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Infrastructure investment for a transition to hydrogen automobiles

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ABSTRACT

This paper describes work undertaken in the MATISSE project to explore the potential for a sustainable hydrogen transition within Europe and the implications for infrastructure investment. Stakeholder engagement work conducted within MATISSE identified unsustainable aspects of current transport and desirable characteristics of sustainable hydrogen road transport. Key criteria were: emissions reduction, security of energy supply, affordability and economic competitiveness.

Results from the ASTRA model show that a transition to hydrogen transport fuels would have an increase in GDP, employment and investment; and growth in a number of sectors (electronic, chemical, mechanical and automotive) associated with hydrogen fuel cell technology. A hydrogen diffusion model shows that in a few years after 2040 all cars in Germany could be hydrogen driven cars. Fast build-up of a network of at least 500 filling stations (in urban areas and at highways) is very important for the market acceptance of hydrogen vehicles and compared with subsidies for vehicles and fuel the necessary investments are very small. For fuel infrastructure:

- Only a total amount of approx. 200 million Euros are necessary for infrastructure build-up in urban areas.
- Additional support is needed for installation of hydrogen filing stations on highways (approx. 100 million Euros).

1. Introduction

This paper reports on work undertaken within the EU 6th framework MATISSE project (http://www.matisse-project.net) to assess the prospects for a transition to hydrogen fuel vehicles within Europe. The analysis is based on the concept of a technological transition as one of the possible transition pathways identified by case studies in transition theory. In addition to the development and adoption of vehicles, the adoption of hydrogen as a fuel requires the development of a new infrastructure to produce and supply the hydrogen. The question then arises as to what extent the infrastructure development and investment costs form a barrier to the adoption of a technology which requires expensive development programmes for the vehicles themselves?

Two models have examined issues of infrastructure provision as part of a transition to hydrogen vehicles. An integrated transport policy assessment model (ASTRA) has been adapted to assess the prospects for – and overall environmental and economic impacts of – a transition to alternative fuel vehicles (including hydrogen fuel cell vehicles (FCVs) within transport). Also, a new

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model has been built to assess the prospects for a hydrogen transition within transport, with a focus on economic policy analysis and exploring the co-evolution or interdependent development of fuel infrastructure build-up and vehicle adoption. Together these tools have enabled us to explore the prospects and sustainability of a transition within the transport sector to a low-carbon vehicle fleet. Both models were calibrated using data for Germany; Germany is a major market for cars with manufacturers in Germany actively developing hydrogen technologies and there are estimates of the necessary infrastructure developments available.

Surprisingly, the results indicate that the provision of a hydrogen distribution (as well as production) infrastructure is not a major economic barrier to the adoption of hydrogen vehicles.

Transport is crucial for our economic competitiveness as well as for commercial and cultural exchanges [1]. However the current transport system does not correspond to the requirements of sustainability in many respects. Recent studies on the negative impacts of transport systems (e.g., [2–6]) highlight problems for environment and health, including climate change, local air pollution, noise and accidents. To date, policy measures to influence individual travel decisions (e.g., congestion charging, vehicle taxation) have had little effect relative to the underlying growth in demand. In some cases, interventions to reduce demand or foster modal shift have had the reverse effect (e.g. [7]). Similarly, the benefit of technical measures to reduce vehicle emissions and noise has often been outstripped by the increase in vehicle numbers, engine size, travel frequency and trip length [8].

It appears that incremental technological or policy improvement (the current use of the usual fiscal, informational and R&D support policies) is unlikely to be sufficient to address this type of persistent problem. Instead, radical, systemic innovation – a ‘transition’ (e.g., [9–11]) – is necessary to move away from the current road-based transport regime and towards a more sustainable transport system. This radical innovation involves the development of new networks of consumers, suppliers and also regulatory structure, to enable a very different technology to become attractive to society.

The literature on transitions highlights the interdependency of institutions and infrastructures constituting societal systems and sub-systems, which has created various types of lock-in that stifle innovation [11]. The dominant transport paradigm constitutes a regime locked-in to a stable state of oil- and car-dependence (personal mobility, using internal combustion and steel chassis technologies) with infrastructure, manufacturing, and consumer behaviours enforcing the regime. In relation to infrastructure, the built environment has co-evolved alongside automobility, so that amenities and workplaces are often only accessible by car. Vehicle manufacturing has developed along ‘technological trajectories’ [12], which constrains the development of vehicle and fuel technologies to the development of core competences, particularly in internal combustion engine and Budd-type steel chassis [13]. Consumer decisions fulfil emotional-symbolic functions (e.g., status, comfort, safety) as well as practical requirements (space, cost, etc.) [14]. Socio-cultural norms – for example, the expectation that quality of life entails vehicle ownership – and habitual behaviour serve to lock in these preferences and patterns of behaviour [15], presenting a major challenge for tackling unsustainable actions. Due to these psychological, technological and institutional dependencies, there is typically widespread resistance to radical change [16]. This is often described as a ‘lock-in’ to the current regime and its technology. It is to overcome this lock-in that radical change is necessary.

The key insight of this literature for the present analysis is that if there is to be a technological transition, an already existing niche technology must have a supportive policy and socio-economic environment if the take-off phase, where adoption accelerates and the technology becomes widely used and accepted as the obvious next main technology, is to be successful. Therefore, it is necessary to identify a niche and then analyse the conditions under which it can expand and diffuse to become a new regime. Hydrogen-powered vehicles have been recognised as such a niche. This interest in developing and diffusing hydrogen and fuel cell vehicle technologies is based on the assumption that hydrogen offers effective solutions to both emission problems and concerns about security of energy supply, since hydrogen is an energy carrier that:

- is emission-free at final use[1]; and
- can be obtained from a variety of different primary sources and readily stored[2]. Furthermore, fuel cell vehicles contribute to reduced noise pollution since:

Furthermore, fuel cell vehicles contribute to reduced noise pollution since:

- the drive system is nearly noiseless.

