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Simulating the Adoption of Fuel Cell Vehicles*

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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 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.

Key words: Diffusion Process – Agent Based Modeling - Hydrogen Economy – Alternative Fuel Vehicles

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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 started. 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 implied 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 not a future vision anymore, 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 - dependent on the energy mix used for the production of hydrogen - a lessening of damages associated with climate change (Barreto et al., 2002). 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 include 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

[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), Barreto et al. (2002), Ogden (2002), 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.

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) implies 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 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), that is assumed to be further optimized with respect to energy efficiency and emissions (EC-JRC, 2004). 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, so as 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 such 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

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

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 introduced 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 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

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

tax scenarios represent extreme cases, one "shock tax" scenario with an instantaneously high tax on ICEVs and a "gradual tax" scenario, where agents can smoothly adjust to the new circumstances. Later on we also 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 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 socioeconomic costs of public infrastructure programs.

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, where their knowledge about 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 of 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 are in the market the more prices approach marginal costs and profits go to zero or that decreasing cost 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 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

[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)).

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 the fuel availability. Moreover, if producers perform badly (according to their market share), they switch in case the market leader is already producing FCVs, i.e. there is some imitation.[7] Finally, the producers are doing R&D so as 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 ordered. 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 her car (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 he can actually end up with nothing and has 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.

[7] Similar imitating behavior could 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, 2004).

[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.

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 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 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 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

[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 dependent on the assumed discount rate, car type, utilization, and lifespan.

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 the current speed at which conventional gasoline stations are equipped with an additional compressed natural gas (CNG) outlet, this is not an overly optimistic assumption (see also *European Commission* (2003)). Following Stromberger (2003) we use the development of CNG outlets also as a basis for our scenarios on the exogenous build up of hydrogen infrastructure from year 2010 on. 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

[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.

0.3% per quarter, but in either scenario we limit the increase of the share to 2%, i.e. no more than about 1100 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 1[14] shows such diffusion curves for FCVs in the compact car segment for the six scenarios and Figure 2 depicts the corresponding development of the hydrogen infrastructure. Figure 1 shows that in the central cases there is no chicken and egg problem prohibiting diffusion. Independent of exogenous H_2 built up, the shock tax immediately induces at least one producer to switch to the production of 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.

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

[14] All graphs are averages of 100 realizations so as 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 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.

can be explained as follows: The gradual tax lets a producer switch to the production of FCVs as soon as she 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 built up together with the tax raise makes it even more likely that another producer switches. 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 beside 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 small producers are. These issues are addressed in the next sections.

4.2 Concentration

There are two main effects on the market shares. 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 3 illustrates market power with the 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 higher impact on the average market price. Thus, they can better predict, how many cars they will sell, now that there is the tax. 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 and this results 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 few periods until expectations and actual market shares match better 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 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 dotted and solid orange lines of 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]

Turning to the gradual tax cases, Figure 3 shows that market power is lower (compared to the no tax baseline) during the time that 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 5) this puts pressure particularly on small producers, which react with price cuts generating higher market shares for them. 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 socioeconomic 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 producer. 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

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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.

Figure 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 so as to avoid the sharp immediate drop of 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 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.

4.4 Impact on producers

The main effects on the producers follow from the results discussed above. Figure 6 and Figure 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. Then profits quickly recover, reaching the level, which 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 firms.

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 substantial 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

[16] The same ranking of preferences should arise if we would derive a consumer surplus measurement from equation (25). 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.

right after the introduction of the tax.[17] But no matter what tax is applied, the big firms are gaining from exogenous infrastructure built up. This result matches with the real world observation that dominating 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 8 shows the diffusion with a 40% ad valorem subsidy. Given today's already high taxes on car buying, owning and usage, this case is equivalent to a situation that 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. Like 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 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 built 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.

[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.

[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 a little bit less than before due to the lack of infrastructure.

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 to buy a FCV.[19] In the central case γ is set to –3. Figure 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 c.p. 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-stations and straightforwardly react to a tax. From Figure 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 in 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 so as 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 doesn't 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 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

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

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. To see the importance of refueling we included the graphs with exogenous H_2, which promotes significant diffusion even for a low η (= 3).

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 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 that some consumers totally ignore their own preferences, which seems to be unrealistic for a major consumption decision like a car. The results in Figure 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 9(a-d). Big producers are gaining 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 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.

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 built up of hydrogen infrastructure. The producers offer heterogeneous but similar cars, so they have some market power. In each period they consider to change 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.

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

We analyze combinations of two different tax and three different infrastructure scenarios. We choose a shock tax and a gradual tax system so as to represent 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 relative 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 like size and price at the low end and distinction and status at the top. 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, 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 (see Greene (2001) and Bunch et al. (1993) for US studies). 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 correctly. Due to its rather general calibration the

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

results are likely to apply also to comparable market segments in other countries or e.g. in 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 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 like 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 down 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 at the market and therefore act fully rational. 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.

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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).

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

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

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 like the car characteristics do. 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

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

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

A.1.1.2 Social need

A car is a prestigious 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 so as to form a torus as described in Hegselmann and Flache (1998).[26]

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 introduced 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, which they are mostly exposed to. Here, consumers adjust their preference associated with a certain car characteristic according to

[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.

[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.

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

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

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.

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 their 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, which optimize only current (expected) profits over time[29]

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

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

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.

[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.

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 that tries to avoid being too small. 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 $\sum_{i=1}^{n_i} INC_{i,t-1} \leq 0$, producers simply maximize expected income.

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 firstly tries to evaluate the competitiveness of its car implied by the prices. Then she 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 its cars with the (weighted)

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

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]

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

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

$E\left[RFE_t(c_{i,FCV,t})\right]$ 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. Customers are those consumers who bought a car from the particular producer in the previous period. Producers estimate how their product contributes to social need by observing $\bar{\beta}_{t-1}$, 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

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

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

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

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

[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.

