of industry | Statistical data |
| | | Identification of investment cycles | Recurrent phase-shifted cycling of prices and investment |
| | | Political regulation | Cost of retro-fitting after regulation, delayed investment due to uncertainty of measures being taken |
| | Economies of scope | Pattern of interactions between production lines | Number and relevance of interactions between the old (new) technology and the entire production network |
| | Learning by doing | | Cost (or price) development as a function of cumulative output |
| | Network externalities | Direct competition with (an)other network(s) | Market share(s) of the competitor(s), availability of gateway technologies |
| | | Compatibility with complementary networks or infrastructure: | |
| | | Existence of public standards | Which requirements are met? |
| | | Availability of an adapter | Cost of the adapter, legal admission possible, payable royalties |
| | Market structure | Market concentration as indicator for competition | Market share of the biggest firm(s), Herfindahl index, legal regulations |

| | Effect | Indicators | Operationalisation |
|---|---|---|---|
| | Potential / risk | Risk ↔ availability of capital | Marginal interest rate, capital share of venture capitalists |
| | | Problem solving capacity ↔ realisation of innovation rent | Technical properties (benchmarks), associated costs |
| | Extra-demand | Readiness to pay for extra-functions | Market research |
| | | Existence of natural niche markets | Higher prices, non-applicability of the established technology |
| | | Creation of artificial niche markets by means of regulation | (Eco-)taxes, tradable certificates, cost of retro-fitting the old technology |
| Socio-cultural subsystem | Scientific confirmation of threat to sustainability | Relevant publications in scientific literature, contributions to conferences | Number of relevant articles (keyword search) in journals etc.; identification of seminal articles and quotation circles |
| Socio-cultural subsystem | | Independence of research | Sources and quantity of research support |
| Socio-cultural subsystem | Public concern about lack of sustainability | Relevant articles in newspapers, reports in broadcast, | Number of articles or reports over time |
| Socio-cultural subsystem | Public acceptance of possible solutions | Formation of major protest campaigns | Number and size of campaigns |
| Political subsystem | Institutional integration | Subsidies | Financial support, tax breaks |
| Political subsystem | | Protection | Duties, other barriers to trade |
| Political subsystem | | Norms and standards | Specificity of specification |
| Political subsystem | Interest groups | Resources under control (power) | Number and economic importance of represented firms/sector |
| Political subsystem | | Structure; homogeneity | Market shares, concentration index |
| Political subsystem | | Influence; earlier success | (qualitative) |
| Political subsystem | Asymmetry of knowledge | Influence of industry in hearings | (qualitative) |
| Political subsystem | | Number of industry-independent research institutions/ projects | Number, financial support, number and size of commissioned projects |
| Political subsystem | Legislative majorities | Stability of majorities | Size of majority, stability of constituting coalition (number and relation of parties) |
| Political subsystem | Election cycle | Distance to next election | *Ditto.* |
| Political subsystem | Singular constraints | Political scandals | Deception by possible interest holders |
| Political subsystem | | Catastrophes | Accidents, unexpected discoveries |
| Political subsystem | Decision-making procedures | Probability of legislative initiatives | Number and relevance of potential initiators, number of cases |
| Political subsystem | | Legislative vs. administrative regulation | Number of laws referring to ordinances, actual number of ordinances |

| Effect | Indicators | Operationalisation |
|---|---|---|
| | Reassessment and resubmission cycles | Deadlines, frequency, possible consequences |
| | Corporate structure | Number, size, and frequency of political involvement of corporate organisations |
| | Participation | Frequency and extent of incorporation of political “outsiders” (e.g. NGOs) into the decision process |
| | Supranational structures | Share of regulation that is *not* subject to national legislation |

# 4 Selection of case study and data collection

It is the main objective of this paper to demonstrate the relevance of time windows and, by means of them, design a time strategy that could increase the effectiveness of governmental support in bringing about a sustainability-oriented transition from existing to forthcoming technological trajectories. The first part of this research agenda is not entirely new: windows of opportunity were postulated repeatedly (David 1987, Erdmann 1993, Witt 1997) and their existence for a variety of technological transitions was demonstrated by Sartorius and Zundel (2005). However, the latter analyses were retrospective and there was hardly an indication that the identified time windows were known beforehand – all the less that they were used strategically to facilitate a technological transition. In this paper, the window of opportunity concept will be applied to an *ex ante* analysis of which the results will be used to develop a political time strategy for the efficient transition to a more sustainable technological trajectory in the future. From this perspective, the development of the fuel cell (FC) in mobile application is a case in point for this study as it will take a couple of years for it to commercialise and there is essentially no way to derive the FC-based automobile propulsion system gradually from the well-established internal combustion engine (ICE). So, the transition towards FC-based transportation would indeed represent a change between technological paradigms – a precondition for the appearance of windows of opportunity.