In respect of transport technologies, hydrogen and fuel cell vehicles have become a focus of considerable investment by public and private sector organisations in Europe (see e.g., [17]). The European Commission has been investing in a range of hydrogen technology research, development and demonstration projects in recent years (e.g., HyWays, HySociety, Zero-Regio, ECTOS, Renewable-H2, CUTE). Furthermore, the Commission has made the hydrogen economy one of its long-term priorities for Europe's energy system. The Commission has also set a target of substituting 20% of traditional fuels by alternative fuels by 2020, with a proportion of hydrogen vehicles of 5%. Hydrogen and fuel cell technologies also contribute to the Commission's vision of Environmental Technology for Sustainable Development [18] which posits that use of clean technologies can create ‘win–win’ situations, where economic benefits can be achieved without resulting in environmental degradation.

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[1] When hydrogen is burnt as a fuel or used in a fuel cell to produce electricity, water is the only by-product.

[2] The relevant advantage of hydrogen compared to oil-based solutions is that it can be produced from all known energy resources and therefore it improves energy supply security drastically because dependency from OPEC states (the majority of oil resources are located in political instable regions) is drastically reduced. The advantage of hydrogen over electricity as an energy carrier is its storage potential; this can help with load levelling and in balancing the intermittent nature of renewable energy sources (see, e.g., [19]).

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However, the adoption of hydrogen will be dependent on the provision of a new infrastructure for hydrogen production and distribution [20]. This has been extensively debated, with the suggestion that providing this infrastructure will be expensive and time-consuming, if a sufficient number of filling stations are to be provided to make hydrogen vehicles acceptable and if consumers' concerns about safety are to be properly addressed. Assuming that a hydrogen vehicle future would have as many refuelling stations as there are petrol stations today, this implies a very large investment. An important question is that for consumers to buy vehicles, a refuelling infrastructure must already be there, but it cannot be used until people have bought vehicles — a version of the chicken-and-egg problem [21]. Therefore, an initial investment in infrastructure for refuelling is necessary, in addition to investment in vehicles.

In the case of hydrogen, society would have to place a high priority on reducing emissions, such that the initial higher costs of hydrogen relative to conventional fossil fuels and their infrastructure are accepted by consumers and firms purchasing new cars. In the current analysis, is assumed that government subsidies are the policy tool that can make the hydrogen technology competitive to at least those consumers and firms who are willing to be technology leaders. An analysis of different policy scenarios provides an insight into the conditions for vehicles and infrastructure necessary for a successful technological transition.

2. Model descriptions

Two models were used for the analysis, because they perform complementary analyses. ASTRA provides an assessment of the economic and overall emissions impact of a scenario of hydrogen diffusion, while the hydrogen transition model explores the economic and consumer choice factors that determine the pathway of the diffusion of hydrogen vehicles and infrastructure. The hydrogen adoption scenario developed using the ASTRA model was used as a calibration basis for transition model to simulate successful hydrogen penetration of the automobile market i.e. the achievement of significant sales in the market and diffusion. While the models do not consider all the aspects of a socio-economic transition as discussed in e.g. [9] or [11], they explicitly consider the economic and policy conditions under which a hydrogen niche can successfully expand to form a mass instead of niche market and hence challenge the current fossil fuel vehicle regime.

We use Germany as the case study for the analyses. Data on German vehicle sales, average vehicle running costs, vehicle emissions, modal split, and transport demand (pkms) were obtained from the Fraunhofer ISI database, and supplemented – where necessary – from the Eurostat database [22].

2.1. ASTRA

ASTRA (=Assessment of Transport Strategies) is a dynamic simulation model generating time profiles of variables and indicators needed for policy assessment. A detailed description of ASTRA is provided by [23]. The ASTRA model consists of eight modules and the version described in this section covers the 25 European Union countries (EU25) plus Norway and Switzerland. The major interlinkages and feedbacks between the eight modules are shown in Fig. 1. The model includes the technical and economic characteristics of road and rail transport. For this project, hydrogen technologies and a scenario of hydrogen diffusion were added to the set of vehicle technologies.

2.2. Modelling a hydrogen economy in ASTRA

Modelling of a hydrogen economy in ASTRA concentrates on the adaptation of the transport system and its related energy supply. It requires input from other studies concerning (1) the time path of adoption of hydrogen cars and the build-up of hydrogen supply infrastructure, and (2) the build-up of renewables' capacity to produce hydrogen from non-fossil energy sources.

The basic framework of the analysis is provided by the business-as-usual (BAU) scenario of the ASTRA model that is extended in particular by inputs on hydrogen technologies from the HyWays project [24] and a study on growth and employment impacts of renewables where ASTRA is connected with the GreenX model [25,26].

Market entry of hydrogen cars is taken from the HyWays project, which involved an intense stakeholder process with car manufacturers and fuel suppliers to develop a scenario for market penetration of H_2 cars [23]. For the presented analysis the HyWays high penetration scenario was taken. For simplification in the ASTRA model H_2-ICE cars and H_2-ICE hybrids were aggregated into one category (H_2-ICE) as well as H_2-FCVs and H_2-FC-Hybrids (H_2-FC). The applied market development of these two categories is shown in Fig. 2. In terms of implementation ASTRA estimates the total purchase of new cars endogenously and then subtracts the exogenously provided numbers of the hydrogen cars to get the distribution between hydrogen-powered cars and conventional cars. In 2030 this leads to shares of hydrogen cars of about 30% of all new purchased cars. In terms of production location of vehicles the structural identity scenario is taken implying that hydrogen cars are manufactured with the same spatial distribution as conventional.

It is expected in HyWays that at the time of introducing the first hydrogen cars in 2013 subsidies by the government have to be provided due to the high cost of the fuel cells. These subsidies diminish over time such that the peak of absolute subsidy amounting to €3 Billion for the EU25 countries, of which about €700 Million are allotted to Germany, is reached in 2020, though the number of H_2 cars sold continuously increases (see Fig. 2).