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

As a third step, equations (10) and (14) together let the producer compare own competitiveness with the estimated market competitiveness $\overline{\vartheta^e_{i,t}}$ so as to estimate its 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, she is tempted to increase prices significantly, because she expects some of her 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 her 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^e_i 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 its 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 $K^r_{i,t} - K_{i,t\text{-}1}(1-\delta) \leq 0$, 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 amount of investments $I^{max}_{i,t}$ the producer can finance is

$$I^{max}_{i,t} = \max\left\{0, NB_{i,t} + D^{max}_{i,t}\right\}, \tag{20}$$

where $D^{max}_{i,t}$ 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. $D^{max}_{i,t}$ 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.

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

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

[33] In this model K_i denotes physical capital that the producer employs for production. Labor is not directly modeled, but rather is 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.

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

$RE_{i,t}$ 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, $\Delta D_{i,t\text{-}1} = D_{i,t\text{-}1} - D_{i,t\text{-}2}\left(1 - \frac{1}{t^{repay}}\right) \geq 0$ is the change in debts at time *t*-1 and $I_{i,t\text{-}1}$ 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 $I^r_{i,t}$, 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 $NB_{i,t} \geq I^r_{i,t}$, the producer has no problem using own financial assets to finance investments, so that $K_{i,t} = K_{i,t\text{-}1}(1-\delta) + I^r_{i,t} = K^r_{i,t}$ (with $I_{i,t} = I^r_{i,t}$), and if the producer has any debts, they are decreased through repayments, i.e.

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

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

$$D_{i,t} = D_{i,t\text{-}1}\left(1 - \frac{1}{t^{repay}}\right) + \min\left\{D^{max}_{i,t}, I^r_{i,t} - NB_{i,t}\right\}, \tag{23b}$$

   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 $D^{max}_{i,t}$, so that $I_{i,t} = I^{max}_{i,t}$ and $K_{i,t} = K_{i,t\text{-}1}(1-\delta) + I_{i,t}$ 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

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

[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.

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 that are willing to buy at that price level, meaning that there are Q consumers that evaluate the cars offered according to equation (2) and order 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 ordered, 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, neither 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 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]

[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.

[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.

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 therefore 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 so as 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 are

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

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 easy check the preferences of their own customers. So taking into account how 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 and that happen to be the ones that are closest and most far 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 $\Delta_{min,t}$ is

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

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

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

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

and $Z \sim Un[0,1]$,

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 to shift the characteristic such that it exactly meets the customers' average preference. However, there are decreasing returns to R&D.

A.4.3 Imitators

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

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 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 if the market was 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

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

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.

[39] This should only be the case after FCVs took 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 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, 2005).[41] 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 1 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. In comparable boundaries are 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

[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.

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 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, we obtain the iso-utility curves shown in Figure 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 the matter of 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 the Greene's (2001) values are more reliable. 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 as 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 (ρ) 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.

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

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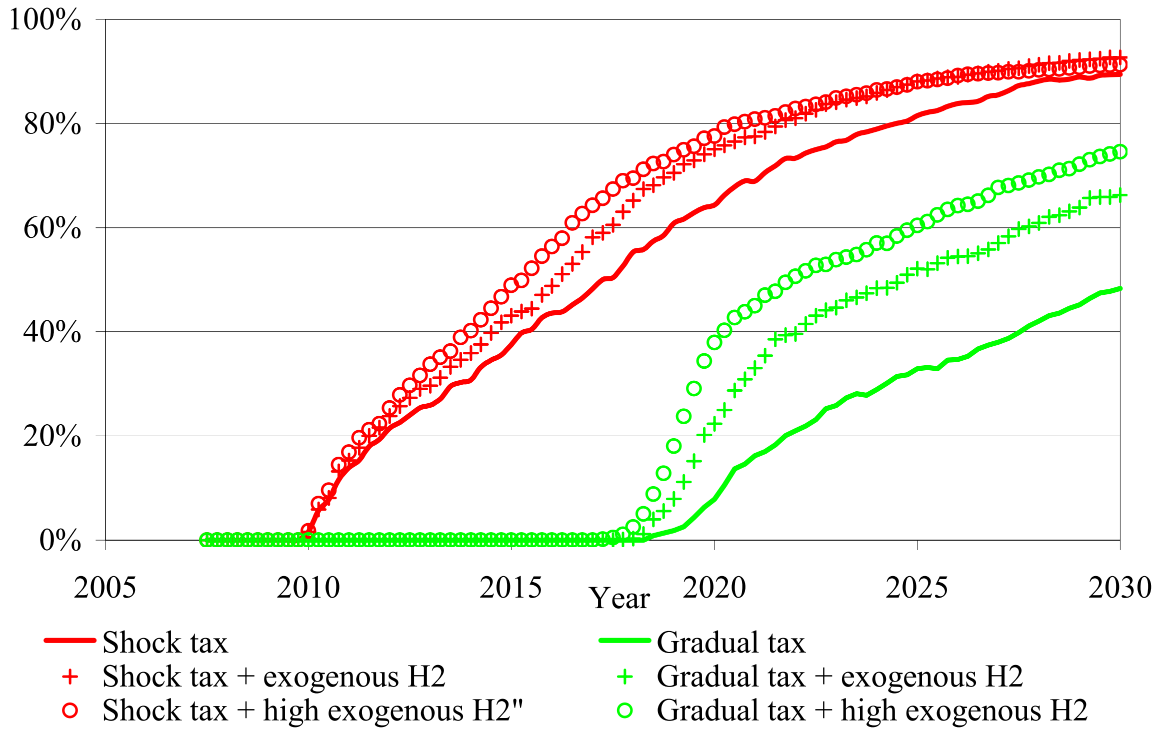

Figure 1 Total share of FCVs sold (in compact car segment)

