Shifting transport towards hydrogen: scenarios and sustainability impact assessment

Paper presented to

11th World Conference on Transport Research

June 24-28th 2007, University of California, Berkeley, USA

Session stream: F4

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Abstract:

High oil prices and a dependency ratio of transport on fossil fuels of 97% in Europe intensify the search for alternatives. One of these alternatives would be hydrogen that can be generated from a number of different feedstock including both fossil and non-fossil sources. This paper presents an assessment of sustainability impacts of a scenario to introduce hydrogen for transport drawing inputs from a number of European projects (e.g. MATISSE, TRIAS, STEPs) and combining stakeholder and expert opinions with model-based results from the ASTRA model. Overall, the introduction of hydrogen into transport seems to be promising for sustainable development.

1 Introduction

The use of hydrogen as energy carrier for the transport system has been discussed and tested in research niches since many years. High oil prices, the growing awareness that this will not be a temporary but a permanent situation and the strong dependency of the European transport system on fossil fuels of more than 97%, which raises the issue of the security of energy supply for transport, fosters the search for alternative fuels and new technologies to propel the transport system.

Besides the strong dependency on fossil fuels today's transport system is causing a number of important adverse environmental impacts. Energy consumption and associated greenhouse gas emissions of transport have been growing in the past decade by more than 20% for the EU15 countries. Some improvements have been achieved for air pollutants from transport (e.g. VOC, CO emissions), while for others the emission levels remain high causing health and environmental damages (e.g. particulate matter, NO_x emissions) (EEA 2006). Transport noise is identified as a significant problem for human health, which lacks a solution, so far (Schade 2003). Transport accidents cause more than 40.000 deaths per year in the EU. Altogether the external cost of transport caused by accidents and environmental impacts were estimated to reach 8% of EU GDP (infras/IWW 2000).

One of the alternative energy carriers for transport to tackle most of the aforementioned problems would be hydrogen. It can be generated from a number of different sources, including both fossil and non-fossil sources, which would improve the security of energy supply for transport due to the diversity of potential energy sources. Depending on the production pathway of hydrogen the emission of greenhouse gases can be reduced or even completely eliminated. Using hydrogen in fuel cells would solve the problem of air pollution, at least at the point of use, but also, depending again on the production pathway of hydrogen, potentially at the point of production. Road transport noise in urban areas where the engine noise plays a significant role would be strongly decreased.

Of course, not all (environmental) problems of transport can be solved by hydrogen. E.g. the land-take for transport infrastructure, the maintenance of a large and ageing infrastructure network and the congestion issue will not be influenced by changing the energy carrier driving the transport system. Further, depending on the feedstocks (e.g., nuclear, coal with carbon capture and sequestration (CCS), or renewables) and the production technology selected, hydrogen use may even lead to an increase of some well-known problems of the transport system (e.g. accidents due to noise reduction) and could lead to new problems (like nuclear waste or competition on land use: renewables vs. food production). Looking on the new arising problems it becomes obvious that with hydrogen as a technical solution, questions about a sustainable transport system are increasingly linked with questions about a sustainable energy system.

Nevertheless, the expected advantages of shifting transport to hydrogen as an energy carrier are that convincing that in all world regions stakeholder networks and research programmes have been set-up to promote and work on this shift. In Europe this is the European Hydrogen and Fuel Cell Technology Platform (https://www.hfpeurope.org/), in the US e.g. the California Fuel Cell Partnership (http://www.fuelcellpartnership.org/), in Japan e.g. the Hydrogen and Fuel Cell Demonstration Project (http://www.jhfc.jp/ e/index.html) and on International Level the International Partnership for the Hydrogen Economy (http://www.iphe.net/). Through such activities the visions for an implementation of a hydrogen transport system and even a hydrogen economy take shape. E.g. the Japanese roadmap for the energy sector foresees that by 2050 households get 70% of their energy from electricity and hydrogen and transport gets 40%. By 2100 for both sectors this is expected to reach 100%, which means zero CO_2 emissions (METI 2005).

Discussions in the field conclude that two major technological barriers have to be overcome to make such hydrogen visions happen: first, the production of a hydrogen drive systems (fuel cell, storage, system integration) is yet too costly to introduce them into a mass market for vehicles and their durability is not sufficient, and, not all technical problems are solved until now (e.g. cold start, for liquid hydrogen the boil-off effects, for gaseous hydrogen the tank size issue can be mentioned).