The higher prices of cars, which is balanced by subsidies, has two impacts in ASTRA: first, car manufacturers increase their revenues and output compared to BAU, and second, a few other sectors that manufacture significant shares of the fuel cell also benefit. HyWays estimates that about one third of a car's price is related to the drive-train. For H_2 fuel cell cars out of this one third

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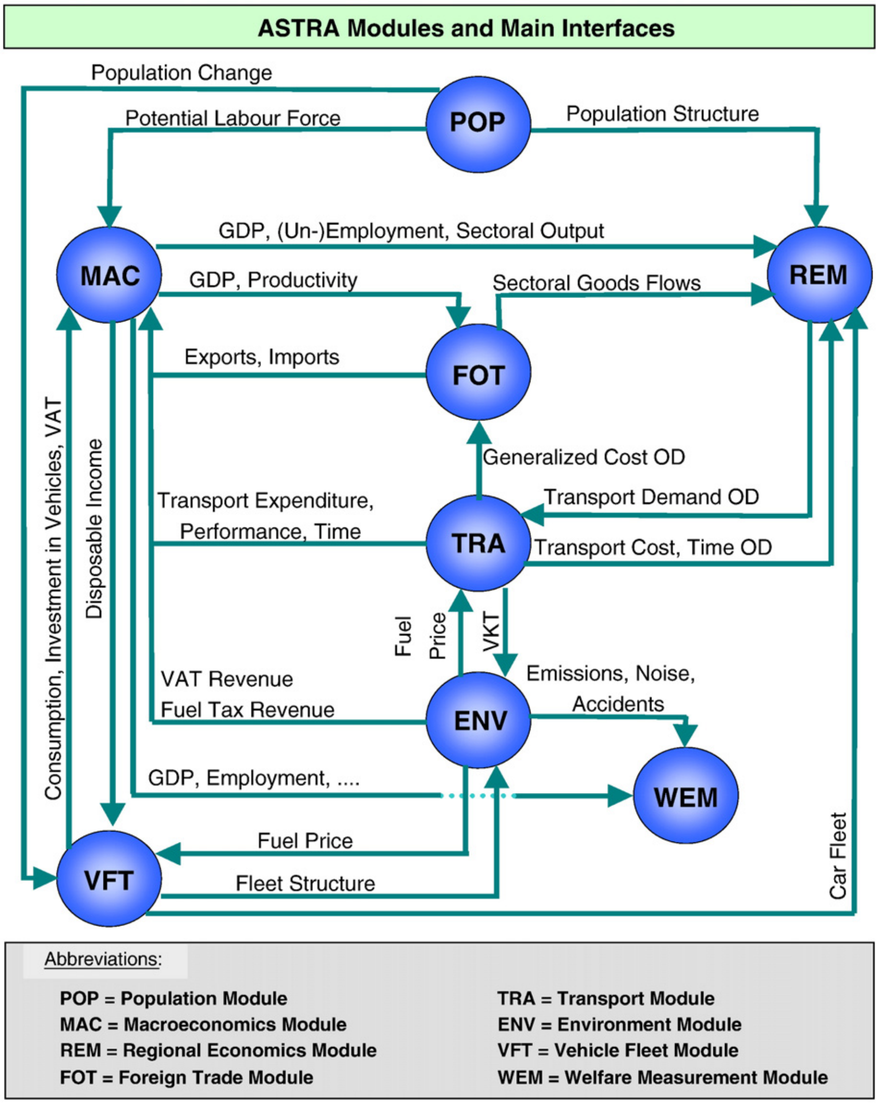

Fig. 1. Overview on modules and feedbacks of the ASTRA model.

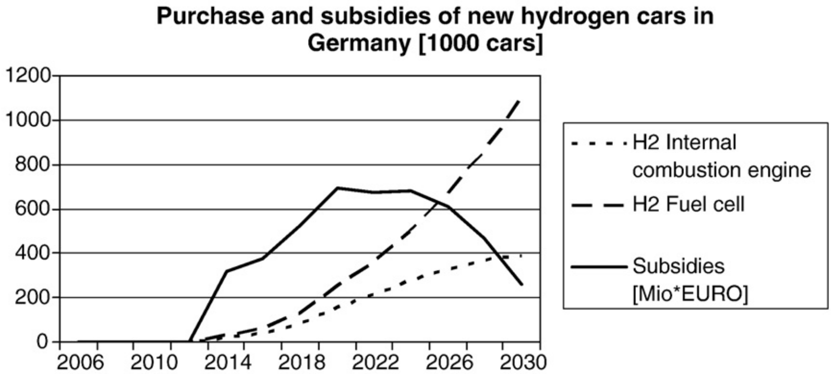

Fig. 2. Subsidies and diffusion of hydrogen cars into car fleet in Germany.
Source: ASTRA results based on HyWays high penetration scenario.

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about 30% are assumed to be provided by the chemical sector and 40% by the electronics sector in ASTRA. The remaining 30% are still manufactured by the vehicle sector. Hence, the shares of demand for hydrogen FCVs are shifted from the vehicles sector, which before produced 100% of the drive-train, to the chemicals and electronics sectors, respectively. This sectoral shift of demand affects the sectoral final demand and the input–output-table calculations in ASTRA.

Analyses on the cost of producing hydrogen conclude that some production pathways even today are competitive compared with fossil fuels for transport [27]. Under this hypothesis it is feasible to build-up the infrastructure for hydrogen production and fuelling from revenues generated by hydrogen sold i.e. there is no financial need to subsidise hydrogen filling stations. Consequently, the required infrastructure investments to build-up the fuelling infrastructure for hydrogen cars are calculated endogenously from the hydrogen fuel demand of the hydrogen cars in service using the efficiency values from HyWays (25.9 kWh H_2/100 km for H_2-FCVs and 46.4 kWh H_2/100 km for H_2-ICEs) in 2010 and an efficiency improvement curve that reduces this hydrogen consumption between 2010 and 2050 by -30%.