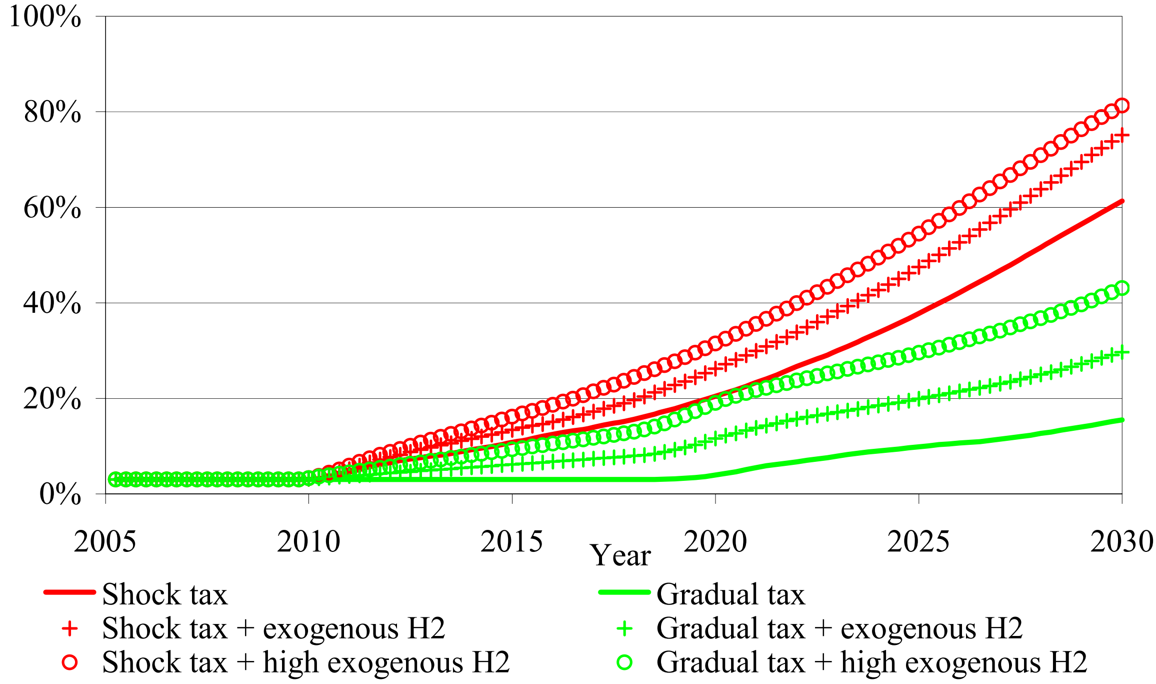

Figure 2 Share of filling stations with H_2-outlet

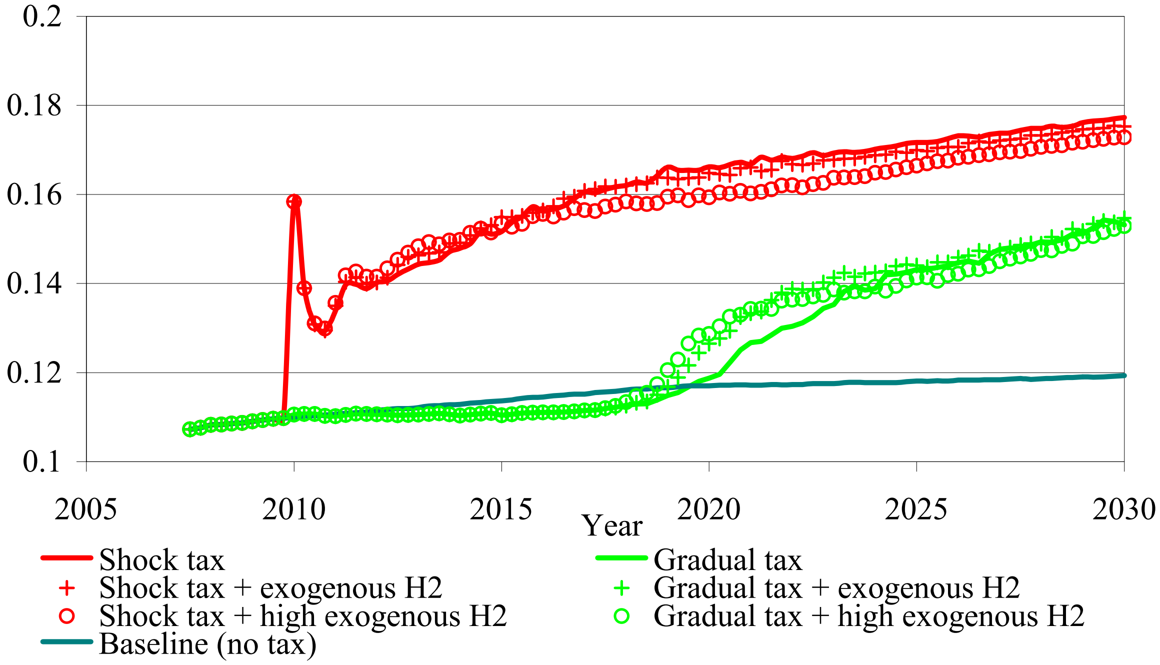

Figure 3 Herfindahl-Index