Due to the economic and ecological relevance of the transportation sector, the fuel cell additionally has the *potential* to contribute in a significant way to the solution of major sustainability problems. Being an electrochemical device that converts the chemical energy of a fuel directly to electricity, the FC (in combination with an electric engine) not only works more efficient than an ICE the efficiency of which is thermodynamically limited; due to its low operating temperature, the FC also causes much lower levels of pollution.[3] Although it depends on the source and conditions of fuel supply whether the FC can bring to bear its efficiency advantage with regard to climate protection and fuel economy on a well-to-wheel basis (compare e.g. LBSt 2002 and MIT 2000), its lesser local pollution with respect to NOx, VOCs and particulate matter is undisputed. Especially in combination with hydrogen as a fuel, the FC

[3] This is true for the *polymer electrolyte membrane* (PEM) fuel cell which is the only type of fuel cell actually employed in automobile applications because it combines high specific power output with short start-up times and a high dynamics.

essentially emits water, which is one reason for hydrogen being appreciated as a particularly clean fuel.

Beyond its ‘clean’ image, further arguments for selecting hydrogen as a fuel for the fuel cell in this study are recent strong political commitments in favour of hydrogen in the USA and the EU and its higher degree of feasibility in technical terms. The former is due to the fact that hydrogen is a secondary energy source that can efficiently be produced from a wide variety of primary sources (including all fossil, renewable and nuclear) and is transported aboard of vehicles more easily than electric power. The latter refers to the problem that the technology needed to convert gasoline into a FC fuel is still in its infancy and adds significantly to the already high complexity and costs of the FC itself.

Finally, there is another, more practical reason for investigating the fuel cell: the fundamental and long-term character of this innovation renders public research institutes and public-private partnerships major drivers of progress in this field. As a consequence, a host of relevant information is freely available from reports, research publications, conference proceedings and various sites in the Internet. Additionally, in-depth interviews were carried out with competent partners from the automobile industry and potential infrastructure providers as an additional source of information, but more so to seek confirmation of the known facts and resolve apparent contradictions.

At this point, it also needs to be emphasised what the selection of the fuel cell and its complementary infrastructure is *not* to imply. The fact that the commercialisation of the fuel cell is not expected to take place within the current decade indicates that the technology is associated with high uncertainties in economic as well as ecological terms. So, this study is not to be seen as an argument for the fuel cell representing the *decisive* component of a superior automotive propulsion system or hydrogen representing the *best* fuel. Instead, it is the purpose of this paper to use the combination of fuel cell and hydrogen infrastructure as a relevant instance of a fundamentally new and promising technology to demonstrate the usefulness and feasibility of time-strategic thinking.

# 5 Causes of windows of opportunity for the mobile fuel cell and a hydrogen infrastructure

After choosing (in section 4) hydrogen as the fuel of choice for operating fuel cell vehicles (FCV), the development of a time strategy must take into account that the transition from gasoline-fuelled ICE vehicles to hydrogen-fuelled FCVs actually involves simultaneous transitions with respect to two ‘technologies’: the propulsion system *and* the fuel infrastructure. Due to the economic relevance of the corresponding industries – the oil industry as the actual and probably future fuel supplier and the automobile industry as foreseen manufacturer of FCVs – it is therefore even more important that the government initiates and further supports this development with the most suitable instruments and with a time strategy that keeps the costs for the concerned industries and the burden for the entire economy as low as possible. In order to develop such a time strategy, the determinants of windows of opportunity from section 3 will be used in the following to identify critical periods of time for both technologies separately, but also for their joint implementation.

## 5.1 Techno-economic determinants

**Economies of scale and learning by doing** are of extreme importance in the automobile industry where the output of a single plant typically exceeds 100,000 units per year and more than one century was needed to reach the present state of technological perfection. By contrast, the current state in FCV development is characterised by prototypes or pilot projects with small-scale (i.e. tens of vehicles) pre-series. Accordingly, cost estimates for the fuel cell propulsion unit, if revealed by the manufacturers at all, are currently around €10,000 per kilowatt of power output – a value that has to be compared with about €50 per kilowatt for a Diesel ICE car with automatic transmission which, in terms of usage, resembles the FCV and will probably compete with it most closely. As shown by ADL (2000), a bit more than half of the necessary cost digression by a factor of about 200 (i.e. specific costs of about €300 per kW) can be achieved by scaling up the production to 500,000 units per year. According to our interviewees from automobile industry, however, a major additional contribution is expected to come from further technical progress, a better choice of the materials used and the growing experience with their manipulation. Gathering this kind of experience is all the more important as the relative demand for both, fuel cell and ICE cars, will depend on their respective operability and reliability at least as much as on their performance and price. Apart from the related resource needs, all this learning will take time. Accordingly, the time schedule for commercialisation of the leading FCV developers (e.g. DaimlerChrysler or General Motors) typically extends over more than one decade and comprises four phases (see Panik 2002): (1) demonstration of feasibility, (2) market preparation and demonstration of 'fit[ness] for daily use', (3) 'ramp up' and (4) the begin of large-scale production expected to take place not before the beginning of the next decade.[4] Especially the later phases are subject to substantial uncertainty such that, so far, it is not even sure that phase 4 will take place at all. While the development entered phase 2 at the end of the year 2002 with a few tens of 'close-to-series' FCVs, 'ramp up' stands for the production and use of hundreds or thousands of FCVs under series-like conditions in the later part of this decade. A more exact specification of the latter phase in terms of time and numbers will only be possible when the uncertainty concerning the prospect of commercialisation will have declined below a certain limit. Conversely, the actual date and number of FCVs characterising this phase will then provide important hints as to the possible launch of phase 4 and, equivalently, to the opening of the corresponding window of opportunity. In this context, it was indicated by interviewees from car industry that with the beginning of phase 4, a minimum of 50,000 FCVs per year would have to be produced and enter the market – with the corresponding requirements in terms of infrastructure (see below) and demand.[5]