2.3. Hydrogen transition model

This model is designed to assess the conditions for a transition to a mass adoption of hydrogen FCVs, through a detailed representation of FCV vehicle and filling station economics and consumers' decisions. The analysis considers three aspects of the introduction of FCVs into the car market: the relations between the stakeholders of the car market, the “costs” for the state (subsidies and tax waiving during the introduction phase) and market penetration curves of FCVs.

Like ASTRA, the model is a dynamic simulation model. The FCV transition model consists of four modules: the FCV demand and supply module, the attractiveness module, the filling stations module and the module of balance of payments. Fig. 3 shows the linkage between the different modules and their impacts on each other. The four modules are shown as the blue titles. In each time period, the evaluation starts from the current values of the green variables. These then determine intermediate (yellow) variables and output (orange) variables.

The “FCV demand and supply” module analyses the impacts of the commercial and social attractiveness[28], which summarizes the effects of technical and economic properties of FCVs, on the demand for vehicles with a hydrogen power train. Public demand involves the demand for FCVs which comes from local bounded commercial traffic (i.e. buses, taxis, etc.) and if 50% of the urban commercial traffic switches to fuel cell vehicles, interurban commercial traffic also adopts FCVs. Private demand includes urban and interurban traffic. Social attractiveness is the main indicator representing the influence of the social environment on individual decision of private people [29,32].

The attractiveness module models the consumer view of the attractiveness of FCV. The introduction of hydrogen driven vehicles depends on different parameters, i.e. price and performance of FCVs, range of the fuel tank, costs for hydrogen fuel, share of hydrogen filling stations (HFS) among all fuel stations. Both the commercial and the social attractiveness are based on the

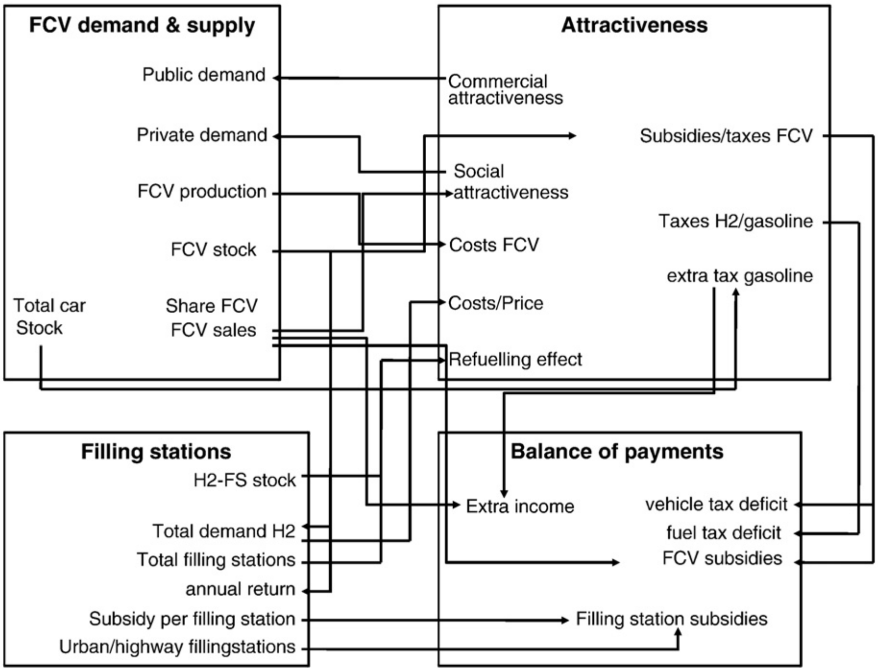

Fig. 3. The four modules and their connections.

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compared utility (CU) function (see Eq. 1). The system elements, which form the compared utility of FCVs, correspond to the price effect (PE), the performance effect (PerfE), the range effect RE, the fuel price effect (FPE) and at last but not least the refuelling effect (RFE). The range effect increases with increasing range of an FCV without refuelling. The refuelling effect increases with increasing availability of filling stations i.e. increasing convenience of refuelling. All effects are ratios between the parameters for FCVs and those for fossil fuel driven ICEVs (internal combustion engine vehicles).

$$CU(t) = PE(t)^{*}PerfE(t)^{*}RE(t)^{*}FPE(t)^{*}RFE(t). \tag{1}$$

The analysis of the amount of subsidies as well as of tax allowance is done in the "balance of payments module". The main elements of this module are the subsidies for urban and highway filling stations, the subsidies for FCVs, the tax deficit and the extra income caused by an extra tax on fossil fuel.

Infrastructure is calculated as the number of available urban and highway filling stations (highway FS), the dominating element is the share of urban FS providing hydrogen fuel (only 376 filling stations of the 14.500 German FS are on highways). A standard HFS with 120 tons annual capacity and €305,000 investment costs is chosen as representative HFS for the model [30]. The number of new filling stations depends on the demand for hydrogen fuel. Initial FSs are also funded by subsidies. Investment in filling stations is calculated using a Net Present Value approach, including subsidies. There is a positive feedback between FCV demand and filling station investment (Fig. 4). The FCV demand and stock have positive effects on the number of hydrogen filling stations (FS) and these in turn affect FCV demand via the attractiveness function (higher number of filling stations increases the attractiveness for FCV from the consumer perspective). Also, if the number of produced FCVs increases, the price of these vehicles will fall. Falling prices will lead to a greater demand and so to a higher production rate. The initial number of filling station is different in different scenarios. This has an important effect, because this strongly influences the starting value of the attractiveness function (Eq. 1) and therefore the speed with which the positive feedback can become an important factor in FCV demand. The number of hydrogen filling stations is asymptotic to the (constant) total number of filling stations.