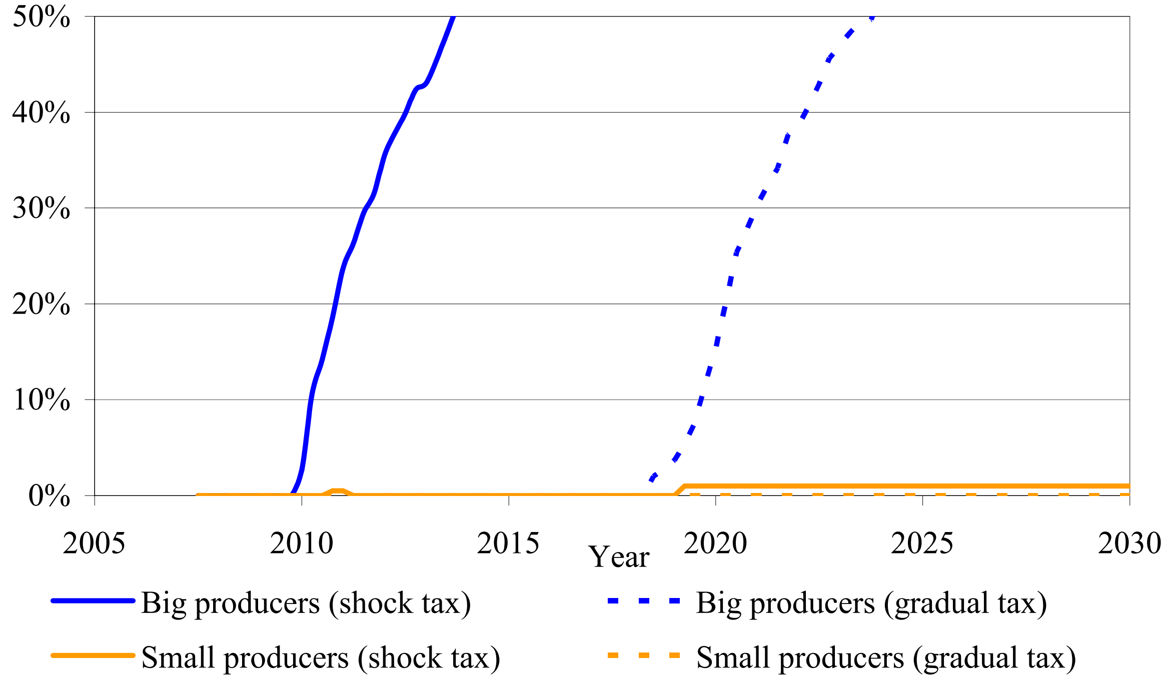

Figure 4 Share of producers manufacturing FCVs

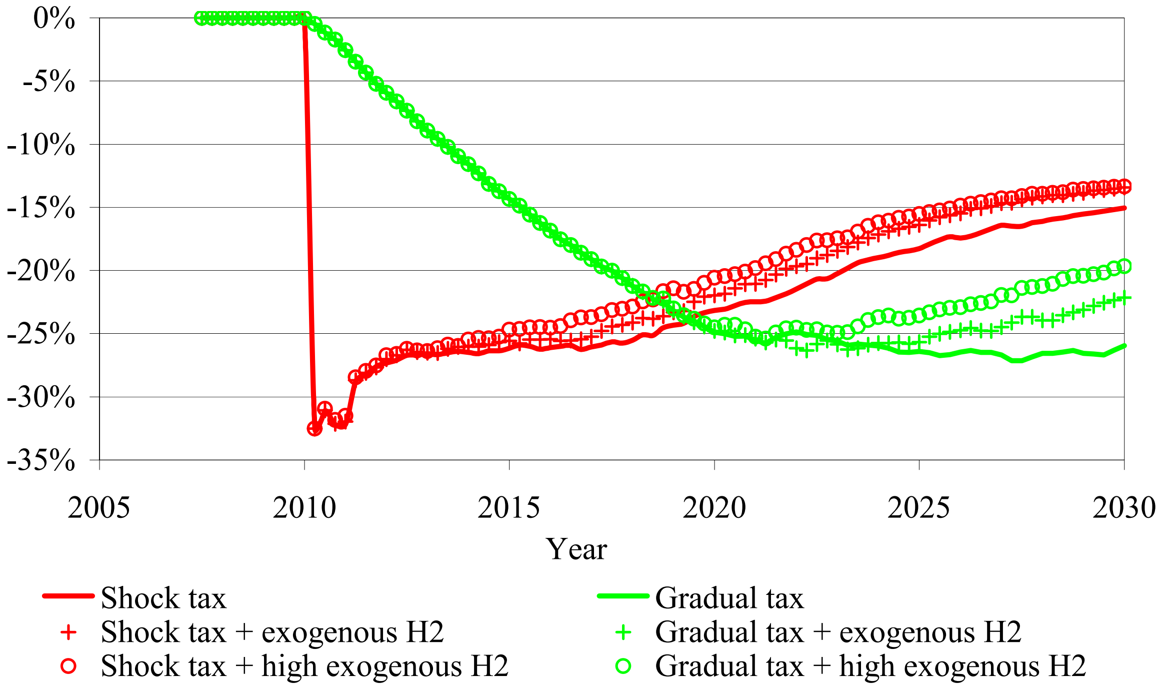

Figure 5 Change in the sum of all cars sold (relative to no tax)