In contrast to the fuel cell technology, the production, distribution and handling of hydrogen essentially represents the state of the art – not for today's fuel suppliers but for the chemical industry which has been handling hydrogen for more than a century. Although some scale or learning effects may well be realised here (Thomas et al. 2001; Valentin 2001), they are essentially negligible in comparison to those of the fuel cell technology and, therefore, do not as such constitute a window of opportunity in the sense that the opportunity for transition is temporally restricted.

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4 In 1998, large-scale production of FCVs was assumed to commence in 2004, while in 2000, the latter figure was shifted to 2006 or 2007. This moving-wall effect is partly due to the problems encountered with regard to FCV development. On the other hand, it also characterizes the uncertainty faced by the FCV manufacturers and, so long as the complementary infrastructure is not available, the lacking competition and, thus, need to enter mass production as early as possible.

5 In the probable case that the number of companies manufacturing FCV exceeds one the latter figure will multiply accordingly. The total number will then determine the supply on the entire world market.

However, it is essential that the production and handling of hydrogen in general is, and in all probability will remain, significantly more costly on an equivalent-energy basis than the manufacturing and distribution of gasoline.[6] To some extent, this disadvantage is levelled out by the higher fuel efficiency of the FCVs. However, whether this effect will in fact be strong enough to decrease the hydrogen costs of transportation by FCV below the gasoline costs of transportation by ICEV as suggested by Thomas et al. (2001) is doubtful. So, over an extended period during its introduction, at least, the fuel costs for a hydrogen-driven FCV can be expected to be higher than the cost of gasoline for an ICEV.

**Network effects** are highly relevant for the mobile fuel cell technology insofar as the complementary hydrogen infrastructure is incompatible with the gasoline infrastructure existing at present.[7] So, the utility of using an FCV will be positively correlated with the number of hydrogen stations available for necessary refills. Conversely, people will prefer to rely on the established ICE/gasoline technology so long as they consider the hydrogen infrastructure as insufficient for a convenient operation of FCVs. At the same time, the potential suppliers of hydrogen will not invest in a dense network of fuel stations so long as the number of hydrogen consumers is small, as this renders their investment into infrastructure unprofitable. Clear evidence for this close connection between vehicle use and infrastructure availability comes from Argentine, the only country world-wide with an alternative fuel and vehicle market making up as much as 15 percent of the total national car fleet (of five million). Here, the increase in vehicle numbers was accompanied by a proportionate increase in the number of CNG fuelling stations reaching about 1000 in the recent past. Except for the very first years, the utilisation rate was always high enough to ensure profitability (Wurster 2002).

With regard to a hydrogen infrastructure, the latter problem may even be somewhat relaxed by the fact that hydrogen fuelling stations could additionally be used by hydrogen-driven ICE vehicles (developed by e.g. BMW) which could be available much sooner (and at lower prices) than FCVs. A further potential cause for a decrease in the cost of conversion consists in a certain comple-

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6 The latter argument applies even more if hydrogen is to be made from renewable sources. To remain fair, however, one would then have to compare 'renewable hydrogen' with gasoline (or Diesel) also from renewable sources (e.g. rapeseed).

7 In principle, gasoline reforming could serve as a gateway technology (David and Bunn 1987) to resolve this incompatibility, but it adds significantly to the costs and technical complexity of the entire system.

mentarity between a potential hydrogen infrastructure and the extensive supply network for natural gas found in countries like Germany, the Netherlands and the UK. For it is reasonable to assume that a significant proportion of the hydrogen fuel will be produced from natural gas. Only in the very beginning (when hydrogen is distributed as a liquid to 'pioneer' fuel stations by truck) and after the hydrogen infrastructure reaches a certain degree of maturation (when the network of fuel stations is dense enough that it pays to distribute gaseous hydrogen via pipelines), will hydrogen be manufactured in centralised facilities. Over the major part of the initial installation of that infrastructure, however, hydrogen will preferably be produced in small on-site reformers, at the fuel station – with the necessity for corresponding natural gas supply (Ogden 1999).

Nevertheless, this does not imply a spontaneous solution of the general ‘chicken and egg’ problem as the costs are still high enough and the willingness of potential fuel suppliers to make the necessary investments in advance is further reduced by the uncertainty as to whether the FCV manufacturers will follow at all.

