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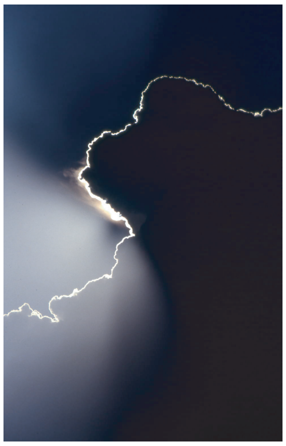
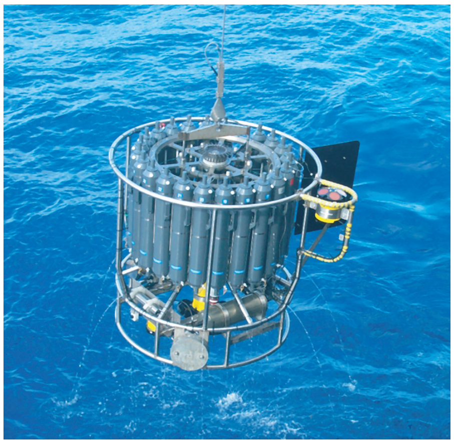
Managing the Transition to Hydrogen and Fuel Cell Vehicles

– Insights from Agent-based and Evolutionary Models –

Malte Schwoon





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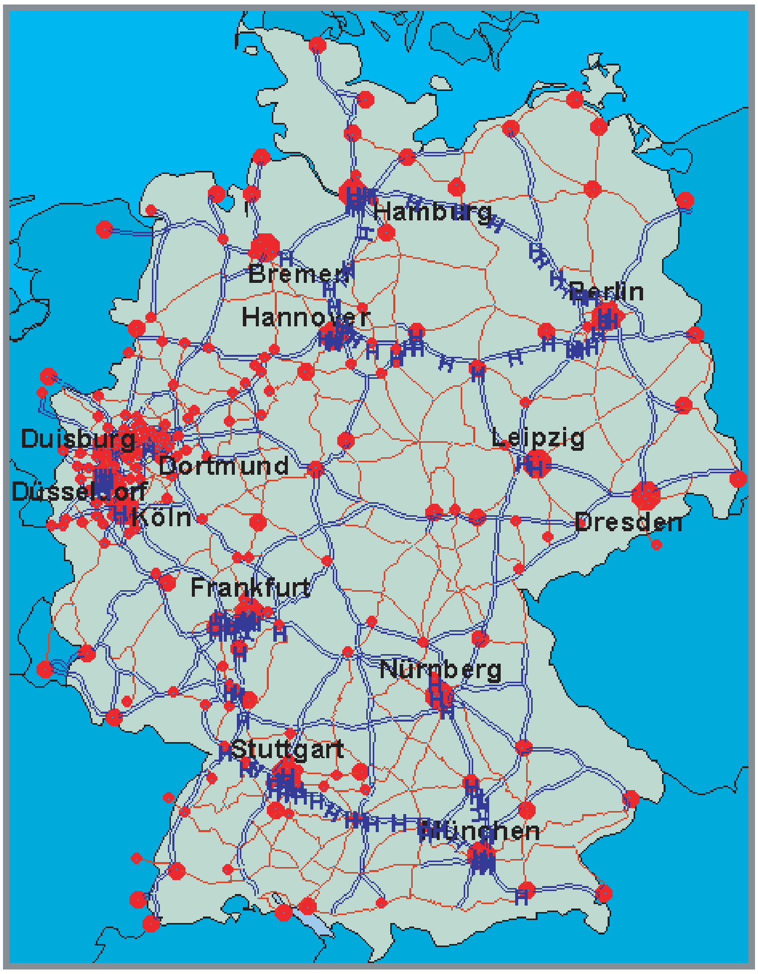

Malte Schwoon

Hamburg 2006

Preface

This cumulative thesis contains four papers that address the management of a transition to hydrogen and fuel cell vehicles applying agent-based and evolutionary concepts.

1. *Simulating the Adoption of Fuel Cell Vehicles*
   This paper is published in the *Journal of Evolutionary Economics,* Vol. 16 (4), 435-472. It was presented at the Annual Retreat of the International Max Planck Research School on Earth System Modelling in Lübeck (November 2004), at the 1st HyCARE meeting in Hamburg (December 2004), and at the SIME Eurolab Course in Strasbourg (April 2005).

2. *Learning by doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles*
   This paper is under review at *Energy Economics*. It was presented at the PhD Day of the DRUID Summer Conference in Copenhagen (June 2005), at the European Summer School on Industrial Dynamics (ESSID) in Cargèse, Corse (September 2005), and at the International Conference on Computational Management Science in Amsterdam (May 2006).

3. *A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations*
   This paper is accepted for publication in *Transportation Research Part D: Transport and Environment*. It was presented at the 2nd HyCARE meeting in Laxenburg (December 2005) and at the Fraunhofer Institut für System- und Innovationsforschung in Karlsruhe (February 2006).

4. *Flexible transition strategies towards future well-to-wheel chains: an evolutionary approach* (jointly with Floortje Alkemade, Koen Frenken and Marko Hekkert)
   This paper is the result of a three month research project at the Copernicus Institute in Utrecht through the IMPRS-Exchange Program. It is under review at *Energy Policy*.

Hamburg, November 2006 Malte Schwoon

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Summary

Environmental and energy security concerns call for alternative fuels and vehicle technologies in road transport. In this thesis, four papers address strategies to introduce, in particular, hydrogen along with fuel cell vehicles (FCVs) as a promising future technology combination.

Starting point of the first paper called *Simulating the Adoption of Fuel Cell Vehicles* is the current problem of a lack of hydrogen refueling infrastructure together with extremely high fuel cell production costs. In an agent-based model that portrays the behavior of car producers, consumers, and filling station owners, public infrastructure development scenarios combined with tax policies in favor of FCVs are implemented. Results based on the German compact car market suggest that a high tax on conventional cars can successfully promote diffusion even without pronounced public infrastructure investments. However, consumers and small car producers are negatively affected by the tax; and the negative impact on the latter is aggravated in case of a major public infrastructure program.

The second paper, *Learning by doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles*, extends the previous model by adding cost decreasing learning effects in fuel cell production. Model projections for the diffusion of FCVs turn out to be very sensitive to changes in the assumed magnitude of learning effects. Apart from that, the model exhibits a substantial first mover advantage, i.e., the producer who switches to the production of FCVs first tends to increase his profits. Moreover, results show that learning spillovers increase the speed of diffusion, because there are some additional producers who can profitably switch. But learning spillovers negatively affect the profitability of some of the producers, implying policy trade-offs.

The third paper presents a different model, which is *A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations*. It is based on the assumption that consumers only consider buying a FCV if they actually perceive sufficient fuel availability. The German trunk road network is implemented in a spatial approach and artificial drivers make long distance trips through the network checking for fuel availability. A frequently advocated ring shaped distribution of initial hydrogen filling stations at trunk roads is tested for its potential success to generate a large scale adoption of FCVs. It turns out to be appropriate only under unrealistic assumptions regarding people's refueling concerns. However, the model indicates promising improvements of the initial distribution.

The last paper, *Flexible transition strategies towards future well-to-wheel chains: an evolutionary approach* (jointly with Floortje Alkemade, Koen Frenken and Marko Hekkert), also includes other potential future fuel and vehicle combinations than hydrogen and FCVs. Changes in the so-called well-to-wheel (WTW) chain are modeled as stepwise transitions in analogy to fitness improving mutations of genes in evolutionary biology. Transition steps are only possible if they reduce greenhouse gas emissions or energy requirements. Transitions are shown to be path dependent, so that current decisions regarding changes in the WTW system predetermine its future characteristics. Thus, flexible initial transition steps seem to be preferable, i.e., those steps that leave open a wide range of different transition paths later on. Analysis of empirical data suggests that improving vehicle technologies as a first step is most flexible in that respect.

Abbreviations

AEGLP	Association Européenne des Gaz de Pétrole Liquéfiés
CBaP	Colin Buchanan and Partners
CBG	Compressed biogas
CCS	Carbon capture and sequestration
CGH_2	Compressed gaseous hydrogen
CNG	Compressed natural gas
CO_2	Carbon dioxide
DME	Dimethyl ether
EC	European Commission
EC-JRC	European Commission – Joint Research Center
EEA	European Environment Agency
FBMVD	Federal Bureau of Motor Vehicles and Drivers
FC(V)	Fuel cell (vehicle)
FF Electricity	Electricity generated from fossil fuels
GHG	Greenhouse gas
H_2	Hydrogen
ICE(V)	Internal combustion engine (vehicle)
LBD	Learning by doing
LCG	Well-to-tank system: Large, centralized, gas-pipeline
LCP	Well-to-tank system: Large, centralized, pipeline
LCT	Well-to-tank system: Large, centralized, truck
LH_2	Liquified hydrogen
LPG	Liquified petroleum gas
LR	Learning rate
LSD	Laboratory for Simulation Development
MLG	Well-to-tank system: Medium, local, gas-pipeline
MLP	Well-to-tank system: Medium, local, pipeline
MLT	Well-to-tank system: Medium, local, truck
NG	Natural gas
NPV	Net present value
NRC	National Research Council
R&D	Research and development
SO	Well-to-tank system: Small, onsite
TTW	Tank-to-wheel
WTT	Well-to-tank
WTW	Well-to-wheel

General Introduction

1. The vision of hydrogen and fuel cell vehicles

Currently, crude oil is the dominant source of fuels in road transport. The share of gasoline and diesel in road fuels is approximately 98% in the European Union (EU). This extensive dependence on a single fossil fuel creates three major problems. Firstly, combustion of fossil fuels inevitably leads to emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs). CO_2 emissions from road transport are responsible for more than 20% of total emissions, exceeding those from the industry sector (EC, 2005). Moreover, there has been a strong upward trend in road transport over the last 15 years that is mirrored by an increase in emissions indicating that the problem is actually aggravating (EEA, 2006). Similar figures apply to other world regions, so that road transport makes a significant contribution to anthropogenic climate change. Secondly, health impacts of local emissions, such as ozone, sulfur dioxide, and nitrogen dioxide remain problematic, because advancements in fuel efficiency, end-of-the-pipe technologies, and cleaner fuels have at least partly been compensated by increases in the number and use of vehicles (Friedrich and Bickel, 2001). Yet, regional differences are considerable, depending on vehicle densities, average vehicle age and climate conditions. Thirdly, oil is a non-renewable resource and there is evidence that – given current demand - the physical peak of global conventional oil production will be reached soon (Bentley, 2002), so that further price increases are likely. Moreover, the majority of estimated remaining reserves are located in the politically instable region of the Middle East. This implies additional uncertainty of oil supplies for net importers like the EU and enhances price fluctuations due to speculation.

These problems call for alternative fuels and vehicle technologies. In this thesis, agent-based simulation models and evolutionary concepts are applied in order to get a better understanding of the dynamics of a large scale transition towards an alternative fuel/vehicle system. Assets and drawbacks of different transition policies are addressed in terms of transition speed, impacts on consumers and certain car producers, risk of transition failure and flexibility regarding future technological developments.

The focus of this thesis is on hydrogen and fuel cell vehicles (FCVs), because this technology combination is exceptional in allowing for a fully sustainable individual transport. Hydrogen can be produced from any renewable energy source via electrolysis ("renewable hydrogen"), and energy conversion in the FCV emits nothing but water vapor.[1] The required technologies for a renewable hydrogen/FCV transport system are fully operational. They include not only electrolysis and the fuel cell, but also biomass gasification for hydrogen production, large scale hydrogen storage and distribution, refueling of liquid or compressed hydrogen, and save and sufficient storage in the vehicle. Hydrogen is a widely used industry gas and, e.g., a 220km pipeline system exists in the Ruhr area in Germany. High-pressure tanks at 700 bar for onboard storage are state-of-the-art. They allow ranges of vehicles of more than 500km. The whole fuel cell, tank, and electric motor system fits into compact cars, providing them with similar performance as conventional cars.

Some technological issues remain, e.g., start up time and durability of the fuel cell, but they are considered teething problems of pilot series rather than insurmountable hurdles. Thus, a hydrogen/FCV transport system is an available technological option. This is different to the battery electric vehicle concept that received substantial public and private R&D investments worldwide until the early 1990s. The concept failed, because it was impossible to construct a "super-battery" that stores enough energy for a range of several hundred kilometers and is rechargeable within minutes – two key criteria for being a valuable substitute for conventional drive trains. Recently, research activities in high performance batteries increased again due to their application in hybrid cars. A "super battery" would render FCVs obsolete, but currently available technologies face limits in the capacity/weight ratio, so that in contrary to the fuel cell, fundamental technological breakthroughs would be required.

FCVs running on hydrogen seem to be a "shared vision" of future individual transport. Stakeholders involved in a potential transition towards this technology combination in industrialized countries have already made substantial commitments. The car industry took the lead with estimated $6-10 billions accumulated R&D spending up to 2004 (van den Hoed, 2005). Almost all major car producers develop FCVs and started small fleet tests handing vehicles over to end-consumers.[2] Fuel suppliers are more unevenly engaged in hydrogen R&D and commercialization activities, however, investments are large, especially at *BP* and *Shell* (with spending of the latter reaching $1 billion by 2006; Solomon and Banerjee, 2006).

On top of the private activities, public funding for hydrogen and FCV projects of the member states of the *International Energy Agency* amounts to $1 billion per year (IEA, 2005). Public expenditures show a (slight) upward trend, especially in the US after the *FreedomCAR* (Cooperative Automotive Research) *and Fuel Initiative* proposed by President George W. Bush in 2003. Ambitious transition scenarios in the EU (EC, 2003) have not yet led to intensified funding, but at least demonstrate that the perspective of a hydrogen economy is established at highest decision level. Japan's

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[1] Hydrogen can also be used in an internal combustion engine (ICE) with basically zero emissions. However, current fuel cells are already about two times more efficient than ICEs (with an even higher theoretical efficiency), so that hydrogen ICEs are likely to be - if at all - a bridging technology towards fuel cells.

[2] Exceptions are *BMW* focusing on hydrogen ICE vehicles and *Subaru* with no hydrogen vehicle program at all.

pronounced hydrogen/fuel cell activities are basically privately driven. There is a general notion of "high fuel cell activities" in China, based, e.g., on the number of fuel cell related patents held by Chinese companies and research institutes (Solomon and Banerjee, 2006). Public and private research focuses on technological issues. Yet, socio-economic and environmental impacts and potentials of hydrogen and FCVs become frequently addressed in a wide range of academic fields. This is reflected particularly by several special issues of scientific journals regarding the topic.[3] Hydrogen and fuel cells also receive noticeable attention in the media (Dunn, 2002), completing the picture of a widespread vision.

2. The challenge of transition

The envisioned FCV transport system fueled with "renewable hydrogen" from, e.g., wind, solar or geothermal power will not be economically feasible within the next decades. Hydrogen production from renewable energy sources implies conversion losses due to electrolysis together with an energy intensive distribution and refueling system. Hence, cost efficient reduction of GHGs suggests using renewable energy sources for substituting fossil fuel based electricity generation instead of producing hydrogen (EC-JRC, 2006)[4]. Another renewable hydrogen source would be biomass gasification, but in that case, hydrogen production not only competes with electricity generation, but also with other alternative biomass based fuels, such as ethanol or bio-diesel, that can be blended with conventional fuels.

Competition in utilization of alternative energy sources between electricity generation and hydrogen production leads to a critical condition for introducing hydrogen: It must be possible to provide hydrogen at prices similar to those of conventional road fuels. For a transitional period, sufficient hydrogen to fuel a significant share of the car fleet at current gasoline prices, e.g., in Germany, can be produced only from reformation of natural gas (Wietschel et al., 2006). As natural gas prices tend to follow oil prices, further increases in oil prices might then make coal gasification break even (perhaps with carbon capture and storage in order to avoid a substantial increase of CO_2 emissions compared to the current situation). This option is projected to remain a much cheaper way of producing hydrogen than using renewable sources for a long time (NRC, 2004). However, this calculation is very region specific, depending on fossil fuel reserves, biomass production potentials or the availability of off-peak electricity from wind or solar power.

A first step to FCVs and hydrogen produced from natural gas can be seen as a hedging strategy with oil dependence immediately reduced (but gas dependence increased). Once, a hydrogen production and distribution infrastructure exits, hydrogen

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[3] Energy Policy Vol. 34 (11), 2006, "Hydrogen"; Science Vol. 305 (5686), 2004, "Toward a Hydrogen Economy"; Proceedings of the IEEE, forthcoming September 2006, "The Hydrogen Economy".

[4] This argument ignores that variability of wind and solar power implies significant demand of backup electricity due to the lack of sufficient electricity storage options. In contrast, hydrogen production would simply follow peaks and dips of power generation.

can directly (via reforming/gasification technologies) or indirectly (via electrolysis) produced from literally any energy source, creating flexibility. New insights with respect to socio-economic or environmental risk associated with extensive use of a specific alternative energy sources can be addressed without changing large parts of the infrastructure system and vehicle technology. Moreover, independent of the energy source, local urban air pollution is inherently avoided.

These benefits, together with the prospect of renewable hydrogen, must outweigh the costs of setting up a (natural gas based) hydrogen infrastructure, in order to justify governmental action. There is a long list of scenario and forecast studies of FCV introduction with a focus on cost estimates of hydrogen production.[5] But they do not provide a consistent picture, because they differ in the study region, assumptions regarding FCV penetration, and cost reductions of large scale hydrogen production. Estimates for investments in the EU that are sufficient to let hydrogen gain a significant market share, are high, but in the same order of magnitude of previous and current infrastructure investments, e.g., in construction of new highways or high-speed internet (Hart, 2005; Wietschel et al., 2006).

In the majority of studies, necessary infrastructure investments are estimated, given certain scenarios of the development of the number of FCVs, starting in certain local niche markets before entering the large market of private consumers. Thus, a smooth and successful transition from local demonstration projects to an area wide market is assumed. This neglects a critical issue frequently referred to as the chicken and egg problem of hydrogen and fuel cells. Fuel cells are currently extremely expensive, and significant cost reductions are only feasible, if they are produced on a large scale, realizing learning effects. But car manufacturers are not willing to make substantial investments in product lines, as long as missing refueling opportunities prevent consumers from buying. On the other hand, oil companies, as the major filling station operators, will not set up a hydrogen production/distribution network and hydrogen outlets at their stations without demand generated from FCVs on the road.

The literature on the costs of a hydrogen infrastructure implicitly calls for public investments. But such a substantial governmental commitment in setting up refueling infrastructure would be unprecedented and unlikely, given budget constraints of public authorities. Moreover, it implies a selection of several involved technologies based on current knowledge. In addition, the lack of noticeable short term environmental benefits in terms of GHG emissions reductions might be a barrier towards pronounced hydrogen/FCV policies as they would be difficult to communicate.

Apart from these problems, infrastructure build-up alone would not be sufficient. The pure existence of refueling possibilities would not make consumers buy (more costly) FCVs. The willingness to pay for "environmental friendliness" of a car is far below the expected additional costs for the fuel cell (Steinberger-Wilckens, 2003).[6]

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[5] Among the most cited ones are Thomas et al. (1998), Moore and Raman (1998), Ogden (1999), Mercuri et al. (2002), Sørensen et al. (2004), Oi and Wada (2004), Ogden et al. (2004), and Hart (2005). Recent estimates for Europe can be found in Wietschel et al. (2006). For a survey on the literature on hydrogen futures see McDowall and Eames (2006).

[6] Even if renewable hydrogen production is assumed, the public good character of benefits associated with FCVs would not permit a significant cost differential to conventional cars.

Moreover, within car buying decisions, the environmental impact is just one aspect besides other characteristic, such as size, acceleration and also psychological motivations (e.g., status). Thus, joint tax and infrastructure policies are necessary to promote the introduction of FCVs.

3. Objectives and contributions of this thesis

The final decision whether to make a policy driven transition to hydrogen and FCVs should ideally be based on cost-benefit analysis, including all financial, environmental and health aspects. A first step towards such analysis would be a consensus on realistic least cost transition scenarios. The four papers of this thesis point out shortcomings of existing scenario studies including neglected costs, ad hoc assumptions and narrow focus on certain technologies. Modeling approaches are introduced to identify winners and losers of transition policies, to spot parameters crucial for transition success, to help minimizing upfront infrastructure investments or to identify low-regret policies. They provide new insights into the dynamics of potential transitions and, thus, help improving existing scenarios.

The first three papers analyze the impacts of combined tax and infrastructure programs large enough to overcome the chicken and egg problem. Agent-based computer simulations are applied that depart from traditional economic analysis, because the neoclassic framework would not allow for normative policy evaluation in the specific context. The reason is as follows: FCVs can be characterized as a perfect example of a good with consumption externalities (also called adoption externalities), as defined by Katz and Shapiro (1985): "(P)ositive consumption externalities arise for a durable good when quality and availability of postpurchase service for the good depend on the experience and size of the service network, which may in turn vary with the number of units of the good that have been sold" (p. 424). The more FCVs have been sold (i.e., the higher the so-called user base), the more hydrogen filling stations and maintenance facilities will be set up, making a FCV more valuable for later adopters. Katz and Shapiro (1985, 1986) and Farrell and Saloner (1985, 1986) introduce a general theoretical framework to analyze welfare and strategy implications in the presence of adoption externalities. It is applied to show that usually two equilibria exist: an adoption and a non-adoption one. The non-adoption equilibrium can also be interpreted as a lock-in situation, with persistence of the old technology. The adoption equilibrium can only be reached if consumers expect a high enough future user base, so that they would benefit from being part of that user base; and it is assumed that firms have some influence on these expectations.

Usually, introduction strategies for new information technologies are analyzed within that framework. There, it is assumed that the utility associated with a product is the sum of a user base dependent component (utility from compatibility) and a direct use component. The direct use component is usually higher for the new technology, compensating for the missing user base at the very beginning. But in the case of FCVs, the (additional) direct use value is negligible, and consumers who make buying decisions consider the compatibility with the current refueling system and not with the future one. Thus, non-adoption would be the only reasonable equilibrium, and the result is basically another description of the earlier mentioned chicken and egg problem.

Within the neoclassic framework, evaluation of different potential policies to promote the transition to the adoption equilibrium (if it is preferred, e.g., due to reduced environmental impacts) in terms of transition speed is impossible. The development of the share of adopters or the duration of the transition cannot be derived in the static setting of adoption and non-adoption equilibria. Yet, an analysis of the transition process is crucial, as for car technologies it might take decades between introduction and full penetration, so that success of different transition policies might vary substantially. Another drawback of most neoclassical models is that consumers, producers, and also products are assumed to be homogenous. In reality, consumers are heterogeneous not only with respect to preferences for a wide range of car characteristics, but also with respect to refueling needs, i.e., their need for compatibility varies.[7] Car manufacturers differ in size, profitability and research success; their products might be similar in a broad sense of functionality, but are certainly not perceived as homogeneous.

The drawbacks of the traditional framework imply the advantages of the agent-based modeling approach. Agents can be heterogeneous in characteristics and behavior. The development of "macro" variables (e.g., the penetration rate of the new technology) during a transition period can be studied. They emerge from dynamic interactions and decision making of agents on the "micro" level.

In *Simulating the Adoption of Fuel Cell Vehicles*, the first paper, I start with an outline of the simulated behavior of the agents. The decision making of car producers and consumers is explicitly modeled. A rather simple feedback between newly registered FCVs and oil companies setting up hydrogen outlets at existing filling stations represents the main adoption externality. The government taxes conventional vehicles and increases the availability of hydrogen through public infrastructure programs. Combinations of tax and infrastructure policies are the exogenous drivers forcing an adoption of FCVs.

The model is calibrated to represent the main features of the German compact car market as a potential segment for introduction of the new technology. The different policy combinations are compared with respect to their success in promoting diffusion and their impact on consumers, different car producers, and on the concentration in the market. Consumers are adversely affected by the tax, but benefit from public infrastructure investments. Large producers tend to gain from any fast diffusion policy and are the first to switch the production of FCVs. They can increase their market power during the diffusion process at the expense of small producers who are, thus, likely opponents of FCV promoting policies. These impacts increase with the size of the public infrastructure program. They are ignored by studies that narrowly focus on costs of hydrogen infrastructure, which, therefore, tend to underestimate total costs.

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[7] Already Katz and Shapiro (1985) identify the missing representation of consumer heterogeneity as a limitation of their approach.

The second paper (*Learning by doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles*) extends the previous model by implementing dynamic cost reductions. The assumed learning rate, which is defined as the percentage reduction of costs per doubling of cumulative production, turns out to be a critical parameter. If learning effects in fuel cell technologies are low, diffusion is likely to fail, but with high learning, diffusion is projected to be extremely fast. Moreover, in the presence of learning by doing, success of diffusion depends on the length of the producers planning horizon. The model extension also allows for learning spillovers, i.e., producers may gain from learning effects of their competitors. In the case of FCVs, spillovers are likely, because some producers already established joint research programs and use common sub-contractors that deliver fuel cell parts or hydrogen tanks. The car industry in general is characterized by technology clusters that facilitate spillovers additionally. Learning spillovers increase the speed of diffusion. But spillovers affect producers differently, depending on whether they tend to be first movers, early followers or switch rather late. A government should take this effect into account if it considers promoting spillovers, e.g., by establishing public private partnerships with several producers in fuel cell development. Moreover, learning by doing may create a substantial first mover advantage. If a government seeks to protect this advantage in case of a national technological leader (e.g., in order to increase export potentials), it might face a policy trade-off between fast diffusion of an environmentally preferred technology due to spillovers and a relatively stronger economic position of a national producer.

A shortcoming of the modeling approach applied in the first two papers is the oversimplified link between FCVs and the build-up of hydrogen filling stations. Some filling stations offer hydrogen at the very beginning due to demonstration projects. Then, oil companies basically increase the number of hydrogen outlets if more FCVs are registered (the actually modeled feedback is slightly more complex). But the decision to invest into a hydrogen pump depends on the regional hydrogen demand in the “catchment” area, i.e., geographical differences matter. Equally simplified is the consumers' notion of fuel availability that is derived just from the share of filling stations with a hydrogen pump. In reality, consumers are likely to judge fuel availability on personal perception of hydrogen stations during their trips rather than statistics; and again, regional differences are decisive.

Modeling of interactions between initial FCV drivers and hydrogen stations in a geographic context constitutes the core of the third paper which presents *A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations*. It follows an approach taken by Stephan and Sullivan (2004) who analyze hydrogen infrastructure build-up in a hypothetical urban area, in which simulated agents make repeated trips to a working place and some leisure trips. But now that driving ranges of the latest FCV prototypes are hardly worse than those of conventional cars, trips within cities seem to be unproblematic anymore. Actually, for FCVs to step out of the niche of vehicles with a local application area as, e.g., taxis, buses or deliverers, refueling at trunk roads seems to be crucial to connect initial small scale urban hydrogen systems. Thus, the model presented here, simulates long distance trips. It is calibrated, so that the individual trips of the agents add up to observed traffic flows on German trunk roads.

In a study for *Linde AG*, Hart (2005) suggests a "HyWay-ring" of 30 hydrogen pumps at existing filling stations connecting major German car production clusters and cities with hydrogen demonstration projects. On the ring, the distance between the stations does not exceed 50km. The efficiency of this initial distribution is tested with the model. It is demonstrated that perceived fuel availability, which (by assumption) drives the adoption of FCVs, can be increased with alternative distributions of the initial 30 hydrogen outlets at trunk roads. Thus, the model allows maximizing the efficiency of upfront infrastructure investments, in order to overcome the chicken and egg problem at low costs. Moreover, it is shown that the maximum distance between two hydrogen stations that consumers consider as sufficient hydrogen coverage determines the optimized initial distribution.

The main assumption of the first three papers in this thesis is that the government selects and promotes FCVs and hydrogen as the most promising fuel/vehicle combination to eliminate local emissions and to reduce oil dependence and GHG emissions in the long-run. The last paper, *Flexible transition strategies towards future well-to-wheel chains: an evolutionary modeling approach*, challenges this assumption for two reasons. Firstly, during a transitional period, in which hydrogen would primarily be produced from fossil fuels, total well-to-wheel (WTW) GHG emissions might temporarily increase. But without short term environmental benefits in terms of GHG emissions, costly hydrogen/FCV policies might be difficult to communicate.[8] Secondly, the direct transition to hydrogen and FCVs would require changes in fuel production, distribution and vehicle technology at the same time. Such a system change can be considered a "technological discontinuity" as defined by Tushman and Anderson (1986). It would require not only high technological investments, but also retraining of repairmen, changes in the institutional environment (e.g., safety regulations), new supplier/producer relations, etc. Therefore, successful technological transitions in the past were usually stepwise changes in subsystems.

Hence, transition paths towards hydrogen and FCVs explored in the fourth paper involve bridging technologies, such as FCVs with an onboard reformer that can be fueled with gasoline using the existing infrastructure. A transition step that changes the technology of a subsystem is only acceptable if it is beneficial in terms of WTW GHG emissions.[9] The methodology follows an analogy to the fitness landscape model in evolutionary biology. Technological changes are only "selected" if the fitness of the system improves (here, if GHG emissions are reduced).[10] This methodology has been applied to describe technological change in a variety of complex technological systems; examples are airplanes (Bradshaw, 1992), wireless telecommunications (Levinthal, 1998) and steam engines (Frenken and Nuvolari, 2004). In the context of the WTW system, transition can actually lead to lock-in into a suboptimal system. Therefore, the

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[8] Given the advancements of end-of-the-pipe technologies together with cleaner conventional fuels due to continuous intensification of regulation, e.g., in the EU, local emissions alone would probably not justify a switch to hydrogen.

[9] WTW studies provide estimates for GHG emissions and energy requirements per vehicle kilometer of certain energy source, car fuel, and vehicle technology combinations.

[10] Transitions based on reductions of well-to-energy requirements are also explored. They do not necessarily end in systems with hydrogen and FCVs.

focus of the paper is on identifying initial transition steps that do not predefine the transition path later on and are therefore considered flexible. Data from existing WTW studies suggests that if GHG emission reductions are the driver of change, a general transition from gasoline to diesel is advisable. That transition offers the highest amount of different paths to the emission optimum, which is characterized by hydrogen produced from biomass and used in FCVs. If, alternatively, WTW energy requirements should be reduced, changes in vehicle technologies are most flexible. They even allow for a later change in objectives towards GHG emission reductions.

The concepts employed in the four papers have not yet been applied in the specific contexts. The models provide valuable insights into transition dynamics and potential policies. Shortcomings inherent to the approaches together with simplifying assumptions and shortcuts necessary for operability, however, confine the validity of the results. The main results and limitations are summarized in a concluding section at the end of this thesis together with potential remedies and extensions as promising starting points for future research.

I

Simulating the Adoption of Fuel Cell Vehicles

Abstract. Supply security and environmental concerns associated with oil call for an introduction of hydrogen as a transport fuel. To date, scenario studies of infrastructure build-up and sales of fuel cell vehicles (FCVs) are driven by cost estimates and technological feasibility assumptions, indicating that there is a "chicken and egg problem": Car producers do not offer FCVs as long as there are no hydrogen filling stations, and infrastructure will not be set up, unless there is a significant number of FCVs on the road. This diffusion barrier is often used as an argument for a major (public) infrastructure program, neglecting the fact that the automobile market is highly competitive and car producers, consumers, and filling station operators form an interdependent dynamic system, where taxes influence technology choice. In this paper, an agent-based model is used that captures the main interdependencies to simulate possible diffusion paths of FCVs. The results suggest that a tax on conventional cars can successfully promote diffusion even without a major infrastructure program. However, consumers and individual producers are affected differently by the tax, indicating that differently strong resistance towards such a policy can be anticipated. Moreover, there is evidence that some producers might benefit from cooperation with filling station operators to generate a faster build-up of infrastructure.

JEL classification: O33, D11, D21, L92

Keywords: Diffusion Process, Agent-based Modeling, Hydrogen Economy, Alternative Fuel Vehicles

1. Introduction

Every large car producer has developed a fuel cell vehicle (FCV) that has already left the laboratories and is being tested in daily life situations. Also, some fleet tests of buses and taxis have been established. Technological issues regarding, e.g., capacity of the tank, safety of refueling or reliability of the fuel cell under extreme temperature conditions seem to be solved or at least solvable in the near future.[1] In the industrialized countries, an increasing demand for hydrogen required by a significant number of FCVs could be satisfied using well-developed commercial hydrogen production technologies such as steam reforming of natural gas (methane), partial oxidation of heavy oil, biomass gasification, methanol reformation, and electrolysis.[2] Put together, a hydrogen-based transportation system is no longer a future vision, but should rather be considered as an option - an option involving a long list of costs and benefits.

Short run benefits would be the reduction of externality costs from local air pollution and noise reductions in cities implying health improvements. Long run benefits would be a reduced dependence on oil imports from instable world regions and - depending on the energy mix used for the production of hydrogen - a lessening of damages associated with climate change (Barreto et al., 2003). Research into a monetary valuation of these cost reductions is rare. To our knowledge, Ogden et al. (2004) were the first to provide a full societal lifecycle cost analysis for different drive trains that includes externality costs for local air pollutants, greenhouse gases (GHGs), and even oil supply security, which is approximated by the costs for the United States of maintaining a significant military capability in the Persian Gulf region.[3] There are high uncertainties associated with the extent and value of externalities. But for rather conservative assumptions regarding the magnitudes of the externalities, they found that hydrogen fueled FCVs offer clear advantages over all compared fuel/engine combinations. Ogden et al. (2004) conclude that this result justifies the major efforts of automakers to commercialize such vehicles. The high current externality costs of transport, together with a generally positive attitude in the media towards fuel cell technology as being "compact, silent, efficient, and emission-free" (Farrell et al., 2003, p. 1357), suggests that governmental action is not only advocated but also likely to happen.

These benefits must be weighed against the costs associated with the fuel cell technologies, the generation of hydrogen and its distribution infrastructure. The literature to date is dominated by technological feasibility studies that analyze different

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[1] For a detailed description of the history of fuel cell applications as well as current technologies used by major automakers, see McNicol et al. (2001). Recent technological breakthroughs are discussed in Lovins (2003).

[2] Such infrastructure scenarios can be found in Thomas et al. (1998), Moore and Raman (1998), Ogden (1999a, 1999b, 2005), Barreto et al. (2003), Stromberger (2003).

[3] Mercuri et al. (2002) calculate social benefits for a small-scale introduction of FCVs in the city of Milan based on the ExternE approach described in Friedrich and Bickel (2001). Schultz et al. (2003) provide a first approximation of the total atmospheric impacts of a major switch to hydrogen (reduction in GHG emissions together with an increase of H_2 in the atmosphere due to leakages in the distribution system), which could be used as input for a detailed benefit valuation with respect to climate change.

scenarios of the development of the number of FCVs on the road, based on estimates for the costs of fuel cell production (see references on infrastructure in footnote 2). The standard approach is to estimate the demand for hydrogen implied by the number of FCVs. Then, production and distribution costs are computed using current costs as a starting point and scale effects are implemented, such that unit costs usually go down with increasing demand. This approach is valuable when it is used to explore the trade-off between infrastructure costs and environmental benefits. There is major consensus in these studies that building up a hydrogen infrastructure at low costs is only possible if hydrogen is mainly produced using steam reforming of natural gas. In that case, the overall (well-to-wheels) emissions of GHGs per vehicle kilometer are only negligibly lower than those of an internal combustion engine vehicle (ICEV), which is assumed to be further optimized with respect to energy efficiency and emissions (EC-JRC, 2006). Thus, a significant reduction of GHGs through shifting to a hydrogen-based transportation system requires regenerative energy sources to generate the hydrogen, which would be costly.[4]

However, these studies have a very narrow focus on infrastructure costs, in order to provide policy makers with an estimate of the resources needed to overcome the so-called chicken and egg problem of hydrogen technologies, which implies that car producers are not willing to offer FCVs as long as there are no filling stations providing hydrogen. On the other hand, a hydrogen infrastructure will not be set up, unless there is a noticeable demand generated by a significant number of FCVs on the road. The strategy implied by infrastructure cost studies to overcome the problem boils down to public expenditures that are large enough, so that 10-15% of the existing filling stations provide hydrogen – a share that is usually considered (based on Sperling and Kitamura, 1986) to be high enough, so that fuel availability becomes only a minor parameter when consumers decide on what kind of car to buy. A cost estimate for reaching that share of stations is only of limited value, because such a major governmental interference would be unprecedented and is considered unlikely. Building up the infrastructure would not only involve setting technological standards very early, but also requires car producers to offer enough FCVs at a reasonable price, requirements that may be prohibitive. Finally, in times of severe budget constraints, major public infrastructure programs are difficult to put on the agenda.

In this paper, an alternative strategy is explored to overcome the chicken and egg problem. As a starting point, it is assumed that a government is likely to use familiar policy instruments to promote the diffusion of FCVs: a tax with tax exemptions (or alternatively subsidies). In most industrialized countries, cars are taxed based on some sort of pollution index, with lower taxes on less polluting vehicles. In the 1980s, tax incentives in favor of low emitting cars and unleaded gasoline successfully promoted 3-way-catalytic-converters. In Germany, for example, it took only five years until more than 75% of all newly registered cars running on gasoline were equipped with the new technology (Westheide, 1998). Of course, the set up of a hydrogen infrastructure is a much more pronounced step than offering unleaded fuel, and switching from internal

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[4] Hydrogen might, of course, be generated using nuclear power, but this would require a wide public acceptance of the technology.

combustion engines to fuel cells requires many more changes to the whole vehicle concept than adding a catalytic converter and a Lambda-sensor. However, the pattern is the same. In order to make consumers demand the new technology, they must be compensated by a tax exemption for the inconvenience of limited refueling opportunities and a higher (pre-tax) purchase price due to higher initial production costs. The advantage of this strategy is that the government requires much less information, because car producers will start producing FCVs, when they observe a significant demand, given a low share of hydrogen outlets (i.e., well below the above-mentioned 10-15%), which will be built in demonstration projects anyway.[5] But, as we will show in this paper, the main drawback of tax incentives is that they asymmetrically affect the agents involved and are therefore likely to raise strong resistance by disadvantaged agents.