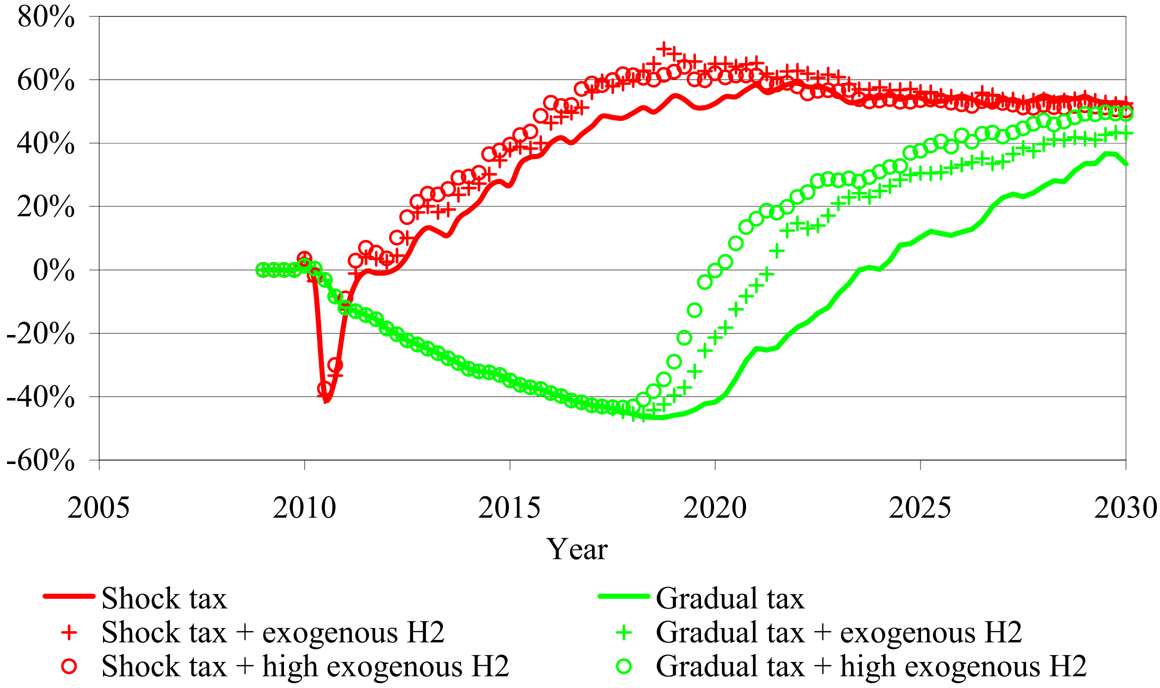

Figure 6 Change of total profit of three biggest producers (relative to no tax)

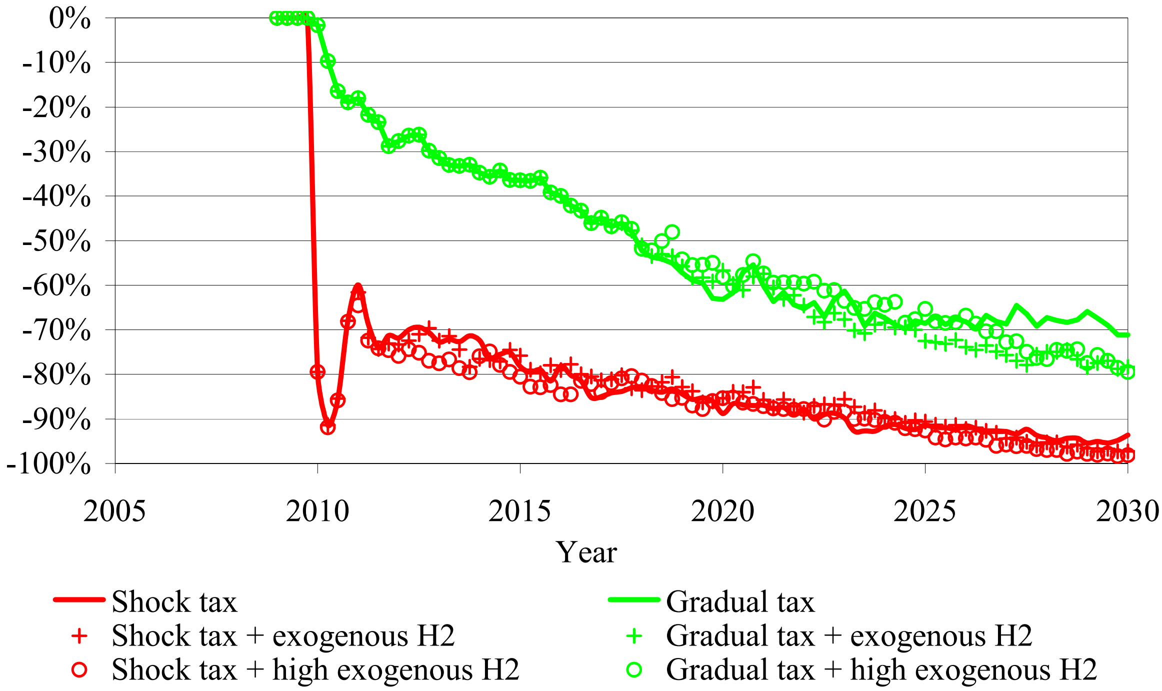

Figure 7 Change of total profit of three smallest producers (relative to no tax)