**Economies of scope** do neither stabilise the ICE technology with respect to a transition to FCVs, nor the production and distribution of gasoline with respect to hydrogen. So, they do not give rise to a limitation in the opportunity for technological transition in both fields. On the other hand, when used as storage and balancing medium for electricity, hydrogen is complementary to renewable energy sources such as wind turbines and photovoltaic cells. Additionally, fuel cells are technically related to electrolysers that are used to produce just this hydrogen from electricity. So, once a hydrogen grid is in place, it can be expected that renewable electricity and hydrogen will stabilize each other.

**Sunk costs** are irrelevant for both hydrogen and fuel cell as the transition is expected to proceed with only moderate pace and over extended periods of time such that existing production facilities and infrastructure will not have to be put out of operation prematurely.

**Market structure** is not relevant as an obstacle to the development of FCVs because the competition between car manufacturers is quite strong. So far, this competition does not come to bear with regard to the FCV; however, this situation will change as soon as a suitable infrastructure exists. While the same argument basically applies for the current providers of fuel infrastructure, it is the chicken-and-egg nature of the problem that gives rise to an asymmetry with regard to expectations and, thus, decreases the incentives (and the competition) for setting up a hydrogen infrastructure. This is one more reason as to why (regulatory) incentives trying to favour the transition towards fuel cell and hydrogen will have to focus on the infrastructure rather than to the propulsion system. On the other hand, it is told by one interviewee that the downstream oil industry as the traditional supplier of gasoline will not be willing to leave the hydrogen fuel business to another (e.g. chemical) industry since they on their own got a lot of experience in producing and using hydrogen (e.g. in cracking processes) and will prefer to remain fuel supplier also for a new generation of hydrogen-driven vehicles.

**Extra-demand.** All car manufacturers are convinced that the willingness to pay significantly more for an FCV than for a comparable ICE vehicle (e.g. because of its environmental advantages or its representative value) will be limited to a small number of consumers and is far too low to render the sale of FCVs a profitable business in the first phase of mass commercialisation. For the average buyer (in Europe), an FCV is worth as much as an advanced (low-noise) Diesel car with automatic transmission. Moreover, it was stressed by all interviewees from car industry that, due to a fundamentally conservative attitude prevalent on the demand side of the automobile market, even equally expensive FCVs will not sell if they are not at least as good as ICE vehicles in most relevant performance parameters and even somewhat better in some. So, in order to enter the mass market successfully, the FCV has to show right from the beginning all those characteristics that took more than a century to emerge in the case of the ICE development. Hardly anything could be more disastrous for the successful commercialisation of FCVs than their premature introduction. This and the limited early availability of fuelling infrastructure severely restrict the potential use of niche markets specifically for the FCV.

By contrast, in a broader sense, fuel cell buses constitute a rather effective niche market for fuel cell-based propulsion systems. They are now being tested in public transportation in the course of the EU-sponsored CUTE project and in a series of more local projects across Europe and the USA. The requirements for their operation are basically similar to those for FC passenger cars but not quite as strict (i.e. lower specific power required and more space available for the FC installation). Also, since they are operated in fleets, the supply with hydrogen can be ensured more easily.

A few more niche markets for the fuel cell in general exist (e.g. stationary fuel cells or fuel cells as power supply for transportable or remote devices). However, the accruing of important synergy effects from them remains doubtful since the specific technical (and economic) conditions of their operation are quite different from those of the FCV. The latter argument applies all the more, if different types of fuel cells (e.g. solid oxide or molten carbonate as opposed to PEM) are employed.

**Potential and risk.** In the short run, a variety of severe technical problems have to be solved before competition can be achieved. In the longer run, representatives of many car manufacturers assure that the technical problems could be solved. Whether or not FCVs and the complementary hydrogen supply can then be commercialized successfully, will depend on the right political conditions, that is, on the political willingness to opt for hydrogen as a alternative secondary energy source and to compensate it for its higher costs (which could be interpreted as reflecting its capability to internalise the external costs of carbon dioxide emission) and to reward the fuel cell for its better fuel efficiency and its lesser air pollution. Another important condition for the commercial success of FCVs (as well as hydrogen) will be the consumers' view of it as a superior alternative.

## 5.2 Socio-cultural determinants

**Problem discovery and public concern.** There is a broad scientific consensus that continued man-made greenhouse gas emissions would cause major changes in the earth climate with severe ecological consequences (IPCC 2001). It is evident that the conditions of human live would be concerned as well, but the economic consequences are so far rather unclear. Due to this uncertainty and the lack of an immediate temporal connection between cause and effect, public concern about a possible climate change is somewhat limited. Nevertheless, the majority of governments of the world came to agree in the Kyoto protocol that the industrial countries must reduce their greenhouse gas emissions by about five percent by the year 2012. FCVs, while coming too late to make a significant contribution to the latter goal, could well play a role in the longer run when an extension of the Kyoto protocol may come into effect. So, since (in Europe) climate change is already part of the political agenda, problem confirmation and public concern are now not so relevant anymore.

In the USA, it is not quite as easy to distinguish the influences of public and political concern with regard to securing the national energy supply. However, since the latter objective is part of the more general 'war against international terrorism', the dominance of political leadership is evident here as well.