However, shifting transport to hydrogen is not at all only a technical issue. Instead, it would induce: structural economic changes developing a large-scale industry producing and distributing hydrogen, trade flow changes reducing trade of fossil fuels and increasing trade of feedstock for hydrogen production, the offer of new employment opportunities.

This paper draws on work currently undertaken in a number of European research projects like TRIAS (http://www.isi.fhg.de/TRIAS/) or MATISSE (http://www.matisse-project.net/projectcomm/). The paper describes the sustainability implications of hydrogen from two angles: first, from a stakeholder perspective, and second, from the results of a model-based approach. It is completed by a concluding section.

2 Sustainability implications of hydrogen: stakeholder view

Stakeholder engagement is relevant to the issue of shifting transport to hydrogen use given the complexity, ambiguity and subjectivity that surround persistent problems of unsustainability, as for transport. The MATISSE project, in which a hydrogen transport case study is undertaken, is developing and testing approaches to Integrated Sustainability Assessment (ISA), which has been defined as a fundamentally participatory approach to sustainability assessment (see Weaver/Rotmans 2005, Gibson et al. 2005).

As part of a cluster workshop on sustainability of hydrogen transport technologies held in Frankfurt during February 2006, MATISSE researchers conducted break-out discussion groups with, and distributed self-completion questionnaires to, stakeholders in hydrogen transport technology. The aims of the break-out groups and the questionnaires were to elicit stakeholders' visions of sustainability in relation to both hydrogen transport technology and transport itself; and their views on viable pathways, and any barriers, to sustainable hydrogen-based transport.

Participants at the cluster workshop included researchers and consultants, an NGO representative, policy-makers, and members of the automotive and energy industries from across Europe, with interests and expertise in hydrogen and transport technologies (see Figure 1). More information on the workshop with a discussion about advantages and disadvantages of such an approach can be found in Whitmarsh/Wietschel (2006). In the following, only the main outcomes with focus on the sustainability issue are presented.

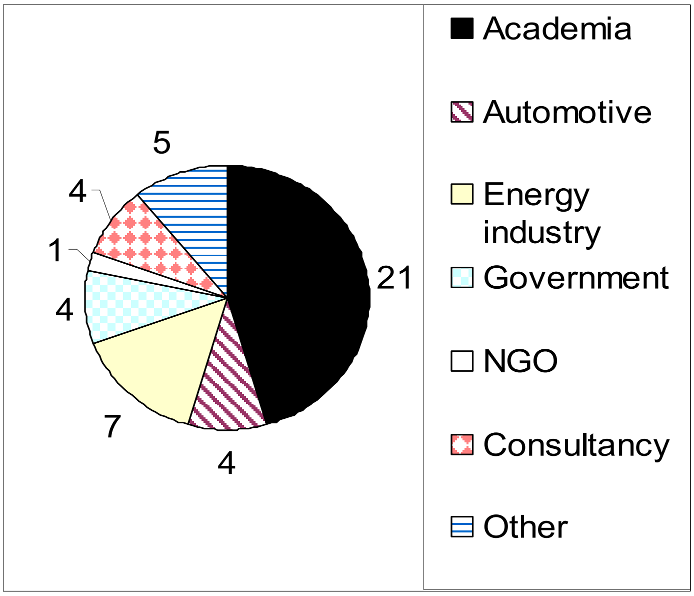


Figure 1: Background of participants (Hydrogen stakeholder meeting MATISSE)

In terms of the characteristics of sustainable hydrogen, stakeholders felt feedstocks are the key determinant. Consistent with previous stakeholder processes (e.g., McDowall/Eames 2006, Wehnert et al. 2004), there was wide-spread support amongst all groups for the ultimate goal of having renewable sources for hydrogen production (see Figure 2). As several participants noted, renewable sources are needed to address air pollution, climate change and dwindling oil and gas supplies. However, renewables are seen as challenging. Several groups talked about the practical and economic difficulties in moving towards a renewables-based transport system and referred to trade-offs, such as demand from other sectors (electricity, heat, industry, etc.) and other land use needs (e.g. for food production).