We use an agent-based model (ABM) to address the complex dynamics in the highly interdependent triangle of consumers, car producers and filling station owners. The general framework of modeling producers and consumers simultaneously follows Janssen and Jager (2002). Compared to their model, we use a simpler representation of the consumer part, but apply a more elaborate producer part, which is based on Kwasnicki (1996, chapter 5). Firstly, we analyze combinations of two different tax and three different infrastructure scenarios. The tax scenarios represent extreme cases, one "shock tax" scenario with an instantaneously high tax on ICEVs and a "gradual tax" scenario in which agents can smoothly adjust to the new circumstances. Later on, we model equivalent subsidies for FCVs. The infrastructure scenarios either assume that there is some exogenous (public) build-up of H_2-stations (called "exogenous H_2"), or alternatively no exogenous built up ("no exogenous H_2") or pronounced public activities ("high exogenous H_2").

We find that, given our central case parameterization, all scenarios show a successful diffusion of FCVs for a reasonable tax rate, i.e., the tax would be sufficient to overcome the chicken and egg problem. Furthermore, the simulations suggest that if consumers were to decide between the "two evils" associated with the two tax scenarios, they would prefer the gradual tax and would appreciate a rather fast public infrastructure program. Moreover, the shock tax increases concentration, so that large producers raise their market power at the expense of small producers. It turns out that large producers, on average, tend to switch earlier to the production of FCVs than small producers. Since public infrastructure build-up accelerates the diffusion of FCVs, this also benefits large producers and increases their market power. Thus, the model results indicate that studies that narrowly focus on costs of infrastructure programs tend to ignore the fact that such programs affect producers asymmetrically, so that existing imbalances of market shares might be enhanced. As the car market is of great economic importance in industrialized countries, ignoring such effects might underestimate the socio-economic costs of public infrastructure programs.

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[5] The government has to make sure that there are at least some hydrogen outlets in the beginning, because there cannot be a demand for FCVs if there are literally no refueling options.

The paper is organized as follows. Section 2 gives a brief overview of the main features of the model. Section 3 sketches the assumptions underlying the scenarios analyzed. Section 4 presents the results of the model experiments, and Section 5 is dedicated to a sensitivity analysis. Section 6 concludes.

2. The model

In this section, we will outline the main assumptions and dynamics that drive the model. A complete description of the equations can be found in Appendix A. The core modeling of the utility consumers associate with different but comparable products (here cars) follows Janssen and Jager (2002). Consumers buy the car that maximizes their utility according to their preferences relative to the price. They are heterogeneous with respect to their preferred car characteristics and are, to some degree, influenced by their neighbors' buying decisions. Following the network literature, we use the expression "neighbors" as a synonym for friends, colleagues or relatives, i.e., all groups that might have an influence on the agent due to proximity. We extend the determinants of the buying decision of the consumers by fuel availability, measured by the share of filling stations with an additional H_2-outlet. If there are no such stations, consumers will not buy a FCV, but with an increasing share they are more likely to consider one. The consumers respond differently to changing refueling conditions, as they are heterogeneous in their refueling needs. This incorporates Dingemans et al.'s (1986) view that consumers considering a car, which is used mainly locally, e.g., for shopping trips or the daily way to work, are most likely to be early adopters of alternative fuel cars compared to, say, a traveling salesman driving regularly in unfamiliar regions.[6]

The supply side of the model is based on Kwasnicki's (1996, chapter 5) behavioral model of producers. His core model is intended to approximate the complex decision making process on the producer level in situations in which their knowledge of the current and future behavior of competitors is limited, and uncertainties due to these limitations cannot be evaluated in terms of probability distributions. The producers are repeatedly confronted with different concentration in the industry and varying competitiveness of their product. Kwasnicki (1996, chapter 6) demonstrates that - despite these uncertainties - an industry in which producers apply his behavioral model, generates several well-known patterns. Among other things, the model shows that the more competitors there are in the market, the more prices approach marginal costs and profits go to zero; and decreasing costs lead to higher concentration.

In the model at hand, the producers offer cars that are heterogeneous but close substitutes. Thus, the producers act as price setters with limited market power

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[6] The heterogeneity of refueling needs seems to be particularly adequate in the context of the choice of a second car if there is access to the first car for long distant trips. Brownstone et al. (1996) estimate car demands and find that one-vehicle households prefer a gasoline vehicle to an alternative-fuel vehicle. For two-vehicle households, this effect vanishes. According to the year 2000 census, more than 55% of the households in the US have more than one car (http://www.census.gov). For European countries, numbers are lower but nevertheless significant (e.g., in Germany more than 25% of all households have more than one car; INFAS and DIW, 2003).

depending on their market share. Given the uncertain behavior of their competitors, they cannot perform intertemporal expected profit maximization. Instead, they optimize a weighted average of expected revenue and market share in each period. The maximization is subject to capital/investment constraints, although they have (limited) access to the capital market. Each producer can either produce ICEVs or switch to the production of FCVs. The switch is made as soon as FCVs imply a higher expected value of the objective function. Since the producers estimate the demand for their car, the decision to switch is mainly determined by information about the refueling needs of their customers and fuel availability. Moreover, if producers perform badly (according to their market share), they switch if the market leader is already producing FCVs, i.e., there is some imitation.[7] Finally, the producers are doing R&D, in order to change the car characteristics according to the consumers' preferences.

Supply and demand are matched in the following manner. Producers set prices first and adjust their production capacity, but they do not actually produce before a consumer orders. So, they do not produce more than is demanded (no excess supply) and, therefore, there are no inventories. This implies that producers which overestimated the demand for their products are penalized by their overinvestment in capacity but not by high variable costs.[8] But if a producer has underestimated the demand for his product (excess demand), production capacity cannot be extended within the period. The classic reaction towards excess demand would, of course, be an increase in prices. But in the model, it is assumed that the length of a period is too short for such an adjustment. If a consumer cannot get his favorite product, because it is sold out, he will choose a less preferred product and can actually end up with nothing, having to wait for the next period.

The final component of the model is infrastructure. Filling station owners react towards the demand generated by the number of FCVs sold. They increase the share of filling stations with H_2-outlet if they observe high increases in the share of FCVs within the number of newly registered cars.

The model is calibrated so as to mimic some of the main features of the German compact car segment. The choice of the number of agents and the parameter values are described in detail in Appendix B. Note that the number of country/segment specific parameters is rather low, so that the model could easily be applied to other markets.

3. Scenario assumptions

The model is run for 100 periods, which could be thought of as quarters. We introduce the policy at time 20 (after initialization effects are negligible), which is set to be the year 2010. Given such a scenario, we cover the period 2010 to 2030, which is

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[7] Similar imitating behavior may already be observed with respect to the number of FCV related patents, which increased after the showcase of the *Daimler-Benz* FCV-*NECAR II* in May 1996 (van den Hoed, 2005).

[8] An equivalent assumption would be that - as long as there are no scale effects – overproduction can be sold at marginal costs at a foreign market or as out of date models in later periods.

usually considered to be the time span in which FCVs can step out of a small niche into the mass market. We (arbitrarily) assume that, by the year 2010, independent of the producer the variable costs of producing an FCV are 10% higher than those for a conventional car with identical features (in the central case, we assume variable costs of 13,000EUR for an ICEV). This implies that, by the year 2010, major cost reductions due to learning or other scale effects have already been realized and we, therefore, do not allow for further economies of scale; the main reason is to keep the variety of dynamics low at the beginning.[9] Note that the cost difference refers to otherwise identical cars, i.e., the ICEVs must have, e.g., a very low noise level, good acceleration performance in city traffic, and automatic transmission - beneficial features usually associated with FCVs. Additionally, emission levels must be low, although environmental benefits alone are usually not considered to have a substantial impact on consumers' buying decisions (Steinberger-Wilckens, 2003). Besides higher variable costs, we, furthermore, assume that the productivity of capital employed for the production of a FCV is reduced by 25%, i.e., to change to the production to FCVs without increasing the capital stock limits the capacity by 25%.

As in Janssen and Jager (2002), we analyze two different tax scenarios. The shock tax is a sudden value added tax of 40% on conventional cars, introduced in the year 2010. Alternatively, the gradual tax is increased by 1% each quarter over a period of 40 quarters, so as to end up at the same tax level.[10] In addition to the purchase tax, this tax also represents the net present value (NPV) of all annual automobile taxes (ownership tax, road tolls), together with the NPV of the differences in fuel costs over the lifetime of the vehicle, where it is reasonable to assume that refueling with hydrogen will be less costly (after taxes) than gasoline/diesel. According to the data of yearly automobile taxes in European countries given by Burnham (2001), a rate of 40% seems to be at the low end of the range.[11] But this can be justified by the fact that, in the model, early adopters of FCVs are likely to use their car less than average, so that their savings in utilization taxes are also less than average.

A more realistic policy might be to also increase taxes on current cars at the same time (as it is common practice in many countries to promote less polluting cars). All else equal, this causes those consumers who would buy a FCV anyway to do so earlier. But the actual number of potential buyers, which is crucial for the introduction of FCVs, is determined by the relative tax advantage referring to the future (lifecycle) taxes of the new car.

The different tax scenarios (shock tax and gradual tax) are combined with scenarios on hydrogen infrastructure build-up. Generally, we assume that, by the year 2010, 3% of all filling stations offer hydrogen. Given that according to the *Association Européenne des Gaz de Pétrole Liquéfiés* (AEGPL, 2003), in 2003 about 15% of all refueling sites in Europe sold liquid petroleum gas, and at the current speed at which conventional gasoline stations are equipped with an additional compressed natural gas

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[9] However, scale effects are on the agenda for future research.

[10] We also analyze equivalent subsidy scenarios.

[11] Burnham's (2001) study is based on *Colin Buchanan and Partners* (CBaP, 2000), who report even higher annual taxes (implying higher lifecycle taxes). Note that total lifecycle taxes cannot be precisely measured, because they depend on the assumed discount rate, car type, utilization, and lifespan.

(CNG) outlet, this is not an overly optimistic assumption (see also EC, 2003). Following Stromberger (2003), we use the development of CNG outlets as a basis for our scenarios on the exogenous build-up of hydrogen infrastructure from year 2010 on; the reason being that equipping a conventional gasoline station with an additional CNG outlet seems to be the best approximation to adding an onsite steam-reforming unit. According to the *Bundesverband der deutschen Gas- und Wasserwirtschaft (BGW)*[12], the number of CNG stations in Germany grew by roughly 80 stations per year. For about 15,500 gas stations in Germany, this is equivalent to an increase of the share of CNG stations by 0.13% per quarter (while the share of newly registered CNG vehicles was well below 1%). In the "exogenous H_2" scenarios, we assume a slightly higher growth of hydrogen stations of 0.15% for two reasons. Firstly, there has been a major decline of the number of filling stations in the last decades, which is likely to go on for some more years. Thus, the same amount of modified gas stations implies a higher increase in the share of all stations. Secondly, it is reasonable to believe that a major tax policy in favor of FCVs would also be accompanied by policies favoring the installation of a hydrogen outlet (e.g., interest-free loans).[13] In our "high exogenous H_2" scenarios, we double the amount to 0.3% per quarter, but in either scenario we limit the increase of the share to 1.5%, i.e., no more than about 900 stations can be converted per year.

4. Results

Two tax scenarios times three infrastructure scenarios makes six different governmental policies. The following subsections show, how these policies will affect the penetration rate of FCVs, concentration (market power) in the market, the number of cars sold, and the producers' profits. Subsection 4.5 is dedicated to subsidies.

4.1. Diffusion of FCVs

The market share of FCVs within newly registered cars is the main benchmark to evaluate the different scenarios with respect to the reduction in externalities associated with ICEVs. Figure I-1[14] shows such diffusion curves for FCVs in the compact car segment for the six scenarios and Figure I-2 depicts the corresponding development of the hydrogen infrastructure. Figure I-1 shows that, in the central cases, there is no chicken and egg problem prohibiting diffusion. Independent of exogenous H_2 build-up, the shock tax immediately induces at least one producer to switch to the production of

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[12] The BGW (*Federal Association of German Natural Gas and Water Suppliers*) regularly updates sales data of CNG vehicles and filling stations at http://www.bundesverband-gas-und-wasser.de.

[13] The growth rate of 0.0015 applies for about 90 filling stations per year with the total number of filling stations around 15000.

[14] All graphs are averages of 100 realizations, in order to minimize the effects of random initialization and random processes during the evolution of the model. As we assume that diffusion takes place predominantly in the segment at study, which represents some 25% percent of the car market, the share of FCVs within all newly registered cars remains if the values in Figure I-1 are divided by 4. Note that the share of FCVs within the total stock of cars increases much slower and mainly depends on the lifetime of cars.

FCVs at year 2010 and these FCVs actually find customers. As should be expected, exogenous infrastructure build-up leads to higher penetration right from the beginning, ending up with higher market penetration of FCVs. Independent of the magnitude of exogenous build-up, the share of FCVs levels off at a similar magnitude. The reason is that, even after a major transition to FCVs, there still is room for a successful niche of ICEVs for consumers with high refueling needs. Only after an (almost) complete infrastructure built up, this niche will vanish.

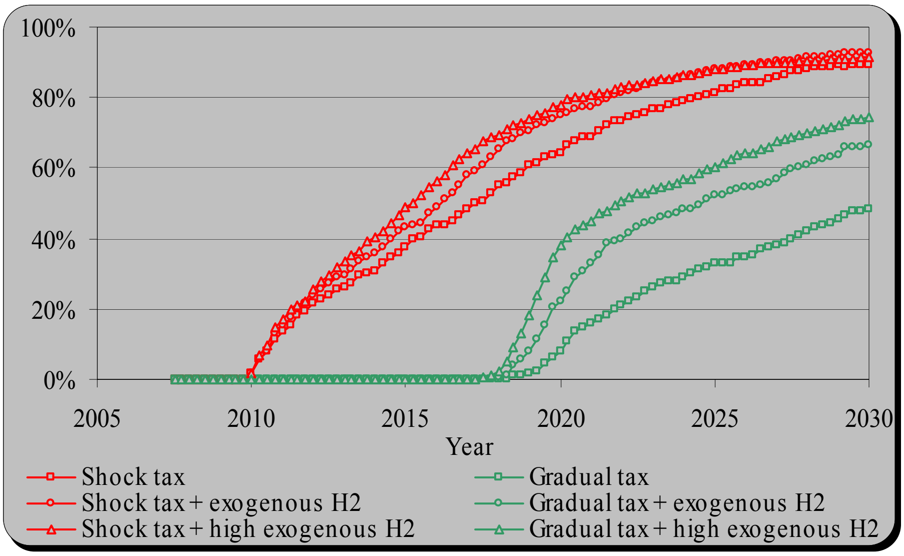

Figure I-1: Total share of FCVs sold (in compact car segment)

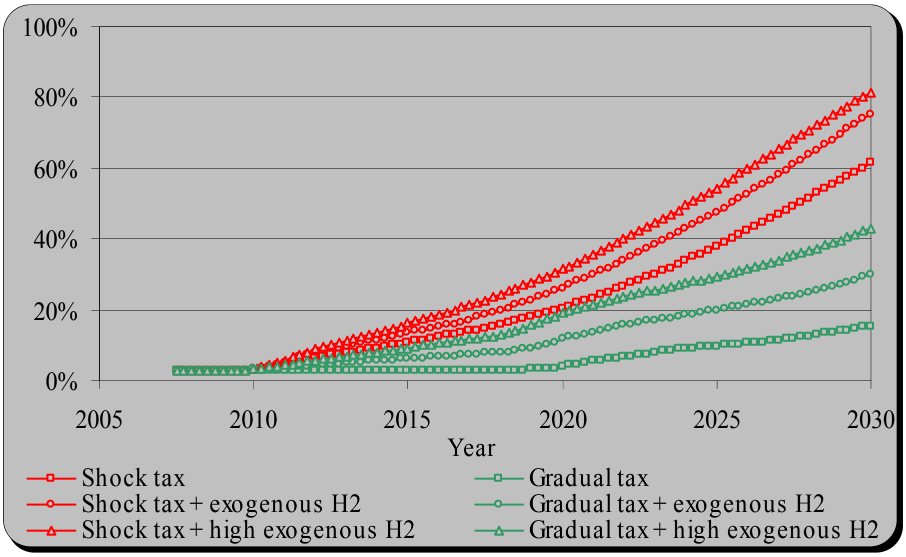

Figure I-2: Share of filling stations with H_2-outlet

The gradual tax cases are characterized by the fact that FCVs are hardly sold before 2020, as the tax has to reach a level of almost 40% before producers start switching to FCVs. The earlier take off in the scenarios with exogenous infrastructure build-up is model inherent, because both effects (infrastructure and tax) are jointly working in favor of FCVs. However, it is remarkable that, in those scenarios, the share of FCVs increases very quickly, such that by the year 2030 the shares are almost as high as in the corresponding shock tax scenarios. This can be explained as follows: The gradual tax lets a producer switch to the production of FCVs as soon as he expects to be better off by doing so. This increases the share of newly registered FCVs above zero (if the producer actually sells at least one) and thereby also increases the expectations of filling station owners, who react with equipping stations with H_2-outlets. The additional infrastructure build-up, together with the tax increase, makes it even more likely that another producer will switch. Thus, the system enters a self-reinforcing cycle. This cycle is more pronounced than in the case of a shock tax, because then producers with different "trigger tax rates" (i.e., the rates at which they decide to switch), say between 35 and 40%, all switch at the same time, and filling station owners only adjust to that one-time switch. The same reasoning does not apply for the comparison of the two scenarios without exogenous build-up, because, in the gradual tax case, it is only one year before the tax increase stops that the first producer switches to the production of FCVs. Thus, the two graphs are mainly similar with the exception of a time-shift, with a slightly more rapid diffusion in the shock tax case, which is due to the fact that the shock tax leads to a higher market concentration and large producers are more likely to switch to the production of FCVs than are small producers. These issues are addressed in the next sections.

4.2. Concentration

There are two main effects on market share. The objective function is constructed, such that small producers tend to set prices, so as to stay in the market, while large producers rather focus on revenue. On the other hand, large producers (i.e., producers with high market shares) influence consumers' preferences and, thus, are likely to increase their market power over time. Figure I-3 illustrates market power with the

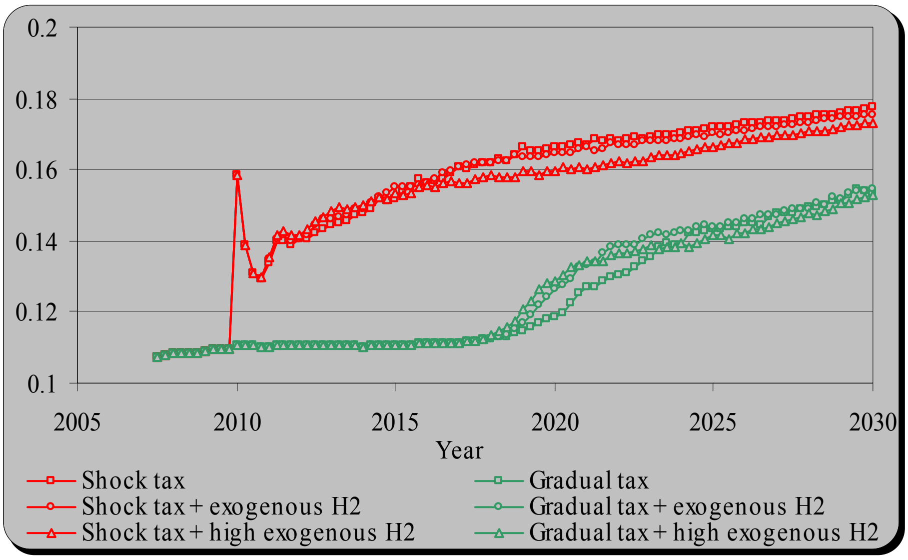

Figure I-3: Herfindahl-Index

Herfindahl-Index. It shows that, in the baseline scenario (without a tax), there is a slight tendency towards higher concentration, so that the influence on preferences operates in favor of larger producers. Now it might be surprising to note that, in the shock tax scenarios, there is a major up and downturn of the Herfindahl-Index right after the introduction of the tax. The explanation is as follows. Large producers have a greater impact on the average market price. Thus, they can better predict how many cars they will sell, now that the tax is in effect. Moreover, they have more accurate expectations in case they decide to switch. In contrast, small producers can basically only react. Thus, large producers can cope better with the sudden tax, resulting in the dramatic increase in the Herfindahl-Index. This peak is, then, overcompensated by the survival strategy of small producers, who react with very low prices to increase their market shares. It takes only a few periods until expectations and actual market shares match again and the system enters a mode with smoothly increasing market power. This latter effect arises, because producers that already manufacture FCVs have an after-tax price advantage and large producers are more likely to switch, as can be seen from Figure I-4. "Big and small producers" refer to the three biggest respectively smallest producers in the year before the introduction of the tax. So, the figure indicates that it actually rarely happens that one of the small producers starts producing FCVs over the time span considered (the lines regarding the small producers are virtually on the horizontal axis), while the big producers promote the diffusion of FCVs. The reason is probably the additional capital requirements, which are easier to finance for a large producer.[15]

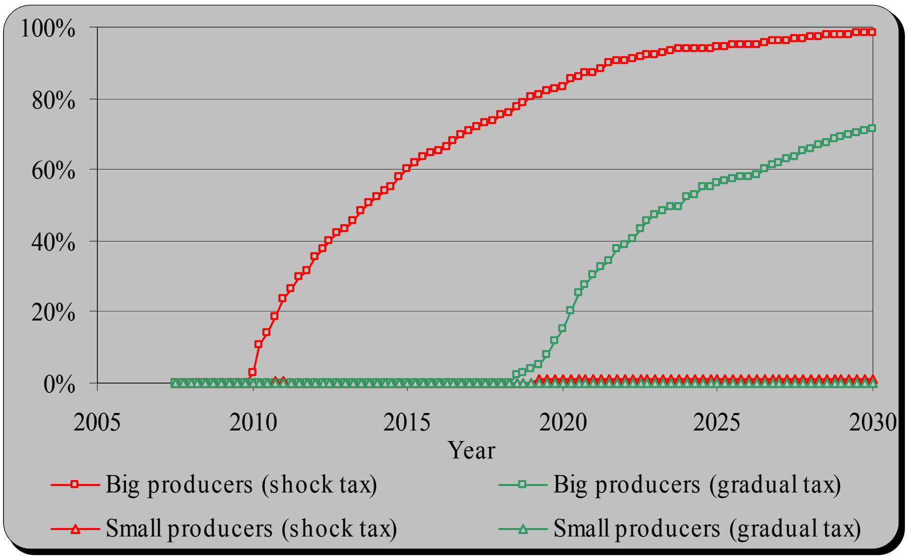

Figure I-4: Share of producers manufacturing FCVs

Turning to the gradual tax cases, Figure I-3 shows that market power is lower (compared to the no tax baseline) during the time the tax is rising without forcing any producers to switch. A likely explanation is that, since the total segment demand goes slowly down due to the increased after tax price (see also Figure I-5), this puts pressure

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[15] The debts of the big producers are actually increasing when they switch, indicating that capital requirements might indeed be the constraining factor preventing small producers from making FCVs.

particularly on small producers, who react with price cuts generating higher market shares. But once some (large) producers start switching, concentration increases for the same reasons as in the shock tax scenarios.

In both tax scenarios, exogenous infrastructure build-up engages large producers to switch earlier, so that concentration also increases faster. This is an important notion, as it suggests that public infrastructure programs tend to enhance existing imbalances in market shares, i.e., promote market power. Ignoring this effect might lead to an underestimation of the socio-economic costs of an infrastructure program, given the economic importance of the car market in industrialized countries.

In the next sections, we focus on how the different agents would rank the different scenarios. We consider consumers as a whole and separate big and small producers. Our hypothetical question is, which tax and infrastructure program combination they would pick if the government had committed itself to promote at least some diffusion of FCVs. This provides the government with a first approximation from which side it should expect particular resistance to a specific program.

4.3. Impact on consumers

Figure I-5 shows the negative effect of the taxes on the number of cars sold, an indicator of the impact on consumers. We conclude from the graphs that, independent of their time preference, they would prefer the gradual tax to the shock tax to avoid the sharp immediate drop in the number of cars sold.16 But in any case, consumers are hit less hard if there is exogenous infrastructure build-up. However, consumers are

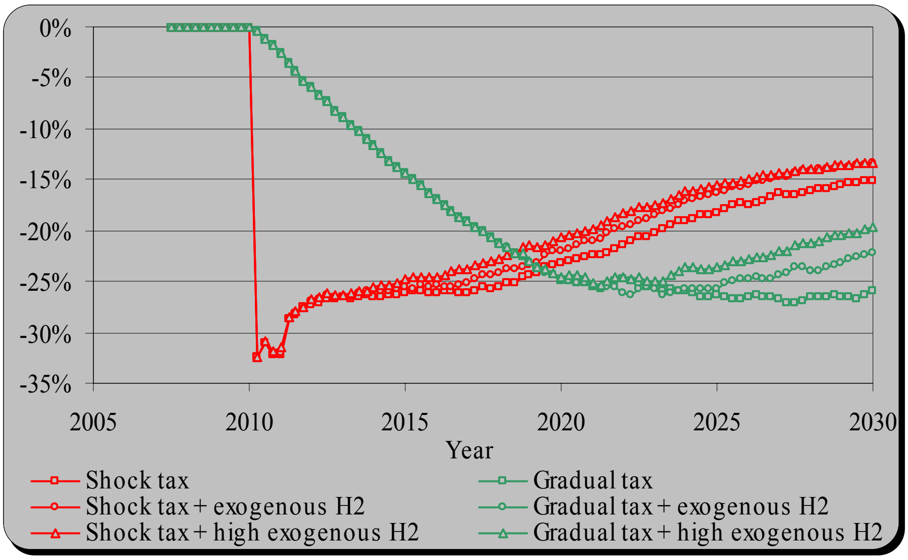

Figure I-5: Change in the sum of all cars sold (relative to no tax)

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[16] The same ranking of preferences should arise if we would try to derive a consumer surplus measurement from equation (25) in the Appendix. But we refrain from doing so to avoid the impression that the current partial model could be used to actually trade off consumer surplus, producer surplus (profit), tax revenue and environmental benefits in a cost-benefit approach.

negatively affected in two respects. Besides the direct price increase due to the tax, which theoretically should level off as soon as all producers switched to FCVs, there is also the enhancement of market power described in the previous section, and this effect is persistent.

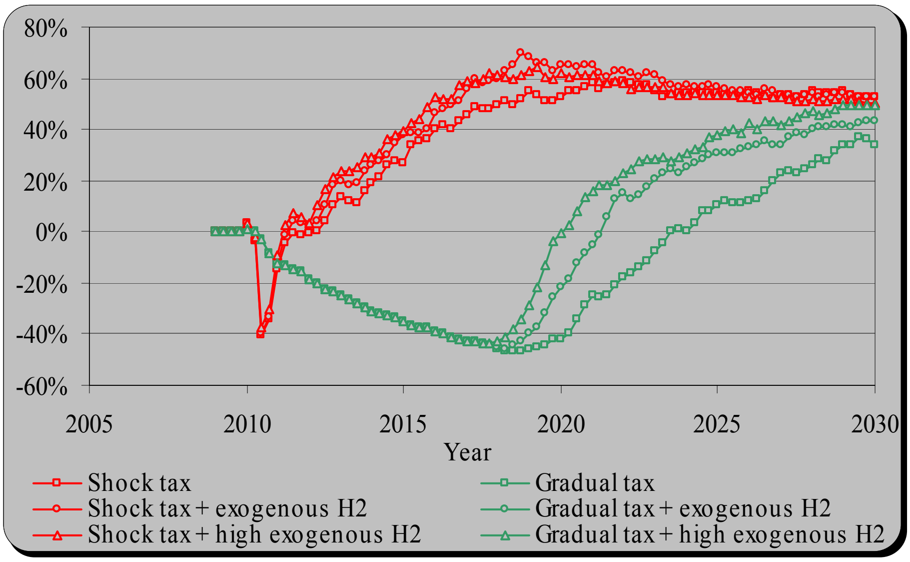

Figure I-6: Change of total profit of three biggest producers (relative to no tax)

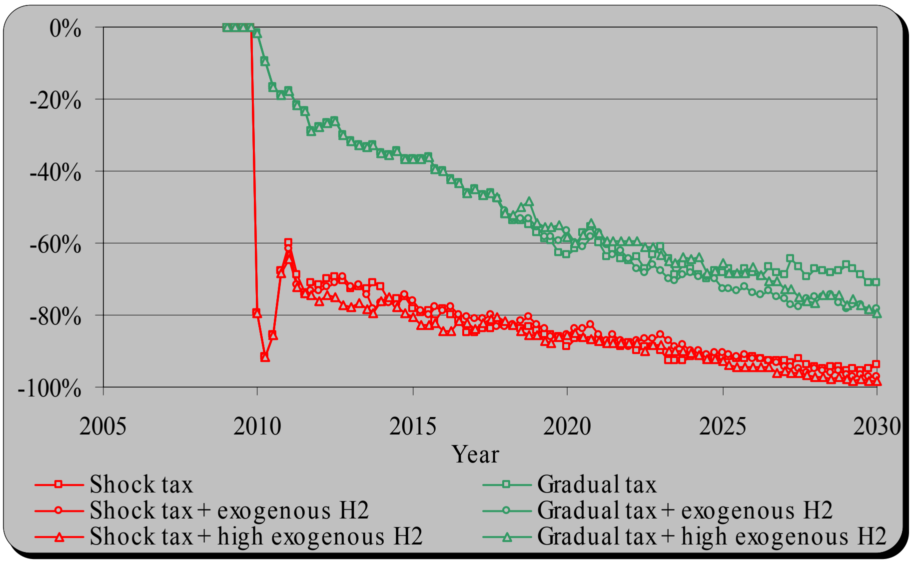

Figure I-7: Change of total profit of three smallest producers (relative to no tax)

4.4. Impact on producers

The main effects on the producers follow from the results discussed above. Figure I-6 and Figure I-7 show the change in the sum of profits of the three biggest and smallest producers. In the shock tax scenarios, profits of both groups are hit by the introduction of the tax. Profits collapse, not only because revenues contract as demand shrinks, but also because the producers are overinvested, i.e., demand falls in excess of depreciation. Profits quickly recover, reaching the level they would have had without the tax within two years. Then, a major advantage of big producers comes into fore. Due to their increased market power, they can steadily increase their profits. This effect is much more pronounced if there is additional infrastructure build-up. This medium to long term gain of the big producers is mirrored by a further reduction of profits of the small ones.

For the gradual tax scenarios, profits go down smoothly and, here again, the large producers recover later on, as they start switching to the production of FCVs, whereas the small producers seem to be stuck in the production of ICEVs, and their profits go further down, although not as substantially as in the shock tax scenarios. It is remarkable that, in the gradual tax cases, the big firms are considerably better off with additional infrastructure, and this is once again at the expense of the small firms. So, the development of profits of the big and small producers suggests the following conclusion: If the big firms were to choose between the different scenarios, they would favor a shock tax, as long as their rate of time preference is not particularly high, because then they would want to avoid the significant drop of profits right after the introduction of the tax.[17] But no matter what tax is applied, the big firms are gaining from exogenous infrastructure build-up. This result matches with the real world observation that dominant producers in the German car market form alliances with oil companies to coordinate the development of a hydrogen infrastructure (see, e.g., Heuer, 2000). Small firms, on the other hand, would prefer a gradual tax without an additional infrastructure development. In other words, they have no interest in a policy that leads to a rather quick introduction of FCVs in the market.

4.5. A subsidy for FCVs

The main impact of the tax on ICEVs is the change in relative prices in favor of FCVs. Thus, a subsidy for FCVs should generally have the same impact on their diffusion as the tax on ICEVs. Figure I-8 shows the diffusion with a 40% ad valorem subsidy. Given today's already high taxes on car buying, ownership and usage, this case is equivalent to a situation in which, by the year 2010, the government decides that FCVs will be completely tax exempted over their total lifecycle ("shock subsidy") or that total tax exemptions are steadily increased ("gradual subsidy"). Compared with the tax, we see a more successful diffusion of FCVs. But this is implied by the fact that reducing the consumer price of the FCVs by the same percentage as in the tax case leads to a lower relative price of FCVs.

As production is quickly switched to the subsidized FCVs, consumers benefit from a higher number of car sales and would actually prefer the sudden subsidy. As in the tax cases, the production of FCVs is dominated by big producers, who, thus, can increase their market power and particularly gain from the sudden subsidy due to an earlier

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[17] Given the simulation results and a moderate discount rate, it would be actually rational for big producers to lobby for the introduction of such a tax. However, a strategy implying a significant near-term drop in profits would be difficult to explain to shareholders and, therefore, it is not likely to be considered by the management.

increase in profits. On the other hand, small producers, who are stuck in the production of ICEVs, suffer substantial losses.[18] Due to the apparently sudden diffusion of FCVs, these effects are rather independent of exogenous infrastructure build-up. Altogether, the subsidy leads to an extension of the market and would, therefore, be welcomed by consumers and those (big) producers who can quickly switch, but there are severe adverse effects for small producers, who are likely to oppose such a policy.

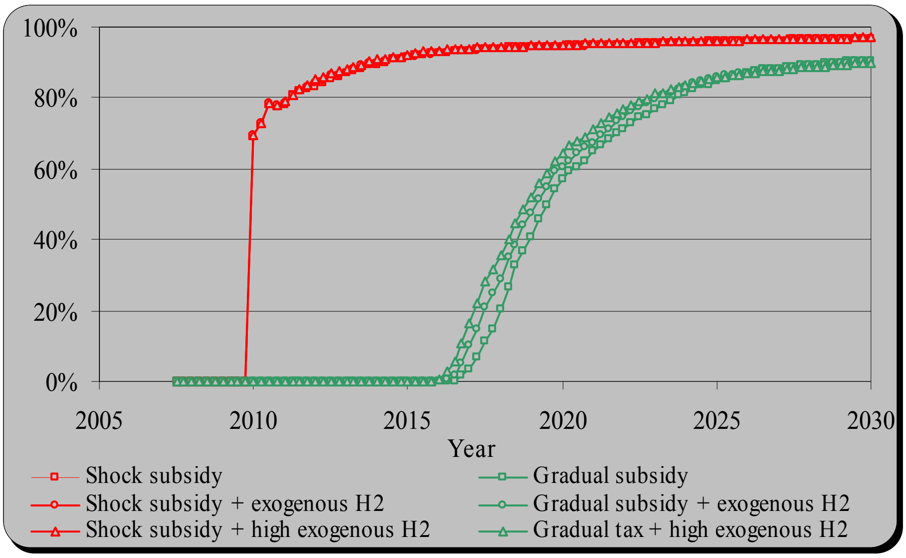

Figure I-8: Total share of FCVs sold (in compact car segment) with subsidy

5. Sensitivity analysis

The general pattern of results is robust, at least qualitatively, to changing the majority of parameters within reasonable bounds. For a start, the sensitivity analysis focuses on the main parameters defining the influence of fuel availability on the consumer decision. If the parameter $\gamma \leq 0$ gets close to zero, consumers require a high coverage of H_2-outlets before they consider buying a FCV.[19] In the central case, γ is set to –3. Figure I-9a shows that, if we change γ to –4, we observe a faster diffusion of FCVs, as consumers care less about fuel availability, while the opposite holds true if $\gamma =$ –2, i.e., the model behaves as expected.

The parameter ε_{own} is the own price elasticity of a specific car and is calibrated to be –3 in the central case. A higher (lower) price responsiveness of demand would *ceteris paribus* imply a higher (lower) relative price advantage of FCVs in case of a tax. The elasticity indirectly also determines the importance of fuel availability, because if consumers are extremely price sensitive, they are less worried about the share of H_2-

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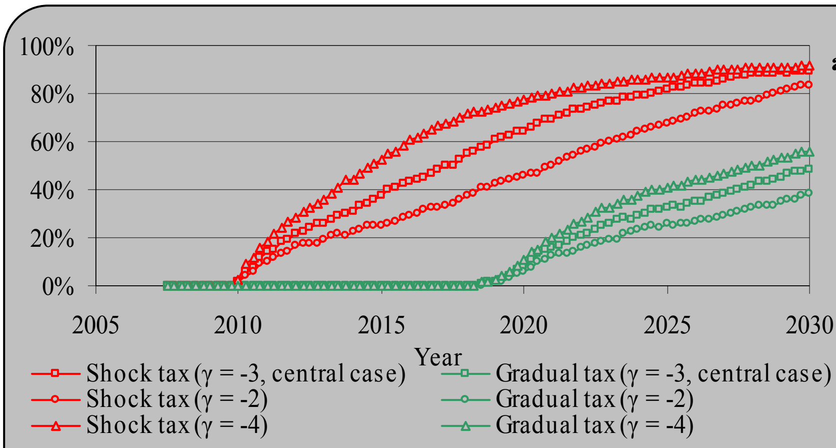
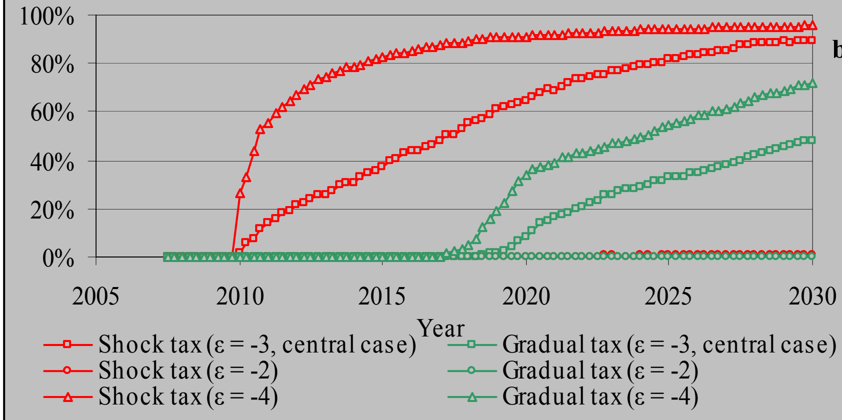
[18] The losses occur in the medium to long-term. In both, the shock and the gradual subsidy cases, the small producers gain for about 3 years, because at that time the first (big) producers switch to the production of FCVs, but sell fewer than before due to the lack of infrastructure.