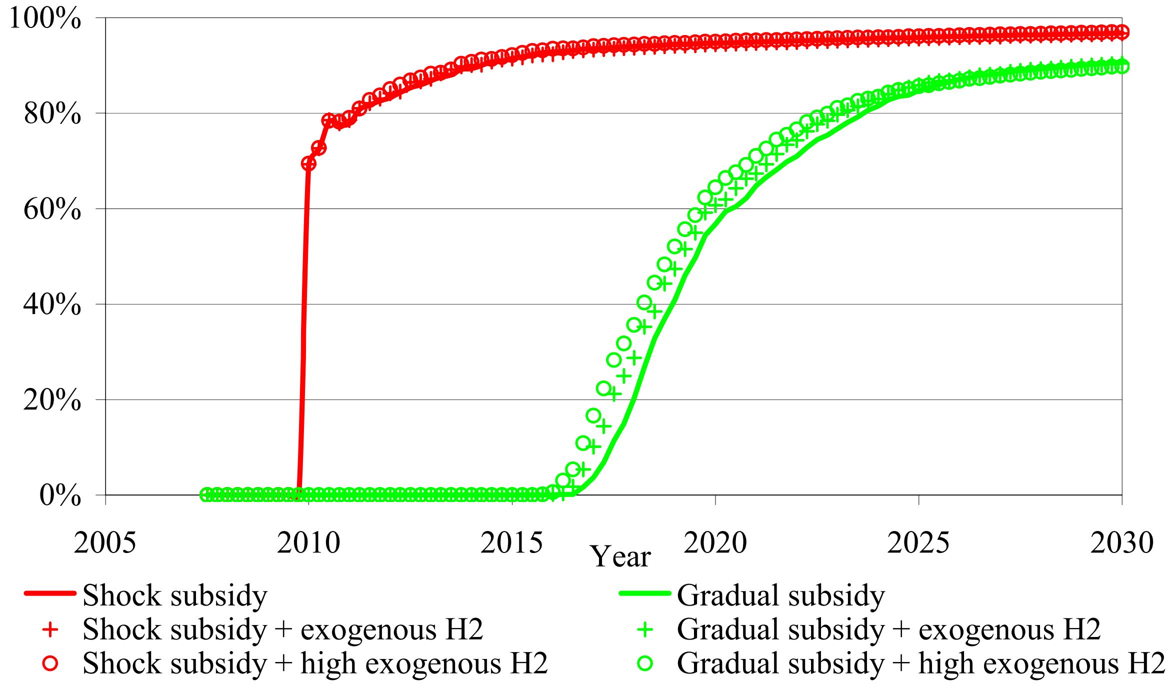

Figure 8 Total share of FCVs sold (in compact car segment) with subsidy

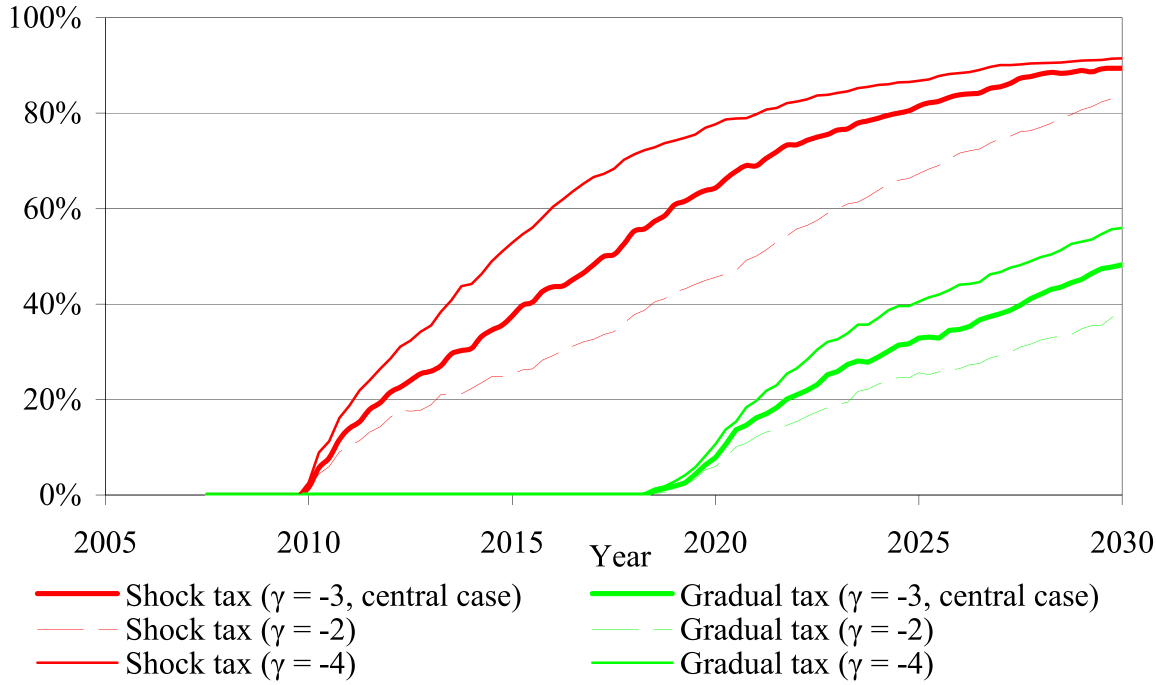

Figure 9a Sensitivity with respect to importance of fuel availability

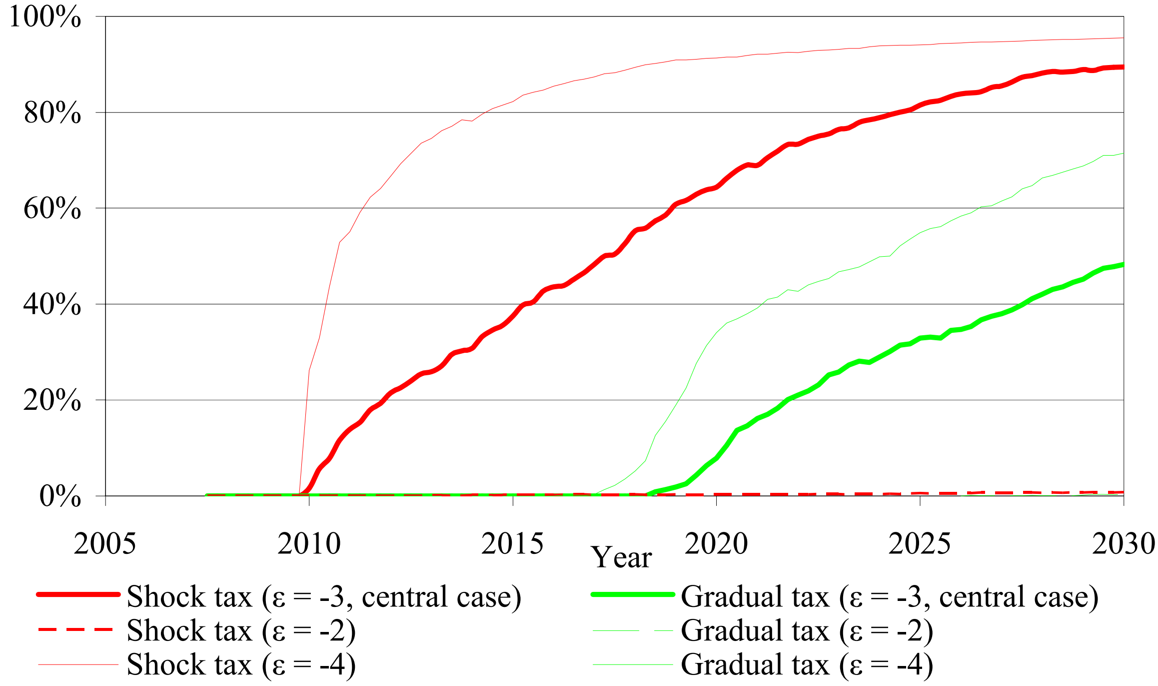