2.4. General assumptions

It is assumed that a production line (capacity 160,000 vehicles/year) which can produce FCVs and a minimum number of hydrogen filling stations exists at the starting time. Further lines are set up as demand increases. There is a learning curve relation between the price and the number of produced vehicles [31], from €63,000 at 1500 production to €24,000 at 2,600,000. Conventional vehicles have a constant cost of €20,000. Petrol prices are also assumed constant, but the price for hydrogen is strongly affected by the demand for hydrogen fuel, especially in the introduction phase, from 280 €/kWh down to 20 €/kWh [31].

The first adopters of FCVs in local traffic are assumed to be in six metropolitan areas (Ruhr area, Berlin, Hamburg, Munich, Stuttgart and Frankfurt) as [32]. Interurban commercial traffic adopts FCVs if the share of local FCVs reaches 50% of the total local used car stock of the metropolitan areas. This value is also the indicator for the establishment of HFS on highways, also subsidised by the State.

3. Results

3.1. ASTRA model results for economic growth, CO_2 emissions and investment

Based on the framework of economic development, energy prices, hydrogen car penetration and structure of renewable hydrogen production described in the previous sections, the hydrogen cars' high penetration scenario of HyWays is simulated with the ASTRA model and the results for Germany are compared to the BAU scenario.

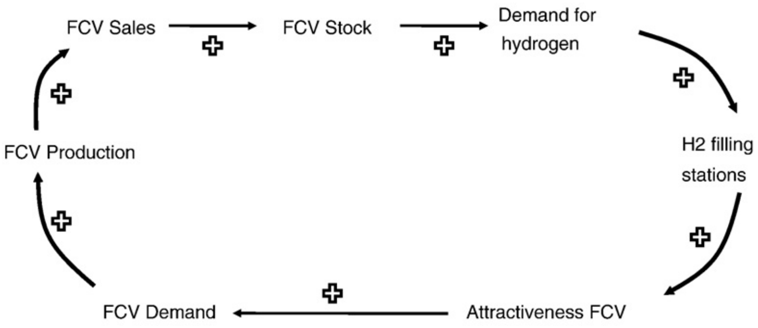

Fig. 4. Causal loop between the FCV demand and the number of filling stations.

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Overall, the economic development proves to be positive with an increase of close to +0.5% of GDP in 2030, +0.3% of employment and a stronger increase of investment by +2.4%. This increase of investment has several reasons: first, the additional investment into hydrogen production and fuelling infrastructure as well as for the additional renewable capacities required to produce ‘renewable’ hydrogen are both funded by revenues of selling hydrogen as a fuel; second, the changed structure of final demand reducing non-transport related consumption by 0.5% and increasing it for the purchase of vehicles, triggers stronger investments in other sectors than the sectors losing consumption shares; and third, the wider economic effects following these additional investments i.e. effects like increased employment and income leading to higher GDP, in turn increase demand, and hence produce a ‘Keynesian’ multiplier effect.

A further positive economic impact besides increased investment is the change of imports of fossil fuels. For crude oil this amounts to a value of annual savings in the year 2030 of €12 Billion for the EU25 and of €2.8 Billion for Germany with a minor compensation of increased imports of natural gas reaching more than €1 Billion (EU25) and €300 Million (Germany) in 2030.

Total CO_2 emissions from transport are reduced by about −3.5% in 2030. However, emissions from driving decrease by −4.6%, which is significantly stronger than the reduction for total transport CO_2. The reason is that ASTRA calculates the life cycle emissions for the total transport CO_2 emissions and these include upstream emissions i.e. those emissions that are generated during the production of fuel. Since to some extent hydrogen is produced by non-renewables, e.g. gas or by-product hydrogen, some upstream emissions occur such that the change of CO_2 emissions while driving and of total CO_2 emissions differ.

The ASTRA results show that a transition to hydrogen transport fuels would have positive economic and environmental impacts. Overall, economic development proves to be positive with an increase of close to +0.5% of GDP in 2030, +0.3% of employment and a stronger increase of investment by +2.4%. This increase of investment has several reasons: first, the additional investment into hydrogen production and fuelling infrastructure as well as for the additional renewable capacities required to produce ‘renewable’ hydrogen are both funded by revenues of selling hydrogen as a fuel; second the changed structure of final demand reducing non-transport related consumption by 0.5% and increasing it for the purchase of vehicles, triggers stronger investments in other sectors than the sectors losing consumption shares; and third, the wider economic effects following these additional investments i.e. effects like increased employment and income leading to higher GDP, in turn increase demand, and hence produce a ‘Keynesian’ multiplier effect.

There are two critical assumptions that underpin the results of the analysis with ASTRA. Firstly, from the HyWays study, there are the market penetration rates of hydrogen cars and associated subsidy levels of hydrogen cars, together with cost of production of hydrogen. Secondly, the positive macroeconomic results are based on the assumption that there is underinvestment in the German economy in the baseline. This is generally acknowledged to be a major issue for German economic growth in the medium to long term, because there has been less investment than desired in recent decades. In this situation, it is not just investment in hydrogen that would improve economic performance, and productive investment will stimulate demand and lead to the multiplier effects described.

3.2. Results from the hydrogen transition model: hydrogen vehicle and infrastructure diffusion

Four scenarios were analysed: a lead scenario of a successful transition to FCVs and three alternative scenarios to examine the sensitivity of the results to the main policy assumptions.

In the lead scenario 500 subsidised Hydrogen Filling Stations are set up at the beginning of FCV transition. These 500 filling stations are built up in the six metropolitan areas. Subsidies for FCVs are assumed to equal the cost difference between FCV and diesel cars minus €2000, assuming that consumers are willing to pay €2000 more for “clean” technology. Besides, the FCV becomes more attractive as the State does not ask for sales taxes at the beginning of market penetration (see above). Another policy achieving a successful market penetration is the tax allowance for hydrogen fuel. In this scenario hydrogen fuel is completely tax-free until the FCV stock reaches a level of 500,000 cars. Having passed this mark the number of FCVs directly affects the amount of taxes on hydrogen. A linear growth relation between the number of FCVs in the system and the tax level is used, whereas hydrogen taxes reach the level of fossil fuel if one million FCVs are in the system. In this case the amount of taxes for hydrogen fuel that is needed for a distance of 100 km is equal to that for fossil fuel needed by a diesel car to cover the same distance. That means that the state has the same tax income from hydrogen fuel as it has now from fossil fuels, if one million FCVs or more are on the roads.