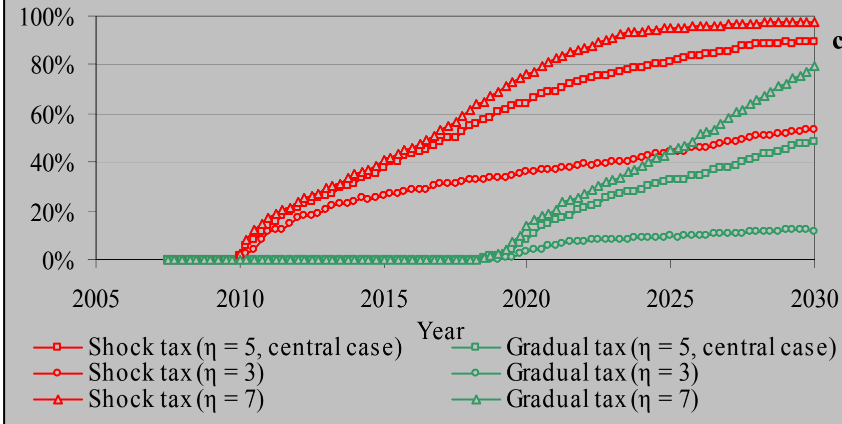
[19] For a detailed description of the parameters and the calibration see Appendix A and B.



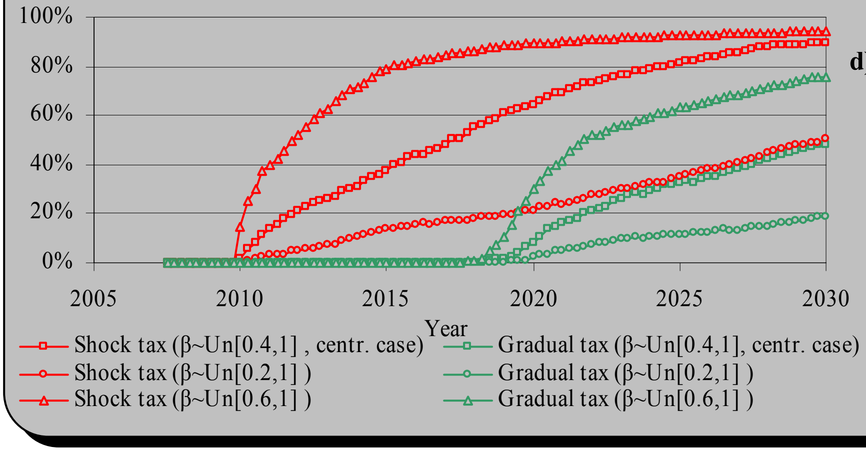
a) Sensitivity with respect to importance of fuel availability



b) Sensitivity with respect to own price elasticity



c) Sensitivity with respect to producers' objective



d) Sensitivity with respect to social influence

Figure I-9(a-d): Sensitivity of the share of FCVs sold

stations and straightforwardly react to a tax. From Figure I-9b one can see that the predicted diffusion is highly dependent on the assumptions regarding the own price elasticity. High price sensitivity (ε_{own} = -4) leads to extremely fast diffusion, whereas low price sensitivity (ε_{own} = -2) prohibits any diffusion, and we end up with the chicken and egg dilemma. In that case, the impact of the tax on the market is rather destructive, because the number of cars sold drops significantly without later recovering, and the profits of the producers contract. Thus, high uncertainty about the own price elasticity could indicate the use of a subsidy instead of a tax in order to avoid the adverse impacts on the market implied by a tax that is too low to successfully change behavior. Alternatively, a tax could be used that does not stop increasing unless a significant amount of FCVs enter the market. But it should be noted that, as discussed Appendix A, the central case value of ε_{own} is already rather low, so that, given the tax rates considered here, a situation without any diffusion is unlikely.

Apart from changes in the (relative) importance of fuel availability, we also test how the diffusion of FCVs depends on the underlying behavior assumptions regarding the producers. A high value for η implies that producers focus on their (relative) profits, whereas a low value implies a focus on market share. Figure I-9c shows that a profit (market share) focus promotes (hampers) fast diffusion. The choice set of the producers includes the price and the option to switch. If producers primarily maximize market shares, they set prices as low as possible (without making losses). In such a situation, switching production is unlikely to be valuable as long as consumers must be compensated for low fuel availability. The picture is different if the center of attention is profit. Then, producers are concerned about their absolute number of sales, instead of just their market share. At the same time, they try to keep their per unit margin as high as possible. With the tax, a producer who switches increases the price (but can still be cheaper after taxes than the competitors) and gets a higher per unit margin, which can offset the loss in sales implied by the low fuel availability.

Figure I-9d shows the sensitivity with respect to the parameter β_k, which defines the relative importance of neighbors on the decision of the consumers whether to buy an FCV or not (see Appendix A.1.1). The parameter is initialized by a random draw from a uniform distribution for every individual. For β_k close to 1, a consumer is rather innovative, i.e., open-minded with respect to new products, and, therefore, focuses on the personal utility. Consumers with a β_k close to 0 are followers, highly influenced by the decisions of their social environment. In the central case, the lower bound of β_k is set to 0.4, so as to rule out the possibility that some consumers totally ignore their own preferences, which seems to be unrealistic for a major consumption decision, such as a car. The results in Figure I-9d are obtained by varying the lower bound of the uniform distribution. A lower bound of 0.2 means that consumers, on average, put more weight on what their neighbors are driving. This hampers diffusion significantly, because innovators who would choose a FCV even though their neighbors all drive ICEVs are rare. Vice versa, a lower bound of 0.6 implies, on average, more innovators and, therefore, leads to much faster diffusion.

We do not present results on how the parameter changes affect the interest groups analyzed in Section 4, because the results are robust with respect to the issue that big producers drive the diffusion of FCVs. Given that, the impacts can straightforwardly be derived from the diffusion curves of Figure I-9(a-d). Big producers gain at the expense of small ones the faster the adoption of FCVs proceeds; and a fast adoption goes together with rather low average after tax prices and high total numbers of sales benefiting the consumers.

Finally, we want to analyze, how the speed of diffusion is affected if some of the consumers do what Janssen and Jager (2002) define as "social comparison". If consumers face a high degree of uncertainty, e.g., with respect to car characteristics, prices and so on, they only evaluate the car that is driven by the majority of their neighbors and compare it with the utility they would get if they bought the latest version of their old car again (see Appendix A.1.1). This means that they reduce their decision space to directly perceivable products. In the social comparison cases in Figure I-10, on average some 50% of the consumers actually do social comparison. We can see that reducing the decision space increases the speed of diffusion at the beginning. The reason is that consumers stick to their brand or choose that of their neighbors even if they are now available only as a FCV.[20] The shock tax case shows that, later on, this effect of a continuation of previous behavior leads to resistance to full diffusion, so that, by the year 2030, the share of newly registered FCVs is lower than without social comparison. Note that these results are driven by the fact that producers radically switch to producing the new technology, so that consumers cannot simply stick to their old product. In a more complex model that would allow producers to offer the same car with different drive trains, social comparison is likely to lead to much slower diffusion in the beginning, because consumers doing social comparison would hardly be exposed to the new technology.

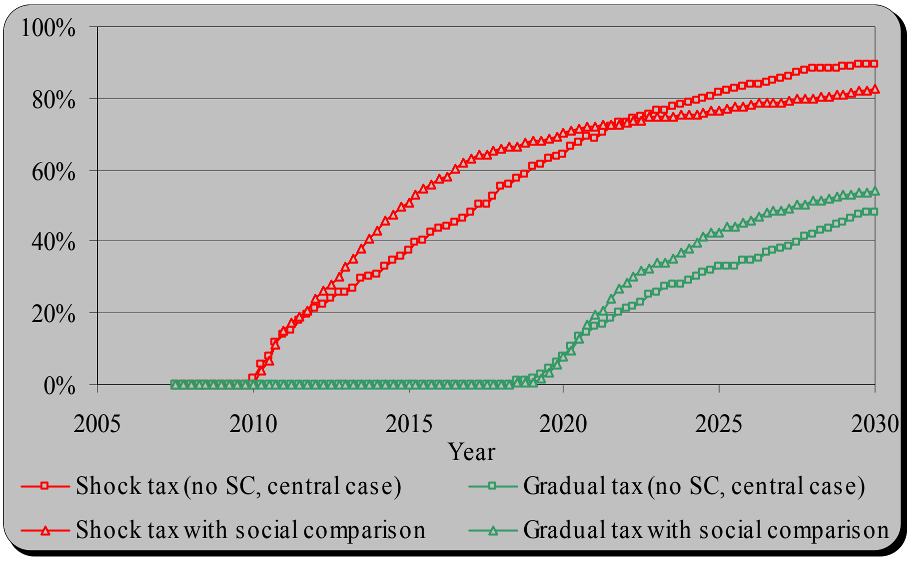


Figure I-10: Impact of social comparison (SC)

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[20] Note that this result is basically in line with Janssen and Jager's (2002) case if firms change the design of their products.

6. Conclusions

In this paper, an agent-based model is applied that incorporates the decision making process of producers and consumers at the same time, following the framework of Janssen and Jager (2002). In contrast to previous papers, decisions are additionally influenced by a simple dynamic representation of the build-up of hydrogen infrastructure. The producers offer heterogeneous but similar cars, so they have some market power. In each period, they consider changing their production to FCVs, which are identical to the ICEVs except for the power train and the required fuel. Consumers have heterogeneous preferences for certain car characteristics and have different social needs represented by the influence of neighbors on their buying decision. Moreover, they differ in their refueling needs. The model is calibrated, so as to capture the main features of the German compact car market, which is considered to be most likely to open a niche for a successful introduction of FCVs.

We analyze combinations of two different tax and three different infrastructure scenarios. We choose a shock tax and a gradual tax system representing extreme cases. The shock tax initiates a diffusion of FCVs right after the introduction of the tax; with a much higher share of FCVs within the newly registered cars if the tax is flanked by exogenous infrastructure build-up. For the gradual tax cases, the diffusion patterns are similar, but shifted in time due to the relatively high tax rate that was necessary for a first producer to offer FCVs. Thus, in the central case parameterization, our model does not show the chicken and egg problem usually associated with the introduction of FCVs and hydrogen infrastructure.

The different tax scenarios have substantially different impacts on concentration in the car segment. While in the long run concentration increases in all scenarios, in the short run a gradual tax has only relatively minor impacts. Consumers would in any case favor a major infrastructure program and are likely to prefer a gradual tax, as this goes along with only a smooth reduction of the number of affordable cars offered. Due to increased market power, large producers could, in the long run, gain from the shock tax. In any scenario, they would be the main winners of exogenous infrastructure build-up, indicating some potential for side payments to filling station owners. On the other hand, small producers would decline any policy that encourages a fast diffusion of FCVs, may it be a shock tax or (high) exogenous H_2 built up.

Furthermore, we find that a subsidy instead of a tax would have the same asymmetric effects on small and large producers and would mainly benefit consumers due to the fact that the market would expand rather than contract. The sensitivity analysis shows that the main qualitative results are robust, but indicates that the model is most responsive to changes in the assumed price elasticity. If producers put much weight on market shares, this could significantly constrain diffusion. Diffusion is positively affected by the share of innovators, i.e., those consumers who make their buying decision independent of their neighbors. Moreover, consumers doing social comparison, instead of evaluating the whole set of cars supplied, increase diffusion at the beginning, but also hamper complete diffusion.

The validity of the results is subject to several limitations. The producers have only the option to radically switch to the new technology. A more gradual and adaptive behavior is basically implied by presenting averages of several simulation runs. However, an explicit modeling of producers who, e.g., introduce the new technology only in certain product lines, remains for future research. The model is restricted to a segment of the total market. This is done to justify the comparability of car types in the market. Economy or luxury cars are usually not considered to be substitutes to compact cars, as buying decisions are dominated by factors, such as size and price at the low end and distinction and status at the high. However, a multi-segment market would have complicated an already complex model and so obscured results. Nevertheless, measuring the overall impact of a tax requires an analysis of likely substitutions to smaller cars as well.

The problem of substitution also indicates that the different scenarios of the model at hand cannot be evaluated with respect to their environmental benefits. At least in the short term, the share of FCVs within the number of newly registered cars does not tell anything about the effect of a tax on total emissions of individual car traffic, not only that people would probably buy smaller cars, but they could also drive their old cars longer (which might actually have an adverse environmental impact). Such subjects are not addressed in the model. Furthermore, the calibration of the trade-off the consumers make between price and fuel availability should be taken with care. This matter calls for more empirical work, especially for Europe (for US studies see Greene, 2001; and Bunch et al., 1993). We also assume that consumers have full knowledge of prices and fuel availability. In reality, consumers may systematically misperceive FCVs as expensive and fuel availability as low. This would reduce the speed of diffusion. Another deficiency is the modeling of the development of filling stations with a hydrogen outlet. Real world experience with a totally different alternative fuel is basically absent. Data from CNG only provide some guidance, as upfront investments at the filling stations for a hydrogen outlet are likely to be much higher than for a CNG outlet. This leads to the most severe limitations of the current version of the model. We abstract from cost considerations in the hydrogen industry. Hydrogen is likely to be more costly at the beginning than gasoline, independent of the energy source used to produce it, but scale effects will probably bring down these costs, as is usually assumed in the literature. However, there will also be a cost increase due to higher demand if FCVs are introduced successfully. Implementing these dynamics will require a separation of vehicle costs and fuel costs - an issue we are planning to address in future versions of the model, together with a representation of scale effects in car production costs, which are ignored so far to limit the variety of dynamics and ensure traceability of the main model behavior.[21]

Despite of the obvious shortcomings of the present model, we believe that it captures some of the main dynamics of the FCV diffusion. Due to its rather general calibration, the results are likely to apply also to comparable market segments in other countries or, e.g., to the EU as a total. Although neither the shock tax nor the gradual tax can be considered as policy options that are expected to end up on any agenda, they,

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[21] Another logical extension is to analyze recycling of the tax for infrastructure.

nevertheless, open the range of alternatives. A rather immediate high taxation might promote almost instantaneous diffusion of FCVs, but at the price of strong declines in sales and an increase in market power for already large producers – a trade-off that must be considered in a cost-benefit analysis of the tax. Even more remarkable is the effect of a public infrastructure program on the market. Large and small producers are asymmetrically affected by such a policy. These impacts on industry performance have so far been ignored by studies addressing the costs of building up a hydrogen infrastructure.

Appendix A: Model description[22]

At time t there are n_i different producers indexed by i. Each one produces a single type of car, which can either have a fuel cell power train or a conventional one. In every period, producers decide on switching to the production of FCVs. Besides the power train, cars from different producers can be diverse in several characteristics such as size, acceleration, design and so on. These characteristics are named z. Thus, a car produced at time t can be fully described by a vector of characteristics

$$c_{i,t} = c_{i,t}\,(FCV,\, z_{i,j,t}), \tag{1}$$

where FCV is an indicator function ($FCV = 1$, else 0). The different characteristics are indexed from $j = 1$ to n_j, which is the number of attributes. Each $z_{i,j,t}$ has values ranging from 0 to 1. The characteristics are initialized randomly. FCVs are, at the time of introduction, assumed to be identical to conventional cars, beside the power source.[23]

A.1. Consumers

A.1.1. Car choice according to utility maximization

After producers have made their production decisions as described below, consumers buy the offered cars. The "consumat" approach, suggested by Janssen and Jager (2002), endows consumers with four cognitive strategies (repetition, deliberation, imitation, and social comparison), so that - depending on their level of need satisfaction and uncertainty - consumers follow one of these strategies.[24] In the context of buying a new car, we assume that need satisfaction is rather low and, therefore, rule out repetition and imitation. Deliberating consumers are certain in their decision making. They evaluate all the cars available in the market and therefore act fully rationally. Uncertain consumers evaluate only the (expected) utility of the car most of their neighbors drive and compare it with the (expected) utility they would get from buying the brand again that they are currently driving. So, they reduce their decision space to their directly perceivable environment, i.e., they do social comparison. In our central case simulations, we let consumers only deliberate, but in the sensitivity analysis we also allow for social comparison.

Within the decision space consumers maximize utility relative to the price $p(c_{i,t})$. The total (expected) utility a consumer k obtains from buying car $c_{i,t}$ is

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[22] The model described in this appendix is written in C++ using the Laboratory for Simulation Development (version 5.2) modeling environment. The model code and configuration files are available from the author upon request.

[23] A more realistic approach would be to put some restrictions on combinations of characteristics with the type of power train, e.g., FCVs always have something like automatic gear shifting. However, we refrained from doing so to reduce complexity.

[24] For a detailed description of the consumat approach see also Jager (2000).

$$U_{k,t}^{tot}(c_{i,t}) = \frac{\left(\beta_k U_{k,t}(c_{i,t}) + (1-\beta_k) SN_{k,t}(c_{i,t})\right) RFE_{k,t}(c_{i,t})}{\left(p(c_{i,t})(1+tax_t(1-FCV))\right)^{|\varepsilon_{own}|}} . \qquad (2)$$

The government uses a value added tax (tax_t) on ICEVs to stimulate the diffusion of FCVs, because price is a crucial determinant of the buying decision. The effectiveness of such a tax depends on the responsiveness of utility towards (after tax) price changes, which is defined by the elasticity ε_{own}. If the absolute value of ε_{own} is high, the impact of the tax on utility and, therefore, on technology choice is also high. The numerator evaluates the utility that the consumer can derive from the features of a specific car. The utility is a weighted average of the direct utility $U_{k,t}$ associated with the characteristics of the car and the social need $SN_{k,t}$ (i.e., the impact of neighbors on decisions), jointly scaled by a variable called refueling effect ($RFE_{k,t}$). The weight β_k varies over individuals and is taken from a random draw from a normal distribution within the boundaries 0.4 and 1 in the central case.

A.1.1.1. Direct utility

The direct utility a consumer k can derive from a specific car depends on his preferences $pref_{k,j,t}$, with $j = 1, \ldots, n_j$, where each $pref_{,k,j,t}$ also varies from 0 to 1 as do the car characteristics. The initial values are taken from random draws from a uniform distribution. So consumer k derives direct utility from a certain car $c_{i,t}$ according to

$$U_{k,t}(c_{i,t}) = 1 - \frac{1}{n_j} \sum_{j=1}^{n_j} \left| z_{i,j,t} - pref_{k,j,t} \right| . \qquad (3)$$

Therefore, the consumer's direct utility can be 1 at the maximum if all characteristics exactly meet his preferences, and is limited to zero in the opposite case.

A.1.1.2. Social need

A car is a prestige good, so consumers take their neighbors' decisions into account. Especially the emotional decision whether to buy a futuristic and unfamiliar FCV might be guided by decisions of neighbors. Such a social need is defined by the share of the product type in the neighborhood (including the deciding consumer), i.e., in the case of a FCV, it is the number of neighbors driving a FCV plus 1 divided by the total size of the neighborhood including the deciding consumer (Janssen and Jager, 2002).[25] For the structure of the social network, we use a regular lattice, where all consumers have the same number of neighbors. The neighbors are connected, forming a torus as described in Hegselmann and Flache (1998).[26]

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[25] This implies that the social need is always defined and greater than zero. An alternative assumption would be that there is a particular value of "being different". In that case "1 – market share" would be a possible representation of the social need.

[26] Variations of the network structure, e.g., to analyze the impact of a "small world effect" as described in Watts and Strogatz (1998) are left to future research.

A.1.1.3. Refueling

Refueling, i.e., the sufficient availability of hydrogen, is a major concern for every consumer considering a FCV. Therefore, we introduce the variable $RFE_{k,t}$ as being essential to total utility in case of a FCV (and being irrelevant for conventional cars). This is in contrast to Stephan and Sullivan (2004), who use an additive "worry factor" of refueling that can be compensated by other characteristics. In our model, a car that cannot be refueled is worthless. However, the refueling effect changes over time if a considerable hydrogen infrastructure gets installed. Furthermore, people are different in their individual refueling needs. Put together, $RFE_{k,t}$ is constructed as a function of fuel availability at time *t,* represented by the share of filling stations that provide hydrogen ($s_{H2,t}$)[27] and individual driving patterns (DP_k):

$$RFE_{k,t}(c_{i,FCV,t}) = 1 - FCV \cdot DP_k \cdot \exp(\gamma s_{H2,t}), \qquad (4)$$

where $\gamma \leq 0$ is a parameter determining the importance of fuel availability. Refueling is irrelevant for ICEVs (i.e., $FCV = 0$). Individual driving patterns are assumed to vary between 0 (only short trips in familiar areas) and 1 (many long distant trips in unknown areas) and are fixed over time.

A.1.2. Dynamics of preferences

Individual preferences may shift over time. They are assumed to move slowly in the direction of the characteristics of the "average car", which is defined by the characteristics of all cars sold in the previous period weighted by their market shares.[28] This mimics the "marketing effect" of products sold (similar to Valente, 1999). It basically says that people prefer those features to which they are most exposed. Here, consumers adjust their preference associated with a certain car characteristic according to

$$pref_{k,j,t} = \zeta(pref_{k,j,t-1}) + (1-\zeta)\sum_{i=1}^{n_i} z_{i,j,t-1} \cdot s(c_{i,t-1}), \qquad (5)$$

$$\text{with} \quad s(c_{i,t-1}) = \frac{q(c_{i,t-1})}{\sum_{i=1}^{n_i} q(c_{i,t-1})}, \qquad (6)$$

where $q(c_{i,t-1})$ is the number of cars of a certain type sold in the previous period, so that $s(c_{i,t-1})$ is the market share of the car and ζ defines the speed of convergence of preferences ($0 \leq \zeta \leq 1$), i.e., for $\zeta = 1$ there is no marketing effect, and preferences stay constant.

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[27] A standard definition for fuel availability used, e.g., by Greene (1998).

[28] It should be noted that, if not expressively stated, "market share" here and in the following sections refers to the share within the car segment at study.

A.2. Car producers

Before consumers choose their preferred car as described above, producers make decisions on the price and corresponding quantity of the car they offer, so as to maximize their objective function. In other words, since the producers offer heterogeneous goods, they act as price setters and estimate the demand for their goods implied by the price. Actually, as long as a producer has not switched to the production of FCVs, he compares the outcome of two optimizations in each period: one based on continued production of conventional cars and one based on the switch to FCVs. The producer switches if FCVs generate a higher expected value of his objective function. Due to uncertainties of the long term development of the market, the producers cannot do intertemporal (expected) profit maximization. Thus, producers optimize only their expected current objective, which is not necessarily profit. Kwasnicki and Kwasnicka (1992) show that producers employing the following objective function can outperform producers who optimize only current (expected) profits over time[29]

$$\max Obj_t = (1-W_{i,t})\frac{INC^e_{i,t}}{\sum_{i=1}^{n_i} INC_{i,t\text{-}1}} + W_{i,t}\frac{q^e(c_{i,t})}{\sum_{i=1}^{n_i} q(c_{i,t\text{-}1})}, \qquad (7)$$

$$\text{with} \quad W_{i,t} = \exp\left(-\eta \frac{q^e(c_{i,FCV,t})}{\sum_{i=1}^{n_i} q(c_{i,FCV,t-1})}\right).$$

The producer maximizes a weighted average of its expected income $INC^e_{i,t}$ relative to total income of all producers in the previous period and its expected number of cars sold $q^e(c_{i,t})$ relative to the total number of cars sold in the car market in the previous period. Previous total income and total number of cars are observed by the producer and therefore taken as constants. The parameter η calibrates the weight $W_{i,t}$, which is constructed such that large producers, i.e., producers with an expected high market share, have a higher preference for income, whereas small producers give more weight to market share. This can be interpreted as a survival strategy. Following Kwasnicki (1996), we take $\eta = 5$ in the central case, but include the parameter in the sensitivity analysis (see Section 5 of the main text). We assume that, if $\sum_{i=1}^{n_i} INC_{i,t-1} \le 0$, producers simply maximize expected income.

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[29] Actually, there can be numerous objective functions which do better than profit maximization in the long run, but according to Kwasnicki and Kwasnicka (1992), the one chosen here turned out to be most successful.

A.2.1. Expected income and profits

Expected income is defined as revenue diminished by variable costs

$$INC_i^e = q^e(c_{i,t})p(c_{i,t}) - q^e(c_{i,t})v_i(q^e(c_{i,t})). \tag{8}$$

Variable costs $v_i(q^e(c_{i,t}))$ are assumed to be constant and equal for all producers.[30] Now, expected profits are

$$\Pi_{i,t}^e = INC_{i,t}^e - K_{i,t}(r+\delta) - R_{i,t}^e, \tag{9}$$

where r is the interest rate and δ is the rate of depreciation. Thus, expected profits are income minus opportunity costs of capital and expected R&D expenditures ($R_{i,t}^e$), which are a function of capital (see equation (27)).

A.2.2. Expected quantity

To estimate the expected quantity $q^e(c_{i,t})$, each producer initially tries to evaluate the competitiveness of its car as suggested by the prices. Then, he estimates its market share and total demand and finally checks, whether the capital stock allows the production of the expected quantity and whether additional investments are required. In the next paragraphs, this chain of computations is shown.

A.2.2.1. Competitiveness

The products have been improved due to previous R&D activities to be described below. It is assumed that a producer compares all of the characteristics of his cars with the (weighted) average of the characteristics of all cars sold in the previous period.[31] So the producer computes the expected competitiveness $\vartheta^e(c_{i,t})$ of its product as[32]

$$\vartheta^e(c_{i,t}) = \frac{\left(\bar{\beta}_{t-1}\left(1-\frac{1}{n_j}\sum_{\mathrm{j}=1}^{\mathrm{n_j}}\left|z_{i,j,t}-\sum_{i=1}^{n_i}z_{i,j,t-1}\cdot s(c_{i,FCV,t-1})\right|\right)+(1-\bar{\beta}_{t-1})E\left[SN_t(c_{i,t})\right]\right)E\left[RFE_t(c_{i,t})\right]}{\left(p(c_{i,t})(1+tax_t(1-FCV))\right)^{|\varepsilon_{own}|}}, \tag{10}$$

$$\text{with} \quad E\left[RFE_t(c_{i,t})\right] = 1 - FCV\cdot\left(\frac{1}{n_{k^*}}\sum_{k^*=1}^{n_{k^*}}DP_{k^*}\right)\cdot\exp(\gamma s_{H2,t}). \tag{11}$$

$E\left[RFE_t(c_{i,FCV,t})\right]$ denotes the producer's expectation about the refueling effect. Producers simply observe fuel availability and are assumed to know the average driving patterns of their customers (indexed by k*) – information that producers can obtain from maintenance records. Customers are those who bought a car from the particular producer in the previous period. Producers estimate, how their product contributes to

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[30] These assumptions will be relaxed in future versions of the model.

[31] In the case of cars, producers can easily obtain the necessary information from registration statistics.

[32] Kwasnicki's (1996) model lacks a specific description of the demand side. Therefore, in his model competitiveness depends on routines employed by the producers, which evolve through generic mutation and imitation of successful competitors, and these routines are evaluated according to a fitness function.

social need by observing $\overline{\beta}_{t-1}$, which is the average weight of preference of their customers. They derive $E\left[SN_t(c_{i,t})\right]$ from the share of FCVs sold in the previous period, assuming that this share can also be found in the individual customer's neighborhood.

A.2.2.2. Market shares

The producer estimates the expected market share in three steps. Firstly, he assumes that the "market competitiveness", i.e., the average competitiveness of all cars in the market

$$\overline{\vartheta_{i,t}} = \sum_{i=1}^{n_i} \vartheta(c_{i,t}) s(c_{i,t}) \tag{12}$$

changed at the same rate as it did in the previous period, so that

$$\frac{\overline{\vartheta_{i,t}}}{\overline{\vartheta_{i,t-1}}} = \frac{\overline{\vartheta_{i,t-1}}}{\overline{\vartheta_{i,t-2}}} \Rightarrow \overline{\vartheta_{i,t}} = \frac{\overline{\vartheta_{i,t-1}}^{2}}{\overline{\vartheta_{i,t-2}}}. \tag{13}$$

For the computation of (12), the producer uses the expected value of the refueling effect of equation (11) as an approximation for the refueling effect also associated with the competitors' FCVs, so that (12) is already uncertain and producer dependent. Secondly, the producer expects his market share to stay the same. Thus, expected market competitiveness is

$$\overline{\vartheta^e_{i,t}} = \frac{\overline{\vartheta_{i,t-1}}^{2}}{\overline{\vartheta_{i,t-2}}}(1 - s(c_{i,t-1})) + \vartheta^e(c_{i,t}) s(c_{i,t-1}). \tag{14}$$

As a third step, equations (10) and (14) together let the producer compare own competitiveness with the estimated market competitiveness $\overline{\vartheta^e_{i,t}}$ to estimate his current market share by

$$s^e(c_{i,t}) = s(c_{i,t-1}) \frac{\vartheta^e(c_{i,t})}{\overline{\vartheta^e(c_{i,t})}}. \tag{15}$$

This basically means that the producer evaluates whether own progress exceeded average progress or not.

A.2.3. Expected average price level

So far, the construction of the model implies that, if the producer has had a non-zero market share, he is tempted to increase prices significantly, because he expects some of his market share to persist, even if the price might be so high that consumers would not even consider buying. This is unrealistic. On the other hand, since the characteristics of the product are changing all the time, the producer cannot directly estimate the demand for it and, therefore, derives the market shares via equations (10) -(15). But the producer has a notion of the change of the total demand to price. Thus, we assume that the producer estimates total demand Q_i^e as

$$Q^e_{i,t} = \frac{M_0 \exp(g_M t)}{\overline{p^e_{i,t}}^{\,|\varepsilon_{seg}|}}, \tag{16}$$

where ε_{seg} is the price elasticity of demand of the whole segment, M_0 is a parameter for the initial size of the market segment in monetary units, and g_M is the growth rate of it. Since the number of producers is small, each producer is well aware of his impact on the price level. Thus, the producer computes the expected after tax price level $\overline{p^e_{i,t}}$ as a market share weighted average of last period's change in the after tax price level $\overline{p}$ and the price of the own product, similarly to the computation of expected market competitiveness, i.e.

$$\overline{p^e_{i,t}} = \frac{\overline{p}_{t-1}^{\,2}}{\overline{p}_{t-2}}(1-s(c_{i,t-1})) + p(c_{i,t})(1+tax_t(1-FCV))s(c_{i,t-1}). \tag{17}$$

Using equation (15) and plugging (17) into (16), the producer now calculates the expected number of cars to be sold as

$$q^e(c_{i,t}) = s^e(c_{i,t})Q^e_{i,t}. \tag{18}$$

A.2.4. Adjustment of capital stock

For producing the amount $q^e(c_{i,t})$, the producer needs capital depending on the productivity of capital, so that

$$K^r_{i,t} = \frac{q^e(c_{i,t})}{A}, \tag{19}$$

where $K^r_{i,t}$ is the required amount of capital[33] and A is the productivity of capital. A is constant over time and across producers. Moreover, there is no qualitative difference in capital used for the production of conventional cars and FCVs.

The producer's possibilities to adjust capital stock depend on his financial leeway. If $K^r_{i,t} - K_{i,t-1}(1-\delta) \leq 0$, the producer has a large enough capital stock left from the previous period, such that he can produce the expected quantity without any problems. Otherwise the producer uses financial assets to close the gap between required and actual capital stock, i.e., the producer tries to finance investments up to the difference of required and actual capital. These requested investments are called $I^r_{i,t}$. The maximal

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[33] In this model, K_i denotes physical capital that the producer employs for production. Labor is not directly modeled, but is rather assumed to be part of variable costs, which enter the calculation of net income (equation (8)). The further construction of the model implies the assumption that each producer can in each period employ just as many units of labor as needed. Although this might be considered a strong assumption, wage agreements in the automobile industry hint in that direction.

amount of investments $I_{i,t}^{max}$ the producer can finance is

$$I_{i,t}^{max} = \max\left\{0, NB_{i,t} + D_{i,t}^{max}\right\}, \tag{20}$$

where $D_{i,t}^{max}$ is the maximal amount of new debts the financial market is willing to provide to the producer, and $NB_{i,t}$ is the net balance of short term financial flows. $D_{i,t}^{max}$ is a fraction μ of the capital of the previous period (mimicking the need for collateral) reduced by the amount of previous (long term) debts, i.e.,

$$D_{i,t}^{max} = \max\left\{0, \mu K_{i,t-1}(1-\delta) - D_{t-1}(1 - \frac{1}{\overline{t^{repay}}})\right\}, \tag{21}$$

where $\overline{t^{repay}}$ is the average repayment duration on the financial market, so that the last expression approximates the repayment of debts, without considering a detailed debt structure. $NB_{i,t}$ is defined as

$$NB_{i,t} = (NB_{i,t-1} + RE_{i,t})(1+r) - \frac{D_{i,t-1}}{\overline{t^{repay}}} - D_{i,t-1}r + \Delta D_{i,t-1} - I_{i,t-1}. \tag{22}$$

$RE_{i,t}$ are retained earnings from the previous period that are now available to finance current investments (determined in equation (26)), r is the normal rate of return (interest rate), which is assumed to be the same for savings and debts, $\Delta D_{i,t-1} = D_{i,t-1} - D_{i,t-2}\left(1 - \frac{1}{\overline{t^{repay}}}\right) \geq 0$ is the change in debts at time t-1 and $I_{i,t-1}$ are last periods investments. So previous savings diminished by debt service mainly determine the short term financial leeway, where the last two terms balance the financial flows in case the producer has increased long term debts to finance investments according to equation (23b) below.

The producer wants to finance as much as possible of $I_{i,t}^{r}$, preferably by own savings (assuming that the return on production is always greater than the interest rate). Distinguishing two cases can do this:

1. If $NB_{i,t} \geq I_{i,t}^{r}$, the producer has no problem using own financial assets to finance investments, so that $K_{i,t} = K_{i,t-1}(1-\delta) + I_{i,t}^{r} = K_{i,t}^{r}$ (with $I_{i,t} = I_{i,t}^{r}$), and if the producer has any debts, they are decreased through repayments, i.e.,

$$D_{i,t} = D_{i,t-1}(1 - \frac{1}{\overline{t^{repay}}}). \tag{23a}$$

2. If $NB_{i,t} < I_{i,t}^{r}$, $K_{i,t}$ and $I_{i,t}$ are as above, but the producer incurs debts according to

$$D_{i,t} = D_{i,t-1}(1 - \frac{1}{\overline{t^{repay}}}) + \min\left\{D_{i,t}^{max}, I_{i,t}^{r} - NB_{i,t}\right\}, \tag{23b}$$

where the last term defines the actual new debts.

In the second case, it is possible that the required investments exceed the maximum amount of investments defined in (20). Then the producer incurs as many debts as possible, i.e., the last term in equation (23b) will be $D_{i,t}^{max}$, so that $I_{i,t} = I_{i,t}^{max}$ and $K_{i,t} = K_{i,t-1}(1-\delta) + I_{i,t}$ and, therefore, equations (18) and (19) must be reconsidered.[34] The quantity produced is then limited by the capital available and must be recalculated as

$$q^e(c_{i,t}) = AK_{i,t}, \tag{24}$$

where $K_{i,t}$ is the actual capital stock that can be realized by the producer. Equation (18), or, due to capital constraints, equation (24), defines the quantity implied by a certain price. Once the price that maximizes equation (7) is found, the producer makes the necessary capital stock adjustments, so the implied quantity is equal to the maximum output the producer can generate in the period.

A.3. Matching supply and demand

The total demand for the cars offered is

$$Q = \frac{M_0 \exp(g_M t)}{\overline{p_t}^{|\varepsilon_{seg}|}}, \tag{25}$$

$$\text{where } \overline{p_t} = \sum_{i=1}^{n_i} p(c_{i,t})(1 + tax_t(1 - FCV))s(c_{i,t-1}),$$

and the parameters are the same as in equation (16). The underlying assumption is that the consumers perceive an average after tax price $\overline{p_t}$, where they use the same market shares as in the previous period. Now Q is the number of consumers willing to buy at that price level, meaning that there are Q consumers evaluating the cars offered according to equation (2) and ordering the car that maximizes their utility.[35] The Q consumers are drawn randomly from a population large enough to clear the market even if the producers choose (unrealistically) low prices. They make their decisions one after the other. It is assumed that no car is produced before a consumer orders, i.e., there is no excess supply. Producers might overinvest in capacity, but are not penalized by high variable costs. On the other hand, if there is excess demand, production capacity cannot be adjusted within one period, nor can prices be changed. Consumers who cannot get their favorite product because it is sold out will choose their second best product. This process goes on, so that some consumers might even be forced to buy their least preferred car, or even end up with nothing. In the case of cars, this behavior seems to be rather unrealistic, because it is more likely that consumers would place an order and

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[34] It should be noted that, since the net balance can be negative, total debts of a producer might actually exceed D^{max}. But in that situation I^{max} is zero, i.e., the producer cannot even replace depreciated capital stock and it starts shrinking very quickly, because its credit-worthiness reduces with a decreasing capital stock.

[35] This formulation becomes unrealistic if the initial average price is determined, e.g., by a few extremely expensive cars, so that the demand gets very low. But this problem would not be persistent, because extremely expensive ones would not be bought.

wait for their first choice rather than to put up with less preferred cars. However, such a set up would increase the complexity of the model significantly.[36]

A.4. Post selling computations

The computations described below take place after the selling process, i.e., after producers and consumers made their optimal decisions. The results define the initial values for the next period and, therefore, close the computation cycle.