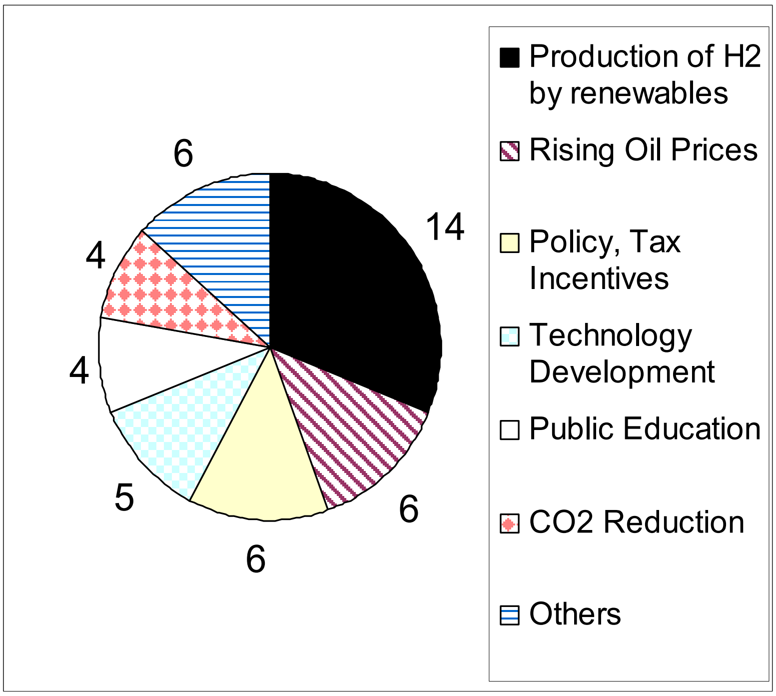


Figure 2: Feedback on the question What, if anything, do you think will ensure that widespread use of hydrogen in road transport is 'sustainable'?

While renewable energy was a widely favoured, if challenging, end-vision for sustainable hydrogen, there also seemed to be some agreement that diversification of supply was an important feature of future energy systems. Furthermore, participants pointed to the risks associated with focussing on, and becoming locked in to one technological solution to the exclusion of possible alternatives. Participants proposed that future energy supply security will depend upon diversification of both energy sources (different primary energies and different geographic sources of supply) and modes of delivery of final energy services.

There was disagreement between the stakeholders over whether nuclear or CCS are ‘sustainable’. For a number of participants, sustainability was equated with zero emissions or ‘CO_2 free’. These feedstocks fulfil this criteria and, additionally, many stakeholders felt these are necessary to achieve energy security and diversified, flexible supply. However other participants pointed out to the problems with these technologies. For example, for nuclear feedstocks, the problem of nuclear waste, concern about the vulnerability of nuclear power to terrorism, and misuse of technology were mentioned. For CCS, the long-term storage problem was raised.

The discussion about appropriate feedstocks, or bundles of feedstocks, for hydrogen production also dominated the discussion in other hydrogen research projects and policy processes with stakeholder involvement (EC 2003a, HyNet 2004, HyWays 2006). The major results of the HyWays project, which aims to develop hydrogen visions at EU Member State level, were that most of the EU-Member States’ end-visions of a hydrogen economy focus on renewable and other CO_2-free hydrogen production options. However, the end-visions vary depending on domestic feedstocks, differences in the design of the national power systems, and country characteristics such as population density or populated islands with special supply requirements (HyWays 2006).

3 Sustainability implications of hydrogen: model results

This paper combines results on the development of hydrogen use for transport of the HyWays project (HyWays 2006) with inputs and model calculations undertaken in the MATISSE project. Quantification and impact assessment of the scenario results is undertaken with the ASTRA model.

An extended approach of this analysis will be undertaken in later stages of the TRIAS project, where ASTRA will be linked with an energy system model (POLES, similar as in STEPs, Monzon/Nuijten 2006), a transport network model (VACLAV), and a model to calculate regional environmental impacts, in particular immission concentrations of air pollutants (Regio-SUSTAIN) (see Fiorello et al. 2005).

3.1 Brief description of ASTRA model

ASTRA (=Assessment of Transport Strategies) is a System Dynamics model generating time profiles of variables and indicators needed for policy assessment. Details of the ASTRA model are described in Schade (2005). Originally ASTRA was developed on the base of existing models that have been converted into a dynamic formulation feasible to be implemented in System Dynamics. Among these models have been macroeconomic models and classical four stage transport models (SCENES, ME&P 2000).