With regard to the importance of transportation and energy supply in all industrial economies, the failure of FCVs or the hydrogen infrastructure to find **public acceptance** would easily rule them out as possible alternatives. While the hydrogen infrastructure seems to be more crucial in this respect, in Europe at least, its good reputation as a clean energy source seems to dominate adversely perceived safety issues (LBSt 1998).

## 5.3 Political determinants

**Institutional integration**. Until now, the use of hydrogen was mainly restricted to industrial production sites and subject to strict *regulation*. In order to allow for a safe, but nevertheless convenient use of hydrogen in FCVs, these regulations and many related technical standards need to be changed or newly developed. In the EU, such standards were developed by the *European Integrated Hydrogen Project* until 2004.

Subsidisation in favour of the FCV (e.g. bonus or tax exemption for the buyer) will be feasible, but will probably not go beyond what is conceded to any other propulsion system with comparable environmental properties. Similarly, hydrogen can be expected to benefit from tax exemptions similar to those granted to compressed natural gas. This would be enough to render the price of fossil fuel-based hydrogen competitive with regular gasoline. In any case, this implies that the present system (i.e. ICE/gasoline) will not be particularly favoured (and the FCV/hydrogen system disfavoured) by the currently prevailing institutional setting.

**Interest groups.** In Germany, in particular, car manufacturing is an important part of the industrial structure. Direct employment in the automobile industry accounts for 12 percent of the industrial work force (DIW 2000). Since FCVs are developed and will be manufactured by the automobile industry, and under the assumption that the oil industry as actual gasoline supplier will also be involved in the production and distribution of hydrogen, interest groups are not expected to oppose the transition to the new technologies. To the contrary, the way the two industries are actually involved in initiatives like HyWays in the EU and FreedomCAR in the USA implies that they both understand FCV/hydrogen as a great chance for the future of their businesses. With regard to the details of such a transition, the agreement of the industries concerned will depend on the appropriate conditions concerning especially the time path and financial support (mainly for the oil industry).

**Knowledge asymmetries** between the government and the FCV or car industry are not relevant insofar as the former is not expected to sponsor the commercialisation of FCVs directly. The asymmetry is however relevant with regard to the earliest point in time at which commercialisation could begin and a basic hydrogen infrastructure would have to be in place. If this date is chosen to be too early, utilisation and profitability of the infrastructure will be low. On the other hand, earlier installation of the infrastructure could force the potential manufacturers of FCVs to engage in fierce competition with each other and thus to reveal the true state of their technical development. This would allow for the resolution of the latter part of the asymmetry and lead to the earliest possible market launch of FCV – however at the risk of being premature and very costly.

Certain knowledge asymmetries could also be relevant with regard to the costs of the hydrogen infrastructure and the size of the necessary subsidies. Whether or not they will be sufficient to delay or even prevent the construction of the infrastructure, eventually depends on the political attitude and, accordingly, the parliamentary majorities (see below) prevailing in the relevant time period.

**Election cycles** are irrelevant since the political measures under consideration do not immediately increase the costs to be borne by the voters. In the long run, the assignment of accruing costs to the beginning or end of a specific election period will simply be impossible.

**Legislative majorities** and their change are important preconditions for the opening and closure of windows of opportunity as the usefulness and successful implementation of FCVs and the complementary infrastructure depends on political long-term objectives that can change at any time as the result of a corresponding change in the government. While the majorities as such are essentially unpredictable and could therefore seriously undermine the formation of a long-term time strategy, undergoing a corresponding commitment on a higher, for instance supra-national level (see below) could be an effective way to generally reduce the influence of changing majorities.

**Singular restrictions.** Basically, the budget available for each political measure is in some way related to the performance of an economy and, accordingly, the total budget available to the government. This relation can be subject to a significant change once public (and political) concern is changed by a dramatic exogenous event (e.g. a catastrophe or accident) or one of the parties concerned gains or loses reputation. More frequent or powerful indications of a dramatic (i.e. harmful) change in the global (or local) climate could be a case in point. But as majorities and singularities are essentially unpredictable, they will not be integrated in the time strategy to be developed.

**Political procedures.** Within the EU, the actual engagement in favour of hydrogen (see e.g. the ‘High-Level Group’) and, to a lower extent, FCVs is based on the joint obligation taken on in the Kyoto Protocol to reduce greenhouse gas emissions. Individual countries can influence the making of such decisions, but once the process is completed, a deviation is not easily possible. This gives the EU policy and that of its member countries a higher degree of continuity. In the USA, by contrast, important initiatives can be launched by small groups of, or even single, policy makers. Additionally the USA refused to ratify the Kyoto Protocol. On the other hand, in his fight against the international terrorism and his search for resource independence President George W. Bush in 2003 announced a strong initiative in favour of hydrogen as a future substitute for oil. It remains to be seen whether the reach of the initiative will exceed Bush’s election term.