A.4.1. Retained earnings

Producers keep a share of their (positive) profits to finance future investments, determined by the relation of the net balance with respect to capital. Producers with relatively high net inflow compared to their capital are assumed to set aside only a small part of their profits, because they have a high financial potential to expand capital if necessary. On the other hand, if their net balance is relatively low (or even negative), they try to increase their financial leeway and, thus, tend to save more. Therefore, the retained earnings available in the next period are

$$RE_{i,t+1} = \max\left\{0, \Pi_{i,t}\right\} \cdot \min\left\{1, -\lambda_1 \exp(\lambda_2 \frac{NB_{i,t}}{K_{i,t}})\right\}, \tag{26}$$

where $\Pi_{i,t}$ is the actual profit[37], λ_1 denotes the share of profits that is set aside if the net balance is zero or $K_{i,t}$ is large, and $\lambda_2 \geq 0$ is a parameter determining the curvature of the retained earnings function.

A.4.2. R&D

The producers are doing R&D in order to make their products more likely to meet the preferences of their customers, i.e., applied R&D with a short timescale and no spillovers. R&D investments diminish profits (see equation (9)) and are set proportionally to capital, i.e.,

$$R_{i,t} = \varphi K_{i,t}. \tag{27}$$

We assume that φ is a fixed percentage. However, it is of course possible to let φ be a function of capital, so that producers with relatively high capital tend to devote more (or less) resources to R&D.

The relationship between R&D activities and success of these activities are poorly understood. Nevertheless, in the case of applied R&D, high investments should at least increase the likelihood of product improvements. In this model, product improvements

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[36] For example, producers would have to adjust capacities to execute previous orders and, at the same time, estimate the current demand, which is not uncorrelated with the number of orders, because potential customers are among the ones who ordered previously. This would also imply that the producer has to offer the same (or at least a very similar) product at two different prices.

[37] The actual profit is computed according to equation (9), where the observed values replace the expected ones.

are described by the fact that the characteristics of the product get closer to consumers' preferences. Producers cannot improve all characteristics at the same time, but rather focus on some particular ones. Moreover, producers can only indirectly observe the preferences of all consumers by monitoring the characteristics of the "average car" sold at the market.[38] But it is realistic to assume that they can relatively easily check the preferences of their own customers. So, taking into account the way in which consumers update preferences via equation (5), each producer has an intuition about the preferences of the potential customers in the next period. Research activities are concentrated on two technical characteristics, which happen to be the ones that are closest and farthest away from the average preferences of the (potential) customers. This means that the producer tries to eradicate the most harmful disadvantage, but still focuses on a part with a particularly strong position (e.g., a sports car maker will almost always try to meet the customers' preference for motor power).

As an example, it is shown, how R&D changes the characteristic that is closest to the average preference of the customers. Updating the characteristic that is most far away is straightforward. Let j^* be the characteristic in question, then the minimum difference $\Delta_{i,min,t}$ is

$$\Delta_{i,min,t} = \left| z_{i,j^*,t} - E\left[\overline{pref_{i,j^*,t+1}}\right] \right|, \tag{28}$$

where $E\left[\overline{pref_{i,j^*,t+1}}\right]$ denotes the expected average preference of the potential consumers for characteristic j^*. The producer can reduce this difference by a (random) weighting function $G(R_{FCV,t})$, so that the characteristic of the following period lies in-between according to

$$z_{i,j^*,t+1} = \left(1 - G(R_t)\right) z_{i,j^*,t} + G(R_t) E\left[\overline{pref_{i,j^*,t+1}}\right], \tag{29}$$

$$\text{with } G(R_t) = 1 - \frac{1}{\left(1 + \sigma_1 Z \cdot R_t\right)^{\sigma_2}}$$

$$\text{and } Z \sim \text{Un}[0,1],$$

where σ_1 and σ_2 are (non-negative) parameters. The expected value of $G(R_t)$ increases with R_t. Thus, high R&D expenditures imply a high likelihood of shifting the characteristic, such that it exactly meets the customers' average preference. However, there are decreasing returns to R&D.

A.4.3. Imitators

If producers perform badly, i.e., if their market share drops below a certain threshold, they imitate the behavior of the most successful competitor. Imitation is limited to the decision to switch to FCV production. This means that, if the competitor with the highest market share already produces FCVs, then those with particularly low

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[38] It should be noted that a car that meets the average characteristics is not necessarily the one that would generate most profits.

market shares follow, i.e., they start producing FCVs, no matter if their internal optimization would suggest staying with conventional cars. We arbitrarily assume that producers imitate if their market share is lower than 50% of the market share they should have had if the market were split into equal sizes.

A.4.4. Development of H_2-infrastructure

Fuel station companies increase the share of H_2-stations if FCVs enter the market. Based on the scenario studies listed in footnote 2, we suggest the following feedback of the infrastructure to an increased hydrogen demand, driven by increasing shares of FCVs within the newly registered cars. If the share of newly registered FCVs is larger than the share of H_2-stations, infrastructure grows by the highest amount that is technologically feasible (g_{H2}^{max}).[39] Otherwise the share of H_2-stations develops as

$$s_{H2,t+1} = s_{H2,t} + \min\left(g_{H2}^{max}, \nu(s_{FCV,t}^{max} - s_{FCV,t\text{-}1}^{max}) + g_{H2}^{exog}\right), \tag{30}$$

where $s_{FCV,t}^{max}$ is the maximum share of newly registered FCVs up to time t and g_{H2}^{exog} is a demand independent increase in the share, which is greater than zero in the "exogenous H_2" scenarios. In general, equation (30) states that the build-up of H_2-stations accelerates if, in the current period, the share of newly registered FCVs reached a new maximum. Then, the difference in maximum shares affects the share of H_2-stations by the factor ν. Based on data of the development of CNG outlets in Germany, we set ν to 1.5, i.e., an increase in the share of newly registered FCVs will lead to an even higher increase in the share of H_2-stations.

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[39] This should only be the case after FCVs take over a major share of the segment. Note that the reaction of the infrastructure is determined by the share of FCVs in the total market and not only in segment. Furthermore, we assume that if the share of FCVs exceeds 20% of all newly registered cars, the infrastructure will grow as fast as possible until full H_2 coverage is established.

Appendix B: Calibration

In this appendix, we discuss the number of agents and the calibration of the model parameters together with underlying assumptions. All parameter values used in the central cases and in the sensitivity analysis can be found in Table I-1. We choose the compact car market in Germany as a reference segment of significant size in terms of sales, so that a successful diffusion of FCVs within the segment would have a significant demand effect on filling station owners. Data from the *Federal Bureau of Motor Vehicles and Drivers* (FBMVD) suggests that there are 12 important producers in the segment of compact cars in Germany with market shares exceeding 2%. However, one producer (*Volkswagen*) dominates the market with a market share of about 1/3. To mimic the fact that the market is unequally partitioned, we draw initial market shares randomly from a normal distribution with mean 100/12% and a standard deviation 10%.[40] We do not assume market growth ($g_m = 0$) and set $M_0 = 2{,}000$, so that, given the choice of the demand elasticity (see below), total demand cannot exceed the number of consumers. To limit computation time (and making use of a technically convenient network structure), we allow for 6400 different consumers, who are assumed to make a replacement decision roughly every 8 years (FBMVD, 2005a).[41] In the control run without any policy, about 125 consumers buy each period, so that, if we assume that each consumer represents about 2,000 similarly behaving ones, we end up at one million sales per year, which corresponds to the size of the segment we are modeling.

A difficult issue of the calibration exercise is to find a reasonable representation of the refueling effect, because the importance of refueling directly depends on the own price elasticity (see equation (2)). For high elasticities, the price may dominate the decision. Thus, we choose a value for ε_{own} first. There are several studies that try to measure own price elasticities of cars. Bordley (1993) reports average own price elasticities of –3.6 for the US. With a sample of cars in overlapping segments, Irvine (1993) finds own price elasticities as high as –4.59 to –16.99. But Bordley's (1994) estimates for the mid-sized car segment are in the range from –2.04 to –6.09. Comparable boundaries are seen in the estimates by Berry et al. (1995), which are –3.1 and –6.8, respectively. These all-together rather high (absolute) values come along with high cross price elasticities, suggesting that the US car market is highly competitive with a lot of close substitutes. For five European countries, Goldberg and Verboven (2001) find similar own elasticities. In our central case model, we use an elasticity of –3, which is rather at the low end of the estimates, so as not to overstate the price sensitivity of the consumers.

Given the choice of ε_{own}, we can now turn to the refueling effect. Starting with consumers' driving patterns, survey data of a sample of some 26,000 German

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[40] The minimum market share is 2% and the sum of all market shares is scaled to sum up to 100%.

[41] Note that the rate of replacement of a new car is shorter than the actual lifetime of a car, because replaced cars enter the used car market.

Table I-1: Parameter values

Parameter	Function	Central case value	Sensitivity	
Consumers				
n_k	Number of consumers	6400		
$t^{replace}$	Ownership duration for a new car (in years)	8		
γ	Factor of fuel availability in the refueling effect	-3	-2	-4
β_k	Weight of own preferences against social needs	~Un[0.4,1]	~Un[0.2,1]	~Un[0.6,1]
ζ	Speed of convergence of preferences	0.99		
Producers				
n_i	Number of producers	12		
η	Scaling of weight function (income vs. market share)	5	3	7
A	Productivity of capital	0.0000625		
r	Interest rate	0.025		
δ	Depreciation rate	0.012		
μ	Share of maximum debts relative to capital	0.3		
λ_1	Scaling of retained earnings function	0.1		
λ_2	Scaling of retained earnings function	5		
φ	Ratio of R&D expenditures relative to capital	0.0012		
σ_1	Scaling of R&D success	1		
σ_2	Scaling of R&D success	0.001		
H_2-infrastructure				
g_{H2}^{exog}	Exogenous growth of the share of H_2-stations	0	0.15%	0.3%
g_{H2}^{max}	Maximum growth of the share of H_2-stations	0.015		
ν	Impact of growth of FCV share on infrastructure	1.5		
General				
n_j	Number of car characteristics	4		
t^{repay}	Average repayment duration on the financial market (in years)	10		
M_0	Segment size	2000		
g_m	Growth rate of the segment	0		
ε_{own}	Own price elasticity of car	-3	-2	-4
ε_{seg}	Elasticity of compact car segment	-1		

households collected by INFAS and DIW (2003) show that the amount of kilometers a car is driven per year follows a positively skewed distribution. The rough picture is as follows: About 8% of the cars are driven less than 5,000km a year. The bulk of cars (~50%) lie in the range 5,000 to 15,000km, 27% are driven 15,000 –25,000km, and the remaining cars are driven more than 25,000km a year, with some even over 70,000km. Assuming that the amount of kilometers driven is a valid proxy for the individual refueling needs, we want to transform this pattern to a range from 0 (only short trips in familiar areas) to 1 (many long distant trips in unknown areas). Thus, we initialize driving patterns through random draws from a lognormal distribution with mean –0.85 and standard deviation 0.65 of the underlying normal distribution. We restrict driving patterns not to exceed 1, so that the impact of few people with extremely high usage on producers' decisions (via equation (11)) is limited. Doing so, we get an average driving pattern of 0.49. Now, given the choice of the own price elasticity, we set γ to –3, thereby obtaining iso-utility curves shown in Figure I-11. The graphs illustrate by how many percent the price of a FCV must be lower than the comparable ICEV, so as to compensate for the limited fuel availability. Graphs are included for a consumer with an average driving pattern of 0.49 and also for those one standard deviation below (DP = 0.22) and above (DP = 0.76). For comparison, the graphs implied by the studies of Bunch et al. (1993) and Greene (2001) are shown. They derive iso-utilities from evaluating stated preferences. The two studies open a rather wide space, with extremely high compensation reductions for Bunch et al. (1993). Arguments in Greene (1998) questioning some of these results give reason to believe that Greene's (2001) values are more reliable.

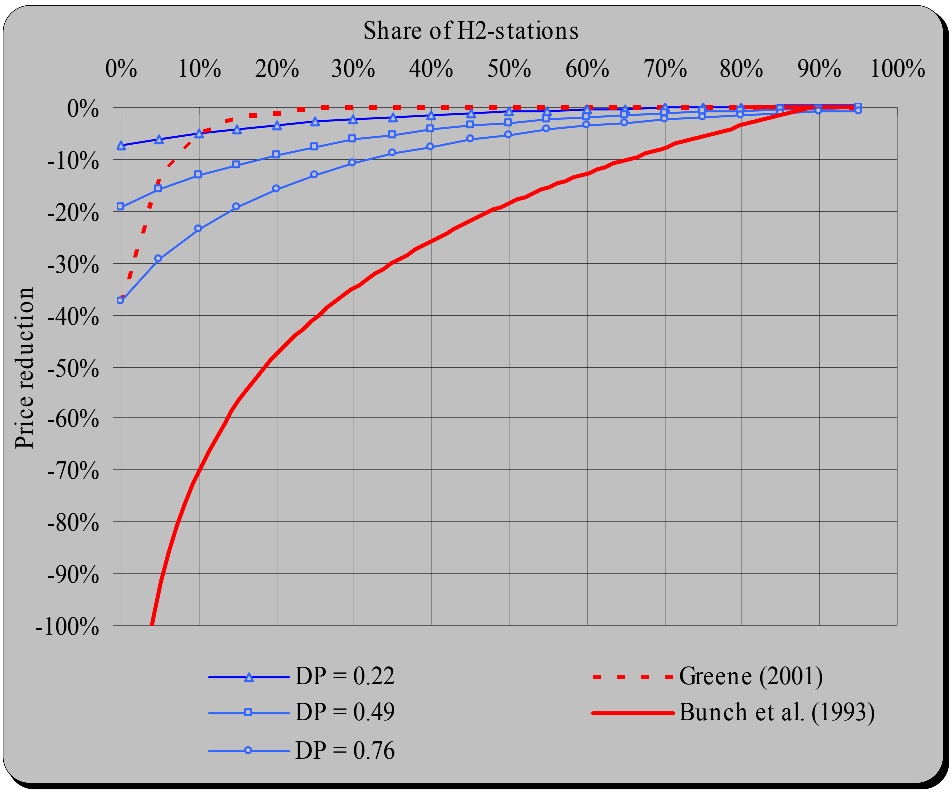

Figure I-11: Iso-utility curves for price and fuel availability combinations

The choice of the functional form of the refueling effect and the parameter values must be seen as a compromise having the following properties: For low shares of H_2-stations, the refueling effect is mainly determined by the driving pattern, i.e., only consumers with very low utilization consider a FCV. On the other hand, if the share of H_2-stations increases, it dominates the overall refueling effect, which rather quickly approaches 1 as hydrogen becomes available almost everywhere. We will not assume a zero share of H_2-stations at the beginning, but rather a share of about 3%. Note that, at that level, the iso-utility curve for the average consumer in our model already crosses that of Greene (2001). For higher shares, our assumed refueling effect is rather unfavorable for FCVs, where even at a 15% share of H_2-stations, which is according to

Greene (1998) usually considered sufficient, the FCV must be more than 13% cheaper to be valued equivalently to the ICEV. This assumption should be seen as a concession to Bunch et al.'s (1993) results, given the low number of comparable studies.

We take data from recent annual reports of several major automobile producers to get a best guess of the parameters used in the producer model. The data suggest that productivity of capital (A) should be around 0.0000625, such that the production of 1,000 vehicles requires capital of 16 million EUR for an ICEV. The quarterly interest rate (r) and depreciation rate (δ) are set to 0.025 and 0.012, respectively. The share of maximum debts relative to capital (μ) is limited to 0.3 and the ratio of R&D expenditures relative to capital (φ) is set to 0.0012. The values for λ_1 and λ_2 try to ensure realistic magnitudes of retained earnings, such that producers neither accumulate extremely high savings for future investments nor ignore future investment possibilities. The values for σ_1 and σ_2 (1 and 0.001) defining the research success as well as the speed of convergence of preferences ζ (= 0.99) are set rather ad hoc to generate small but noticeable changes in preferences and car characteristics over a time horizon of 100 periods.

The price elasticity of cars in general is found to be around –1.[42] Segments of the car market are usually estimated to be more sensitive. Bordley (1993) estimates segment elasticities for economy to midsize classes ranging from –0.9 to –2.3. Similarly, Bordley (1994) derives an average segment elasticity of –2 with a confidence interval from –1.5 to –3. As our analysis focuses on a rather broad segment accounting for about 25% of the total car market, we assume in our central case that the segment elasticity is close to the total market elasticity and thus use a rather low responsiveness of –1.

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[42] See, e.g., Bordley (1993). McCarthy (1996) lists several studies with estimates in the range of –0.6 to –1.2.

II

Learning by doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles

Abstract. Fuel cell vehicles (FCVs) running on hydrogen do not cause local air pollution. Depending on the energy sources used to produce the hydrogen they may also reduce greenhouse gases in the long term. Besides problems related to the necessary investments into hydrogen infrastructure, there is a general notion that current fuel cell costs are too high to be competitive with conventional engines, creating an insurmountable barrier to introduction. But given historical evidence from many other technologies it is highly likely that learning by doing (LBD) would lead to substantial cost reductions. In this study, we implement potential cost reductions from LBD into an existing agent-based model that captures the main dynamics of the introduction of the new technology together with hydrogen infrastructure build-up. Assumptions about the learning rate turn out to have a critical impact on the projected diffusion of the FCVs. Moreover, LBD could imply a substantial first mover advantage. We also address the impact of learning spillovers between producers and find that a government might face a policy trade-off between fostering diffusion by facilitating learning spillovers and protecting the relative advantage of a national technological leader.

JEL classification: O33, D11, D21, L92

Keywords: Fuel Cell Vehicles, Hydrogen, Learning by Doing, Agent-based Modeling

1. Introduction

Current activities of major car producers indicate that fuel cell vehicles (FCVs) running on hydrogen are likely to start displacing fossil fueled internal combustion engine vehicles (ICEVs) in the next decade, or at least capture a substantial niche market. Inherent in the use of fossil fuels are emissions of carbon dioxide (CO_2), with their well-known effect on global warming.[1] Thus, a large-scale introduction of FCVs has the potential to shift to carbon free individual transport, implying also lower geostrategic risks associated with fossil fuel supply. It should be seen as a potential, because the actual reduction of carbon dioxide emissions and fossil fuel demand depends on the mix of energy sources used to generate the required hydrogen. Current scenarios of a shift to a "hydrogen society" indicate that for most countries low cost production of hydrogen requires the reformation of natural gas, which would still imply significant CO_2 emissions, as long as no (costly) CO_2 sequestration technology is applied. But due to the fact that hydrogen can be produced from any energy source, a long term decarbonization of energy generation would directly lead to lower emissions from individual transport (Barreto et al., 2003; Ogden, 2002, 2004; EC-JRC, 2006). Particularly promising seem to be recent scenarios to produce hydrogen from photovoltaics and particularly from (offshore) wind energy, as this would circumvent problems related to fluctuations in energy production implied by sun and wind as energy sources (Altmann et al., 2001; Gonzales et al., 2003; Sørensen et al., 2004).

Further advantages of the FCVs are the low noise generation and the general absence of any local emissions like particulate matter, ozone, sulfur dioxide, and carbon monoxide. Strong emission regulations, particularly in the US, Japan, and Europe have initiated major technological progress of catalytic converters and the use of cleaner fuels (unleaded and desulfurized gasoline), so that local emissions from ICEVs have substantially been reduced over the last decades. But some of these reductions have been compensated by increased car travel and heavy-duty transports, so that future reductions of total emissions would require even more complex (and expensive) end-of-the-pipe technologies.

Even though the fuel cell technology itself is nowadays well developed and tested in daily life situations, there are two major economic barriers to a fast diffusion of FCVs. Firstly, there is the so-called chicken and egg problem saying that people are not willing to buy FCVs as long as there is no area-wide coverage with hydrogen outlets, and on the other hand, filling station owners (or "the oil industry") would not invest in a hydrogen generation and distribution system unless there is a significant demand for the new fuel. Secondly, fuel cells are at the moment simply too expensive to compete with internal combustion engines. Schwoon (2006) uses an agent-based diffusion model to investigate, whether different tax systems and infrastructure scenarios in favor of FCVs are able to lead to a successful introduction of the new technology. Calibrated for the German compact car market, his model results suggest that a tax on ICEVs in the range

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[1] Internal combustion engines also emit other greenhouse gases like methane and nitrous oxide.

of today's car taxes in most European countries - together with an infrastructure build-up comparable to the rather slow development of compressed natural gas (CNG) outlets in Germany - is sufficient to overcome the chicken and egg problem. But Schwoon (2006) employs a simple point estimate for the costs of fuel cells if produced on a large scale.

Therefore, the current paper will extend the model by implementing a more realistic approach towards the costs of fuel cell production. There is a general notion that fuel cells costs at the moment are prohibitively high, but on the other hand learning by doing in the technology will lead to substantial cost reductions (Rogner, 1998; Lipman and Sperling, 1999; Tsuchiya and Kobayashi, 2004). If costs follow an experience curve, the assumed learning rate turns out to be critical, so that too low gains from experience might create an insurmountable obstacle. Additionally, if the producers' planning horizons are short, diffusion might also be severely hampered.

The car industry is characterized by technology clusters and common sub-supplier of major parts - two important preconditions for the existence of learning spillovers. Including learning spillovers in the model increases the speed of diffusion. Moreover, spillovers are important when it comes to the question, which producers gain during the diffusion period. In any case, there is a substantial first mover advantage due to learning, but with spillovers this advantage is reduced for the benefit of early followers.

The outline of the paper is as follows. The next section gives a brief overview of the existing model that is extended by LBD. Section 3 starts with a general discussion of the experience curve concept and its implementation in the model. Then calibration issues and simulation scenarios are discussed, before results of FCV diffusion in the presence of LBD are presented. In section 4 we argue why learning spillovers are likely to occur in fuel cell production and show their impact on the speed of diffusion. Furthermore, we address interactions between spillovers and first mover advantages. Section 5 is dedicated to policy implications and section 6 concludes.

2. Dynamics of the model

The model at hand is an extension of an existing agent-based diffusion model. A detailed description of the structure and calibration can be found in Schwoon (2006) and in the Appendix of the first paper in this thesis. Figure II-1 shows a scheme of the model. An arrow from variable A to variable B indicates the order of computations (within one period) and should be read as "A is a major determinant of B". There are four types of agents: consumers, producers, filling station owners and the government. The government acts as an exogenous driver by implementing a tax on ICEVs and increasing the speed of the built up of hydrogen outlets. Filling station owners simply react to the development of the share of FCVs on the road and can increase the share of stations with an H_2-outlet.

Consumers buy the car that maximizes their utility according to their preferences relative to the price. They are heterogeneous with respect to their preferred car characteristics and are, to some degree, influenced by their neighbors' buying decisions.

The expression "neighbors" is used as a synonym for friends, colleagues or relatives. A high share of neighbors already driving FCVs increases the likelihood of a consumer to also buy one.[2] Consumers are heterogeneous in their driving pattern. Some consumers considering a car will use it mainly locally, e.g., for shopping trips or the daily way to work, whereas others, such as a traveling salesman, will regularly drive in unfamiliar regions. According to Dingemans et al. (1986) the former are likely to be the first ones to buy an alternative fuel vehicle, whereas the latter will wait until there is substantial infrastructure coverage.

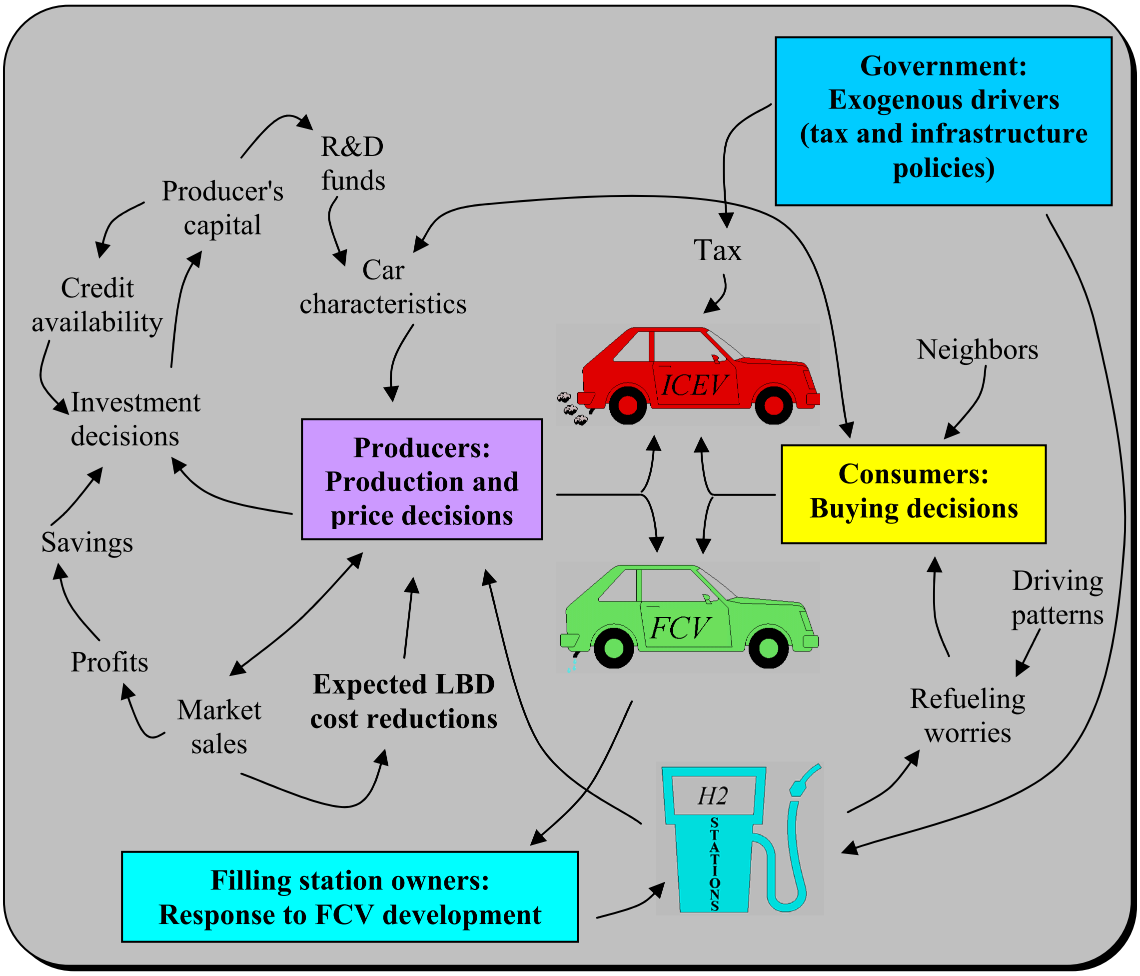

Figure II-1: Model scheme

The utility maximization of the consumer does not take environmental friendliness of the car into account. The reason is that, first of all, high efficiency and environmental benefits are usually considered to have only a minor impact on buying decisions (Steinberger-Wilckens, 2003). Moreover, in a stated preference analysis, Bunch et al. (1993) revealed that fuel availability is a much more important determinant of vehicle

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[2] Consumer behavior mainly follows "deliberating consumats" as in Janssen and Jager (2002).

choice and people are only willing to pay a premium on low emission vehicles if emissions are drastically reduced compared to conventional vehicles. But in the model conventional ICEVs are assumed to be already low emitting using for example hybrid technologies. Recent studies show that overall environmental benefits of FCVs will significantly exceed those of low emitting advanced (hybrid) ICEVs only if hydrogen is generated by renewable energy sources (Ogden, 2004; EC-JRC, 2006; Demirdöven and Deutch, 2004). As this is not likely to be possible on a large scale in the near future, early adopters of FCVs cannot claim extraordinary environmental awareness. However, if consumers considered FCVs as more ecological and were willing to pay a premium for that, this would, in the model, simply require a lower tax on ICEVs to promote diffusion of FCVs.

Producers offer cars that are heterogeneous, but close substitutes.[3] Thus, the producers act as price setters with limited market power depending on their market share. In each period, they maximize a weighted average of expected revenue and market share.[4] The maximization is subject to capital/investment constraints, where credit availability is higher for larger producers than for small ones (as indicated by the backward loop from producers' capital in Figure II-1). Each producer can either produce ICEVs or switch to the production of FCVs, which is assumed to be more capital intensive.

The switch is made, as soon as FCVs imply a higher expected value of the objective function. Producers are more likely to switch, the higher the tax on ICEVs, the higher the share of filling stations with an H_2-outlet, and the higher the expected cost reductions from LBD. The latter impact, which significantly adds to the original model, is described in the next section. Producers are also doing R&D so as to change the car characteristics according to the consumers' preferences.

Supply and demand is matched as follows. Producers set prices first and adjust their production capacity, but only produce as many cars as consumers order. So there is no excess supply and inventories are omitted. This implies that producers, which overestimated the demand for their products, are penalized by their overinvestment in capacity but not by high variable costs. In the case of excess demand, not all consumers can be satisfied, because a period is not long enough for capacity extensions or price increases. If a consumer cannot get his favorite product, because it is sold out, he will choose a less preferred product and he can actually end up with nothing and has to wait for the next period.

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[3] The supply side of the model is based on Kwasnicki's (1996) behavioral model of producers.

[4] The objective function is constructed, such that small producers try to increase their market share (survival strategy), whereas large producers focus on profits. Kwasnicki and Kwasnicka (1992) show that such a behavior, in the long run, outperforms a pure profit maximizing strategy, given the uncertainties about the behavior of competitors, R&D success, and so on, which prohibit intertemporal profit maximization.

3. Learning by doing

3.1. The experience curve concept

LBD is an appealing view of technological progress, as it models an intuitively comprehensible relationship between experience and process or product optimization. Empirical studies go back as far as 1936, when Wright described the cost development in the aircraft industry. While studies addressing macroeconomic implications of learning trace back to Arrow (1962), managerial decision-making on the basis of so-called experience curves became popular particularly due to the influence of Boston Consulting Group (1970). The experience curve concept attracted a lot of attention recently for determining future potentials of renewable energy technologies (Neij, 1997; Mackay and Probert, 1998; Wene, 2000; Neij et al. 2003; Junginger et al., 2005) and has become a crucial tool in energy system modeling (Messner, 1997; Grübler and Messner, 1998; Rasmussen, 2001; Manne and Richels, 2004; Manne and Barreto, 2004).

Throughout the paper, we will use the expressions learning by doing and experience curve interchangeably for a rather wide notion of experience.[5] Following Abell and Hammond (1979) sources of experience - besides the directly improved labor efficiency due to learning - are work specialization and enhanced methods, new production processes, better performance from production equipment, changes in the resource mix, i.e., employment of less expensive resources, product standardization, and product redesign. All these sources are likely to be exploited during mass production of fuel cells, hydrogen tanks, and other drive train related components. We restrict cost reductions from learning to these components and assume that they are learning at the same rate.[6] Other car components of the FCV are learning at the same rate as the ICEV. Actually, we assume that the cumulative production of other car components (and also of the internal combustion engine) is already so high that cost reductions due to learning are negligible.

We follow the standard approach of modeling LBD by using cumulative output as a proxy for experience and apply the following experience curve for the fuel cell drive train:

$$c(unit_T) = c(unit_1)\left(\sum_{s=1}^{s=T} unit_s\right)^{-E}, \qquad (1)$$

i.e., the costs to produce the T^{th} fuel cell unit equals the costs for the initial unit $c(unit_1)$ times cumulative output of all units up to unit T raised to the negative of the experience

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[5] Some studies also use the terms learning curve and progress curve to describe the same phenomenon (Argote and Epple, 1990).

[6] Neij et al. (2003) point out the difficulties to derive aggregate learning rates for several subsystems. But the fuel cell itself is by far the most expensive component in the drive train, so that its learning rate dominates the overall learning rate of the system.

parameter E.[7] A high experience parameter indicates rapid cost decreases. A more intuitive indication of the learning potential of a certain technology is the learning rate (LR), which is the reduction of costs due to a doubling of cumulative output. Using equation (1) it can be easily confirmed that

$$LR = 1 - \frac{c(unit_1)\left(2\sum_{s=1}^{s=T} unit_s\right)^{-E}}{c(unit_1)\left(\sum_{s=1}^{s=T} unit_s\right)^{-E}} = 1 - 2^{-E} \tag{2}$$

holds, so that, e.g., an experience parameter of 0.23 implies a learning rate of 0.15, i.e., unit costs fall by 15% each time cumulative output doubles, independent of the initial costs or the level of cumulative output.

3.2. Limitations of the approach

One drawback of the experience curve concept is that production costs can fall infinitively if production volumes increase. Thus, we use the costs for a conventional internal combustion engine ($\overline{c}$) as a lower bound for cost reductions ($c(unit_T) \geq \overline{c}$). Lipman and Sperling (1999) identify two justifications why reduction limits are indicated. Firstly, cost reductions cannot go further than material costs. The current requirements of noble metals for fuel cells would imply a particularly high lower bound. Even though it is also reasonable to expect that material substitution options will be identified, material requirements will nevertheless prevent infinite cost reductions.[8] Secondly, Lipman and Sperling (1999) state that institutions like the *Partnership for a New Generation of Vehicles* established cost targets for fuel cell drive trains. Once these targets are met, companies' efforts to further reduce costs are limited. This argumentation should be taken with care, as it implies a pure satisficing behavior and companies would forego potential competitive advantages. However, it seems reasonable to believe that once the fuel cell drive train costs approached those of an internal combustion engine, their costs would leave the center of attention for the benefit of quality improvements or cost reducing potentials of other vehicle components.

A more severe limitation of the experience curve concept refers to difficulties in parameterization. Estimated learning rates ex post usually have a high statistical goodness of fit, which is not surprising for non-stationary variables. McDonald and Schrattenholzer (2001) collect learning rate estimates from 26 data sets of different studies for energy related technologies and find the majority of estimates in the range of

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[7] The presentation of the experience curve follows mainly Wene (2000), but can similarly be found e.g., in Abell and Hammond (1979), Dutton and Thomas (1984), Argote and Epple (1990) or Lipman and Sperling (1999) in the context of FCVs. The specific notation is chosen so as to make clear that costs are a function of output quantities (q) and not of time. However, if $q_t \geq 1$ for $t \leq T$, i.e., if at least one unit is produced in every period, we observe monotonously decreasing costs, leading to a common misinterpretation of the experience curve that costs are decreasing over time.

[8] See also Spence (1981) and Ghemawat and Spence (1985).

5-25%. For 21 learning rates, the R^2 as a measurement for the goodness of fit between the data and the experience curve is reported. 17 have an R^2 higher than 0.75; and of those, 11 even exceed 0.9. However, ex ante parameterizations for new technologies are extremely difficult. Due to the exponential impact of the learning rate on production costs, only small changes in the rate might determine the success of a new technology. Low expected learning rates might lead to prohibitively high production requirements for the new technology to become competitive. On the other hand, high expected learning rates might involve too optimistic cost reductions. Moreover, exact cost measurements of the very first units produced would be necessary for a reliable cost prediction. But actual costs of prototypes and initial limited-lots for testing are not only difficult to evaluate within a firm, but are also kept secret, as they would provide competitors with important information on potential market introduction.

Finally, there are some objections against the general validity of the concept of experience curves. Hall and Howell (1985) criticize that industries starting from scratch usually have substantial financing costs, which decline over time if being successful. Therefore, the long run correlation between cumulative output and costs might be spurious and real gains from learning are likely to be exhausted after a relatively short period of time at least at the plant level. Furthermore, they find that regressing price (which is usually taken because of the difficulties of getting cost data) on cumulative output has no additional explanatory power than just using current output, so that LBD cannot be separated from scale effects. But these criticisms do not apply for our model. Our main focus is indeed on the early cost reductions due to learning and mass production, without differentiating between. These reductions are crucial for the decision of a producer to switch to the production of FCVs. Financing costs play only a minor role, because car producers, who are introducing FCVs, are not starting a completely new industry, but rather make a major advancement within an established one. Moreover, they are big enough to get loans without a noteworthy risk premium for applying a new technology.

3.3. Implementing LBD in the existing model

Learning by doing enters the model by changing producers' expectations about future income due to changes in variable costs. The expected income of the producer is computed as

$$INC^{exp} = \sum_{s=t}^{s=t+\tau} \left(q_t^{exp} p_t(\mathbf{car_{t,FCV}}) - \sum_{T=q_{s-1}}^{T=q_s^{\exp}} c(unit_T) \right) e^{-(s-t)r}, \qquad (3)$$

where τ represents the length of the producers' decision horizon, $\mathbf{car_{t,FCV}}$ is a vector of characteristics of a car produced by a specific producer, with FCV = 1 if the car has a fuel cell drive train (otherwise FCV = 0) and $p_t(\mathbf{car_{t,FCV}})$ is the price of the car. The expected number of cars sold q_t^{exp} is a function of the price $(q_t^{exp} = q_t^{exp}(p_t(\mathbf{car_{t,FCV}})))$, where the demand is determined by certain market conditions (like competitors prices and market shares). Moreover, the expected number of cars sold cannot exceed production capacities. The right hand side of equation (3) reduces to the term in large brackets, if the producers' forward looking horizon does not go beyond the current period ($\tau = 0$). Then, income is simply expected revenue minus expected variable costs. But in contrast to the earlier model, variable costs $c(unit_T)$ now follow an experience curve as in equation (1), if the car in question is a FCV. Then variable costs depend on the number of FCVs already constructed in previous periods and each unit produced reduces the costs of the next one. Thus, if the producer expects to sell, e.g., 50,000 units ($q_t^{exp} = 50,000$) and has already produced a cumulative number of FCVs of 100,000 units until the last period, then the total variable costs expected for the current period are the sum of the individual costs of car number 100,001 ($c(unit_{100,001})$) to car number 150,000 ($c(unit_{150,000})$). In the case of an ICEV learning potentials are already exhausted. Thus, costs are independent of cumulated productions, so that the second term in the large brackets of equation (3) equals $q_t^{exp}\overline{c}$.