The *first alternative scenario* analyses the importance of subsidies for FCVs during the introduction phase. In this scenario the consumers will not get any subsidies for the vehicles. So the costs for the State will be lower at the beginning of market penetration. The *second alternative scenario* compares the high level of available hydrogen infrastructure (see Lead scenario) with that of a low infrastructure at the beginning of FCV market penetration. Instead of 500 filling stations only 50 are assumed to be installed via subsidies, before the first cars are in the market. This is also a scenario which reduces the costs in the introduction phase. The *third alternative scenario*, another cost-reducing scenario, at least at the beginning of market transition of FCVs, is the hydrogen fuel taxing scenario. In this scenario the State introduces hydrogen taxes, even at the beginning of market penetration. So the comparison with the lead scenario should identify the lagging effects of hydrogen taxing policy. Fig. 5 compares the results of the lead and alternative scenarios for the most important output variable, the FCV vehicle stock. The lead scenario shows a transition by 2040, with a fleet of 16 million vehicles in Germany (approximately 30–40% of the total projected vehicle fleet). The alternative scenarios are much less successful, with only the second alternative scenario showing signs of a large scale adoption by 2043 with a fleet of almost 4 million vehicles.

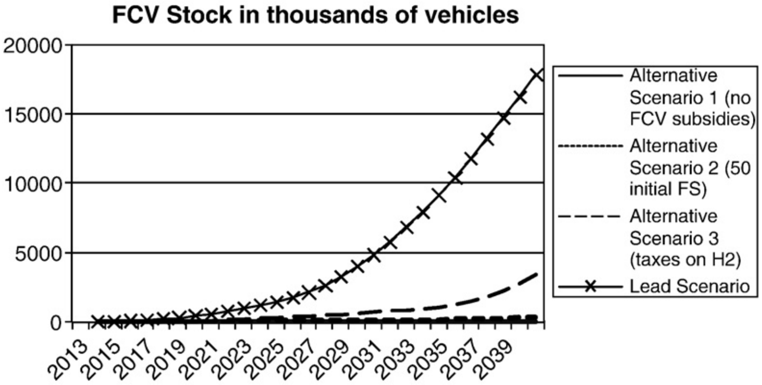

Fig. 5. FCV stock development in the hydrogen diffusion model — all scenarios.

3.3. Lead scenario

The policy-mix and the assumptions in the lead scenario are defined so that the market penetration of FCVs succeeds within an acceptable time period. In fact the FCV stock increases from the starting year 2013 to more than 17 million vehicles in 2040 in Germany, i.e. more than one third of all passenger cars. The development of the FCV stock conforms at first to that of exponential growth (Fig. 5). Later, after 2040, it is assumed that the growth of FCV stock slows and is asymptotic to the upper limit “total car stock”. The pattern of growth is thus logistic and is typical for the market penetration of innovations [33].

Similarly to the development of FCVs the number of hydrogen filling stations increases very rapidly after 2020 in this scenario. Nearly all of the some 14,700 filling stations are equipped with hydrogen filling pumps in 2040 (Fig. 6).

Due to the learning effects in production caused by a higher production rate, the costs of FCVs sink rapidly to the level of diesel cars, so that the state has to subsidy FCVs only for a short period. Fig. 7 shows subsidies and tax deficits for the lead scenario. With rapidly increasing FCV sales the amount of subsidies is high at the beginning. However, after around five years the production costs will fall so much that vehicle subsidies are not necessary anymore. That means the sum of vehicle subsidies given by the state will be less than those which are necessary in scenarios of low penetration, because in scenarios of low penetration the costs for FCVs do not fall as fast as they do in the lead scenario. The same effect can be noticed for the *tax deficit*. After a short time period with a high level of hydrogen tax deficit the policymakers can ask for the same level of taxes as they do for fossil fuel, because the critical mark of one million FCVs will be achieved. After around ten years these policies will pay off and there is nearly no need for subsidies or tax waiving in the lead scenario. After this the only subsidies necessary are for highway filling stations, if 50% of the vehicles in the six metropolitan areas are FCVs — in the lead scenario this occurs in 2025.

3.4. Alternative scenarios

The impacts of vehicle subsidies are significant, if the results of the lead scenario are compared with those of the first alternative scenario. The State keeps its costs at a low level, but the market penetration of FCVs fails, because in the first alternative scenario high production rates will never be reached and so production costs will not decrease.

The results of the second alternative scenario stress the necessity of a sufficient starting hydrogen infrastructure. The small number of available hydrogen filling stations blocks the penetration of FCVs and it takes some decades to overcome the well-known “chicken-and-egg problem” – that no one buys hydrogen cars because there are no filling stations, but because there is no

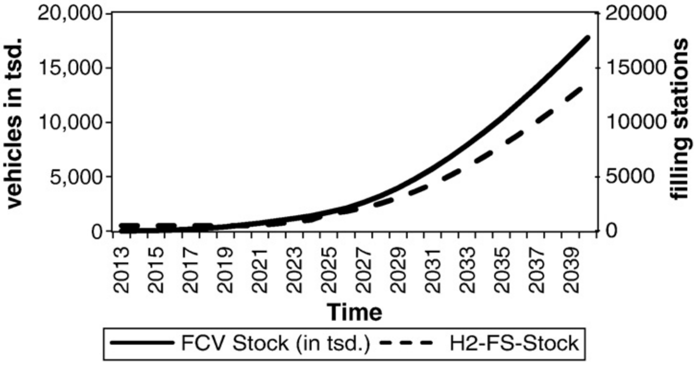

Fig. 6. Simulation results of the lead scenario (high growth scenario due to favourable policies) — FCV and filling station development.