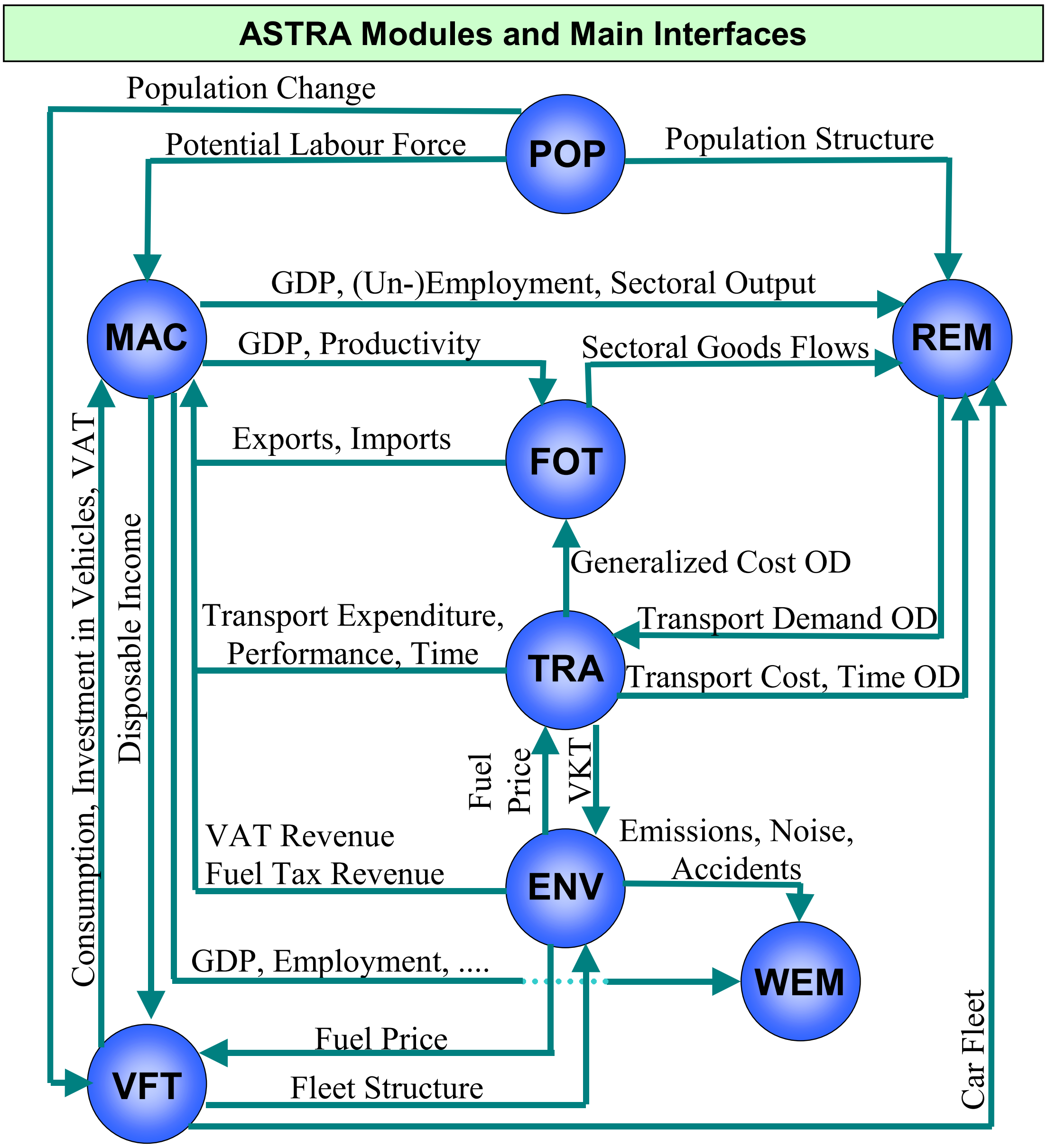
ASTRA runs scenarios for the period 1990 until 2030 using the first twelve years for calibration of the model. Data for calibration stems from various sources with the bulk of data coming from the EUROSTAT (2005) and the OECD online databases (2005).

The ASTRA model consists of eight modules and the version presented in this paper covers the 25 Western European Union countries (EU25) plus Norway, Switzerland, Bulgaria and Romania (EU29). The major interlinkages between the eight modules are shown in Figure 3.