As a further deviation from the original model, a producer now bases his optimization on a longer time horizon ($\tau > 0$), so according to equation (3), INC^{exp} becomes the sum of the discounted expected incomes. This extension is a concession to the problem that otherwise the likelihood to switch to the production of FCVs would depend on the length of the time step of the model. In the original model, the producer sets the price that maximizes his objective function, which is determined by expected income (normalized relative to total income in the whole industry) and expected (relative) market share, where expectations are limited to one period, representing a quarter of a year. As long as the producer has not switched to the production of FCVs, he computes optimal prices for the car, being either a FCV ($\mathbf{car}_{t,1}$) or an ICEV ($\mathbf{car}_{t,0}$). With learning by doing, this switching decision also includes the notion that aggressive low pricing might pay off via increased quantities, which lead to lower costs.

The rather short decision horizon of a quarter ignores the fact that switching now implies cost reductions in future periods due to learning. Moreover, as the switch requires additional capital, it is even more unrealistic that such a major decision is based only on the next three months. Thus, we assume that producers evaluating the production of FCVs focus on their income over the next periods. Based on the duration of a lifecycle of a car, we set the decision horizon to three years in our central case. In reality, producers might consider a strategy of switching to the production of FCVs and not only setting low prices initially to sell high quantities, but also increasing prices later on (Dasgupta and Stiglitz, 1988). However, implementing such a strategy would require intertemporal optimization, which is ruled out in the modeling framework due to substantial uncertainties about the behavior of competitors, the development of H_2-infrastructure, the acceptance of the technology by consumers, and changing taxes.

3.4. Parameterization of the experience curve

McDonald and Schrattenholzer (2001) compile learning rates for energy technologies in general, which occur to be in the range from 5% to 25%.[9] Table II-1 lists several studies, which explicitly use learning rates to predict future costs of fuel cell technologies. The data show that researchers calculate with learning rates, which are within a wide range and rather high. The comparability of the underlying experience curves is limited due to the different assumptions regarding initial fuel cell costs and the initial cumulative production. Further differences arise from the different units of measurement. Some studies focus on the overall wattage produced, where also an increase in the number of stationary fuel cells has a cost decreasing impact on fuel cells in mobile applications. Others fix the power of a fuel cell at 50 or 70kW and derive learning rates for the number of units produced. In general, the model specifications deviate from the theoretical setup of the experience curve, because initial costs do not refer to the very first unit produced, but rather are cost estimates for a certain initial "mass production".

Table II-1: Learning rates, initial FC costs and initial number of units

Reference	Learning rates used for simulation (in %)	Base fuel cell costs in US$/kW	Base cumulative production
Rogner (1998)	10; 20; 30; 40	2,500; 4,500; 10,000	2MW
Lipman and Sperling (1999)	15; 20; 25	1,800; 2,000; 2,200	5MW
Gritsevskyi and Nakicenovic (2000)	20	n.a.	10MW
Lovins (2003)	20-30	100-300 by year 2010	n.a.
Schlecht (2003)	20; 30; 40	129-516	10,000 units
Sørensen et al. (2004)	10; 20	392(€/kW)	50,000 units
Tsuchiya and Kobayashi (2004)	26	167	50,000 units

In our model, we use a rather low learning rate of 15% for the central case and vary it from 10 to 20%. This can be justified by the assumption that several parts of a FC drive train system (electric motors, batteries or super-capacitors, generators for recovery of breaking energy etc.) would also be implemented in an advanced (hybrid) ICEV and would, therefore, not represent FCV specific learning. Roughly in line with current cost projections of Arthur D. Little (2000) and the detailed cost estimates by Tsuchiya and Kobayashi (2004), we expect (for an initial production size of 10,000 units at 50kW)

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[9] Learning rates in energy technologies turn out to be in the same range, as observed, e.g., by Dutton and Thomas (1984), for a variety of industries. For the case of wind power, see also the overview of learning rate estimates in Junginger et al. (2005).

initial costs of 13,000€, which are five times the drive train costs of an ICEV.[10] Initial costs are of course also uncertain and additional model runs with different initial costs have been conducted. Beside the straightforward result that lower initial costs lead to earlier diffusion, the linear impact is dominated by the exponential impact of the learning rate, so we refrain from presenting those results and focus on different learning rates.

3.5. Main calibration and scenario assumptions

All other parameters unrelated to LBD have not been altered from Schwoon (2006). The model is calibrated, so as to mimic some of the main features of the German compact car segment. There are 12 important producers in the segment of compact cars in Germany with market shares exceeding 2%. However, one producer (*Volkswagen*) dominates the market with a market share of about 1/3. To mimic the fact that the market is unequally partitioned, we draw initial market shares randomly from a normal distribution with mean 100/12% and a standard deviation of 10%.[11] Restricted by computation time, we allow for 6400 different consumers. In the control run, without any policy, about 125 consumers buy each period, i.e., if we assume that each consumer represents about 2,000 similarly behaving ones, we end up at one million sales per year, which corresponds to the size of the segment we are modeling. Initially, there are about 400 fuel stations with an H_2-outlet. Like in the "exogenous H_2" scenarios of Schwoon (2006), we assume a public infrastructure program that provides 80 filling stations with a hydrogen outlet each year. Moreover, the tax scheme implemented by the government lies in-between the "gradual tax" and the "shock tax" scenarios, by assuming, that the government shocks the market with a 5% tax by the year 2010 and increases it by additional 5% in the consecutive years, until a tax level of 40% is reached. The tax represents not only purchase taxes, but also the net present value of total lifecycle taxes (on ownership, insurance, fuel etc.). Therefore, a 40% level can be considered as rather low, compared to current taxes in Europe (Burnham, 2001).

A major problem with calibration in the context of LBD is that learning would occur globally, i.e., producers selling FCVs, e.g., in Japan or the US, would achieve cost reductions, providing them with different starting positions for the German market. On the other hand, concerted governmental action in these countries is unlikely. Thus, the results should be seen as relevant for a situation, in which a government decides to push, in a solo attempt, the introduction of the new technology in a market of comparable size to the German market. Looking at the history of pollution regulation of cars, this seems to be not unrealistic. The independent introduction of unleaded fuels and the support of 3-way catalytic converters in Japan, the US, and later on in Germany, which preceded most other Western Europe countries, as described in Westheide (1987), can be seen as examples for successful policies on a national level. Moreover, the substantial impact of the zero emission vehicle regulations of the State of California

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[10] In Schwoon (2006), unit costs of 13,000€ for an average compact car are used. As a rule of thumb, drive trains of ICEVs account for about 1/5 of total costs, i.e., 2,600€. Thus, with fuel cell drive train costs of 13,000€, initial FCV costs add up to 23,400€.

[11] The minimum market share is 2% and the sum of all market shares is scaled to sum up to 100%.

on the R&D activities of car producers world wide (Hekkert and van den Hoed, 2004) show how influential policies for a single (but significant) market can be.

The model is implemented in the Laboratory for Simulation Development (LSD) and the code is available from the author upon request. The LSD environment includes a user-friendly graphical interface that allows testing, e.g., parameter changes without a detailed knowledge of the underlying program.[12]

3.6. Diffusion curves in the presence of LBD

Figure II-2 shows, how predictions of the penetration of the German compact car market with FCVs depend on the actual learning rate in fuel cell drive train technology. The diffusion curves are averages of 100 simulation runs with different random seeds. The time horizon producers employ to evaluate the switching option is set to three years. The figure clearly demonstrates that even rather small variations in the assumed learning rate determine the diffusion process. For a low learning rate of 10% fuel cell costs do not sufficiently decline within the decision horizon, so that hardly any producer switches production and FCVs do not gain a noticeable market share over the computed time horizon. With higher learning rates, producers successfully introduce FCVs; and the higher the learning rates the earlier and faster FCVs take off. Note that for a learning rate of 15 to 20% the share of newly registered FCVs increases at an increasing rate for the first three years after initial introduction and then continues increasing on a rather steady rate. The reason is that hydrogen infrastructure does not reach full coverage within the first few years of fast FCV diffusion, and small producers can establish a temporary (relative) successful niche serving those consumers with high infrastructure demand.[13]

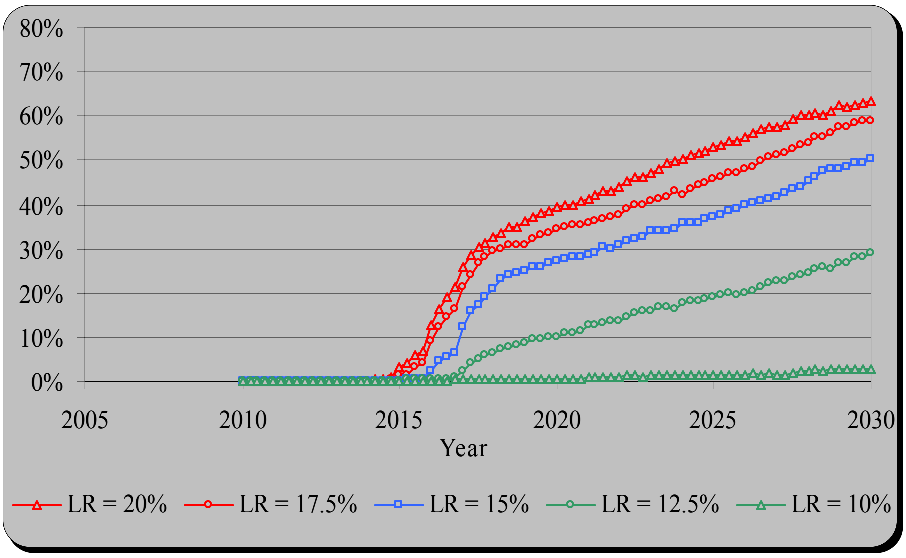

Figure II-2: Percentage share of FCVs within newly registered cars in the German compact car segment (different learning rates in fuel cell technologies)

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[12] For a description of LSD see Valente and Andersen (2002).

[13] The niche is only temporary, because the model setup implies that as soon as every filling station offers hydrogen all producers switch production, so as to avoid the (high) taxation of the ICEV.

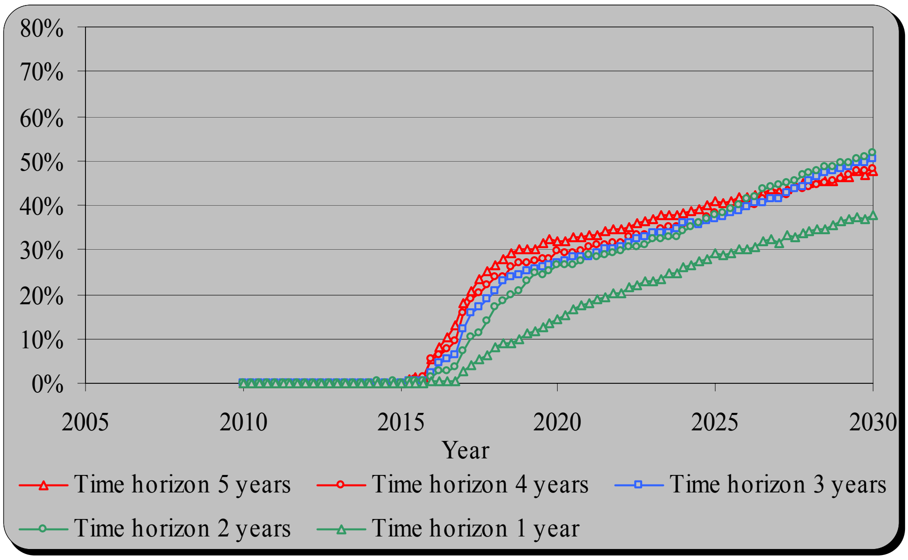

Figure II-3: Percentage share of FCVs within newly registered cars (different lengths of the producers' decision horizons)

Figure II-3 shows that the longer the producers' decision horizon the earlier and faster the diffusion; or conversely, a very short perspective can severely hamper diffusion.[14] Thus, in the presence of LBD a limited time horizon creates a major barrier against the introduction of the new technology. Even though this result is not surprising, given the discussion of the model setup in section 3.3., it has an interesting policy implication. The government could foster diffusion by supporting long term investment decision-making by appropriate depreciation allowances or options to carry forward losses associated with the production switch.

4. Learning spillovers

4.1. Channels of learning spillovers

So far, learning effects have been treated as being only dependent on the producers' own experience. This is usually referred to as proprietary learning in opposite to spillover learning, where producers can also gain from their competitors' experience. There are various channels for such spillovers, e.g., reverse engineering, inter-firm mobility of workers, proximity (industry clusters), or learning on sub-supplier level. All these channels can be expected to apply for fuel cell technologies. Once the first FCVs are sold at the market, producers lagging behind technologically are likely to dismantle FCVs of their competitors.[15] According to Franco and Filson (2000), inter-firm mobility of workers and the active poaching of high skilled experienced workers is particularly

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[14] Note that the main influence of the decision horizon is on the date, when the first producers switch. After about ten years of diffusion, there is no significant difference in the share of newly registered cars anymore, as long as the decision horizon is at least two years long.

[15] Reverse engineering has previously played a major role in car production (see Lee, 2000).

observable in high-tech industries. The existence of car technology clusters like Detroit/US or Stuttgart/Germany facilitates such learning spillovers. In the Canadian fuel cell producer *Ballard Power Systems*, several major car producers have a common sub-supplier, so that producers would gain from experience accumulated there.[16]

A rarely addressed channel for spillovers is weak patent rights. A government might force producers to license environmental friendly technology to competitors. Thornton and Thompson (2001) analyze wartime ship building in the US as an extreme case. At that time the government actively transferred knowledge from one firm to the other. They find a small but significant spillover effect: 15 ships produced within the industry increased productivity of the individual firm by the same amount as one ship produced by its own. Empirical evidence of spillovers in general is rather inconclusive. Spillover effects are existent but low also in the case of nuclear power plants (Zimmerman, 1982; Lester and McCabe, 1993) and semiconductors (Irwin and Klenow, 1994; Gruber, 1995). But for agricultural production (Foster and Rosenzweig, 1995) and samples of the manufacturing sectors in the US (Jarmin, 1996) and Spain (Barrios and Strobl, 2004), there is evidence for extremely high learning spillovers, with industry experience being even more important than own experience. Barrios and Strobel (2004) suppose that this rather counterintuitive result is due to the general diffusion of (other) new technologies. This effect is difficult to separate from pure learning effects. However, given that all the studies agree that learning spillovers exist, they should not be ignored from the analysis. The empirical evidence also suggests that learning spillovers are industry dependent and therefore hardly transferable to new industries. Thus, their magnitude in fuel cell technologies is subject to substantial error. But recalling the above discussion of potential spillover channels there, a sensitivity analysis should also include simulations with high spillover potentials.

4.2. Spillovers facilitate diffusion

Figure II-4 illustrates how different assumptions regarding learning spillovers change the predicted diffusion of FCVs. The proprietary learning graph is identical to the central cases in Figure II-2 and Figure II-3. The 5% case implements the assumption that 20 FCVs produced by competitors lead to cost reductions equivalent to one own produced FCV. Correspondingly, with 100% learning spillovers cost reductions only depend on cumulative production of all producers. A possible situation, in which this assumption holds is if, e.g., *Ballard Power Systems* was the only supplier of fuel cells and would pass on all its cost reductions to the car producers (because they jointly own the company). Figure II-4 indicates that already rather small spillovers encourage much faster diffusion. High spillovers increase the speed of diffusion at the very beginning, but at the end of the simulated period the difference in penetration between, e.g., 10% spillovers and 100% spillovers is rather small. The graphs using averages of 100 simulation runs slightly understate the impact of learning spillovers, because some of

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[16] *Ballard Power Systems* is actually partly owned by *DaimlerChrysler* and *Ford* and holds supply contracts with *Volkswagen*, *Mazda* and *Nissan*. Similar cooperations exist between *Hyundai*, *BMW* and *International Fuel Cells* or *Renault*, *PSA* and *Nuvera Fuel Cells*, while *GM* and *Toyota* directly collaborate in fuel cell R&D.

the individual runs show no diffusion at all. In opposite to the learning rate and the forward-looking horizon of the producers, spillovers do not affect the switching decision of the very first producer. Therefore, the number of simulation runs without diffusion is independent of the assumed learning spillovers and all graphs would be shifted by the same factor, leaving qualitative insights unchanged and implying a (small) linear scaling of magnitudes. Figure II-5 compares the impact of small changes in the learning rate with changes in the magnitude of spillovers. Not only the starting point of diffusion, but also the main development is determined by the learning rate. However, once diffusion starts, learning spillovers enforce diffusion noticeably. Thus, policies that facilitate learning spillovers are advisable if fast penetration of the environmental friendly technology is intended.

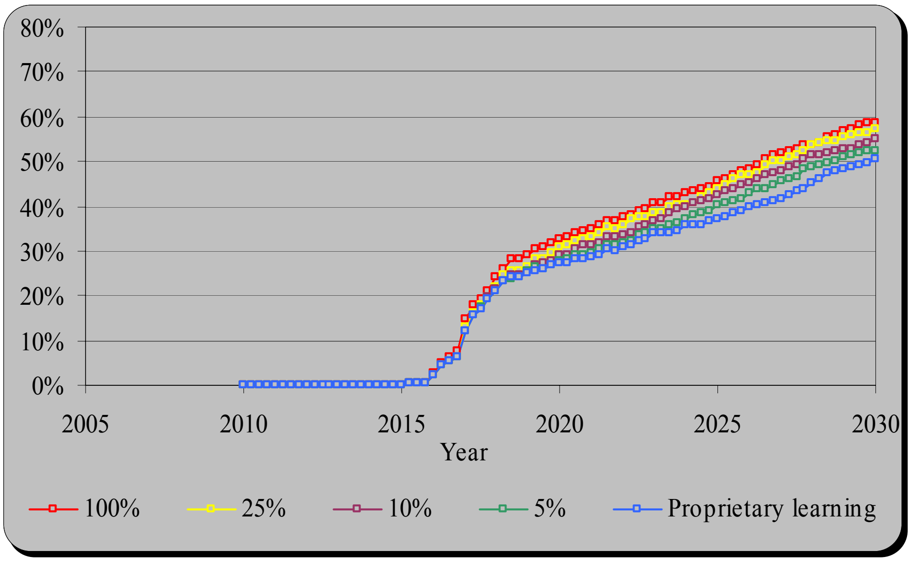

Figure II-4: Percentage share of FCVs within newly registered cars (different rates of learning spillovers)

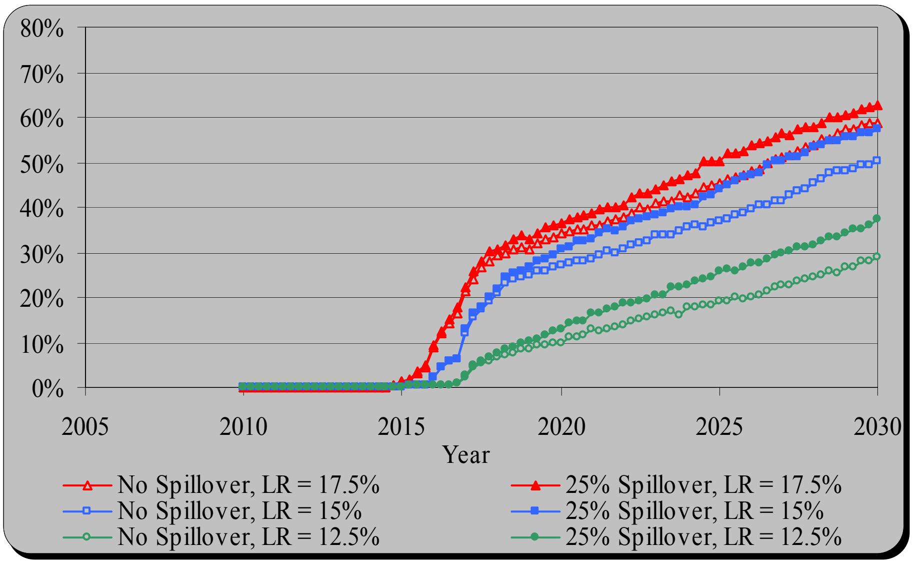

Figure II-5: Percentage share of FCVs within newly registered cars (impact of learning rates vs. impact of learning spillovers)

4.3. First mover advantage

In a stylized theoretical model, Dasgupta and Stiglitz (1988) show that in the presence of LBD there is a tendency for a dominant producer to emerge. The reason is that an initial advantage in scale can be extended over time, as LBD implies dynamic increasing returns in production. The consequence is a substantial first mover advantage of the first producer starting to accumulate experience. There is some empirical evidence for first mover advantages due to LBD (Gruber, 1998; Madsen et al., 2003, Hansen et al., 2003). According to Ghemawat and Spence (1985), learning spillovers generally increase market performance by reducing the relative advantage of the biggest producer.[17] While a first mover advantage is noticeable in the present model, the implications of spillovers are not clear cut. To get an impression of how the first mover performs, we identify from each random simulation the producer who switches to the production of FCVs first. Then we compute for each period the average relative change in profits compared to the profit level before the introduction of tax. We compare these averages with the performance of the producers switching as second, third, and so on.

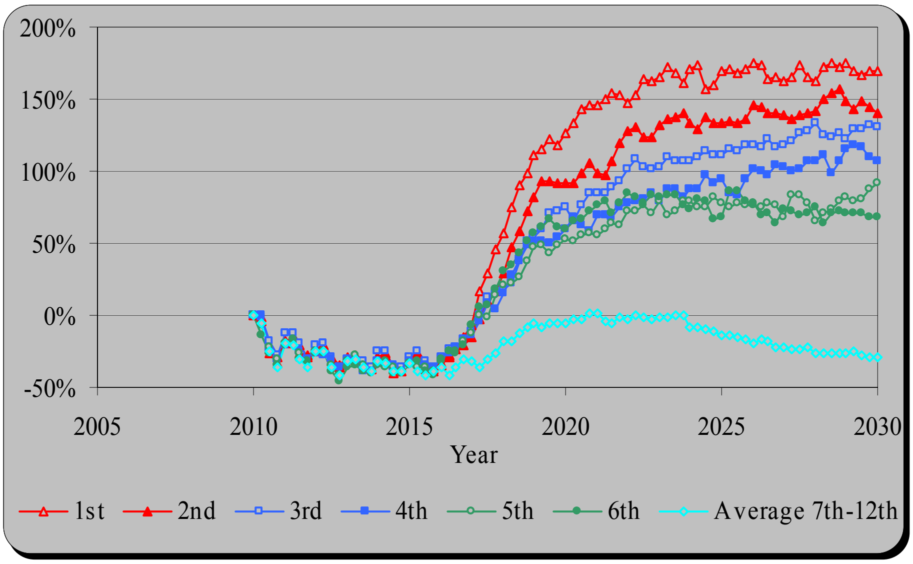

Figure II-6: Change in producers' profits relative to pre-tax level, dependent on their order of switching to the production of FCVs

Figure II-6 shows the results, where we pool the 7th to 12th producers for the matter of clarity of the overall picture. Actually, they usually do not switch at all during the simulated period (otherwise we would have complete diffusion until 2030, which is not the case according to the figures above). In general, the notation 1st to 12th should only indicate the relative behavior of switching, with a major focus on the first mover and early followers. The figure shows that the first mover (like all other producers) suffers losses due to the tax. The average switching period is around 2016, when (relative) profits of the first mover starts rising substantially, exceeding pre-tax levels within few years and further increase until a level of about 160% is reached. The reason for this

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[17] Fudenberg and Tirole (1983) show that market performance may decrease if producers behave strategically, recognizing their spillovers to competitors. Such behavior requires intertemporal optimization and can, therefore, not be implemented in the current model.

substantial increase is that costs of FCVs decline rather quickly, implying higher profit margins (given that there are still highly taxed ICEVs in the market). Moreover, the tax driven technology switch forces some smaller producers to exit the market, so that market power and, hence, profits increase. Switching later (as a second mover, third mover, and so on) also pays off, but the gains are not as big as for the first one. Note that this first mover advantage is observed on average. In some of the simulations the gains for the second or third mover exceed those of the first, so that we cannot conclude that producers should generally aim for being the first.

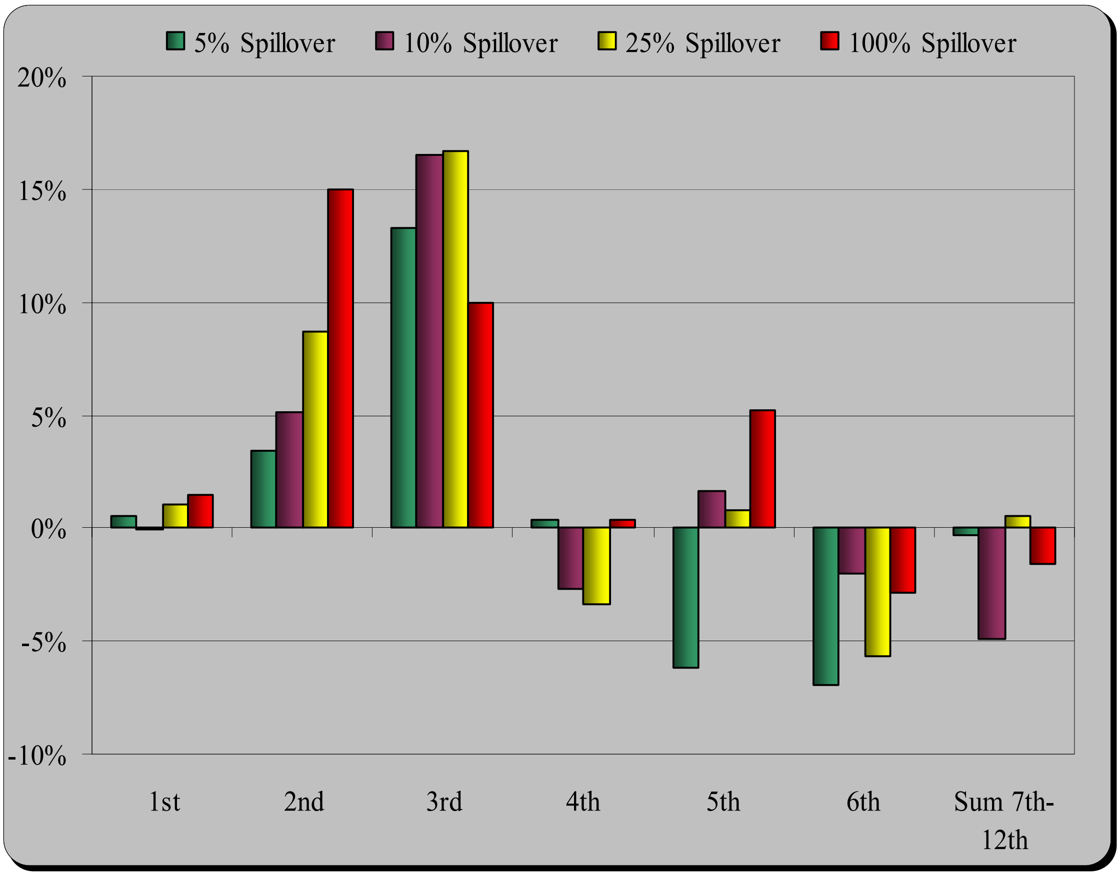

Figure II-7: Change of producers' profits with spillovers relative to no spillover case

Figure II-7 shows, how the net present values (NPVs) of profits change if spillovers exist, using the same interest rate of 10% per year that is also applied for investment decisions during simulations. Surprisingly, the first mover is hardly affected by spillovers. The reason is that there are two balancing impacts. On the one hand, the first mover loses some of his cost advantage due to learning to his early followers. But on the other hand, he gains from the generally faster penetration of the new technology, which implies a faster infrastructure build-up and adoption externalities, as consumers depend on their neighbors decisions. It can be seen from Figure II-7 that the spillover magnitudes determine, which effect dominates. For rather small learning spillovers, similar balancing effects hold for the second mover, but he can also gain from the cost reductions of his predecessor. But the real winner of small spillovers is the third producer with increases of 14 to 17% of his NPV for spillovers less or equal to 25%.

The higher the spillovers, the more favorable they are for the second mover. The relative benefit of the second and third mover, compared to the first, can be seen as weak support for Ghemawat and Spence's (1985) result that learning spillovers should increase market performance. But note that the increased speed of diffusion is only clearly beneficial for the first three switchers. Depending on the actual magnitude of spillovers, some of the later followers are actually worse off, so that the benefit of early followers comes at the expense of later ones.[18]

5. Policy implications

The previous sections showed that high learning rates, long planning horizons of the producers and high learning spillovers have a positive impact on the diffusion of FCVs. The government can hardly affect learning rates, but we stated earlier that governmental regulations have some impact on the length of planning horizons. Furthermore, according to Fudenberg and Tirole (1983) the government can influence learning spillovers, e.g., via patent and cartel laws. But especially a mandatory licensing of patents is problematic, as it reduces R&D incentives. Following the channels of spillovers discussed above, another option would be to relax regulations of headhunters to facilitate mobility of high-skilled workers. But this would require accepting a severe intervention into the mutual trust between employer and employees. Less problematic policies seem to be the support of technology clusters, whose importance is widely accepted (see, e.g., Krugman, 1991; Porter, 1998; Hansen et al., 2003), or public R&D for the benefit of common sub-suppliers.

While promoting learning spillovers as a diffusion policy has rarely been addressed, learning gains and first mover advantages have repeatedly been used as arguments for substantial support of environmentally friendly technologies. If the government expects national producers to be most likely to adopt such technologies, they could "ride down the experience curve" (Neij et al., 2003) and gain a cost advantage over their competitors. This would strengthen their international market position, once global demand increases.[19] As a result, the support of "green" technologies would have an environmental and economic benefit. The simulation results suggest that a similar argumentation in favor of support of FCVs, first of all, requires some knowledge about the actual learning rate of fuel cell technologies, because learning potentials might be too small for a successful introduction. Moreover, if the government is interested in maximizing the relative advantage of a national first mover, it should prevent learning spillovers. Conversely, if for environmental reasons the government wants diffusion of FCVs to be as fast as possible, it should facilitate spillovers. Thus, the simulations imply that fast diffusion due to spillovers and high first mover advantages might be

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[18] If we look at the Herfindahl index as a standardized measure of market performance, spillovers seem to have no noticeable impact in this model.

[19] This infant industry argument is made in the context of the Danish wind power industry, where the national market was totally dominated by home producers (Hansen et al., 2003).

conflicting targets.[20] Actually, the optimal policy depends on the market structure. If national producers are expected to be early followers, then promoting spillovers not only accelerates diffusion, but also supports national industry. Governments of Germany, France, Japan or the US with dominant national producers would face the above trade-off. On the other hand, for China, which currently builds up an own car industry, it might actually be beneficial to force foreign producers to switch and let national producers gain as early followers, ending up with a fast diffusion of FCVs.

6. Conclusions

This paper extends an existing agent-based model to simulate potential diffusion paths of FCVs in a large but confined market, such as the German compact car segment, with LBD in fuel cell technologies. While the original model uses fixed unit costs of mass-produced fuel cell drive trains, in this paper unit costs follow an experience curve and producers' decisions to switch to the production of FCVs include cost projections. Diffusion is driven by a tax on ICEVs that is phased in at the beginning of 2010. The results suggest that diffusion strongly depends on the underlying assumption regarding the learning rate, so that low learning can even prohibit diffusion. Moreover, the tax can only successfully induce diffusion, if the planning horizon of the producers is long enough, such that they can incorporate long term cost reductions.

We also allow for learning spillovers and find, unsurprisingly, that higher spillovers lead to faster diffusion. There seem to be substantial first mover advantages, as the producer, who switches first, starts accumulating experience first. Learning spillovers can decrease this first mover advantage. Since regulation has at least some influence on learning spillovers, the model results suggest that if the government is not only interested in fast diffusion of the new technology, but also cares about national champions, the government faces a trade-off when setting the regulatory environment. But there is no trade-off if national producers are early followers, because they appear to be the main beneficiaries of high spillovers.

The current model has the advantage of being detailed enough to represent the main dynamics that drive the complex diffusion process of a new power train technology without concealing the major cause and effect relationships. The setup can be easily adjusted to comparable market segments in other countries or, e.g., in the EU as a total. Updated estimates of cost developments or prospects of the timing and character of taxes (or subsidies) are implemented right away.

As discussed in Schwoon (2006), there are several limitations of the model, which are inherent in the setup itself. These include the restriction to a certain segment of the car market, so that consumers cannot evade to a cheaper segment; the assumption, that producers make a radical switch to fuel cell technology, instead of introducing it smoothly in parts of the product line; and the simplistic representation of hydrogen

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[20] In any case, producers face substantial losses during the introduction of the tax, and there is a significant increase in market power later on. This seems to be unavoidable downsides of the tax-induced diffusion process.

infrastructure. Now, the current representation of LBD adds other potential shortcomings. The empirical base of the parameters of the experience curve is weak. The same is true for the learning spillover potentials. We addressed these uncertainties with sensitivity analysis. A more realistic behavioral model of the producers would involve different expectations of own learning rates (and spillovers), which could follow probability distributions and, perhaps, a risk averse understatement of learning potentials. But such improved realism is likely to obscure the general model behavior without changing qualitative insights. Another limitation is the simple price setting and technology switching behavior of the producers that ignores their own spillovers to others via LBD and the externality via an increased share of filling stations with H_2-outlet. Moreover, a more realistic model would also allow producers to support filling station owners to provide more H_2-outlets, because they could then sell their FCVs at higher prices, since consumers need less compensation for limited fuel availability.

III

A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations

Abstract. An important barrier towards the introduction of fuel cell vehicles (FCVs) running on hydrogen is the lack of widespread refueling infrastructure. The niche of buses for public transport, taxis and deliverers with a local application area might not be large enough to generate the reductions of FCV costs that are necessary for a general technology switch. Thus, fuel availability at trunk roads probably plays a crucial role in generating demand for FCVs also from private consumers. In this paper we assume that consumers are more likely to consider buying a FCV the more frequently they are exposed to hydrogen refueling opportunities on long distant trips. We introduce a tool to test different small scale initial distributions of hydrogen outlets within the German trunk road system for their potential success to generate a large scale adoption of FCVs. The tool makes use of agent-based trip modeling and Geographic Information System (GIS) supported spatial modeling. We demonstrate its potentials by testing a ring shaped distribution of hydrogen outlets at highway filling stations. We find that the structure of an optimized initial distribution of filling stations depends on what drivers consider a sufficiently small distance between refueling opportunities.

JEL classification: L92, R19, R40, Q42

Keywords: Agent-based Modeling, Alternative Fuels Hydrogen Infrastructure, Fuel Cells

1. Introduction

Fuel Cell Vehicles (FCVs) running on hydrogen are a medium to long term option to reduce externalities related to individual transport. There are basically no local emissions from driving but water and the noise level is low (compared to internal combustion drive trains). Greenhouse gas emissions can be decreased, depending on the energy mix that is used for the generation of hydrogen. Moreover, displacing oil as the main transport fuel reduces costs associated with supply security due to the uneven distribution of oil reserves worldwide (Ogden et al., 2004). There has been long experience with hydrogen production and pipeline or tank vehicle distribution even at larger scales, because hydrogen is a widely applied industrial gas. On the vehicle side, several major car producers handed over small series of FCVs to end consumers for testing in everyday life. Former technological problems related especially to high pressure hydrogen refueling, on board hydrogen storage or cold start of the fuel cell system seem to be resolved. Current research is mainly focused on size and weight of the fuel cell and the reduction of material inputs, especially noble metals like Platinum and Ruthenium (depending on the fuel cell type). So there is a general shift of attention from technological issues towards economic ones.

To launch FCVs at the market at reasonably competitive prices would require setting up production lines to achieve cost reductions from fuel cell mass production. But car producers are probably reluctant to do so as long as a sufficient initial hydrogen infrastructure does not exist, because demand for such cars crucially depends on fuel availability. On the other hand, filing station operators are not willing to make major infrastructure investments as long as there are hardly any FCVs on the road. Ignoring this start up problem, which is also termed the "chicken and egg problem of H_2 and FCVs", the majority of economic studies that focus on estimating the costs and/or the environmental benefits of pathways into an "H_2-economy" are basically best-case scenarios of a successful system switch. The standard approach is to assume a certain number of FCVs and estimate the necessary infrastructure investments to supply them or alternatively to take certain infrastructure developments as given and derive the number of FCVs that can be supplied (see, e.g., Schneider et al., 2004; Thomas et al., 1998; Moore and Raman, 1998; Ogden, 1999a, 1999b, 2002; Stromberger, 2003; Mercuri et al., 2002; Sørensen et al., 2004; Oi and Wada, 2004; Hart, 2005).

In this study, we suggest a tool for filling station operators to test the potentials of initial small scale distributions of hydrogen filling stations. The idea is that to overcome the “chicken and egg problem”, initial infrastructure investments should be low, but at the same time sufficient to generate a general notion of fuel availability for potential FCV buyers. Explicit models on the dynamics of the early stages of an H_2-infrastructure system and FCV driving are absent with the exception of one by Stephan and Sullivan (2004), who suggest an agent-based model, in which drivers tend to buy a FCV, if they are frequently exposed to H_2 filling stations on their usual trips. Conversely, filling station owners add an H_2-pump if they observe sufficient FCV traffic. They test these behavioral assumptions in an artificial urban area with surroundings covering

160x160km. Within this area, commuters drive regularly to a specific business district and some other attractors. In this study, we integrate Stephan and Sullivan's behavioral model into the real German trunk road system combining features from geographic information systems (GIS) and agent-based trip modeling. In doing so, we provide a tool that decision makers can apply to test the potential of different initial distributions of H_2-pumps at trunk road filling stations to initiate a successful transition of the road fuel system. We demonstrate the functionality of the approach by analyzing different initial distributions as, e.g., the "HyWay-ring" suggested by Hart (2005). The placement of H_2-pumps on trunk road filling stations will connect initial urban hydrogen filling stations, which are already set up or planned as demonstration projects. Trunk road refueling is, therefore, crucial for generating a private demand for FCVs and letting them step out of the niche of buses for public transport, taxis or local deliverers. Given today's statements of car producers and energy suppliers, this step could be made in the middle of the next decade.