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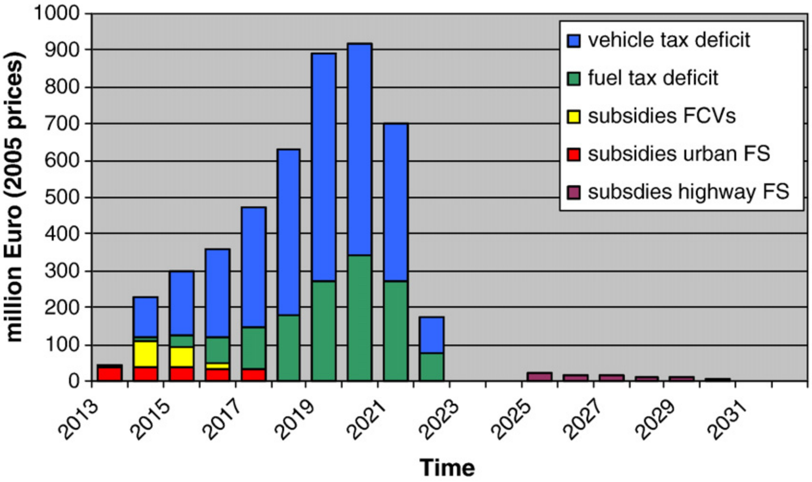

Fig. 7. Simulation results of the lead scenario (high growth scenario due to advantageous policies) — subsidies and tax deficit.

demand, no filling stations are built. In this scenario the State saves some hundred million Euro subsidies at the beginning, but the critical mark of one million FCVs is not even reached in 2040, while the cumulative total deficit rises above the deficit in the lead scenario in 2040.

In the third alternative scenario, due to the small cost reduction, it does not make sense to introduce hydrogen taxes at the beginning, because their impacts on the FCV sales and FCV stock are immense. Only 20% of the lead scenario's FCV stock is reached in the third alternative scenario in 2040. Because the FCV stock is lower the demand for hydrogen fuel does not grow as fast as in the lead scenario and so the growth of hydrogen filling stations is slower. While in the lead scenario more than 90% of all filling stations offer hydrogen fuel in 2040, only 20% do so in the third alternative scenario. Therefore the refuelling effect and the attractiveness of FCVs are also lower in this alternative scenario.

The main conclusion is that the lead scenario is the only one with a high penetration rate, although the cumulative costs for the State are nearly the same or lower than the costs in the other scenarios. So it is advisable that the State supports the market penetration of FCVs with a higher deficit during the introduction phase, as in the lead scenario. Both price support for hydrogen vehicles and a minimum level of investment in filling station infrastructure are necessary. However, subsidy or tax waiving policies are not necessary eventually, because the penetration succeeds.

The lead scenario shows a comparable level of market penetration to that assumed for the model analysis with ASTRA (the market penetration is 20% lower than the ASTRA assumption). This shows that the assumptions made for model calculation of ASTRA are optimistic, but seem to be achievable by designing an appropriate policy scheme for market introduction of hydrogen vehicles.

4. Implications for sustainable transport infrastructure and policy

The development of a sustainable transport system involves overcoming a current regime that is very strongly locked-in to fossil fuel vehicles. It is therefore a very suitable case for the application of a transition theory analysis. Transition theory considers the levels of landscape, regime and niche. If a transition is to occur, a niche must arise and either grow to form a new regime or force the regime to change to adopt the new technology and practices of the successful niche.

The models applied here show that it is possible to simulate the growth dynamics of a new niche technology. This is a well-known result; the original aspect of this paper is that infrastructure provision does not form a major barrier, if there is a moderate initial subsidy. The major factor here is that hydrogen cars are designed to use the same transport infrastructure as current cars, so it is not necessary to builds a new transport infrastructure network, only the refuelling network has to be developed. The vehicles themselves can also be produced using the current regime technology; it is only the prime mover and power train that involve a change in technology. In transition theory language, the hydrogen vehicle niche has strong complementarities with the regime.

The development of a hydrogen refuelling infrastructure may require new entrants for the supply of equipment. Current ownership and operation of filling stations is diverse, with the major international oil companies, national oil companies, but also retailers all owning and operating filling stations. There is also rapid entry and exit in filling stations, because filling stations are operated as single units and the investment for a filling station is not very large. Therefore, if there is a moderate financial incentive, it can be expected that there will be a range of filling station operators prepared to enter the hydrogen niche.

At the landscape level, there has to be an increasing consensus in society that climate change is a major social issue that must be addressed, even if it involves considerable initial expense. Only then will there be enough pressure on the regime for the government to provide a significant level of subsidy to the new technology for a considerable length of time, probably up to 10 years in the case of hydrogen vehicles.

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The hydrogen FCV transition model shows that, since a transition to hydrogen as an energy fuel in the transport sector is a disruptive innovation, relevant support is needed in different areas for a limited time period — in an optimistic case around eight to ten years. In particular, support is needed in three areas:

- subsidies for vehicles (highest support necessary);
- subsidies for at least 500 filling stations (in urban areas and on highways); and
- no VAT and no taxes for hydrogen in the introduction phase (first one million H_2 FCVs).

After a period of support hydrogen vehicles will have a lower total cost compared with conventional vehicles (assuming that the cost reduction targets of hydrogen vehicles will be reached; this depends on learning curves). It is important to reach very rapidly – within around 10 years from the start of the policy – a certain level of market penetration of hydrogen vehicles and infrastructure build-up. If this does not happen, hydrogen will fail. Also, overall financial support is much lower in a case of quick market penetration compared with a low market penetration (this is approximately €5 Billion overall costs in the lead scenario). If the penetration rate is lower, the State has to do without hydrogen taxes for a longer time period to make hydrogen vehicles still attractive, leading to a higher tax deficit.