## 5.4 Time-critical factors – a conclusion

After analysing a variety of potential determinants of windows of opportunity in the preceding part of this section, it became evident that in the case of the mobile fuel cell and its hydrogen infrastructure, many determinants are not relevant because they do not play a role as potential stabilising factors for the established gasoline-based ICE technology. In Table 2, those irrelevant factors are marked by ‘0’. The remaining factors could have played a role in locking out the new technologies, but during the period of analysis, many of them in fact never do. They constitute a ‘window’ that is open all the time and are marked by ‘1’. Fortunately, a window that never opens and would thereby inhibit any kind of strategy could not be identified. Finally, seven *time-critical* determinants of a potential window of opportunity were found to indeed constitute a window. They are marked by ‘X’ in Table 2 and will be used for the development of a time strategy in the next section.

Table 2: Characterisation of the determinants of windows of opportunity for automobile fuel cells and a hydrogen infrastructure

| Subsystem | Determinants | Relevance* |
|---|---|---|
| Techno-economic | **Economies of scale / learning by doing** | **X** |
| | **Network effects** | **X** |
| | Economies of scope / complementarities | 1 |
| | Sunk costs | 0 |
| | Market structure | 1 |
| | Extra-demand | 0 |
| | **Potential / risk** | **X** |
| Socio-cultural | Problem discovery / confirmation | 1 |
| | Public concern | 0 |
| | Acceptance of solution(s) | 1 |
| Political | **Institutional integration** | **X** |
| | Interest groups | 1 |
| | Knowledge asymmetries | 1 |
| | Election cycle | 0 |
| | **Legislative majorities** | **X** |
| | **Singular restrictions** | **X** |
| | **Political procedures** | **X** |

* X = time-critical, 1 = relevant, but not time-critical, 0 = irrelevant

# 6 Development of a time strategy

In order to develop a successful innovation policy for the mobile fuel cell and its infrastructure, it is useful not to consider the time-critical factors (X) in the order listed in Table 2, but to proceed along the time scale in which the time-critical determinants become effective. Additionally, Zundel et al. (2005b) distinguish four time-strategic approaches corresponding to the developmental stage of the new technology. If the new technology is nearly competitive and the window exists already, it can be *used* immediately. If the technology is promising but far from competitive and the window is foreseen somewhere in the future, it makes sense to support the development and *prepare* the window in order to use it as soon as possible. If a strong public or political pressure towards technological change does not allow policy makers to wait, they can make the more risky attempt to force the technological development and *create* a window. Finally, it can be useful to *maintain* a window, when the economic success of one new technology would itself lock-out other even more promising new technologies. Since window creation is not an issue and window maintenance is not important in this case, only the former two strategies will be drawn up in this paper.

## 6.1 Window preparation

The first determinant to be considered is the institutional integration or, more specifically, the specific regulations concerning the operation of a hydrogen infrastructure and the transport of hydrogen in FCVs. Within the EU, the necessary changes are currently under way and will probably be completed by the year 2004 or 2005.

The next point relates to the basic potential and risk of FCVs (and hydrogen) in terms of profitability. At present, it is not only unclear when the commercialisation of FCVs can be expected to begin; it is even unsure whether it will take place at all. This is only in part a question of technical feasibility. Instead, the main question is: will there be sufficient demand? Why should people buy an FCV? Here, it would be an important contribution in terms of political *guidance* to make clear in the first place that, together with hydrogen, FCVs are indeed considered a possible solution to an urgent environmental or sustainability problem and appropriate support will be provided. At the moment, in Germany, political signals going in that direction are far from unambiguous; the rather low importance assigned to FCVs and a hydrogen infrastructure by the German government is reflected in its low subsidy efforts (compared with the USA or Japan, see HyWeb 2000) and in the opinion expressed by the Federal

Environment Agency (*Umweltbundesamt*) that FCV and hydrogen may become useful alternatives only in the longer run – 2040 and later. So, many car manufacturers continue to be engaged in the technical development of FCVs in order to maintain their competitiveness, but due to the immense risk associated with the commercialisation of a completely new type of car, they are not in a hurry with regard to the actual market introduction.[8] If politics was really interested in the FCV being commercialised as quickly as possible, it could indeed support this process by simply demonstrating its interest more explicitly. A way of doing so could consist in the government and its agencies expressing a more coherent, positive, attitude towards FCVs and in a stronger support of R&D and demonstration projects in this field. The latter point is important not only for the maintenance of technological progress; it also contributes to people developing a higher familiarity with, and trust in, the new technology. It needs to be emphasised, however, that at this early stage with high uncertainty involved, policy should support a variety of technological options rather than a specific one in order to allow for the possibility of experimentation. A lucid example for this kind of approach is the *Californian Fuel Cell Partnership*, a cooperation of major US-based car and fuel cell manufacturers, oil companies and governmental agencies which, while trying to push the mobile fuel cell, do not limit themselves with regard to the fuel options to be investigated.

Although the influence of changing parliamentary majorities and singular events on technological progress cannot be affected by single policy makers, some procedural aspects in the political system allow for a partial compensation of this shortcoming. Commitments to pursue long-term political objectives and the joining into supra-national political agreements (as e.g. the Kyoto Protocol) are some of the more prominent means to ensure the continuity of policy. So, with regard to the technologies considered here, an extension of the Kyoto Protocol into another decade or the inclusion of (so far) outsiders such as the USA could be quite advantageous.