Our results suggest that a carefully located small amount of H_2-pumps on trunk road filling stations can initiate a transition. Moreover, knowledge about what potential FCV buyers consider a sufficiently short distance between H_2 filling stations changes the structure of the initial placement that performs best. However, if there is uncertainty about this distance, filling station operators should not overstate the assumed distance, in order to prevent complete failure of the distribution.

The paper is organized as follows: The next section describes all parts of the model, i.e., the road network used, the set up of a gravity trip model and the behavior of agents. It also provides information on the data used for calibration. Section 3 demonstrates the functionality of the model by applying it to the "HyWay-ring" and Section 4 shows how the model can be used to optimize initial H_2 filling station distributions. Section 5 concludes with a summary of the main results and points out some weaknesses of the current model.

2. The model

Figure III-1 shows the German trunk road network as used in the model, where the bold blue roads are expressways ("Autobahnen") and the red ones are highways ("Bundesstraßen"). All drivers are assumed to reside in one of about 200 cities with populations larger than 50,000 including a few bordering cities like Basel (Switzerland) or Strasbourg (France). The focus is on cities, because initial H_2-stations (this term is used from now on to refer to an existing filling station that adds an H_2-pump) are likely to be set up in larger urban areas, e.g., to supply buses in public transport or taxis. The labeled cities are the 15 largest German cities with respect to population and they are split in up to 8 city parts. In contrast to Stephan and Sullivan (2004), long distance trips are modeled. The reason is that with current H_2 tank capacity, a range of more than 400km is no problem. This is enough for trips within a city. Thus, a few H_2-stations at arterial roads seem to be sufficient. However, a major benefit from car ownership is the flexibility to do spontaneous long distance trips. This is what people are believed to have in mind, when they state that they would buy an alternative fuel car if they were able to refuel it "everywhere".

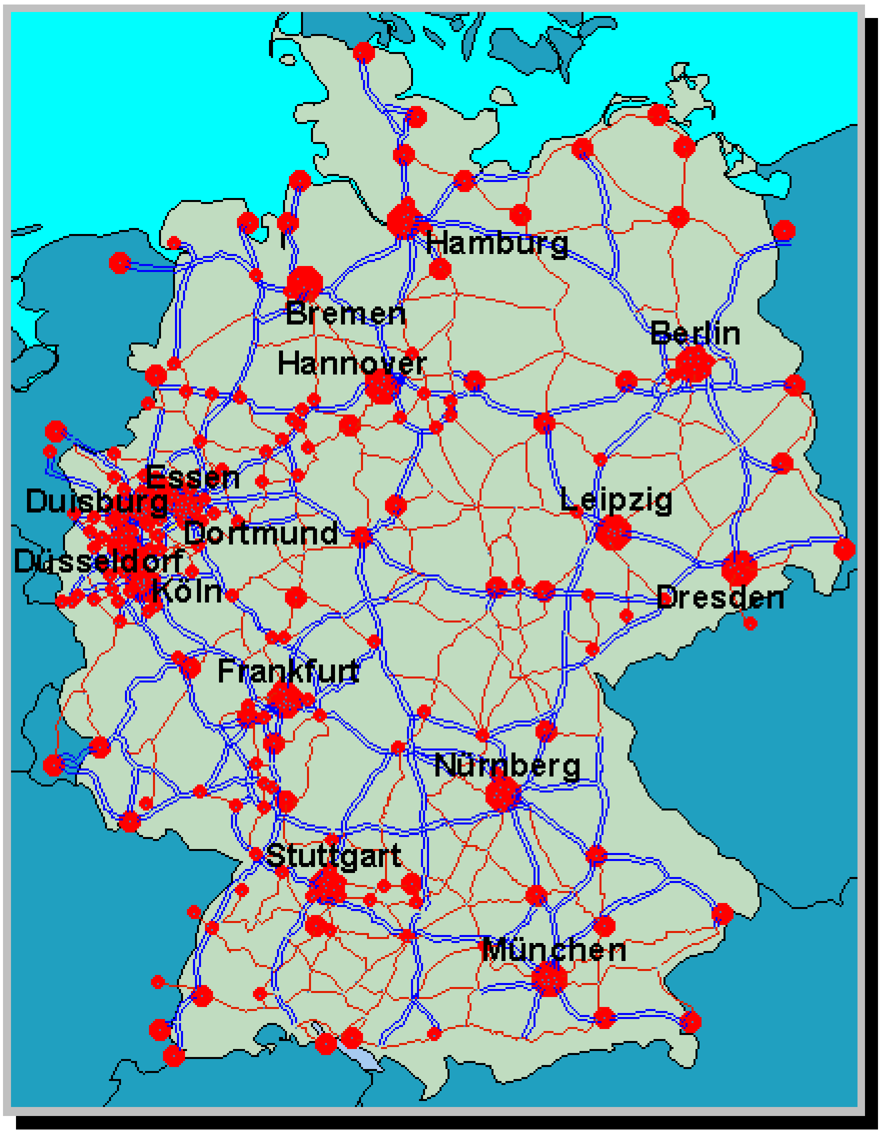

Figure III-1: German trunk road network

2.1. Gravity trip modeling

To get a first approximation of long distance traveling behavior, a gravity model of travel is used (see, e.g., Sheppard, 1978, Erlander and Stewart, 1990, Roy and Thill, 2004). For each city as an origin of a trip it generates for each city as a potential destination a probability that a trip is made between them. The gravity model implies that traffic between two cities increases with the size of the cities but decreases with distance. We estimate the gravity model by applying the maximum entropy approach that goes back to Wilson (1967) and has been applied to regional science by Anas (1983). The maximum entropy concept defines the most probable distribution as the one that has the highest micro level uncertainty (maximum entropy), but generates the observable macro level patterns. In other words, given that the actual individual trip making behavior is unobservable, no restrictions should be made on the individual level, given that aggregated inflow and outflow data emerge. The standard notation of the maximum entropy approach is

$$\begin{aligned} &\max_{t_{i,j}}\ E = -\sum_{i,j} t_{ij} \log t_{ij} && && (1)\\ \text{s.t.}\quad &\sum_{j} t_{ij} = outflow_i && i = 1, \ldots, I \\ &\sum_{i} t_{ij} = inflow_j && j = 1, \ldots, J \\ &C = \sum_{i,j} c_{ij} t_{ij}\ , \end{aligned}$$

where t_{ij} is the probability that a trip is made from origin i to destination j. The sum of all trips starting at origin i must be equal to the (observable) $outflow_i$ and the sum of all trips ending at a destination j must be equal to the (observable) $inflow_j$. The third restriction limits total trip costs to a constant C. The costs of a trip c_{ij} are assumed to be proportional to distance, thus C can be represented by the total amount of kilometers traveled. The required data are obtained from the German Federal Statistical Office (FSO-GOR) for inflow/outflow of commuters and tourist arrivals;[1] total kilometers traveled are derived from GFMTBH (2005). We depart from the standard entropy approach by including additional constrains that make sure that the generated trip probabilities match with traffic count data from Lensing (2003).

2.2. Behavior of drivers

Drivers make randomized trips according to the probabilities of the gravity model. During their trips they recognize the distance between H_2-stations on their way, no matter whether they drive a FCV or a conventional car. As long as this "H_2-distance" is lower than a certain "don't worry distance" (*DWD*), e.g., 50km, they perceive this as sufficient coverage. For greater distances drivers get worried about refueling and the total worry for one trip is then computed as the squared sum of H_2-distances exceeding the *DWD*, so that

$$Worry_{trip} = \alpha \sum_{n} (H_2distance_n - DWD)^2\ , \tag{2}$$

where α is a parameter and $H_2distance_n$ is the distance between the n^{th} and the $(n+1)^{th}$ H_2-station passed by that actually exceeds the *DWD*. When a driver makes a decision to buy a new car he first of all checks whether H_2 is available at his home city and if so, he buys a FCV only if

$$\text{Indiv. Benefits + Soc. Benefits + Tax Exemp.} > \text{FCcosts} + \sum_{trip} Worry_{trip}\ . \tag{3}$$

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[1] Since the values are correlated with population, missing data are approximated using population figures.

Individual benefits are add-on benefits of driving a FCV, as, e.g., being a technological precursor or showing environmental awareness by driving a "zero emission car". Social benefits are derived from group pressure and other network externalities associated with the increased use of the new technology, like the number of garages specialized on fuel cells. These impacts are approximated with the share of people driving FCVs in the home city. Moreover, tax exemptions are assumed to be granted for "zero emission cars". These positive effects of driving a FCV must outweigh the additional costs of the fuel cell system (FCcosts) compared to an internal combustion engine. Costs decline with the number of FCVs sold due to learning by doing, but are extremely high at the beginning. The benefits must also compensate the "refueling worry" associated with driving a hydrogen vehicle, which is computed by summation over the trips during the last six month.[2]

To calibrate the buying decision, we compute the relative benefit of driving a FCV compared to an advanced internal combustion engine vehicle (ICEV) with hybrid electric transmission, automatic gear box, and complex end-of-the-pipe emission reduction. When first offered to the public, we assume that replacing the engine with a fuel cell increases costs per kilowatt by a factor of five. Costs then decline with a learning rate of 10%[3]. Given that drive train costs amount for roughly one fifth of total costs, a FCV would initially cost twice as much as a comparable ICEV. We use a tax exemption of 25% of the end price and assume that individual benefits are correlated with income. Thus, we let the distribution of individual benefits follow the (right skewed) German income distribution.[4] We have to jointly calibrate individual benefits and refueling worries to get the initial amount of potential FCV buyers.[5] Figure III-2 shows the share of people who would buy a FCV, given the underlying distribution of individual benefits and a *DWD* of 50km for different densities of the H_2-station distribution and cumulated numbers of FCVs produced. A diffusion process would start with combinations in the down right corner with long distances between H_2-stations and low cumulated numbers of FCVs produced. Here, between 0.5% and 1% of the buyers would actually buy a FCV. This share of "enthusiasts" is actually far below the share of people with a taxable income of more than 100,000€ per year, and therefore could also represent people who buy a second car and are therefore less dependent on refueling. A successful diffusion would then lower the distance between H_2-stations and increase the cumulated number of FCVs produced, so that we would "climb up the hill" towards the top left corner.

The actual amount of buying decisions and, therefore, of newly registered cars and replaced old ones are fitted against data from the Federal Bureau of Motor Vehicles and

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[2] We implement the *DWD* as if it was independent of drivers. In reality, though, drivers differ in their *DWD* and therefore, all else being equal, potential buyers could be ranked according to their individual *DWD*. However, during our experiments we are interested in the relationship between the (average) *DWD* and the geographic distribution of H_2-stations, and these qualitative insights are not affected by our simplifying assumption.

[3] A learning rate of 10% means that costs decline by 10% each time cumulative production doubles.

[4] Data of German income distribution can be obtained at, e.g., at http://www.sachverstaendigenrat-wirtschaft.de.

[5] Social benefits increase linearly with the share of FCVs but are negligibly low at the very beginning. Later on, they stop increasing after a share of 10% of newly registered cars has been reached.

Drivers (FBMVD, 2005a, 2005b). Driving behavior, i.e., the number of long distance trips people tend to do, is derived from the German Mobility Panel (GFMTBH, 2005).

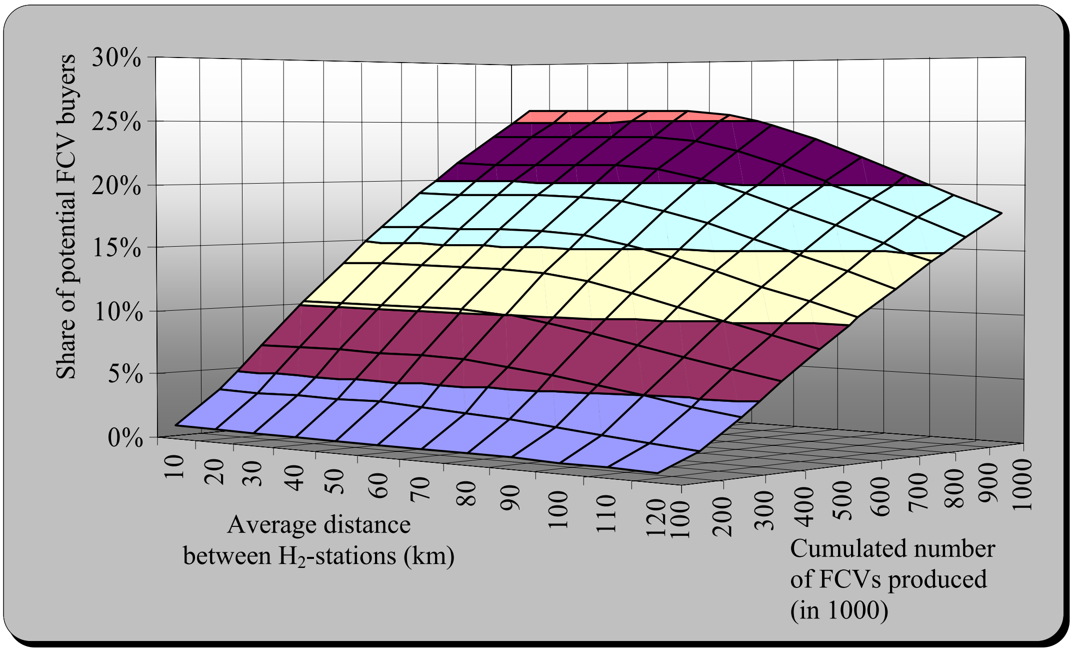

Figure III-2: FCV demand implied by H_2-station density and cumulated production

2.3. Behavior of filling station owners

As in Stephan and Sullivan (2004), filling station owners add an H_2-pump, if they observe sufficient demand for H_2 as implied by the number of FCVs at their road. Stephan and Sullivan (2004) are unclear about the threshold they use. We assume that on average one potential customer per hour observed over a period of six month (with more weight on recent months) is enough for a start, given that a filling station owner would from then on expect increasing demand. In reality, filling station owners cannot observe the traffic on their road.[6] But they do know where their customers come from (e.g., from asking them for their zip code) and they can combine this information with the sales figures of FCVs in these areas. The new H_2-pump is kept at least six months. After the initial six months, the H_2-pump is shut down, if actual FCV traffic (i.e., H_2 demand) is below half of the expected. Thus, we implicitly assume that operation and maintenance costs of the new pump technology together with H_2 transport costs to a remote filling station are considerable, so that shutting down the pump, which can be done at no costs, might be a reasonable option.

A basic H_2 coverage within a city (i.e., H_2-stations at selected arterial roads) is set up, if the number of potential FCV buyers who would have bought a FCV, but didn't, because of the lack of H_2 in their home city, exceeds 1% per quarter. Given usual sales frequencies, this implies roughly 50 potential buyers within a year for an urban area

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[6] Future traffic control and toll systems could actually provide such information.

with 50,000 inhabitants – a number of vehicles served per station well in line with other scenarios (Bevilacqua Knight, 2001; SINTEF, 2005). Depending on the actual number of FCVs in the city later on, this basic H_2 coverage might also be shut down. Again, in reality the necessary information for filling station operators to decide on adding H_2-pumps is not directly observable. What they do observe, though, are constructions of H_2-stations at surrounding trunk roads and, therefore, likely increases in the number of potential FCV buyers.

The thresholds to set up H_2-pumps cannot be validated with empirical observations, because future investment costs for an H_2-pump are not clear and neither are future revenues from selling hydrogen to end consumers. However, these values can be influenced by governmental decisions, e.g., by granting loans with low interest rates and tax exemptions for hydrogen. The general success of the diffusion process modeled is highly dependent on the thresholds used. But comparing the success of different geographic placements of H_2-pumps, as it is done below, is independent of the thresholds.[7]

3. Testing an existing infrastructure scenario

The upper left graph of Figure III-3 shows an initial distribution of H_2-stations (blue "H") at trunk roads following the "HyWay-ring" suggested by Hart (2005) in a study for *Linde AG*. This ring connects major German car production clusters and cities with H_2-station demonstration projects. The distance between the stations does not exceed 50km. In all the model runs presented in the paper, the connected cities (Berlin, Leipzig, Nürnberg (Nuremberg), and so on) are assumed to have a basic H_2 coverage at year 0, which is supposed to be somewhere between 2010 and 2015.

Figure III-3 illustrates the resulting development of H_2-stations, given the initial "Linde scenario" distribution after 5, 10, and 15 years for a *DWD* of 100km, implying that refueling worries are extremely low. After 5 years, some H_2-stations particularly in the West and in the East have been deconstructed due to insufficient demand; while particularly in the South there has been a small increase in H_2-stations. Note that even after 15 years parts of the initial ring remain empty, while the connection between the two largest cities Berlin and Hamburg has been established. This indicates that the suggested initial ring distribution might be suboptimal.

Figure III-4 displays the corresponding numbers of urban areas with basic H_2 coverage, trunk road H_2-stations and the cumulated number of FCVs sold. In Figure III-5, results are shown for a lower *DWD* of 50km, representing a higher concern about refueling that seems to be more realistic. Here, the system is severely hit after the first 4 years, implying that the initial coverage was insufficient. In this scenario, given the initial H_2 coverage, FCVs would not enter the mass market for at least another 20 years.

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[7] Due to the straightforward impact of varying the thresholds, we refrain from showing the results from sensitivity analyses with respect to them.

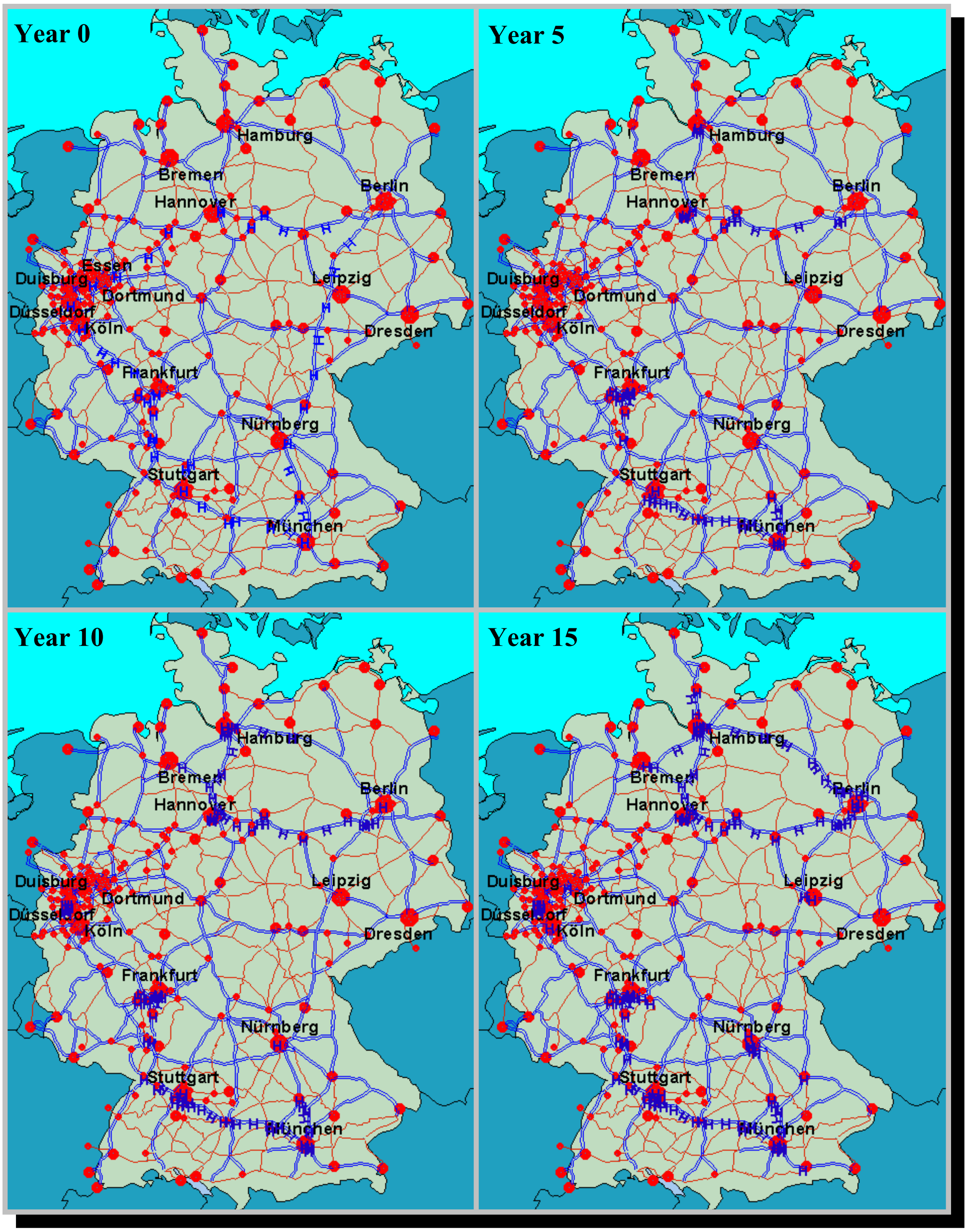

Figure III-3: H_2 trunk road station development for Linde Scenario (*DWD* = 100km)

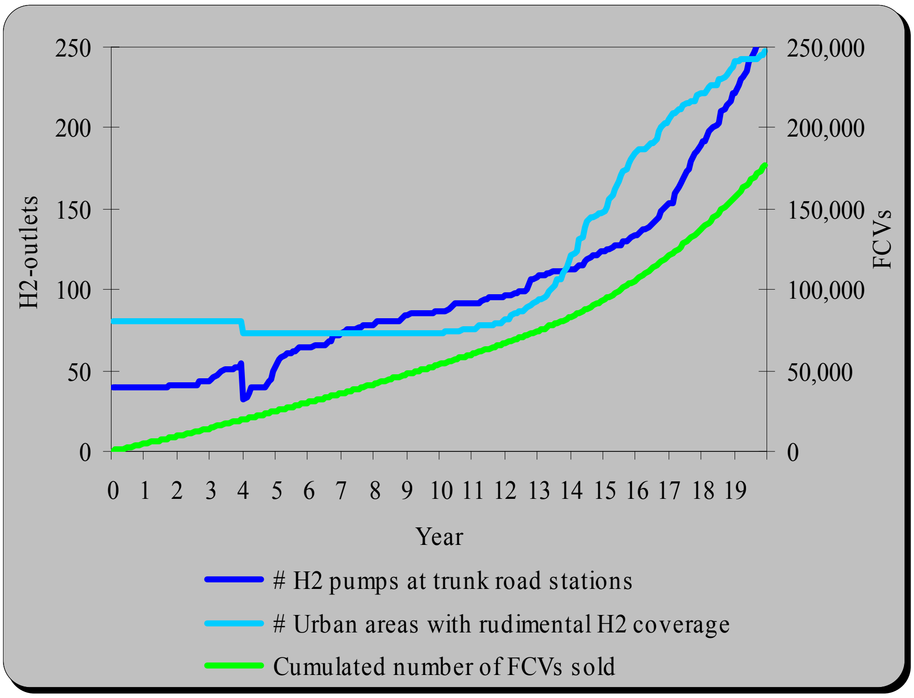

Figure III-4: Infrastructure development and vehicle adoption of Linde Scenario (*DWD* = 100km)

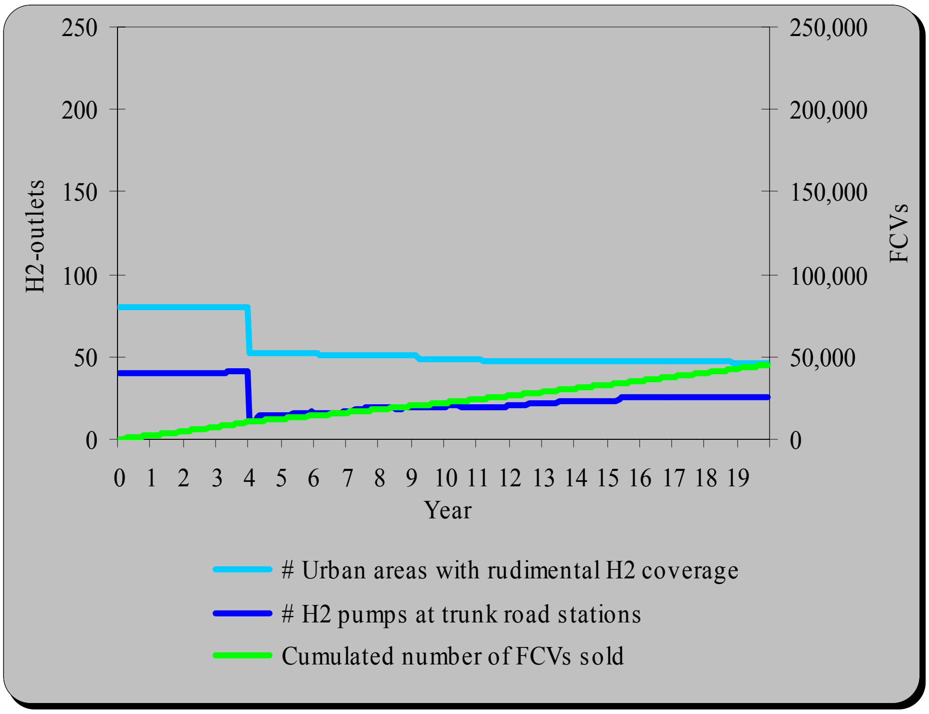

Figure III-5: Infrastructure development and vehicle adoption of Linde Scenario (*DWD* = 50km)

4. Optimizing an initial H_2-station distribution

Given the number of potential initial locations of H_2-stations, it is impossible to search for the optimal distribution.[8] Nonetheless, results from the simulations presented above provide useful information to improve distributions substantially. For example, H_2-stations that are shut down after the initial four years period should rather be located at roads with high FCV traffic. Figure III-6 shows results from using two different improved initial distributions, one derived from the *DWD* = 50km and the other one from the *DWD* = 100km case above. With the same amount of initial trunk road filling

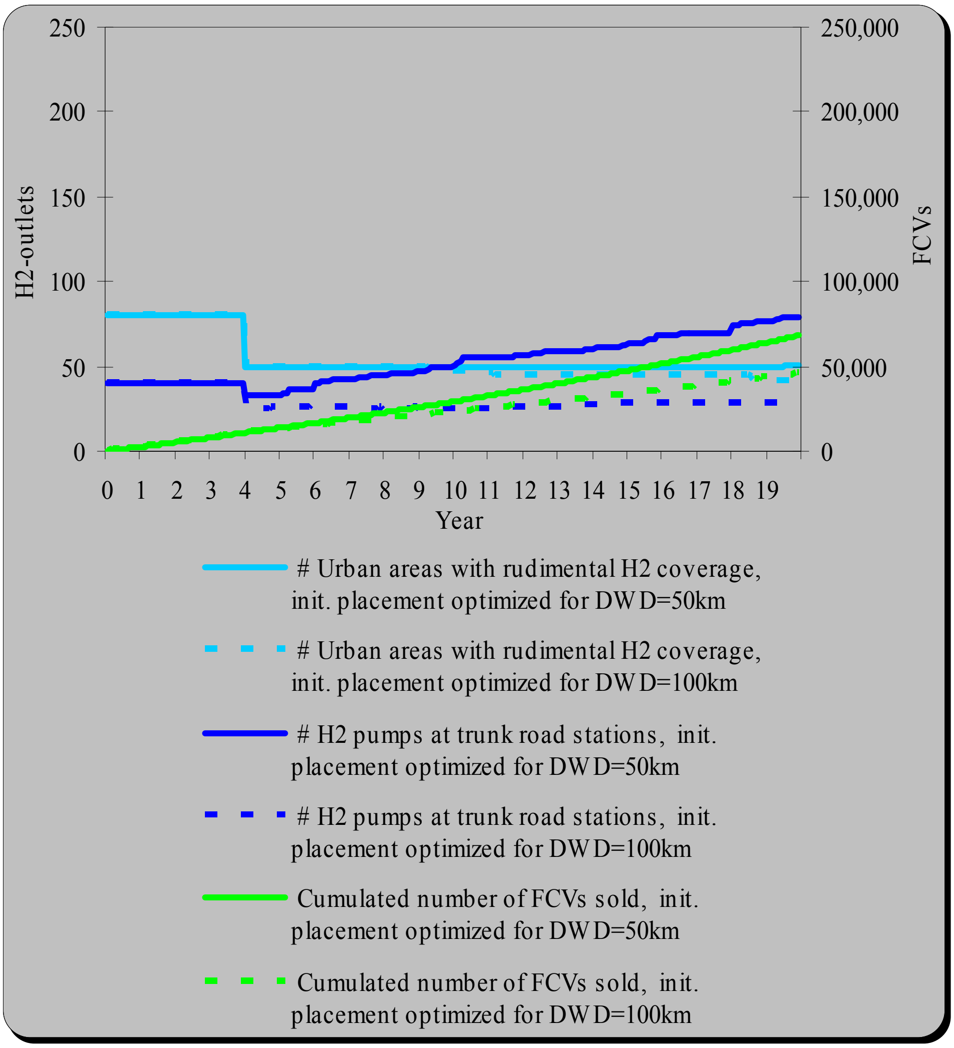

Figure III-6: Infrastructure development and vehicle adoption if the actual *DWD* turns out to be 50km (high refueling worries)

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[8] Even if we were able to reduce the number of potential initial locations to 50, there would be more than 10 billion theoretical combinations of placing 40 initial H_2-stations. There are methods like genetic algorithms to search combinations for a (local) optimum. Each search step requires evaluation of one combination (i.e., running the simulation with that combination), which takes about an hour on a Pentium IV. However, the size of the problem would probably require at least a few thousand search steps.

stations as before, the improved initial distribution derived from the *DWD* = 50km case (solid lines) starts up a slow but steady infrastructure build-up that outperforms the situation in Figure III-5. The new initial distribution is superior, and should be applied instead of Hart's "HyWay-ring".

Figure III-6 also shows the performance of an initial distribution that is fitted to a *DWD* of 100km overstating the actual *DWD*. This refers to a situation in which filling station operators have been too optimistic with respect to refueling worries of drivers when setting up the initial distribution. In consequence, the transition fails.

The impact of fitting the initial distribution to the actual *DWD* rather than a low one can be seen from Figure III-7. Here, the actual *DWD* is indeed 100km and the accordingly fitted initial distribution performs better than the one fitted to the in this case too pessimistic *DWD* of 50km. But differences are rather small; the transition is successful in both cases. So putting together the information of Figure III-6 and Figure III-7 leads to the conclusion that in order to avoid the transition to fail, filling station operators should rather err on the conservative side if there are uncertain about the actual refueling worries of drivers; that is, a low *DWD* should be assumed.

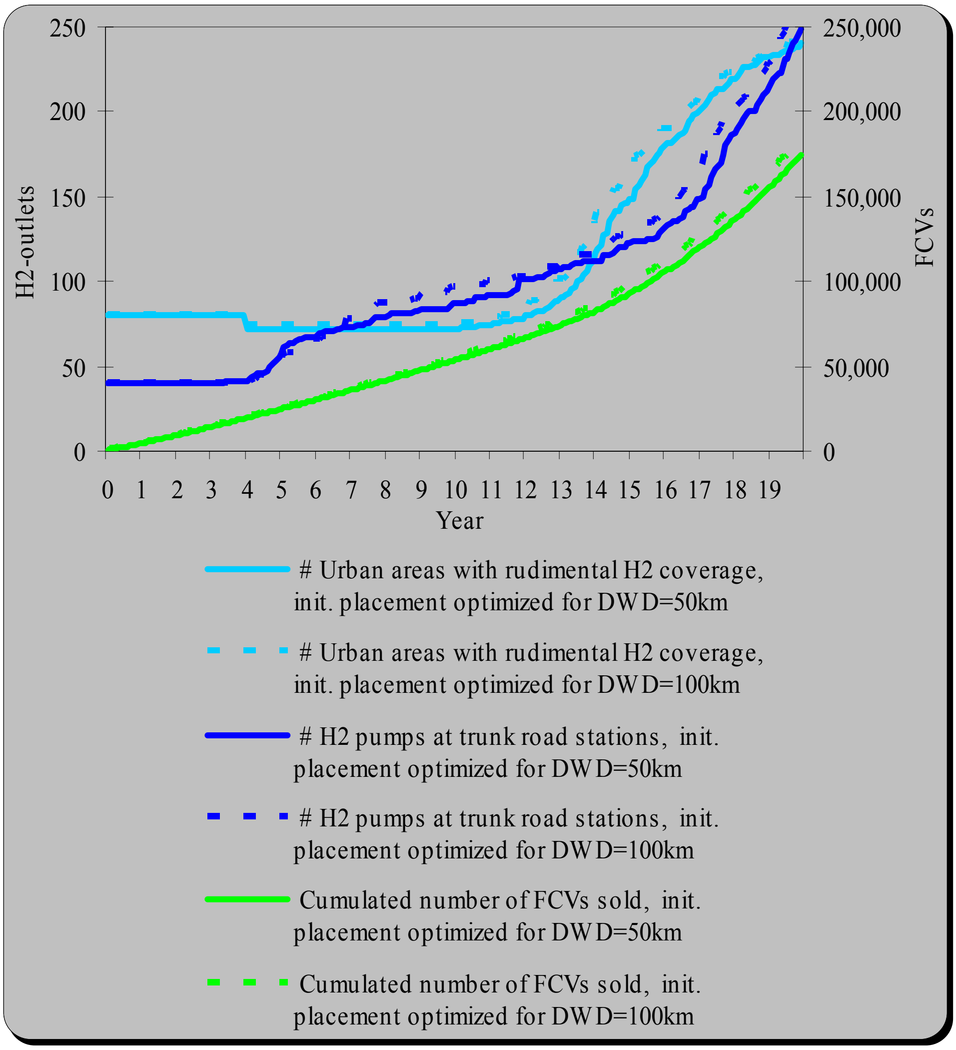

Figure III-7: Infrastructure development and vehicle adoption if the actual *DWD* turns out to be 100km (low refueling worries)

5. Conclusions

There must be at least some initial H_2-stations to overcome the chicken and egg problem associated with H_2 and FCVs (or with alternative fuels in general). To keep upfront infrastructure investments as low as possible, the initial distribution should include just as many H_2-stations as necessary to be self sustained, i.e., to "survive" until vehicle costs go down sufficiently, such that large scale demand for FCVs and H_2 arises. Such an initial H_2-stations system requires careful design, because inappropriate placement can lead to a collapse of major parts of the system due to the lack of hydrogen demand, endangering the whole introduction of the new technology.

In this paper, we introduce a tool to test different initial distributions for their potential success. The tool combines spatial modeling with GIS support and agent-based trip modeling. It is applied to the German trunk road system. For demonstration purpose we implement the "HyWay-ring" distribution suggested by Hart (2005). The ring is originally motivated as a connection of major German car production clusters and cities with H_2-station demonstration projects. Results suggest that this ring can only be a promising starting point if the distance between H_2-stations that drivers consider sufficient (“don’t worry distance”) is rather large. But with small refinements in the initial distribution a transition is possible even if drivers are more sensitive with respect to refueling. In general, the optimal placement of initial H_2-stations depends on the assumed “don’t worry distance”. However, if filling station operators are uncertain about the refueling worries of drivers, their assumptions should be rather conservative in order to prevent failure of transition.

Given the magnitude of infrastructure investments required to implement an alternative fuel system, savings from an optimized initial distribution should be significant. This calls for further research into this issue to overcome limitations of the current model: First of all, the trip distributions generated by the gravity model are "most likely distributions", but do not necessarily reflect real travel behavior, which is often characterized by specific habits or work requirements. Moreover, holiday trips to specific sights at the seaside or the Alps are not included and the same holds for trips abroad in general. Thus, a more complex travel model, perhaps on a European level would be preferable. Furthermore, the - to some extent - ad hoc parameterization of the agent behavior restricts the model to qualitative results from comparing different initial conditions. Finally, it would be desirable to increase the overall resolution of the model to also account for optimal H_2-station distributions within the cities.

IV

Flexible Transition Strategies Towards Future Well-to-Wheel chains: An Evolutionary Modeling Approach

Joint work with
Floortje Alkemade, Koen Frenken and Marko Hekkert
(Utrecht University)

Abstract. Well to wheel (WTW) analyses mainly focus on alternative road fuel/vehicle systems that are very different from the current crude oil based individual transport system. A large share of WTW chains evaluated require changes in the energy source, new fuel production facilities, different fuel distribution systems and also modifications of the vehicles. An immediate transition to such a new system would be an unprecedented technological discontinuity. Historical examples of successful technological changes are characterized by stepwise transitions of subsystems. In this paper, we present a model that identifies likely sequences of stepwise transitions in analogy to the fitness landscape model in evolutionary biology. Applying this methodology allows for a dynamic interpretation of otherwise static WTW information. We show that sequences of transitions are path dependent, so that current decisions predetermine the future WTW system. We, therefore, argue that flexible initial transition steps that allow for different transition paths later on are favorable. Results suggest that improvements of vehicle technologies are most flexible if decision makers focus on decreasing WTW energy requirements. A full transition to diesel, as a first step, is advisable if WTW greenhouse gases should be reduced.