The Population Module (POP) calculates the population development for the EU29 countries with one-year age cohorts. The model depends on fertility rates, death rates and immigration. Based on the one-year-age cohorts for each country, important information is provided for other modules like the number of persons in working age.

The Macroeconomics Module (MAC) provides the national economic framework. The MAC combines different theoretical concepts as it incorporates neo-classical elements like production functions; Keynesian elements like the dependency of investments on consumption extended by influences from exports or government debt; Or elements of endogenous growth theory like the implementation of endogenous technical progress as one important driver for the long-term economic development.

Six major elements constitute the functionality of the macroeconomics module. The first is the sectoral interchange model that reflects the economic interactions between 25 economic sectors of the national economies. Demand-supply interactions are considered by the second and third element, where the demand side model depicts the four major components of final demand: consumption, investments, exports-imports and the government consumption, and the supply side model reflects influences of three production factors: capital stock, labour and natural resources as well as the influence of technological progress that is modelled as total factor productivity (TFP). Endogenised TFP depends on investments, freight transport times and labour productivity changes.



Abbreviations:

POP = Population Module
MAC = Macroeconomics Module
REM = Regional Economics Module
FOT = Foreign Trade Module
TRA = Transport Module
ENV = Environment Module
VFT = Vehicle Fleet Module
WEM = Welfare Measurement Module

Figure 3: Overview on the ASTRA model

The fourth element is constituted by the employment model that is based on value-added as output from input-output table calculations and labour productivity. Employment is differentiated into full-time equivalent employment and total employment to be able to reflect the growing importance of part-time employment. In combination with the population module unemployment can be estimated. The fifth element of MAC describes government behaviour. As far as possible government revenues and expenditures are differentiated into categories that can be modelled endogenously by ASTRA.

Sixth and final of the elements constituting the MAC are the micro-macro bridges. These link micro- and meso-level models, for instance the transport module or the vehicle fleet module to components of the macroeconomics module and enable to calculate the indirect economic effects of transport changes originating on the micro level. Hence, the micro-macro bridges and their counterparts the macro-micro bridges form important elements to close the feedback loops between transport and the economy.

The MAC provides several important outputs to other modules. The most important output is endogenous Gross Domestic Product (GDP) for each EU29 country e.g. influencing trade flows between the European countries. Employment and unemployment are two influencing factors for passenger transport generation. Sectoral production value drives national freight transport generation. Disposable income exerts a major influence on car purchase affecting finally the vehicle fleet module including the introduction of new vehicle types like hydrogen fuel cell vehicles. By changing the vehicle fleet structure also the passenger transport emissions are adapting.

The Regional Economics Module (REM) mainly calculates the generation and distribution of freight transport volume and passenger trips. The number of passenger trips is driven by employment situation, car-ownership development and number of people in different age classes. Trip generation is performed individually for each of the 76 zones of the ASTRA model. Distribution splits trips of each zone into three distance categories of trips within the zone and two distance categories crossing the zonal borders and generating OD-trip matrices with 76x76 elements for three trip purposes. Freight transport is driven by two mechanisms: Firstly, national transport depends on sectoral production value of the 15 goods producing sectors where the monetary output of the input-output table calculations are transferred into volume of tons by means of value-to-volume ratios. For freight distribution and the further calculations in the transport module the 15 goods sectors are aggregated into three goods categories. Secondly, international freight transport i.e. freight transport flows that are crossing national borders are generated from monetary Intra-European trade flows of the 15 goods producing sectors calculated by the Foreign Trade Module (FOT).

The FOT is divided into two parts: trade between the included EU29 countries (INTRA-EU model) and trade between the EU29 countries and the rest-of-the world (RoW) that is divided into 9 regions (EU-RoW model). Both models are differentiated into 25 economic sectors and relationships between country pairs. The INTRA-EU trade model depends on three endogenous and one exogenous factor. World GDP growth exerts an exogenous influence on trade. Endogenous influences are provided by GDP growth of the importing country of each country pair relation, by relative change of sectoral labour productivity between the countries and by averaged generalised cost of passenger and freight transport between the countries. The latter is used as a kind of accessibility indicator between the countries. The resulting sectoral export-import flows of the two trade models are fed back into the MAC as part of final demand.