So far, the proposals for governmental measures in support of the fuel cell and hydrogen technology path are only moderately time-critical insofar as it is more crucial that those measures are taken at all than when they are taken exactly. Due to this more conditional character, they help to *prepare* a(n anticipated)

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8 Due to the current lack of a suitable infrastructure, there is no actual risk that a competitor could begin with the mass production of FCVs. So, competition so far proceeds on the technical level rather than with regard to commercialization.

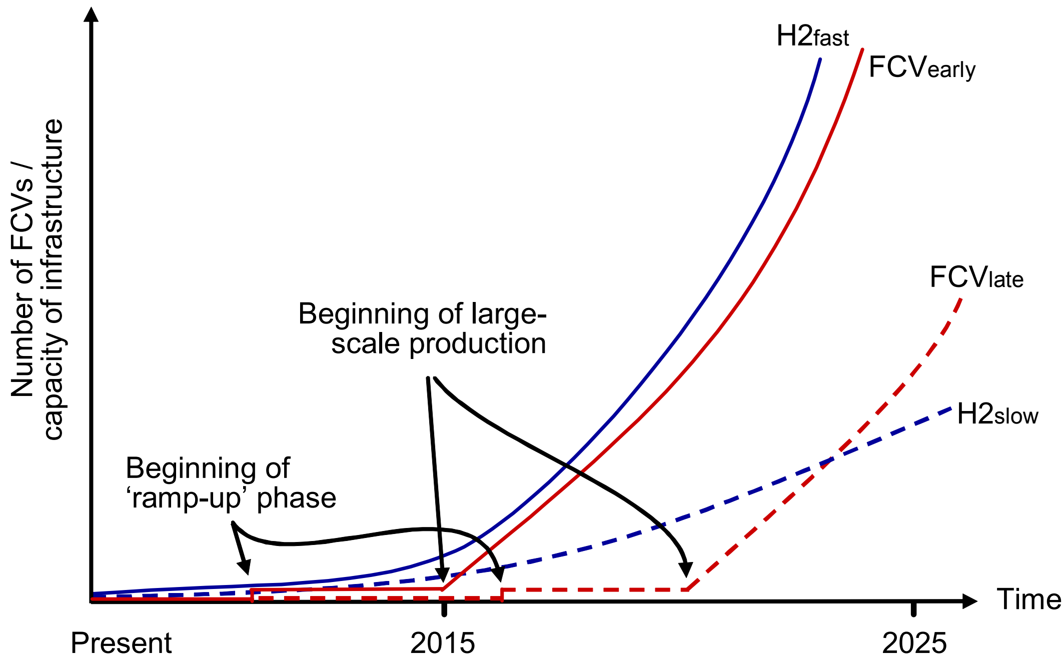
window of opportunity. By contrast, a variety of more time-critical measures are discussed in the following that are related to the opening of a window more directly.

## 6.2 Use of a window

In order to allow FCVs to become (cost) competitive with regular ICE vehicles, it is necessary to make extensive use of economies of scale with annual production capacities exceeding 50,000 units per plant right from the beginning (This figure specifies the slope of the FCV curves in Figure 1 at the right-hand side of their respective kinks). Such quantities of FCVs will however be sold only, if the potential users can rely on a satisfactory network of complementary (hydrogen) infrastructure. From the FCV manufacturers' perspective, a certain proportion of this infrastructure will need to be assembled prior to the launch of FCV commercialisation and the remainder as quickly as possible afterwards. In order to keep the financial losses of infrastructure providers from under-utilised infrastructure low, it is, on the other hand, essential that the installation of the infrastructure occur neither too early nor too quickly. In this trade-off, the government plays a central role as *coordinator* and *mediator*, and it is this point where the time strategy in the narrower sense sets in. After a roadmap for the development of the smallest, but nevertheless effective, hydrogen infrastructure has been specified (see e.g. Wurster (2002) for Germany and Melaina (2002) for the USA), it is necessary to reach an agreement between the FCV manufacturers and the infrastructure providers specifying the schedule for both the mass production of FCVs and the installation of the infrastructure. Additionally, it may be necessary to reach an agreement as to how the unrecoverable capital costs of (initially) under-utilised infrastructure are to be shared between the different parties. In the absence of uncertainty, it could well be argued that these costs are an investment into the business of the infrastructure provider to sell hydrogen and, therefore, are to be borne by him alone. Since it may not be that sure, however, that the FCV manufacturers can really produce (and sell!) according to the agreed-upon schedule, it appears to be more incentive-compatible to make the latter party pay a certain specified part of these costs. With regard to the size of the necessary initial investments, it may nevertheless turn out that both industries find themselves incapable of even commonly bearing the risk of a rapid enough installation of the necessary infrastructure. It would then be up to the government to (partially) subsidise the construction of the basic infrastructure and, thus, to render its schedule compatible with the requirements of the FCV manufacturers. In Figure 1, this effect is reflected in the different slopes of the curves ‘$H2_{slow}$’ (without specific governmental support) and ‘$H2_{fast}$’ (with support). On the other hand, in order not to waste the tax payers’ money, the major launch of the infrastructure should precede the launch of FCV commercialisation by not more than, say, a year or two. But how does the government know when the mass production of FCVs can be expected to start without exclusively relying on the corresponding, possibly biased, information from the industry (see knowledge asymmetries, above)? Although policy can influence this point to some extent through measures of window preparation (see above), only the FCV manufacturers will know this point exactly. Actual predictions reach from 2010 to the mid or even end of the next decade (illustrated by the curves ‘$FCV_{early}$’ and ‘$FCV_{late}$’, respectively, in Figure 1). Beside direct communication between the parties involved within institutional arrangements such as the *Verkehrswirtschaftliche Energiestrategie* (energy strategy for transportation, Germany) or the *Californian Fuel Cell Partnership* (USA), one way to reduce this uncertainty is to have a closer look at the specific shape of the FCV production curve (as displayed in Figure 1): about four years prior to the potential big kink of a beginning mass production, a much smaller kink indicates the beginning of the ‘ramp-up’ phase. This phase is essential as FCVs are a completely new type of vehicle such that they and their production facilities need to be subjected to a final large-scale operability and reliability test. While this phase could hardly be shorter than four years, there is no guarantee that the next phase (i.e. mass production) will ever be entered. Here, the number of FCVs produced in the ramp-up phase may be a useful indicator: while output figures in the, say, lower hundreds would raise doubts about a foreseeable transition into mass production, the high costs alone of producing several thousands of FCVs would only make sense in terms of an investment, if they were followed by the beginning of mass production not too much later. So, it is the size of the ramp-up production as well as its chronological appearance that allows policy makers to independently form expectations about the schedule and the appropriate measures to push the commercialisation of FCVs.