JEL classification: B52, L92, O33, Q42

Keywords: Alternative Fuels, Hydrogen, Lock-in, Fitness-Landscape

1. Introduction

Gasoline and diesel are the dominant fuels in road transport. Their current advantage over alternative fuels is a well developed infrastructure including crude oil production, long distance transport, refining, and area-wide refueling coverage. They are easy to use because of their high energy density at room temperature and are generally considered to be safe (especially compared to gaseous fuels). Altogether, this allows for transport services at relatively low costs and implies high barriers for alternative fuels to become competitive. However, there are three problems associated with a continuation of the current use of crude oil based fuels that require evaluation of alternatives. Firstly, oil is a non-renewable resource. Even though in the past discoveries of new oil fields and especially improved exhaustion methods have repeatedly extended the statistical reach of oil, there is evidence that global oil production will peak within the next decades (Bentley, 2002). Given current demand, prices are, thus, likely to increase substantially in the future. Moreover, the majority of crude oil reserves is concentrated in the politically instable region of the Middle East, implying additional supply security problems. Secondly, road vehicles are major contributors to greenhouse gas (GHG) emissions. They account for more than 20% of total GHG emission in the US (EPA, 2006) and for about 16% in the EU (EEA, 2006). Thirdly, local air pollution is still a problem even with advancements of end-of-the-pipe technologies, as technological progress has often at least partly been compensated by an increase in the number of cars and/or car use (Friedrich and Bickel, 2001). The focus of this paper is on potential technological transitions to alternative fuels (in the broad sense of not being gasoline or diesel refined from crude oil) combined with new vehicle technologies that reduce GHG emissions and energy requirements of road transport, which, therefore, require substantial changes of the current system.[1]

Alternative fuels and vehicle technologies are not per se beneficial. E.g., hydrogen used in a fuel cell is an efficient way of converting energy in a vehicle. But if the hydrogen is generated via electrolyses of water and the necessary electricity is produced with coal fired plants, overall GHG emissions and energy requirements per vehicle kilometer would significantly increase. GHG emissions could be reduced, though, if carbon capture and sequestration (CCS) technologies would be applied, but this would further increase energy requirements. Performance of alternative fuels and vehicle combinations in terms of GHG emissions and energy requirements is compared in so-called well-to-wheel (WTW) analyses, which evaluate the whole chain from the energy source ("well") to the transmission in the vehicle ("wheel"). As already indicated in the above example, GHG emissions and energy requirements are not necessarily correlated and, therefore, might be conflicting targets.[2] Thus, it depends on the actual preferences

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[1] Local air pollution can be further reduced with wide spread application and improvement of existing technologies, including particulate filters, catalytic converters, high pressure combustion and cleaner conventional fuels (e.g., with low sulfur content).

[2] In many cases reductions in energy requirements imply also GHG emission reductions, but, e.g., GHG emission reductions from CCS always imply higher energy requirements.

of the decision makers, which WTW chain is most desirable. In this sense, WTW analyses are an essential tool to compare different visions of future road fuel systems.

However, their insights with respect to optimal transition strategies towards such new systems are limited. In the standard approach, WTW analyses focus on chains, which often differ from the current one in terms of the energy source, fuel processing technology, fuel distribution system and additionally also in the vehicle technology. The chains represent end states after a successful large scale technological transition. But forcing such a transition implies a technological discontinuity in the sense of Tushman and Anderson (1986), with not only high investments in new technologies, but also radical changes in the institutional environment. Thus, there are high barriers to such a fundamental change.

In this paper, we assume that future transitions in the WTW system are characterized by a sequence of transitions of parts of the chain (e.g., a modification in vehicle technology first, followed by a change in the fuel distribution system and so on), rather than by a single radical system switch. We suggest an evolutionary model that explores such stepwise transitions in analogy to the fitness landscape model in evolutionary biology (Kauffman, 1993). Future WTW systems are considered optimal if their performance cannot be improved with further steps. We show that stepwise transitions imply path dependence, so that initial steps can predetermine the characteristics of the future WTW system and, therefore, decrease the flexibility regarding possible end states. For demonstrative purpose we construct a dataset that reflects the main patterns of current WTW analyses. We approach WTW GHG emissions and energy requirements (per vehicle km) as two separate performance measures. It turns out that the optima of the two dimensions are not "close" to each other in a technological sense.

Because of path dependence, we focus our analysis on potential initial steps. We check, whether they shift the system closer to a specific optimum and apply two different measures of flexibility. One is the number of different optimal WTW systems that can be reached within a certain number of later transition steps. The second flexibility measure counts the number of different paths, i.e., different sequences of transition steps that lead to these optima. We put particular emphasis on flexibility, because information about future WTW data is uncertain. Data are derived given current assumptions about technological feasibility, technological progress and economies of scale, basically in every part of the chain. Thus, a first transition step that leaves open a wide range of future steps, as implied by the flexibility measures, can be seen as robust if, e.g., certain future WTW chains turn out to perform much worse later on than predicted now. Moreover, initial steps that improve energy requirements and reduce GHG emissions at the same time are considered preferable, because they allow for a later change in preferences. Thus, initial steps that move the system closer to the optima in both dimensions and allow from thereon reaching the optima on many different paths, can be interpreted as being most flexible and, therefore, having a low regret potential. We find that changes in vehicle technologies are most flexible if reductions of WTW energy requirements are addressed. If the focus is on GHG emission reductions, a general switch from gasoline to diesel appears to have the lowest regret potential, as many different paths later on lead to an emission optimum.

In the next section, we show how stepwise transition can lead to path dependence and lock-in into suboptimal systems. In section 3, we suggest a decomposition of the WTW chain into subsystems, constituting the so-called design space of WTW chains. Thereafter, section 4 describes the dataset we constructed for demonstrating the potentials of the approach. In section 5, we present results and we conclude in section 6 with pointing out limitations of the current study and provide recommendations how to improve future WTW studies.

2. Stepwise transition and path dependence

Implementation of one of the chains that are usually evaluated in WTW analyses would often require a radical departure from today's technologies along the whole chain. However, historical examples show that successful technological transitions can often be characterized by sequences of (using the terminology of Henderson and Clark (1990)) "incremental innovations", i.e., changes of subsystems rather than single "radical innovations".[3] In the context of WTW chains, an example for an incremental change is the introduction of unleaded gasoline during the 1980s, which was required by cars equipped with a 3-way-catalytic converter. Existing distribution systems, pump technologies etc. could be used; and a major advantage for its fast penetration of the market (in many countries way ahead of the cars with 3-way-catalytic converter) was that most conventional engines could also run on unleaded gasoline, so that the innovation was fully compatible with the existing system (Westheide, 1998). In contrast, the introduction of hydrogen as an alternative fuel would be radical, as it requires several changes in the whole fuel production, distribution, and end use system at the same time.

Given the size of the WTW system, "incremental changes" actually already imply huge investments and we, therefore, refer to them rather as transition steps. We argue that the investments necessary for making transition steps will not achieve public acceptance if they do not improve the overall performance of the WTW chain. This notion of stepwise transition can be described in analogy to the fitness landscape model in evolutionary biology (Kauffman, 1993). The fitness of an organism, in a Darwinian sense, depends on the combination of genes in a genotype. Correspondingly, the performance of a WTW system is given by the combination of subsystems, such as fuel production or vehicle technology. The fitness of an organism changes through mutations of its genes, while WTW system performance is altered by a transition step that changes a subsystem. According to evolution theory, a mutation is only selected

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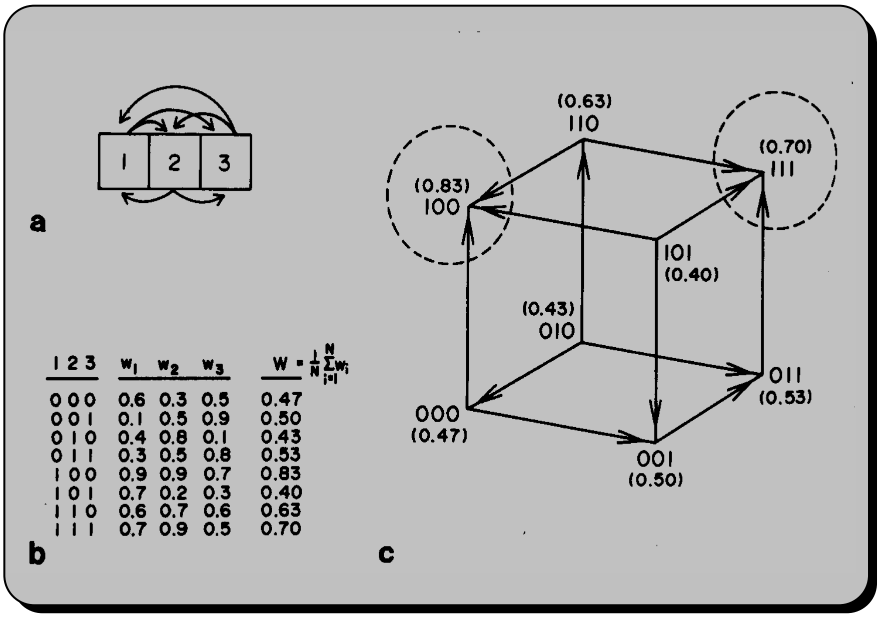
[3] Classifying technological change to be incremental or radical is similar to Dosi's (1982) differentiation between change along the same "technological paradigm" and emergence of a new paradigm. A discussion of these evolutionary views of technological change in the context of environmentally friendly products can be found in Kemp (1994).

(e.g., by survival) if the new combination of genes has a higher fitness.[4] If a fitness value is assigned to each sequence, a (multidimensional) "landscape" with peaks and valleys results (see Figure IV-1 for a three-dimensional example). The peaks are the optima (global or local) in a fitness landscape and are defined by the fact that any mutation implies a lower fitness value, i.e., no further mutations will be selected. Describing technological developments in analogy to evolutionary processes becomes increasingly popular (Kauffman, 1993; Ziman, 2000; Frenken, 2006). We follow the established terminology by interpreting all possible future WTW chains as the technological "design space" (Bradshaw, 1992) of an alternative fuel system.

Stepwise transition in the WTW chain may actually lead to a lock-in in a local optimum. A transition towards a local optimum cannot be reversed, as this would imply a decrease in performance (combination 111 in the example in Figure IV-1). This means that the whole transition process is characterized by path dependence, i.e., early decisions can predetermine potential end states.[5] An example of path dependence in Figure 1 is when a designer starts from string 010 and the first transition leads to string 000, and the second transition to the globally optimal string 100. However, when search starts again in 010, but the first transition leads to 011, the only remaining possible transition will inevitably lead to the local optimum 111.



1 2 3	w_1	w_2	w_3	$W = \frac{1}{N}\sum_{i=1}^{N} w_i$
0 0 0	0.6	0.3	0.5	0.47
0 0 1	0.1	0.5	0.9	0.50
0 1 0	0.4	0.8	0.1	0.43
0 1 1	0.3	0.5	0.8	0.53
1 0 0	0.9	0.9	0.7	0.83
1 0 1	0.7	0.2	0.3	0.40
1 1 0	0.6	0.7	0.6	0.63
1 1 1	0.7	0.9	0.5	0.70

Figure IV-1: (a) architecture of a complex system with three subsystems, (b) fitness table, (c) design space and corresponding fitness landscape (from Kauffman, 1993, p. 42). The design space contains eight combinations. Combination 100 is the global optimum and combination 111 is a local optimum.

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[4] As an example, lets assume that an organism has the following sequence of genes 1 0 1 0 0 (i.e., the genotype) with a fitness of A. Its offspring now appears to have a sequence 1 1 1 0 0 with fitness B. If B > A the offspring is "fitter", will survive in the selection environment and might reproduce. But if B < A the offspring will die before reproduction. Note that this mutation/selection process corresponds to a trial and error (random) search, while a technological transition step would be a controlled decision.

[5] Note that this notion of lock-in into local optima is static, in the sense that the performance levels are inherent to the technology. This is different from lock-in phenomena due to increasing returns to adoption, as initially described by David (1985), Arthur et al. (1987) and Arthur (1989).

3. The design space of WTW chains

3.1. Five subsystems

Complex technological systems generally contain several semi-independent subsystems (Simon, 1969). Each subsystem has certain specifications and the performance of the overall system depends on the combination of the specifications. All theoretically possible combinations form the design space of the technological system. Analyses of technological developments in the past show that successful improvements are often characterized by detecting new combinations of already existing specifications. Examples are early airplanes (Bradshaw, 1992), wireless telecommunications (Levinthal, 1998) and the development of steam engines (Frenken and Nuvolari, 2004). These evolutionary dynamics are well captured by the combinatorial nature of a design space and by having innovation be represented as a move in this design space.

The decomposition of the WTW chain into subsystems involves some degree of arbitrariness and is, therefore, debatable. As a first approximation for this study, we suggest a rather high aggregate level as shown in Figure IV-2. We define the initial energy source (the well) as the first subsystem, which may include extraction, initial cleaning processes, transport to the conversion site etc. We consider seven different sources, i.e., this subsystem can have seven different states. We include all different fossil fuels (crude oil, coal and natural gas) as a direct source or in an energy mix for producing electricity (implying hydrogen production via electrolysis later in the chain). Under “biomass” we subsume a variety of agricultural sources, such as wood, straw, rapeseed and so on. We do not differentiate between them (even though differences can be substantial), because we wish to analyze all sources at a similar level of aggregation. Non biogenic waste (also referred to as municipal waste) can be seen as an indirect use of fossil fuels, too, but at low costs, as it is assumed to be generated anyway. We included wind power as a representative for all (non biomass) renewable energy sources, which are characterized by high investment costs and low operating costs.[6] Nuclear is not evaluated, because intensified use for car fuel production seems to be an unrealistic option, given perceived hazardousness and the unsettled problem of long term radioactive waste storage.

Second, we allow for a binary choice whether to apply CCS during the fuel processing or not. This implies the assumption that there are sufficient sites for dumping carbon dioxide available.

Third, we differentiate seven combinations of production scale, location of production, and distribution to the filling stations. We combine these measures, because they are not fully independent. Applying fuel processing in large scale facilities requires centralized production, and, therefore, implies rather long distances to filling stations that must be covered by either pipelines or trucks. Medium scale production would be

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[6] Fuel production from wind power can follow variability of wind. This is an advantage over wind power fed into the grid, which must be backed up with conventional power generation due to the lack of efficient large scale electricity storage options.

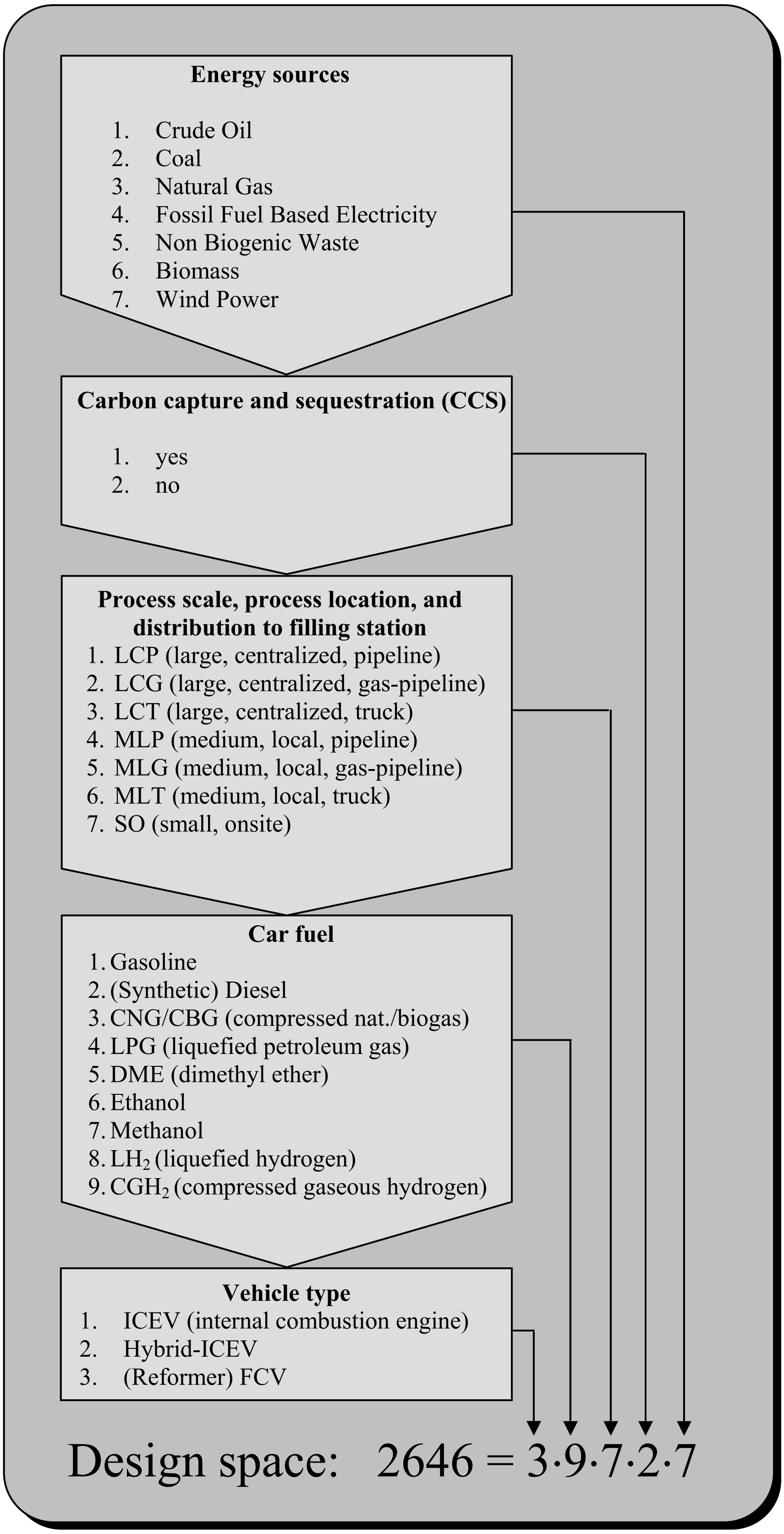

Figure IV-2: WTW chain decomposed to subsystems

on a local level with rather short distances to the filling stations. The distribution system (pipeline, gas-pipeline or truck) could be modeled as a separate subsystem, but since we also want to consider onsite fuel production, which basically does not require any additional alternative fuel transport infrastructure, we grouped scale, location and distribution system to seven mutually exclusive options.

Fourth, we include nine different car-fuels covering almost all options that are currently considered as potential medium to long term substitutes for gasoline. Note that only for a few combinations the well to tank (WTT) part we described so far is really a chain with successive steps as indicated by Figure IV-2.[7] In most cases, the chain should be read, e.g., as "generating compressed gaseous hydrogen (CGH_2) in a large, centralized facility, with CCS, and distributing it with trucks."

Fifth, and finally, we separate three vehicle types, conventional internal combustion engine vehicles (ICEVs), Hybrid-ICEVs, which combine an ICE with a battery allowing for regenerative braking, and fuel cell vehicles (FCVs). The FCVs are required to have an onboard fuel reformer if not fueled with CGH_2 or liquid hydrogen (LH_2) and are also assumed to be "hybrids" by having a battery for regenerative braking.

Even for the high level of aggregation with only five subsystems, there are $7 \cdot 2 \cdot 7 \cdot 9 \cdot 3 = 2646$ theoretical combinations of energy sources, CCS, scales/distribution systems, fuels and vehicles. These combinations form the design space of the WTW system. There are three different measures of the overall performance that are usually estimated for each combination: WTW energy requirement per km driven (or similarly WTW energy efficiency), WTW GHG emissions per km driven and local vehicle emissions. Even though local emissions are an important decision parameter, we do not investigate them further, as they are mainly determined by (future) end-of-the-pipe technologies or are absent if hydrogen fuels are applied. With respect to the other two performance measures, almost 2/3 of the combinations would never be seriously considered, as, e.g., generating gasoline with wind power or transporting LH_2 in pipelines over long distances, given that liquid hydrogen must be cooled to less then 20 Kelvin. Such combinations are excluded from the analysis.

3.2. Design space search

In the simplified WTW system the (dominant) current state is represented by gasoline refined from crude oil without any carbon scrubbing in large scale facilities. Trucks are responsible for delivery to filling stations and the cars have internal combustion engines. From that starting point, there are theoretically 23 different first transition steps possible (six in sources, one regarding CCS, six in distribution, eight in fuels and two in vehicles). The definition of a design space requires that the subsystems are fully technologically independent, i.e., one part in the chain may change without requiring any modifications at other parts of the system. This does not hold in a strict sense. A change from gasoline to methanol, for example, requires modifications in the ICE or the reformer of the FCV (depending on what vehicle type is applied when the fuel is switched). We assume, though, that necessary adjustments in other parts of the

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[7] An example for a chain that actually follows the structure is: NG $\rightarrow$ no CCS $\rightarrow$ small, onsite $\rightarrow$ CGH_2.

chain are negligible compared to the major commitment that a change in the state of a part implies in general. This leads to another necessary assumption regarding switching costs. The current debate about alternative fuels puts strong emphasis particularly on necessary infrastructure costs. If we were to address switching costs, we would theoretically require data for a switch from each chain to all different other chains with the (impossible) task to estimate switching costs from one future system to another future system. We refrain from including switching costs and assume that a transition step is an extremely costly and, thus, rare event. When evaluating different initial steps with respect to flexibility later on, we analyze no more than four further future transition events, because we just want to allow all five subsystems to be potentially changed (even if it is also possible that more than one transition occurs in the same subsystem).

4. Construction of the data set

A large share of the theoretical transitions actually implies dramatic increases in WTW GHG emissions and WTW energy requirements compared to the current system. This problem that is due to the technological dependence between subsystems can be handled in the model by simply assigning an extremely low performance level, so that no transition path can lead through this combination of subsystems. In terms of the fitness landscape metaphor, these options represent the valleys in the landscape. This actually holds for many of the 23 different initial first transition steps (e.g., switching directly from crude oil to wind power). After "eliminating" WTW systems in that way, 987 chains remained to be evaluated in terms of energy requirements and GHG emissions. To gather the necessary data, we screened the most recent WTW analyses available (GM et al., 2002; Ahlvik and Brandberg, 2001; EC-JRC, 2006), which cover a broad range of energy sources, car fuels and car technologies. Moreover, there are several studies available that focus on particular energy sources as, e.g., biomass (Delucchi, 2003) or NG (Hekkert et al., 2005). Others address pathways to particular car fuels, especially LH_2 and CGH_2 (Wang, 2002; Lipman, 2004; Ogden et al., 2004), certain car technologies (Lave et al., 2000) or the fuel supply side as a whole (MIRI, 2004). Thus, there seems to be sufficient data available. However, a large part of the data is redundant in the sense that the majority of studies evaluate the same WTW paths, which are considered most interesting with respect to long term environmental performance or most likely, given short term feasibility. But the remaining different chains cannot be merged into one data set, because they lack comparability for several reasons. In general, studies differ in their application area. Countries or regions are different in their availability (and therefore costs/efficiency) of different energy sources. They vary in the distance to oil or gas fields, the size of farm land that could be used for biomass production or the amount of off-peak electricity available for electrolyses and so on. Besides these geographic characteristics, differences may also arise from the driving pattern (number of cold starts, average speed etc.) or the efficiency of the current car fleet as a benchmark. These region specific variation in results is inherent in the research questions the studies address and can, therefore, be considered inevitable.

But sources of divergence lie also in the assumptions with respect to future efficiencies of the technologies applied in each part of the chain.

To achieve the highest possible consistency in the dataset, we take the EC-JRC (2006) as a starting point, because it offers the widest range of different WTW chains. It reports an estimate for WTW GHG emissions and WTW energy requirements per 100km traveled. With the exception of wind power (where variable costs are basically zero), the latter can be used as a proxy for the required resource amounts and, therefore, the implied operating costs of the fuel system.[8]

For missing chains that are available from other studies we use comparable chains as reference points (e.g., basically all studies provide data on a chain with FCVs fueled by CGH_2, which is generated from large scale natural gas steam reforming) and then compute the relative difference to the reference point. If missing chains are also not available from other studies, we take data from the most comparable chains available. For example, several non biogenic waste chains (without CCS) are derived from biomass chains assuming a slightly higher energy requirement for the waste processing.

Given the data in EC-JRC (2006), CCS can be applied to basically all chains, however, for distributed and particularly onsite fuel production we put a high penalty, because it implies maintaining a widespread CO_2 pipeline system. The changes in environmental benefits and also the energy requirements depend mainly on the amount of carbon that can be sequestered. For example, according to EC-JRC (2006) if coal is used for H_2 production, huge amounts of carbon can be captured (WTT GHG emissions, which are equal to total WTW emissions in the case of H_2 go down by 80%), but only with high additional energy input (+27%). But in a gas to liquid production of synthetic diesel, the majority of carbon remains in the fuel, so that WTW GHG emissions are reduced by only 13% requiring 9% more energy at the WTT side. When assigning available data to missing values by making percentage changes, we differentiate according to the process as “hydrogen” or “non-hydrogen”, “coal based”, “gas to liquid”, “liquid to gas” etc. Increases in energy requirements are in the range of 5% to 25%, while decreases in GHG vary within 5% to 80%, however, the vast majority of changes are at the low end of theses ranges.

Differences in scale are jointly addressed with differences in the distribution system. For several chains there are offsetting effects. For example, producing hydrogen from natural gas at a decentralized medium scale requires less energy compared to the large scale option, but, on the other hand, the hydrogen is already closer to the end use at the filling station. In the WTW chain, we relate differences in distribution costs to the fuel. We assume that the bulk of transportation costs/energy requirements associated with the energy source is inherent to the source option itself (e.g., homegrown biomass vs. imported natural gas), so that further distribution to the fuel production sites can be neglected. Given the changes in costs and GHG emissions reported in NRC (2004) and

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[8] The costs of a feedstock vary of course. However, if the use of a rather cheap resource implies high energy use per km, then opportunity costs are high, because it might be more profitable (in terms of energy service per unit of resource) to use the resource for other energy generation rather than car fuel production. But for wind power energy (cost) estimates remain arbitrary. With respect to GHG, though, its environmental benefit for fuel production can be assessed with alternative uses, e.g., the replacement of fossil fuel based electricity production (EC-JRC, 2006).

Lipman (2004), differences from the best to the worst (feasible) production scale and distribution system do not exceed 25% (for non-onsite production systems).

As the data refer to energy requirements and GHG emissions per 100km traveled, the vehicle efficiency directly affects the WTT values. For the few cases the EC-JRC (2006) data is not available for different car types, we use the efficiencies reported by Ahlvik and Brandberg (2001).

Instead of taking the actual values (energy requirements in MJ/100km and GHG in grams of CO_2equivalents/km), we applied a monotone transformation to a 0 to 100 scale for energy requirements and a -30 to 100 scale for GHGs; and we round to integers. The reason is twofold. Firstly, we want to point out that we applied several (ad hoc) assumptions to create the dataset that prevent us from having precise point estimates. Secondly, the scaling shifts the focus to a more qualitative measure (better or worse performance), which is decisive in the methods we apply.

We also know that uncertainties associated with the WTW data from different data sources are high. Even estimating a simple index, like the one used so far, can be considered as rather ambitious. In the following, we will, therefore, present also results for an even less precise measurement. Instead of rounding to an integer index, we round to a multiple of five.

We depart from the EC-JRC (2006) methodology in that "negative emissions", i.e., reductions of atmospheric CO_2, can only occur using biomass together with CCS. EC-JRC (2006) reports negative emissions also for fuel processing from municipal waste. But the negative emissions are then only due to the improvement relative to the current practice of waste burning. We, therefore, assume that in a "CCS world" alternative use would also imply CCS. Moreover, in the case of biomass, we assume that negative emissions arising from hydrogen production are independent from vehicle technology. In EC-JRC (2006), CO_2 reductions are particularly high if hydrogen is used in an ICEV. Efficiency of ICEVs is low, i.e., they require more fuel and therefore imply more biomass production, so that a higher amount of carbon can be sequestered. In our approach, this would imply that in a biomass/CCS chain no switch to more efficient vehicles would be made according to GHG emissions. We circumvent this peculiarity by addressing the same negative emissions also to the more efficient Hybrid-ICEVs and FCVs. Thus, we indirectly assume that the same amount of biomass is produced. The share that is not required for fuel production would then substitute fossil fuels in electricity production.

Figure IV-3 and Figure IV-4 provide a notion of the data used in the model. Figure IV-3 plots a selection of the feasible chains grouped by the different sources, with and without CCS. The large triangle identifies the state of the current system. Note that chains with identical values are plotted on top of each other, so that differences might be exaggerated. However, some general patterns can be identified that most WTW analyses have in common. With respect to GHGs, the majority of chains performs better than the current system, where natural gas based chains are only slightly better and biomass chains, particularly with CCS, perform best. Most of the chains, which are worse, generate fuels from coal or fossil fuel based electricity. In terms of energy requirements, the current system performs quite well. One might expect chains with

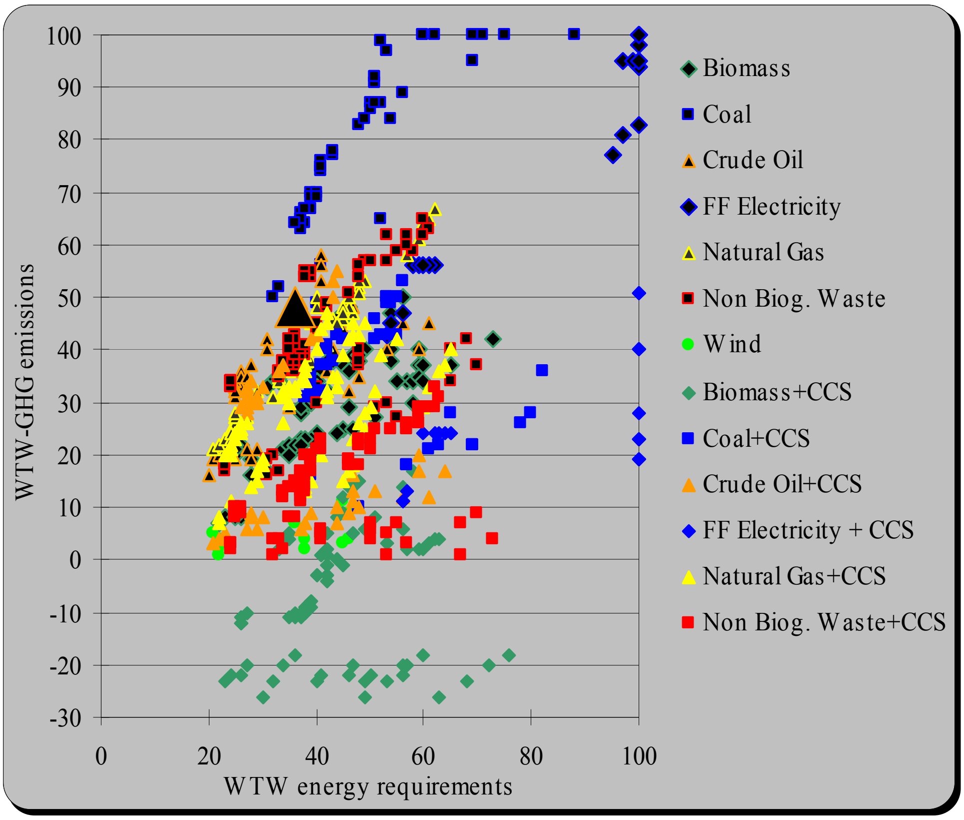

Figure IV-3: WTW-chain performance grouped by energy sources and CCS applied

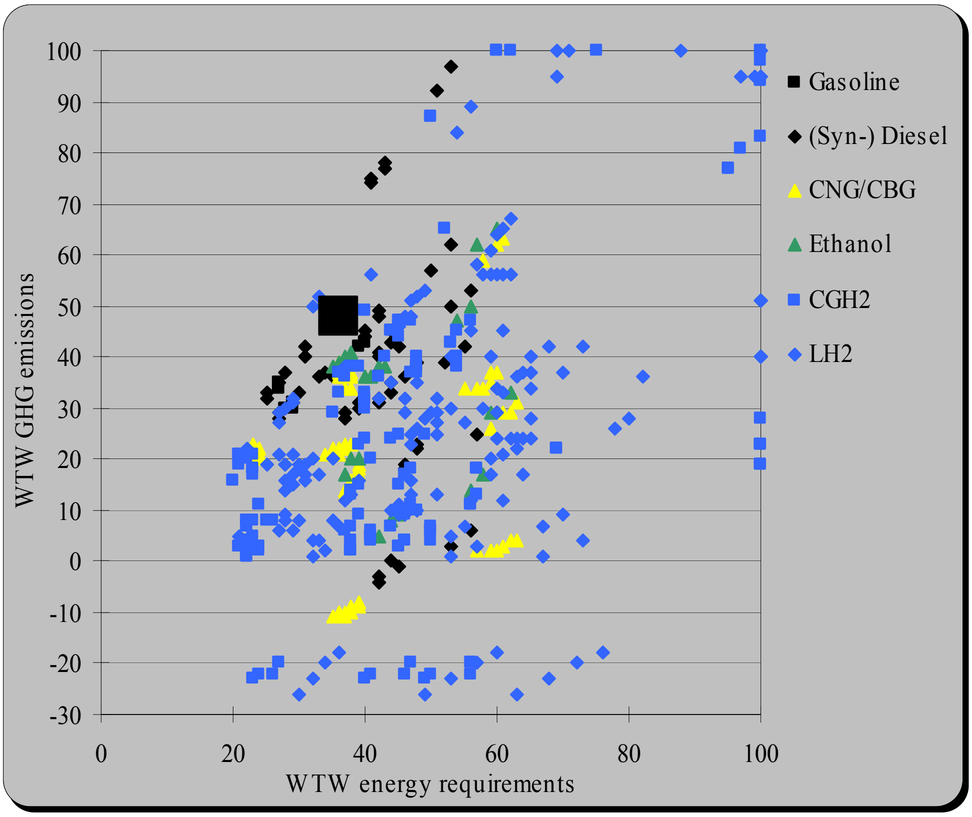

Figure IV-4: WTW-chain performance grouped by car fuels

wind power to have basically no energy requirement (and, therefore, no emissions). But here, only the fuel production is assumed to be generated by wind power, but maintenance, and hydrogen distribution and storage still requires conventionally produced energy.

In Figure IV-4 chains are plotted according to the car fuel. The large square refers to the current gasoline chain. Note that most fuels are to some degree gathered in certain “areas”, but the hydrogen chains seem to be “all over the place”.[9] Together with Figure IV-3 it can be seen that the hydrogen chains perform well (in both dimensions) if produced from biomass and perform worst if produced from fossil fuel based electricity.

5. Results

5.1. Description of optima

We define a (local) optimum as a combination of five subsystems for which holds that any further transition in any subsystem leads to a decline in performance, which, in the given context, translates in an increase in the WTW energy requirement index or the WTW GHG emission index respectively. As the indices are rounded to integers, chains with identical performance occur. Thus, optima can consist of more than one chain, which are "neighbors" in the sense that they are no more than one transition step away from each other.[10] We refer to the number of neighboring chains within an optimum as the size of it.

Table IV-1 contains a full list of the optima in the WTW design space. In the WTW chain with lowest energy requirements CGH_2 is generated from crude oil without CCS at a large scale.[11] The most energy efficient use of hydrogen is in a FCV. Distribution to the end use is indifferent (given the precision of the data) between truck and gas-pipelines, so that the optimum is of size two. There are two local optima, i.e., suboptimal chains that would be end states of a transition process. In local optimum *A,* wind power is used to generate LH_2. The second local optimum (*B*) contains basically all natural gas (NG) to compressed natural gas (CNG) paths. As "compression" is the main fuel procession, scale and distribution is of minor relevance. Note that burning CNG in a Hybrid-ICEV is more efficient than using an FCV with an onboard reformer.

Turning to GHG emissions, the use of biomass together with CCS implies the highest emission reductions and is therefore optimal. As discussed above, reductions occur (by assumption) independent of the vehicles type. A simple measure for the distance between two chains is the so-called Hamming distance, which denotes the

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[9] For the sake of clarity we left out methanol, DME and LPG, which are basically in the same “area” of ethanol and CNG/CBG.

[10] In the notion of a fitness landscape such optima would represent a "plateau" in case of a maximum and a "plane valley" for a minimum.

[11] Note that EC-JRC (2006) does not provide any crude oil to hydrogen chain information. The index values here are computed using the (MIRI, 2004) data which imply a conversion to naphta first. Thus, we cannot rule out that the high performance of these chains might be due to problems of merging different data sources.

Table IV-1: Optima of WTW performance measures

	WTW energy requirements			**WTW GHG emissions**
	20 (Global optimum)	**21 (Local optimum *A*)**	**22 (Local optimum *B*)**	**-26 (Global optimum)**
Energy sources	Crude Oil	Wind Power	NG	Biomass
CCS	no	(no)	no	yes
Process scale, process location, and distribution	LCG LCT	MLT	LCG LCT MLG MLT SO	LCT
Car fuel	CGH_2	LH_2	CNG	LH_2
Vehicle type	FCV	FCV	Hybrid-ICEV	ICEV Hybrid-ICEV FCV

number of transitions necessary to get from the one chain to the other.[12] Applying this measurement, the GHG emission optimum is at least three transition steps away from the global energy optimum and at least two steps from a local optimum (*A*).[13] Given that the maximum distance is 5 and one transition step implies a major technology shift, we conclude that the two performance measures are conflicting targets not only with respect to CCS, which is generally more energy intensive. A transition driven by energy requirements would, therefore, look very different from a transition driven by GHG emissions.

As explained, we also analyzed the data using a rounding to a multiple of five. As we can see from Table IV-2 not surprisingly, the optima become larger. The global optimum and local optimum *A* are now merged, because new connections of one step transitions come into existence, which have the same performance of 20. Due to the rounding, the local optimum *B* is now also part of the global optimum (performance of 20), but the NG/CNG based chain still remains separate.

The global GHG emission optimum is also larger for the less precise measurement, because CGH_2 and LH_2 chains become equivalent. According to the Hamming distance, the GHG emission optimum gets close to the energy optimum *A*. The difference is

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[12] The concept also originates in biology to measure the genetic difference in a genotype space (Kauffman, 1993).

[13] The distance here depends on the direction of transition. To get from local optimum *A* to the GHG emission optimum takes three steps (changing the source, CCS and scale/distribution). The other way around, CCS becomes obsolete in the special case of wind power and should therefore not be counted; but the distance increases, if the vehicle type must also be switched.