Figure 9b Sensitivity with respect to own price elasticity

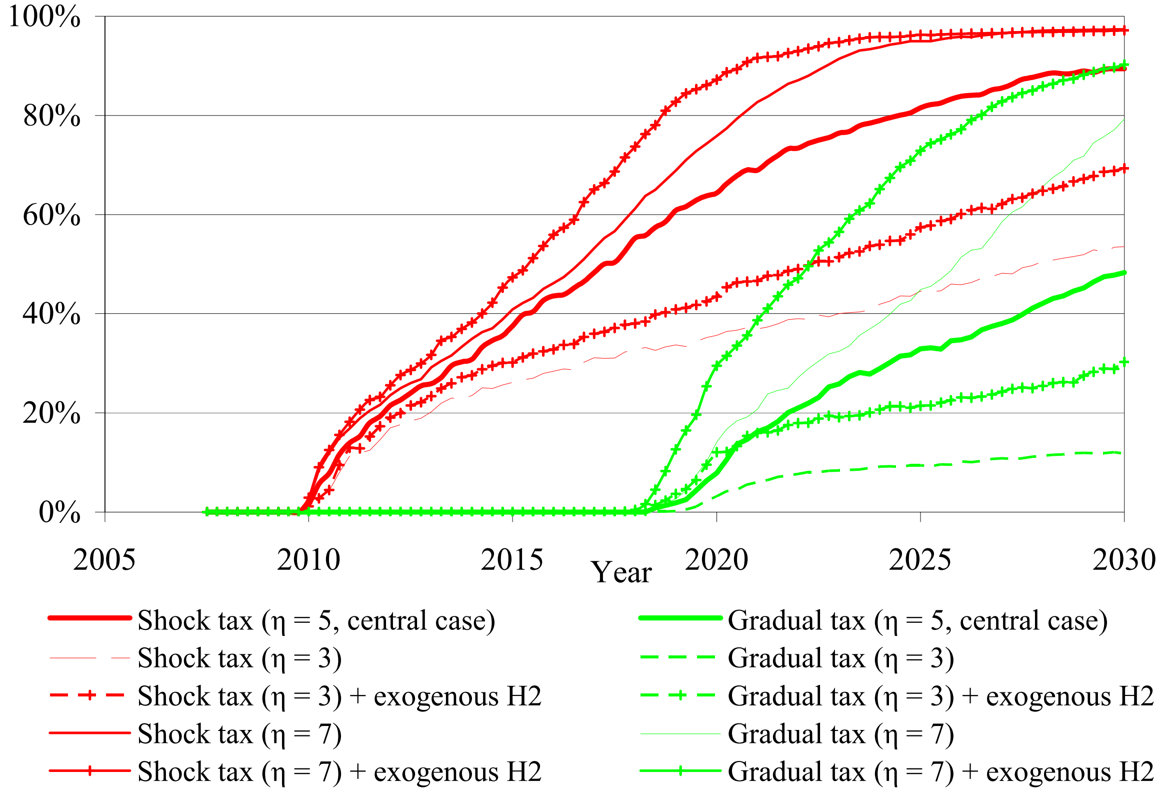

Figure 9c Sensitivity with respect to producers' objective

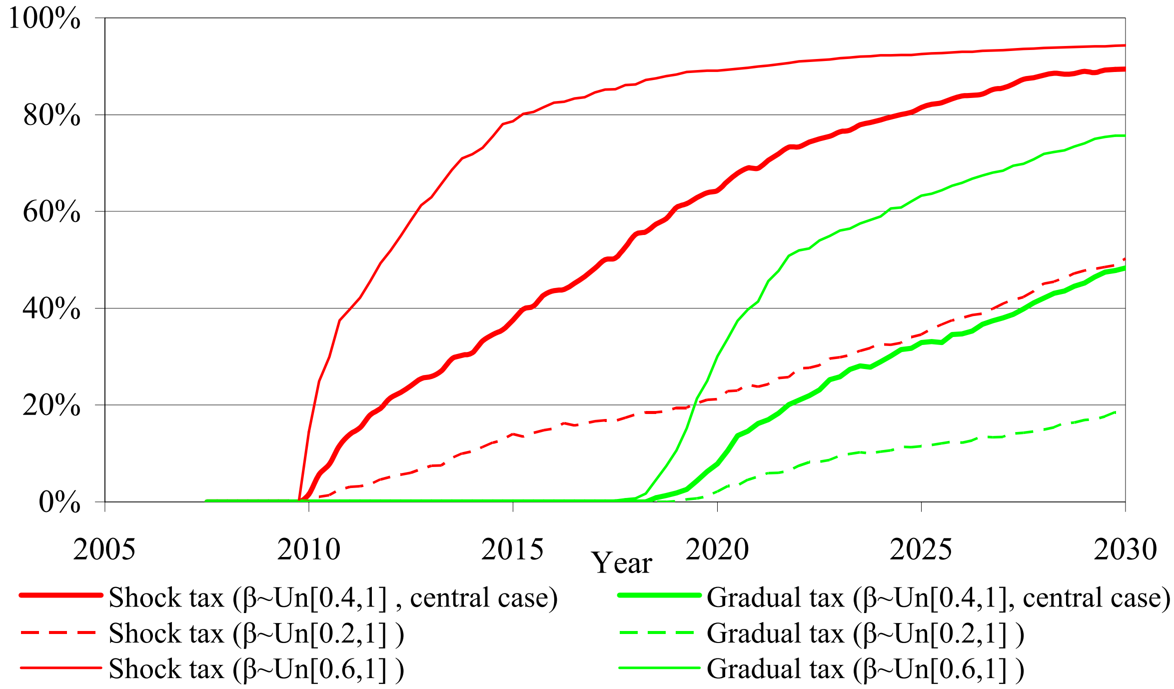

Figure 9d Sensitivity with respect to social influence (β_k)