With regard to potential alternatives to FCVs and hydrogen, it needs to be emphasised that the actual use of the window by building up the infrastructure leads to the closure of windows for all those (new) fuels that could not be distributed by the then existing infrastructures. In this sense and in view of the trade-off between methanol and hydrogen, representatives of the oil industry made clear that they would under no circumstances support more than one new fuel alternative.

**Figure 1**: Time-critical techno-economic aspects of a possible time strategy for a technology policy in favour of the mobile fuel cell and a hydrogen infrastructure. The beginning of the ramp-up phase can serve as an indicator for the beginning of commercialisation. It is crucial that the installation of the infrastructure ($H2_{fast}$) precedes the mass introduction of fuel cell vehicles (here: $FCV_{early}$)




## 6.3 Closure of the window and beyond

After a while, the strong increase in the number of FCV users together with strong initial learning and scale effects would considerably relax the competitive situation of the new technology. At the same time, this would increase the degree of utilisation of the hydrogen infrastructure such that a subsidisation beyond a basic network of fuel stations (about 1000 in Germany) would not be necessary. Particularly when based on regenerative sources, the production and distribution of hydrogen would probably remain more costly than that of gasoline and Diesel even in the long run. This would make it necessary to permanently subject the latter fuels to a higher tax than hydrogen. The resulting higher price for fuels in general should then be considered as to reflect the internalised costs of environmental pollution and climate protection.

# 7 Conclusion

The automobile fuel cell can play an important role as solution to problems related to climate protection, sustainable resource use, and avoidance of local emissions from transportation. Whether or not it really gets a chance to bring to bear these advantages depends on the willingness and capability of a government to clear up a variety of obstacles to the successful market entry. While, in this respect, the emphasis is traditionally put on static effects such as externalities, the present analysis shows that a more important role is played by dynamic effects leading to the opening and closure of windows of opportunity – periods in which a successful transition is greatly facilitated.

Important determinants for such a window were found to be economies of scale, learning and network effects – the latter because FCVs will exert the most advantageous effects in combination with hydrogen for which an infrastructure needs to be installed first. Other more political determinants of windows of opportunity are institutional integration, supra-national agreements and political guidance – the latter expressing a kind of commitment for the technology in question, the second maintaining this commitment despite possible changes in parliamentary majorities. Although no obstacles against the mobile fuel cell are expected to accrue in the social sphere, political guidance could be influential here as well by bringing about a more positive social attitude towards the new technology.

When developing a time strategy for the successful implementation of the mobile fuel cell technology by means of the above-mentioned factors, two major stages could be distinguished. In the first phase of *preparation* of a window of opportunity, the opening of an anticipated window is supported by adaptation of the institutional framework to the new technology and by subsidising demonstration projects that allow the companies involved to realise important learning effects. Only when the window is actually about to open, that is, the fuel cell itself is ready for commercialisation, the second phase of *using* the opening window sets in. Now, policy makers are supposed to adjust the basic conditions (such as the complementary infrastructure) in such a way that the window can effectively translate into a successful commercialisation.

In the longer run, most of the measures undertaken to open and use the window of opportunity for the mobile fuel cell can successively be withdrawn once the new technology has reached a state comparable to that of the incumbent technology. From this point on, it should be left to the market to select the technology that is in fact superior.

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