Table IV-2 Optima of WTW performance measures with higher uncertainty (interval length 5)

	WTW energy requirements									**WTW GHG emissions**	
	20 (Global optimum *A*)								**20 (Global optimum *B*)**	**-25 (Global optimum)**	
Energy sources	Biomass	Crude Oil	Crude Oil	Crude Oil	NG	NG	Wind Power	Wind Power	NG	Biomass	Biomass
CCS	no	no	yes	no	yes	no	(no)	(no)	no	yes	yes
Process scale, process location, and distribution	LCT	LCG LCT MLT SO	LCG LCT MLT	SO	LCG LCT MLG MLT	LCG LCT MLG MLT	MLG MLT SO	MLG MLT SO	LCP LCT MLG MLT SO	LCG LCT	LCG LCT
Car fuel	CGH_2	CGH_2	CGH_2	LH_2	CGH_2	CGH_2	CGH_2	LH_2	CNG	LH_2	CGH_2
Vehicle type	FCV	FCV	FCV	FCV	FCV	FCV	FCV	FCV	Hybrid-ICEV	ICEV Hybrid-ICEV FCV	ICEV Hybrid-ICEV FCV

reduced to the application of CCS (given that CGH_2 is generated in large scale centralized production with truck distribution and used in FCVs). Thus, a transition based on energy requirements targeting into the direction of optimum *A* leaves open the option to get also close to the emission optimum. Conversely, getting into optimum *B* leaves the emission optimum far away, even in the less precise measure.

5.2. Flexibility of first transition steps

In the previous section, we described potential end states of transition processes. Now, we turn to the transition itself. Figure IV-5 shows, as an example, one potential stepwise transition from the current WTW system to the optimum with respect to GHG emissions. It is derived in a backward approach applying the knowledge about the characteristics of the optimum. Note that during the whole transition process, each transition step is required to raise performance. The first step is the general substitution of gasoline by diesel. In a second step, Hybrid-ICEVs displace conventional ICEVs. Thereafter, diesel is not refined from crude oil anymore but synthesized from biomass. In the fourth step, the then existing biomass production for fuel generation is used to

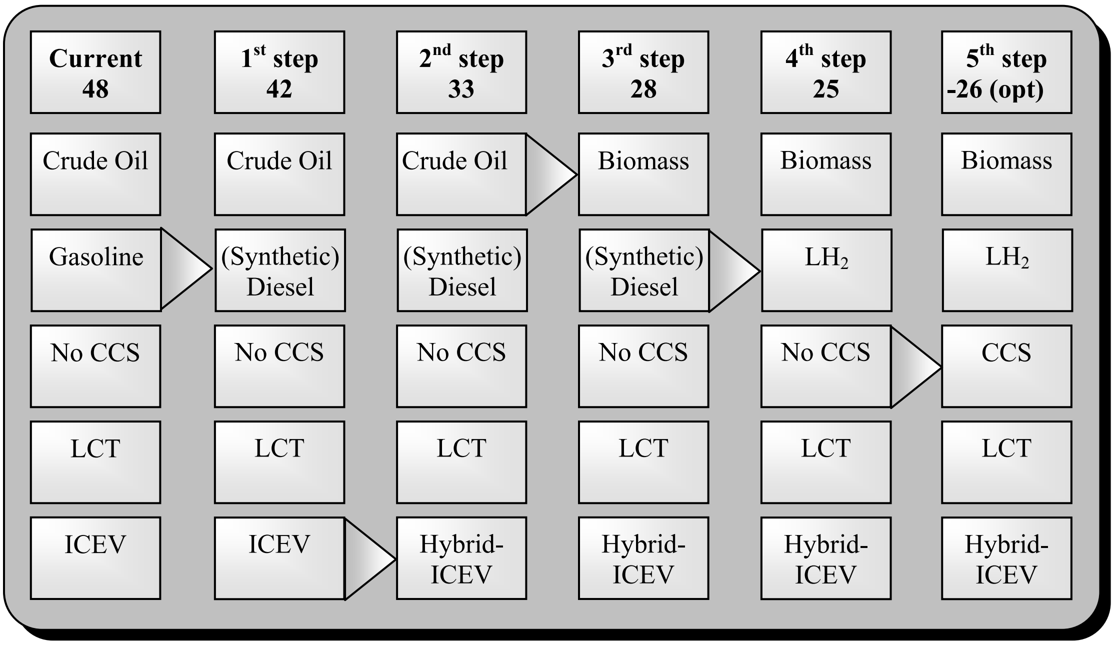

Figure IV-5: Example for an emission reducing transition to the GHG emission optimum

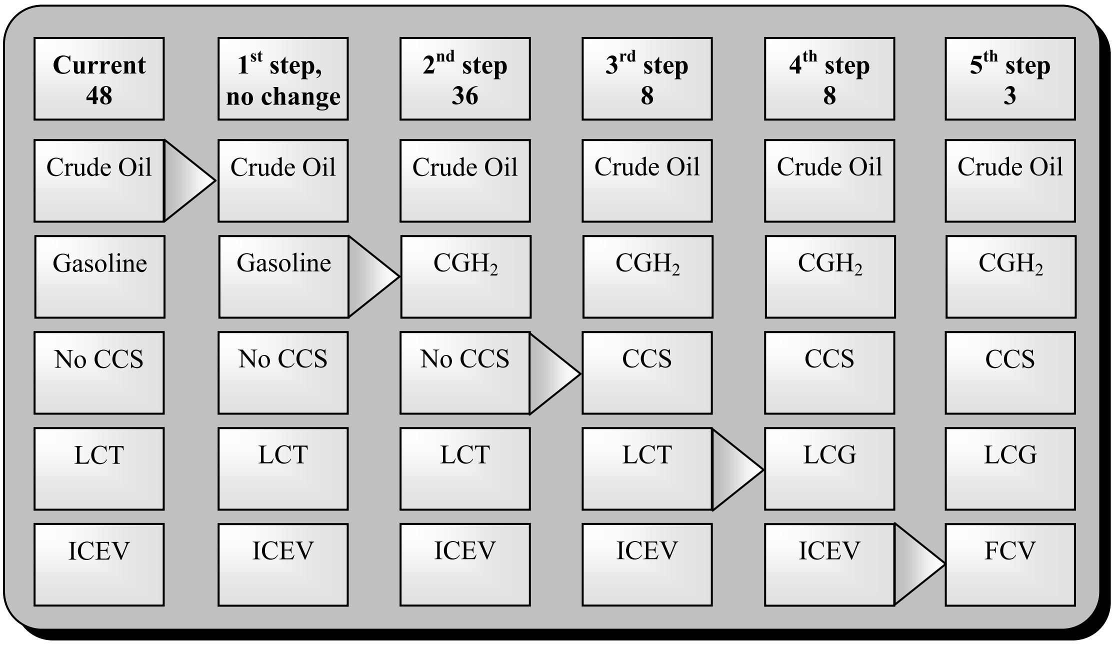

Figure IV-6: Example for an emission reducing transition following a myopic decision rule

produce LH_2 instead of diesel.[14] Finally, the most significant emission reduction step is made by introducing CCS. In the example, GHG emissions strictly decrease in each step. In general, we allow transition steps to be taken, even if performance remains unchanged, so that bridging steps that lead to improvements later on are possible.

In contrary to the successful transition process based on knowledge about the optimum, Figure IV-6 provides an example of a transition following a myopic decision rule. The rule applied forces a change in every subsystem, starting with the energy source, followed by CCS, and so on. Always the best alternative is selected. There is no energy source available that performs at least equal to crude oil at the beginning, so that the energy source remains unchanged. Then, gasoline is substituted by CGH_2 (for reasons described in footnote 14), CCS is applied and a possible switch to a gas pipeline system is made (at the same emission level). Finally, FCVs are introduced. During the transition, emissions are reduced just to an index value of 3 compared to the -26 in the optimum. If the decision rule is changed in order to start with a possible change of fuels instead of the energy source, the fifth transition step would allow for a change to biomass. This would lead to an emission index of -22, which is still suboptimal. Thus, myopic transition strategies should be rejected. Specific ones might actually get to the optimum within five steps, but they would do so, if at all, by chance.

We argued above that making a transition step might take up to a decade. Thus, managing the transition process beyond the first step can hardly be framed in a credible policy. Moreover, within that time horizon, technological development, new information about WTW chains or changing preferences is likely to prove the original transition plan obsolete. Nevertheless, decisions about the first step have to be made given today's information. This implies that a first transition step should move the system closer to what we now consider an optimum. Table IV-3 shows the shortest paths to the optima implied by all potential first transition steps, and the values in brackets refer to the average performance index value along the path. Initial transitions that lead to an increase in GHG emissions and energy requirements are excluded. Transitions that are emission reducing but require more energy are marked with a (-). There are only four transitions that are emission reducing and energy efficiency improving, which are a change to a pipeline distribution system, a general replacement of gasoline by diesel and changing vehicle technology to Hybrids or FCVs (which would initially require an onboard reformer). These four potential transitions would not be regretted if there is a later change in objectives towards emission or energy optimization.

If the focus is on WTW energy requirements at the beginning, a switch to FCVs with onboard reformers requires just one more step to reach the global optimum, so that the length of the shortest path is two. That switch is also flexible in the sense that the two other (local) optima are still reachable if, what is now perceived as the global optimum, later on turns out to be technologically (or economically) infeasible.

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[14] An ICE running on diesel (or other hydrocarbon fuels) not only emits CO_2 but also methane and nitrous oxide which have a high climate forcing. These emissions are abated if hydrogen is used as a fuel. Since energy input is not considered in this transition path (energy input for LH_2 production and distribution is substantially higher than for diesel, but is generated from emission neutral biomass), it is, therefore, beneficial to switch to hydrogen.

Table IV-3: Shortest transition path (average performance along the path in brackets)

	WTW energy requirements			WTW GHG emissions
First transition step:	**Global optimum**	**Local optimum (*A*)**	**Local optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	-	3 (9.3)
Transition to LCP	4 (27.5)	5 (27.6)	6 (26.2)	5 (23.6)
Transition to Diesel	3 (26.3)	5 (26.8)	5 (25.4)	4 (13.8)
Transition to LH_2	-	-	-	4 (-1.5)
Transition to CGH_2	-	-	-	3 (8.7)
Transition to Hybrid-ICEV	3 (24.7)	5 (25.8)	4 (24.5)	4 (12.0)
Transition to FCV (+reformer)	2 (23.5)	4 (25.5)	5 (24.2)	4 (8.3)

Moreover, the average energy requirements along the paths to the optima are always lowest compared to the other potential first switches. An initial switch to Hybrid-ICEVs has similar characteristics, but shifts the system one step closer to the local optimum *B*.

Currently, car manufacturers seem to favor direct hydrogen vehicles over onboard reforming technologies. A major problem has been to reform sufficient amounts of hydrogen "on demand" for acceleration. However, the latest FCV prototypes are "hybrids" having also a battery, so that a smaller fuel cell could run with a constant amount of hydrogen reformed. Thus, we consider reformer FCVs to still be a valuable option.

If emission reductions are the center of attention, those switching options that move the system close to the optimum (switch to CCS or switch to CGH_2) and the one with the lowest average emissions during the transition (switch to LH_2) directly imply a significant increase in energy requirements.[15] In that respect, they are inflexible and have a high regret potential. Out of the remaining switching options changing vehicle technology also performs best with respect to distance to optimum and average emissions along the transition path.

After the first transition step is made, new information about the performance of specific WTW chains might become available. In a risk averse setting, it would be desirable to have transitions that are flexible in case of "bad surprises". In the transition example of Figure IV-5 a (hypothetical) "bad surprise" would be that after the first two transition steps it turns out that large scale biomass production to generate synthetic fuels does not decrease GHG emissions as much as expected, so that the emission index of all biomass chains must be increased by, say, 10 units. Then, the optimum remains optimal (-16), but the switch to biomass (3rd step) could not be done anymore, because it implies an increase in emissions (from 33 to 28+10 = 38).

As a benchmark of how vulnerable the transition path are to such "bad surprises", we compute the actual number of paths that lead to an optimum, given the initial

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[15] The first step of switching to hydrogen produced from gasoline hardly reduces GHG emissions. Zero TTW emissions slightly compensate for higher WTT CO_2 emissions implied by higher energy requirements for production, storage and distribution of hydrogen. The overall change in emissions is well within the range of data uncertainty, so given the unquestionably higher energy demand, we consider the two options unrealistic.

transition step. We only look at transitions, which are not longer than 5 steps; so that all parts of the chain could be altered once (five transitions already imply a time horizon of some 25-50 years)[16]. This measurement can only be interpreted in relative terms, because it depends on the construction of the dataset. Including more different (realistic) options in the subsystems or increasing the number of subsystems is likely to raise the absolute number of potential paths (and vice versa).[17] The results are shown in Table IV-4. If GHG emissions are optimized, replacing gasoline with diesel offers the highest number (59) of different paths to get to the optimum. Of those options, which also lead to reduced energy requirements, the second most flexible one is the switch to Hybrid-ICEVs with only a bit more than half as many different paths (32), followed by the switch to FCVs with reformers (22). Changing to pipeline distribution predetermines a single transition path of 5 steps (see Table IV-3) and can, therefore, be considered extremely risky.

Table IV-4: Number of transition paths to the optima within 5 transition steps

	WTW energy requirements			WTW GHG emissions
First transition step:	**Global optimum**	**Local optimum (*A*)**	**Local optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	-	50
Transition to LCP	11	1	0	1
Transition to Diesel	14	1	2	59
Transition to LH_2	-	-	-	47
Transition to CGH_2	-	-	-	11
Transition to Hybrid-ICEV	15	2	7	32
Transition to FCV (+reformer)	27	5	4	22

If transition steps are evaluated according to energy requirements, changing vehicle technology offers the most paths towards the global optimum. It is noticeable that, no matter which first transition is made, there are much more potential paths towards the global optimum than to the two local optima. This can be interpreted as an indication that chances of a lock-in in a suboptimal system due to current decisions are rather low.

To sum up, the optimal initial switch depends on the relative importance of the objectives. Changes in the vehicle technology are favorable with respect to energy requirements in terms of flexibility, shortness of distance to the optima and average energy requirements over the shortest transition path. We conclude that they have, therefore, the lowest potential regret. Only if the focus is on emission reductions and flexibility alone, the general switch to diesel becomes the best option.

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[16] However, in most potential transitions, certain parts of the chain are changed more than once leaving others unmodified.

[17] A potential normalization would be a division by the number of feasible transition paths to the optima, but that number would also be subject to specific characteristics of the system set up.

In Table IV-5 and Table IV-6 we provide the same type of results for decreasing resolution to five units (high uncertainty). Then, more chains become equivalent, so that the optima become larger and the number of paths to get there increases. Furthermore, more first step options (of equivalent performance to today's chain) arise, namely changing to medium scale refining with pipeline or truck distribution. Theoretically, LPG can be generated from crude oil, but we do not evaluate that option, because it requires more energy.[18] The pattern in the results is not different from the one reported

Table IV-5: Shortest transition path (average performance along the path in brackets, high uncertainty)

	WTW energy requirements		WTW GHG emissions
First transition step:	**Global optimum (*A*)**	**Global optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	3 (6.7)
Transition to LCP	4 (26.3)	6 (25.8)	5 (22.0)
Transition to MLP	4 (26.3)	6 (25.8)	5 (23.0)
Transition to MLT	3 (26.7)	5 (26.0)	5 (11.0)
Transition to Diesel	3 (26.7)	5 (25.0)	4 (13.8)
Transition to LPG	-	-	4 (15.0)
Transition to LH$_2$	-	-	3 (8.3)
Transition to CGH$_2$	-	-	3 (5.0)
Transition to Hybrid-ICEV	3 (23.3)	4 (23.8)	4 (11.3)
Transition to FCV (+reformer)	2 (22.5)	5 (24.0)	4 (7.5)

Table IV-6: Number of transition paths to the optima within 5 transition steps (high uncertainty)

	WTW energy requirements		WTW GHG emissions
First transition step:	**Global optimum (*A*)**	**Global optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	106
Transition to LCP	36	0	2
Transition to MLP	36	0	2
Transition to MLT	49	1	26
Transition to Diesel	51	1	134
Transition to LPG	-	-	156
Transition to LH$_2$	-	-	134
Transition to CGH$_2$	-	-	77
Transition to Hybrid-ICEV	53	8	79
Transition to FCV (+reformer)	97	5	68

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[18] Note that LPG production from crude oil is listed because it does not increase GHG emissions beyond the five unit interval.

before for the values with higher precision. In the previous section, we argued that the global energy optimum *A*, which is a merger of the previous global optimum and the local optimum *A*, is closer to the GHG emission optimum (compared to optimum *B*) and might, therefore, be preferable. All initial transitions move the system actually closer to optimum *A*, and in any case, there are much more different paths leading to it, so that chances are much higher to end up in the preferred optimum. Changes in vehicle technology are still most flexible and have the lowest average performance values along the (shortest) paths. A switch to diesel remains most appealing if the focus is on GHG emissions and flexibility. The fact that these patterns remain, even if precision is decreased substantially, indicates robustness of results.

5.3. Win-win transitions

In addition to transitions either driven by emission reductions or by reductions of energy requirements we also analyzed win-win transition steps, which increased performance in one dimension without decreasing the other one (i.e., dominant strategies). We find that all three energy optima can be reached with no more than five win-win steps. Table IV-7 shows the number of win-win transition paths to the energy optima. With 16 (at the global optimum), 5 (at local optimum *A*), and 22 (at local optimum *B*) GHG emissions remain high, at least compared to the GHG optimum (-26). In that respect, local optimum *B* can be considered worst. In general, the GHG optimum is infeasible, no matter how many transition steps are made, because reaching the GHG optimum requires a switch to CCS at some point. That switch cannot be made "win-win", as energy requirements increase.[19]

Table IV-7: Number of win-win transition paths to the optima within 5 transition steps

	WTW energy requirements		
First transition step:	**Global optimum**	**Local optimum (*A*)**	**Local optimum (*B*)**
Transition to Diesel	9	2	-
Transition to Hybrid-ICEV	-	-	2
Transition to FCV (+reformer)	5	-	2

Table IV-7 demonstrates that there are only three potential initial transitions that allow for a win-win transition to the energy optima later on. Moreover, the first step predetermines, which optimum will be reached later on. The extreme case is switching to Hybrid-ICEVs at the beginning. Then, local optimum *B* is the only energy optimum

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[19] If precision is decreased the GHG optimum becomes feasible, because for some subsystem combinations the increase in energy requirement due to CCS is within the five unit rounding.

that can potentially be reached.[20] We conclude that path dependence is much stronger if transitions should be win-win and switching to FCVs or diesel would then be most flexible with respect to the number of optima and the number of paths to the energy optima, especially to those with lower emissions. This implies that a government policy that requires all decisions concerning transitions to be beneficial for both energy requirements and GHG emissions is not desirable. There are important trade-offs between the two performance measures, and trying to satisfy both at the same time in all transition steps may be too ambitious and too risky in terms of irreversibilities in technological development.

6. Summary and conclusions

Transitions in complex technological systems have been previously analyzed in analogy to mutations of genes that enhance the fitness of an organism. In this paper, we apply this methodology to potential future changes of the WTW chain in individual transport. WTW chains can be interpreted as a complex system in terms of the analogy, because they can be described by two necessary characteristics. Firstly, the WTW system contains subsystems that can change independent of the other subsystems, and secondly, the overall performance of the system depends on the combination of states of the subsystems.

WTW studies usually compare WTW chains, which represent end states after a successful system change. But simultaneous transitions to a different energy source, different fuel production and distribution system and different vehicle technology would be a technological discontinuity which bares a lot of uncertainties and is, therefore, unlikely to happen. We argue that a stepwise transition described by successive changes in subsystems of the WTW chain is in better accordance with what has been observed historically in other technological transition processes (Levinthal, 1998; Frenken and Nuvolari, 2004). We assume that steps will only be taken if they reduce GHG emissions or energy requirements (as a proxy for operation costs) over the whole WTW chain. Which criterion matters, depends on preferences of decision makers. But stepwise transitions imply path dependence of the system and the potential existence of local optima. In the data, we find local optima with respect to energy requirements, which would be end points of transition processes. With respect to GHG emissions, we find only one global optimum. Knowledge of the optima makes it possible to identify successful transition paths, which might be undetected if myopic transition rules were applied.

We compare the different energy optima according to their distance to the emission optimum, where distance is denoted by the number of necessary transition steps to get from one optimum to the other. We find that a (local) energy optimum characterized by NG/CNG is particularly far away from the emission optimum. Thus, a transition that is

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[20] This does not mean that all later win-win transitions will actually get to that optimum. We actually find that most transitions end in a system with higher than optimal energy requirements and emissions way above the emission optimum.

initially driven by energy optimization could end there. If then, later on, GHG emissions are considered more important, it would be particularly expensive to decrease emissions.

The main focus of our analysis of potential transition paths is on flexibility. One transition step is not only extremely costly, but is also likely to take up to a decade. Thus, after this period, new information (and technologies) will probably be available, and even preferences of decision makers might shift. Therefore, it is favorable if the initial transition step does not predetermine the later transition path, but allows for alternatives. We find that changes in vehicle technology are most flexible if the initial focus is on energy requirements, suggesting that R&D efforts should focus on the vehicle subsystem in the short term. Moreover, the GHG optimum remains feasible if a later shift in preferences occurs. If GHG emissions are the center of attention right from the beginning, a replacement of gasoline by diesel appears to be most flexible. We also look at what we call win-win transitions that decrease GHG emissions without increasing energy requirements (or vice versa). In those cases, the initial decision becomes critical, as it might actually fully predetermine the later end states of the transition.

The advantage of our approach is that it allows making dynamic interpretations of existing (static) WTW information. Given substantial uncertainties related to future energy systems, policy makers are particularly interested in current transition steps that have low regret potential by being flexible. The method is simple and can also be applied to more complex WTW systems containing any number of subsystems. More (smaller) subsystems would allow for a more detailed transition analysis, as, e.g., more than one subsystem may change within one transition step.[21] A higher number of subsystems implies an exponentially higher number of theoretical combinations (and, therefore, greater data requirements). Such a detailed analysis might, thus, be appropriate only for a subgroup of WTW chains. A subgroup with particular policy relevance would be biomass-biofuel pathways.[22] Different biomass sources, fuel conversion technologies, and so on can be distinguished. Initial paths might be preferred that allow for more different fuels later on, given the uncertainties in vehicle technology development.

The methodology we present also has its limitations. We ignore investment costs for the transition steps, so there might be trade-offs between transition costs and flexibility. Besides this general problem, there are several issues that need to be addressed in future research that qualify the results as preliminary. We interpret energy requirements as a proxy for variable costs of a WTW chain. This works sufficiently well only for those energy sources that use a feedstock as a costly input, but a direct cost estimate would be preferable. The data we use is only for demonstration purpose. It combines information from different studies with different assumptions and foci. Thus, data uncertainty is very high. We address uncertainty by deriving results for different degrees of precision

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[21] We didn't allow for that in the current chain with just five subsystems, because this would correspond to a radical system switch that we consider unlikely.

[22] Several EU countries have specified targets for the share of biofuels within all fuels for automotive applications.

and find that the general patterns of results remain. Nevertheless, a reestimation of the dataset using a single consistent WTW framework is indicated as welcome.

To facilitate evaluation of transition strategies, it would be beneficial if future WTW analyses would not only focus on the comparison of potential end states of complete transitions, but also look at chains that are likely to be intermediate steps (usually less efficient than the end states). In terms of flexibility, particularly interesting intermediates are those that are to a large degree compatible to the current system and do not predetermine the likely final state of the transition process. The results presented in this paper indicate that FCVs with onboard reforming might be a crucial technology in that respect.

Overall Conclusions and Outlook

The aim of this thesis was to investigate transition management policies that achieve a large scale introduction of alternative fuel and vehicle technologies in road transport. Even in the absence of any policy, increasing oil prices due to resource depletion are likely to promote technological change. However, GHG emissions and local air pollution associated with road transport, call for an accelerate transition. Focused R&D of the car industry, public research programs, and media coverage draw particular attention towards hydrogen and FCVs as a promising combination of alternative fuel and vehicle technologies. It allows for sustainable individual transport, if hydrogen is produced from renewable energy sources. But transition policies must be designed carefully due to the economic importance of the road transport system (not only in countries with a major car industry). First steps towards a hydrogen system, in which, e.g., hydrogen is generated via natural gas reforming, already imply substantial costs to set up a hydrogen distribution and refueling system over and above the costs for FCVs. Current cost estimates are based on scenarios depending on assumptions about technological feasibility. But actual adoption of the new technologies will depend on policies that create economic incentives for the car industry, oil companies and consumers to do so.

In the first two papers of this thesis, I explored the impacts of such policies on technology diffusion, consumers and certain car producers. In the third paper, I addressed the problem of minimizing costs of an initial refueling infrastructure that is sufficient enough to make consumers buy FCVs. The final paper investigated flexible transition strategies towards alternative fuel and vehicle systems assuming that hydrogen and FCVs are not preselected as the desired technology combination. In the papers, agent-based and evolutionary concepts of technological transitions are used and their functionality as tools to investigate and optimize transition policies is demonstrated. In contrast to neoclassic approaches of technology diffusion, in which adoption and non-adoption equilibria are analyzed in terms of feasibility, but adjustment processes are assumed to be instantaneous, the focus of these alternative concepts is on the transition itself. The dynamics of the transition are crucial, given that the process of technological change in the road transport system is likely to take decades. Thus, an advantage of the new approaches is that the impact of different transition policies throughout the process can be investigated. Transition is influenced by sequential decision making of myopic agents and exhibits path dependence, so that a wide range of possible end points exist that are determined during the system change.

The scope of potential applications of the models presented is large. The agent-based simulation models of the first three papers are not restricted to hydrogen and FCVs. They could also be applied to the introduction of other alternative fuels that need a specific infrastructure and vehicle technology, such as natural gas or biogas. All models (i.e., basically also the evolutionary transition model of the last paper) are transferable to different regions and time frames. Updates on the data and starting conditions are easily employed and so are more specific policies. The main results are here summarized and limitations are discussed together with possible remedies and potential extensions.

In the first paper, I analyzed different effects of certain tax and infrastructure policy combinations in an agent-based model that explicitly represents interactions between car producers, consumers and oil companies. An immediately high tax on conventional cars initiates a diffusion of FCVs right away. This fast diffusion benefits large producers who tend to be the first to switch to the production of FCVs. Their success increases concentration in the market at the expense of small producers. This effect is aggravated if the government also engages in a faster hydrogen infrastructure build-up. Moreover, consumers are adversely affected due to higher after-tax prices leading to a substantial decline in car sales in general. The implied economic costs and expected resistance of interest groups have not been addressed in earlier analyses due to their sole focus on infrastructure and FCV costs. Magnitudes of the effects depend on the actual design of the policies and so do the predicted adoption rates. A careful construction of realistic transition scenarios should, therefore, incorporate the impact of the policies necessary to initiate transition in order to keep disruptive impacts in the car market as small as possible. Identifying the resulting winners and losers of the policies in advance also allows for compensation policies that might reduce resistance to changes.

In the second paper, the previous model was extended by implementing learning by doing in fuel cell technologies. Assumptions concerning the magnitude of learning effects appear to have a strong effect on projected technology adoption. Transition is likely to fail if learning effects are low, but high learning effects together with a rather long decision horizon of the producers foster diffusion. If learning spillovers exist, transition is accelerated. Producers benefit from spillovers differently, depending on their position in the chain of technology switchers and the magnitude of spillovers. Early followers, i.e., those who are second or third in offering FCVs, tend to benefit most from spillovers. In general, the model exhibits a substantial first mover advantage, because an early switch provides a head start for experience accumulation. Combining the findings regarding spillovers and the first mover advantage shows that the government might face a policy trade-off with respect to the optimal regulatory environment. If it tries to secure the relative advantage of a national technological leader being the first mover, it should prevent spillovers. But, if on the other hand, the government tries to promote a fast diffusion of the beneficial new technology, it should facilitate spillovers.

The results derived in the first two papers are subject to two types of modeling issues that limit their validity. The first one is related to the methodology of simulations as such. The simulations underlie uncertainties regarding parameters and behavioral assumptions. Uncertainties are particularly large, because the model addresses a very specific technological transition that is unprecedented in history, so that standard calibration/validation methods cannot be applied. These issues can be summarized as parameter uncertainties. They are addressed with sensitivity analyses in order to identify those parameters (or behavioral equations) that have the most severe impact on results. Especially parameters concerning the consumers' trade off between fuel availability and price drive the results. The base case parameterization is derived from US consumer surveys by Bunch et al. (1993) and Greene (2001), because of a lack of European equivalents. Apart from a potential regional bias due to different average driving behavior, these surveys do not account for latest developments in vehicle range and also in other technologies, such as navigation systems that indicate refueling options. Thus, reliability of results would substantially benefit from (country specific) up-to-date consumer surveys.

In addition to parameter uncertainties, the model itself generates uncertainty as a simulation of reality, in which decisions are at least partly driven by random events. These model inherent stochastic developments are accounted for by comparing averages over hundreds of simulations. But the future will not follow an "average path" but will be, so to say, a singular chain of events. Thus, even if parameter uncertainties could be minimized with extensive empirical analyses, model inherent stochastic developments rule out that simulation results could be interpreted as forecasts. However, the model results are the key to understand the main dynamics of a complex technological transition.

Specific simplifications are the second source of limited accuracy (also referred to as model uncertainties in contrast to parameter uncertainties). They are generally necessary in order to keep a complex system manageable and not creating a "black box", in which too many parameters and behavioral equations tend to obscure results. A major simplification is that producers can only fully switch to FCVs or continue producing conventional cars. In reality, producers are more likely to introduce the new technology in certain product lines and cross-subsidize it in the beginning. From a modeling perspective, joint optimization over two products is doable, but cross-subsidizing is a long term strategy that can hardly be implemented into the otherwise myopic behavior of producers.

Another simplification is the restriction to a single market segment. The tax might force consumers, e.g., to switch to cars in a cheaper segment rather than to adopt the new technology. This change, however, is likely to have only minor quantitative impacts that would not justify much higher complexity. On the contrary, a generally desirable feature would be to compute the environmental performance of the policies. But in order to compute, e.g., emission reductions relative to the tax burden, a different structure of the consumer model would be necessary. The reason is that consumer pay-offs cannot be derived in the current approach. Consumers compare utilities from heterogeneous products and, therefore, do not have a specific willingness to pay that could be compared with the product prices.[1] But the results already indicate that environmental performance of the policies could be a particularly interesting issue for

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[1] Note that changes in aggregate producer rents are straightforwardly derived.

future work. The taxes lead to substantial declines in sales of newly registered cars, suggesting that old cars tend to be driven longer. This might imply adverse environmental effects under the assumption that environmental performance of new cars (even of conventional ones) is generally higher than the average of the car population.

A potential extension that could be implemented in the existing framework without major changes is a more detailed representation of fuel supply. Explicit behavior of oil companies could be incorporated, including decisions about the energy sources to produce hydrogen or about blending gasoline with ethanol, hydrogen's main competitor for carbon-neutrality and energy security. Then, the impact of different cost scenarios for renewable and fossil fuel based hydrogen and other alternative fuels could be analyzed.

Another shortcoming of the model is that the consumers' decision to buy a FCV is strongly determined by rather abstract information about the percentage of filling stations offering the new fuel. In reality, choice is probably based on actually perceived fuel availability, i.e., on how frequently people drive past hydrogen stations. Thus, decisions of fuel suppliers and potential FCV buyers should be modeled in a geographic context with an explicit representation of driving. This consideration was the starting point for the development of the different model presented in the third paper. A new model was constructed, instead of extending the existing one, to address specific geographic issues with a fast executing computer program that omits modeling the complex behavior of car producers and reduces consumers' buying decisions basically to fuel availability.[2]

The model presented in the third paper is a tool to test different initial small scale distributions of hydrogen outlets at trunk road filling stations for their potential success of starting a transition. Distributions are successful if they generate a high awareness of the new fuel by potential FCV buyers. The model is fitted to the German trunk road system. A "HyWay-ring" distribution suggested by Hart (2005) is tested, because it received substantial attention as being a feasible and, therefore, realistic scenario. The ring turns out to be sufficient to initiate a general transition only if people (i.e., artificial drivers in the model) are assumed to be rather unconcerned about refueling. But the simulation results allowed for optimizing the initial distribution, so that transition becomes likely, even for more realistic assumptions regarding the behavior of the drivers. Furthermore, it is shown that the distance between hydrogen stations that drivers consider sufficient, determines the structure of the optimized distribution. Thus, if fuel suppliers are uncertain about that distance, they should calculate with rather conservative assumptions to minimize the risk of transition failure.

The optimal initial distribution cannot be calculated due to limitations in computing capacity. Identifying it would be theoretically desirable, but of low practical value. The reason is that potential initial distributions are likely to be pre-determined by factors beyond the scope of the model. The "HyWay-ring" is motivated, among other things, with connecting car industry clusters. Alternative introduction scenarios focus on

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[2] The different utility functions of the consumers in the two models could be merged, so that a coupled model is feasible. But it is generally doubtful - given the earlier discussion of simulation uncertainties - that it is beneficial to tackle all the different aspects of technology transition in a single simulation model.

locations near existing or potential hydrogen production infrastructure as starting points (see, e.g., Ball et al. 2005) or involve a single oil company that decides to offer hydrogen at all of its stations. Model experiments with such alternative scenarios should be addressed in future research, in order to evaluate their potential success.

But again, uncertainties regarding parameters and behavioral assumptions exist. Calibration could now be improved using data on the spatial development of natural gas stations in Germany that has recently become available (Seydel, 2006). Furthermore, given regional differences in the density of the natural gas station network, a national consumer survey of perceived natural gas stations, coupled with regional natural gas car sales figures, would be a desirable empirical basis for parameterization of what is considered sufficient fuel availability.

The gravity model for long distance trips represents only a very rough first approximation of real travel behavior. A problem is that recreational trips that end, e.g., in rural areas or seaside resorts are excluded. Trips abroad are also insufficiently represented. Thus, the gravity model should be complemented with consumer surveys of traveling behavior, but existing large scale studies usually aim at the number and distance of trips and do not consider particular destinations (probably because the amount of interviews necessary for representative results is prohibitive). A straightforward improvement that would also capture some of the recreational trips would be an extension of the study area, so that trips are continued abroad. A lack of hydrogen infrastructure outside Germany might reduce the number of potential FCV buyers substantially.

In the last paper, the restriction of a direct technological switch towards hydrogen and FCVs was relaxed. Potential changes in the so-called well-to-wheel (WTW) chain were modeled as stepwise transitions in analogy to fitness improving mutations of genes in evolutionary biology. The approach was taken, because a direct switch would imply a risky technological discontinuity, whereas a successive (stepwise) transition seemed to be in better accordance with historical examples of successful technological transitions. In the model presented, transition steps are only possible if they reduce GHG emissions or energy requirements, where the latter are interpreted as a proxy for operation costs. The two criteria represent different preferences of decision makers. It is shown that stepwise transition implies path dependence of the transition process and, therefore, a (potential) existence of local optima. Thus, the present decision regarding the first transition step may predetermine characteristics of the future WTW system. Full implementation of the first step is likely to take up to a decade. Thereafter, the decision space might have changed due to new information or a shift in preferences. Hence, a flexible initial step that opens a range of alternative paths rather than predetermining the subsequent transition is preferable. The number of paths that lead to optimal WTW chains later on is applied as a simple flexibility measure. This measure is computed using data compiled from several existing WTW analyses. Results suggest that total replacement of gasoline with diesel is the most flexible first transition step if GHG emissions should be reduced. But if energy requirements are optimized, changes in vehicle technology are most flexible. They even allow for switching to the optimization of emissions if preferences shift towards GHG emissions reductions after the initial transition. The same flexibility measure is computed for "win-win" transitions that reduce energy requirements and GHG emissions at the same time. In that case, only very few initial steps are feasible at all, and predetermination of the future system is substantial.

The higher the flexibility after a decision, the lower is the risk of regretting it later on. Thus, the flexibility measure can be interpreted as a proxy for potential regret and can, therefore, be decisive for risk-averse policy makers. However, flexibility is not the exclusive criterion to evaluate different transition options. Investment costs for transition steps are equally important, but not represented in the model. Since they are likely to vary considerable between potential transitions steps, policy makers might face trade-offs between transition costs and flexibility.

Apart from this general limitation of the approach, there exist some drawbacks of the implementation of the evolutionary methodology in the given context. The classification of subsystems that are subject to change was chosen rather simple and, hence, required several ad hoc assumptions regarding compatibility of different technologies and necessary adjustments along the chain. This was a concession to demonstrate the functionality of the approach using well-known existing data. The suggested methodology would be more appropriate, if applied to a subgroup of WTW chains. Chains within the subgroup would be technologically more similar and could then be explored in greater detail, using a higher number of subsystems. The increased realism of the technological system would directly increase reliability of results. Transition of biomass-biofuel chains could be analyzed using such a detailed approach. They include a large number of different sources and different fuels, but nevertheless with comparable technological characteristics. In contrast to some of the chains presented in the paper, WTW energy requirements would be a reasonable proxy for variable costs of different chains, because they use a similar feedstock. Given that uncertainties regarding, e.g., environmental impacts of large scale growing of certain energy crops are high, identifying flexible initial steps seems to be particularly valuable. Moreover, several EU countries have already set targets for the share of biofuels, i.e., they are high on the decision agenda, so that future research is particularly advisable.

The main focus of the thesis was on developing a better understanding of the economic dynamics of potential transitions towards alternative fuel and vehicle technologies. Despite existing shortcomings, the results of the different papers provide valuable guidelines to get a more complete picture of the impacts of transition policies. Advocates of a transition to hydrogen and FCVs might argue that the shared vision is powerful enough to be self-fulfilling, so that we will inevitably observe a large scale introduction of those technologies in the future. If they were right, this would not let transition management policies become obsolete, but rather call for an immediate intensification of research efforts in order to make it an unqualified success.

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