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

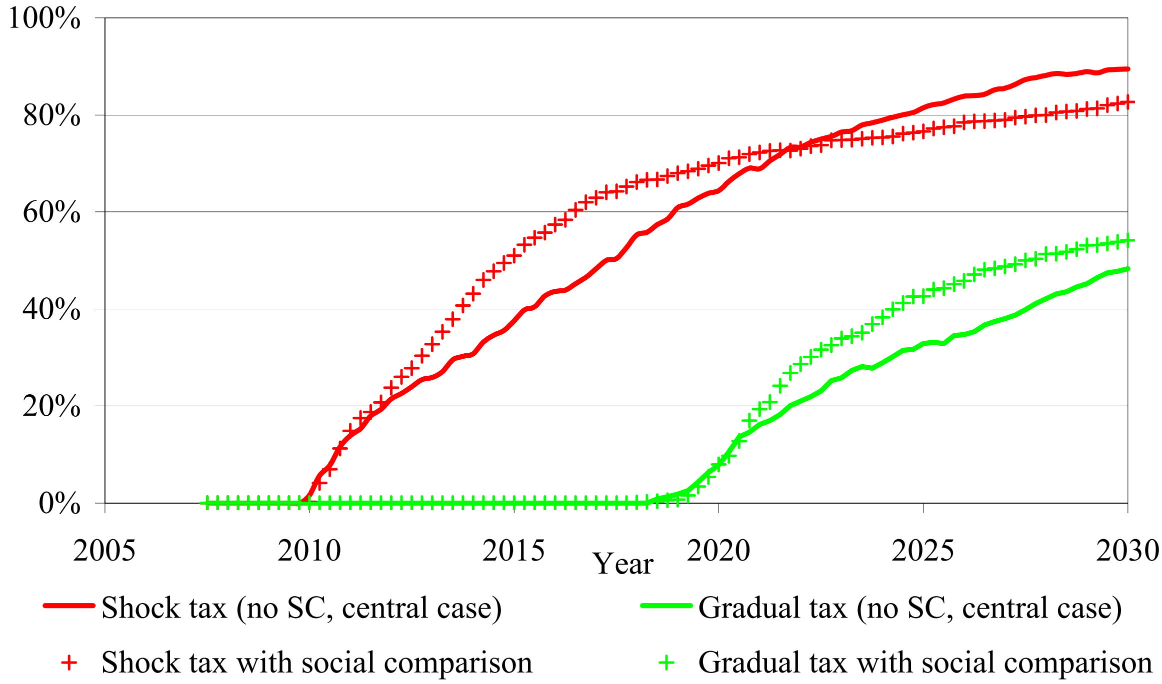

Figure 10 Impact of social comparison (SC)

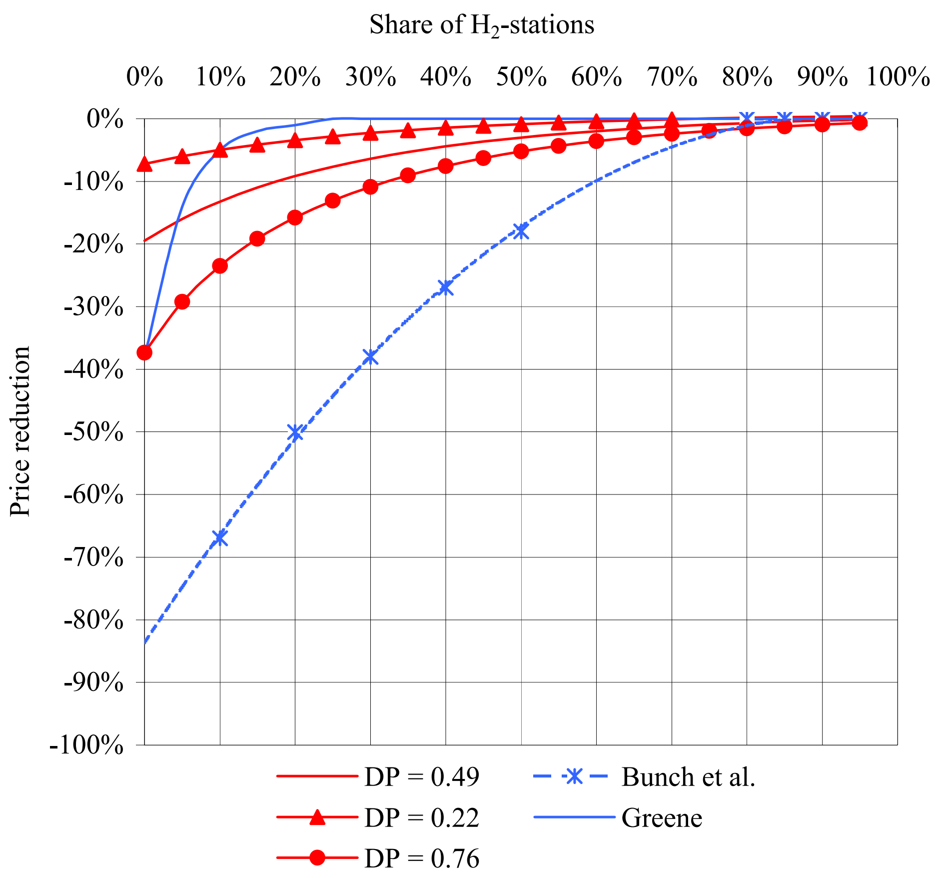

Figure 11 Iso-utility curves for price and fuel availability combinations

Table 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