Financial support is needed to bring the hydrogen vehicle cost down (the policy area of highest priority); additionally, tax policies to support hydrogen are necessary (starting with no tax on hydrogen). The conclusions relating to policy support for vehicles are:

- The State should avoid VAT on hydrogen vehicles to achieve a higher acceptance.
- The amount of subsidies for hydrogen FCVs should compensate the cost difference to ICEVs.
- Without the willingness-to-pay amount of €2000 per hydrogen the State has to support hydrogen production with an additional €500 Million to bring down the prices of the vehicles.

There are some important implications for infrastructure. A transition to hydrogen cars has the fundamental advantage that the service provided by the vehicle remains more or less the same. It provides personal mechanised transport using the same road network as current road vehicles. This means that the requirement for new infrastructure is limited to refuelling facilities. Our study has shown that for low levels of adoption of vehicles, a small number of filling stations (500) can cover an adequate urban area. Since there are very few filling stations on highways (376 of 14,500 total in Germany) the investment cost is not very high. However, these filling stations must be provided *before* hydrogen cars are sold on the market, as consumers will not buy vehicles that they cannot fuel. Therefore, filling stations do require an initial subsidy, if the new technology is to be successfully adopted.

Fast build-up of a filling station network (with at least 500 filling stations at the beginning) is very important for market acceptance of hydrogen vehicles, and compared with subsidies for vehicles and fuel the necessary investments are very small. This conclusion will also hold if the investment costs of a filling station are up to twice the value assumed. Conclusions relating to policy support for fuel infrastructure are:

- Only a total amount of approx. €200 Million are necessary for infrastructure build-up in urban areas.
- Additional support is needed for installation of hydrogen filing stations on highways (approx. €100 Million).

However, even with a massive relevant financial support only one third of all vehicles will switch to hydrogen vehicles by 2040. Nevertheless, exponential/logarithmic growth means that in a few years after 2040 all cars in Germany could be hydrogen-powered cars.

There are two surprising policy conclusions:The most important result of this work is that the subsidy required to provide enough supply and distribution infrastructure for the initial adoption and take-off of hydrogen vehicles is small, compared with the necessary subsidy for vehicle costs. The common conclusion that the move to a hydrogen transport technology faces a major barrier because of issues of infrastructure provision is not supported by our analysis. However the overall result is that, as shown in other studies, a transition to hydrogen vehicles will take a long time and will require sustained (fiscal) policy support for their introduction. Given the large uncertainties in the future costs of hydrogen vehicles and fuel, policymakers should not solely concentrate on hydrogen technology as the solution for reducing the carbon emissions of transport. It is still necessary to support a range of low-carbon transport technologies.

Secondly, the overall impact on the economy is positive: growth and employment increase, because of the increased investment compared to a business-as-usual case. Eventually, there will be large scale investment in infrastructure. This is in contrast to the common perception that environmental technologies are expensive and will therefore divert economic resources away from more ‘productive’ uses. This, however is quite a general result in the literature on macroeconomic analysis of environmental policies in a world which is not at an ideal economic optimum. In real-world economies with significant unemployment and periods of low demand and economic growth, a policy-driven increase in demand can improve economic performance.

5. Summary

This paper describes the work undertaken within the MATISSE project to explore the potential for a sustainable hydrogen transition within Europe and the implications for infrastructure provision and policy for infrastructure support. Two models have examined issues of infrastructure provision as part of a transition to hydrogen vehicles. An integrated transport policy assessment model (ASTRA) has been adapted to assess the prospects for – and overall environmental and economic impacts of – a transition to alternative fuel vehicles (including hydrogen fuel cell vehicles (FCVs) within transport). Also, a new model has been built to assess the prospects for a hydrogen transition within transport, with a focus on economic policy analysis and exploring the co-evolution of fuel infrastructure build-up and vehicle development. Together these adapted/new ISA tools have enabled us to explore the prospects and sustainability of a transition within the transport sector to a low-carbon vehicle fleet.

There are two surprising policy conclusions. Firstly, the subsidy required to provide enough supply and distribution infrastructure for the initial adoption and take-off of hydrogen vehicles is small, compared with the necessary subsidy for vehicle costs. This is in contrast to [34], who find that infrastructure for a transition in the electricity supply system will require major investment. This also supports the findings of [35]. They also use an agent based model to examine the diffusion of hydrogen vehicles and find that the availability of hydrogen refuelling stations is a prerequisite for the widespread adoption of hydrogen vehicles.

The main assumptions for these results are that a production line and a minimum number of hydrogen filling stations exist at the starting time. There is a learning curve relation between the price and the number of produced vehicles such that with mass production, hydrogen vehicles are 20% more expensive than conventional vehicles. Petrol prices are assumed constant, but the price for hydrogen rapidly decreases as demand increases. Interurban commercial traffic adopts FCVs and hydrogen filling stations are established on highways if the share of local FCVs reaches 50% of the total local used car stock of the metropolitan areas.

Secondly, the overall impact on the economy is positive: growth and employment increase, because of the increased investment compared to a business-as-usual case. There are two critical assumptions that underpin the results of the analysis with ASTRA. Firstly, from the HyWays study, there are the market penetration rates of hydrogen cars and associated subsidy levels of hydrogen cars, together with cost of production of hydrogen. Secondly, the positive macroeconomic results are based on the assumption that there is underinvestment in the German economy in the baseline.

The overall result is that, as shown in other studies, a transition to hydrogen vehicles will take a long time (at least 30 years from today) and will require policy support for their introduction.

In terms of transition theory, the paper shows how engineering-economy models of technological change can be used to assess the conditions under which a transition can occur. In the case of a transition to hydrogen vehicles, this niche has the major advantage of having strong commonalities with the fossil fuel transport regime. It uses the same road infrastructure and can use the same production technology, with only the prime mover and power train being radically different. It is necessary for climate change to become a strong part of the landscape, such that the regime (i.e. the government part of the regime) is willing to direct considerable public funds to subsidising hydrogen vehicles and to a lesser extend filling stations for a period of up to 10 years until the niche can be expected to take off.

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