Simulation Modelling Practice and Theory 16 (2008) 1463–1476

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Learning by doing, learning spillovers and the diffusion of fuel cell vehicles

Malte Schwoon *

International Max Planck Research School on Earth System Modelling, Hamburg, Germany
Research Unit Sustainability and Global Change, Centre for Marine and Atmospheric Sciences, Hamburg University, Bundestrasse 55, 20146 Hamburg, Germany

ARTICLE INFO

Article history:
Received 10 October 2007
Received in revised form 6 August 2008
Accepted 6 August 2008
Available online 15 August 2008

Keywords:
Agent-based modeling
Fuel cell vehicles
Hydrogen
Learning by doing

ABSTRACT

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

1. Introduction

Current activities of major car producers indicate that fuel cell vehicles (FCVs) running on hydrogen might be an attractive option to displace fossil fueled internal combustion engine vehicles (ICEVs) by the end of the next decade, or at least capture a substantial niche market. Inherent in the use of fossil fuels are emissions of carbon dioxide (CO_2), with their well-known effect on global warming.[1] Thus, a large-scale introduction of FCVs has the potential to shift to carbon free individual transport, implying also lower geostrategic risks associated with fossil fuel supply. It should be seen as a potential, because the actual reduction of CO_2 emissions and fossil fuel demand depends on the mix of energy sources used to generate the required hydrogen (carbon intensive pathways to hydrogen, e.g., based on coal could actually increase transport related CO_2 emissions substantially). Current scenarios of a shift to a “hydrogen society” indicate that for most countries low cost production of hydrogen requires the reformation of natural gas, which would still imply CO_2 emissions, as long as no (costly) CO_2 sequestration technology is applied. But due to the fact that hydrogen can be produced from any energy source, a long term decarbonization of energy generation would directly lead to lower emissions from individual transport [1–4]. Particularly promising seem to be recent scenarios to produce hydrogen from photovoltaics and especially from (offshore) wind energy, as this would circumvent problems related to fluctuations in energy production implied by sun and wind as energy sources [5–7].

Further advantages of the FCVs are the low noise generation and the general absence of any local emissions like particulate matter, ozone, sulfur dioxide, and carbon monoxide. Strong emission regulations, particularly in the US, Japan, and Eur-

---

* Address: Research Unit Sustainability and Global Change, Centre for Marine and Atmospheric Sciences, Hamburg University, Bundestrasse 55, 20146 Hamburg, Germany. Tel.: +49 (0)40 42838 6593.
E-mail address: m.schwoon@gmx.de.

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

1569-190X/$ - see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.simpat.2008.08.001

ope have initiated major technological progress of catalytic converters and the use of cleaner fuels (unleaded and desulfurized gasoline), so that local emissions from ICEVs have substantially been reduced over the last decades. But some of these reductions have been compensated by increased car travel and heavy-duty transports, so that future reductions of total emissions would require even more complex (and expensive) end-of-the-pipe technologies.

Even though the fuel cell technology itself is nowadays well developed and tested in daily life situations, there are two major economic barriers to a fast diffusion of FCVs. Firstly, there is the so-called chicken and egg problem saying that people are not willing to buy FCVs as long as there is no area-wide coverage with hydrogen outlets, and on the other hand, filling station owners (or "the oil industry") would not invest in a hydrogen generation and distribution system unless there is a significant demand for the new fuel. Secondly, fuel cells are at the moment simply too expensive to compete with internal combustion engines. Schwoon [8] uses an agent-based diffusion model to investigate, whether different tax systems and infrastructure scenarios in favor of FCVs are able to lead to a successful introduction of the new technology. Calibrated for the German compact car market, his model results suggest that a tax on ICEVs in the range of today's car taxes in most European countries – together with an infrastructure build-up comparable to the rather slow development of compressed natural gas (CNG) outlets in Germany – is sufficient to overcome the chicken and egg problem. A major focus of that study is on the impact of diffusion policies on market shares, profits and competition with producers using a simplified optimization strategy. Although relative costs are one of the main decisive factors, producers are assumed to only use a point estimate for the costs of fuel cells if produced on a large scale. This setup has been employed to reduce complexity of modeling the producers decision. However, the implied assumption that producers do not create expectations about their cost developments cannot be observed in reality.

Therefore, the current paper extends the model by implementing a more realistic approach towards the costs of fuel cell production. There is a general notion that fuel cells costs at the moment are prohibitively high, but on the other hand learning by doing (LBD) in the technology will lead to substantial cost reductions [9–11]. If costs follow an experience curve, the assumed learning rate turns out to be critical, so that too low gains from experience might create an insurmountable obstacle. Additionally, if the producers' planning horizons are short, diffusion might also be severely hampered.

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

LBD and learning spillovers have to the best of our knowledge not been incorporated into agent-based models before. Both phenomena play a major rule in technological development and therefore increase the realism of the model significantly. On the other hand, the agent-based setup helps understanding orders of magnitude of offsetting effects in the context of first mover advantages vs. benefits of being an early follower, which so far have mainly been explored theoretically.

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

2. Dynamics of the model

The model at hand is an extension of an existing agent-based diffusion model. A detailed description of the structure and calibration can be found in [8]. Fig. 1 shows a scheme of the model. Consumers and producers are the two main agents modeled as classes. Individual agents are differentiated by certain attributes, e.g. market share in case of a producer or driving pattern of a certain consumer. There are two more agents represented in the object "market environment". Firstly, the government uses a tax on conventional cars and can increase the speed of the built up of hydrogen outlets. These two policies in combination are exogenous drivers of the model. Secondly, filling station owners in total also determine the market environment by simply reacting to the development of the share of FCVs on the road and can increase the share of stations with an H_2-outlet.

Consumers buy the car that maximizes their utility according to their preferences relative to the price after tax ("buying decision"). For the matter of simplicity, fuel prices are not included in the model. The assumptions here are that, firstly, consumers discount their expected fuel expenditures over the lifetime of the car and add this to the car price when making the buying decision and, secondly, that fuel expenditures per kilometer are based on the energy content of the fuel and are therefore (at least after taxes) the same for FCVs and conventional cars. Thus, consumers ignore fuel prices.[2]

---

[2] In reality, there will be differences in fuel prices. For example, significant price increases of fossil fuels might increase the total costs of driving a conventional car compared to a FCV (assuming that especially renewable energy sources used for producing hydrogen become more competitive). In the model such a scenario can be represented by an increasing tax on conventional cars.