Major input of the Transport Module (TRA) constitutes the demand for passenger and freight transport that is provided by the REM in form of OD-matrices. Using transport cost and transport time matrices the transport module applying a logit-function calculates the modal-split for five passenger modes and three freight modes. Cost and time matrices depend on influencing factors like infrastructure investments, structure of vehicle fleets, transport charges, fuel price or fuel tax changes. For road transport network capacity and network loads are considered for four different road types such that congestion effects may affect the road transport time matrices in a simplified way. For other modes rough capacity models and capacity constraint functions are developed such that interactions between load and travel times can also be taken into account. Depending on the modal choices, transport expenditures are calculated and provided to the MAC as well as changes in freight transport times such that the latter can influence total factor productivity. Considering load factors and occupancy rates respectively, vehicle-km are calculated.

Major output of the TRA provided to the Environment Module (ENV) are the vehicle-kilometres-travelled (VKT) per mode and per distance band and traffic situation respectively. Based on these traffic flows and the information from the vehicle fleet model on the different vehicle fleet compositions and hence on the emission factors, the environmental module is calculating the emissions from transport. Besides emissions, fuel consumption and fuel tax revenues are estimated. Expenditures for fuel, revenues from fuel taxes and value-added-tax (VAT) on fuel consumption are transferred to the MAC.

The Vehicle Fleet Module (VFT) is describing the vehicle fleet composition for all road modes. Vehicle fleets are differentiated into age classes based on one-year-age cohorts and into emission standard categories. Additionally, car vehicle fleet is differentiated into gasoline and diesel powered cars of different cubic capacity and into hybrid vehicles, hydrogen internal combustion engine (H2-ICE) vehicles and hydrogen fuel cell vehicles (H2-FC). Car vehicle fleet is developing according to income changes, development of population and of fuel prices. In the current model, the purchase of hydrogen vehicles is taken exogenously from the European HyWays project. Vehicle fleet composition of bus, light-duty vehicles and heavy-duty vehicles mainly depends on driven kilometres and the development of average annual mileages per vehicle. The purchase of vehicles is translated into value terms and forms an input of the economic sectors in the MAC that cover the vehicle production.

3.2 Scenario description

The scenario definition for this paper follows the business-as-usual (BAU) scenario of the current ASTRA model, which is expected to change slightly when the final calibration is completed e.g. the GDP growth between 2005 and 2030 is expected to follow a more moderate growth path. The ASTRA scenario determines economic variables (like GDP, employment, investment, trade flows), transport variables (like passenger and freight transport performance per mode divided into trip purposes and distance classes, vehicle fleets) and environmental variables (like consumption of the different types of fuels, emissions, accidents). Trends of the major variables from the different fields are shown in Figure 4.

Some further variables that determine a scenario are taken exogenously. This includes the energy prices for oil (see Figure 4) and gas that are taken from the WETO-H2 reference case (World Energy Technology Outlook-2050, not published, yet), which is an extended project of the first WETO study providing an outlook until 2030 (EC 2003b).

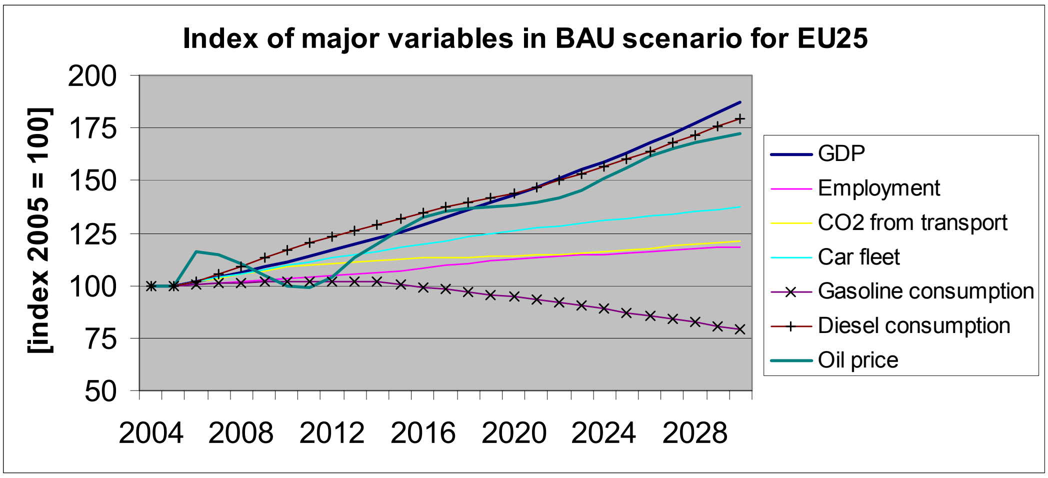


Figure 4: Overview on the trends in the BAU scenario

Market entering of hydrogen cars is taken from the HyWays project, which involved an intense stakeholder process to develop a scenario for market penetration of H2 cars (HyWays 2006). For ASTRA the HyWays high scenario was taken. For simplification H2-ICE cars and H2-ICE hybrids were aggregated into one category (H2-ICE) as well as H2-FCs and H2-FC-Hybrids (H2-FC). The development of these categories is shown in Figure 5. ASTRA estimates the total new purchase of cars endogenously and then subtracts the exogenously provided numbers of the H2 cars, which reach a share of 30-35% of new purchased cars in 2030. In terms of production location of vehicles the structural identity scenario is taken implying that H2 cars are manufactured with the same spatial distribution as conventional cars. In a further scenario changes of location of H2 car manufacturing leading to adapted trade patterns will be analysed.

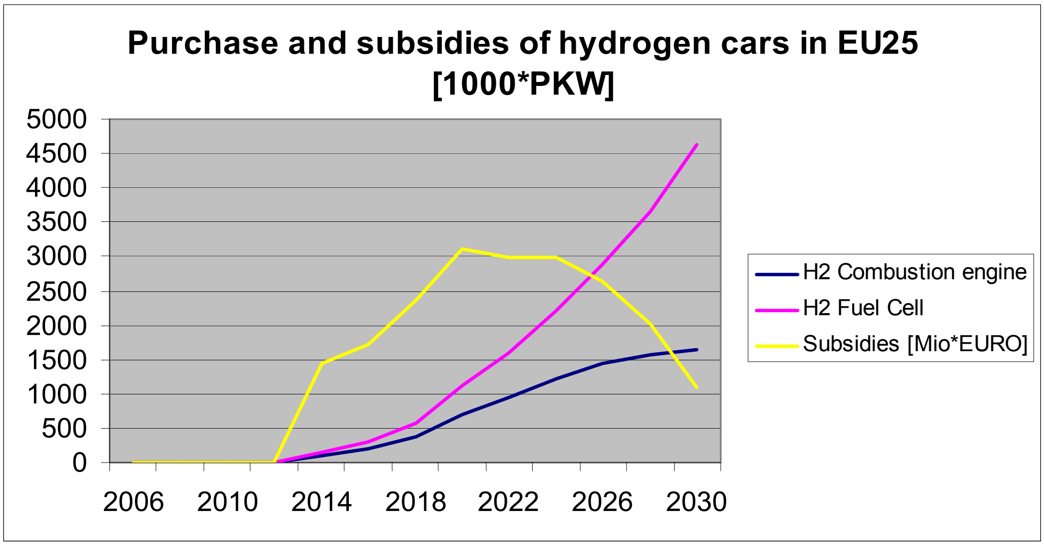


Figure 5: Subsidies and diffusion of hydrogen cars into car fleet of EU25

It is expected in HyWays that at the time of introducing the first H2 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 subsidisation is reached in 2020, though the number of sold units continuously increases (see Figure 5).

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 cars price is related to the drive-train. For H2 fuel cell cars out of this one third 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. In ASTRA the according shares of demand for H2-FC vehicles are shifted from the vehicles sector to the chemicals and electronics sectors, respectively, which changes the sectoral demand and the input-output-table calculations.

Analyses on the cost of producing hydrogen conclude that some production pathways even today are competitive compared with fossil fuels for transport (Hilkert 2003). Under this hypothesis it is feasible to built-up the infrastructure for hydrogen production and fuelling from revenues generated by hydrogen sold. Consequently, the required infrastructure investments to build-up the fuelling infrastructure for H2 cars are calculated endogenously from the H2 fuel demand of the H2 cars in service using the efficiency values from HyWays (25.9 kWh H2/100km for H2-FCs and 46.4 kWh H2/100km for H2-ICEs) in 2010 and an efficiency improvement curve that reduces this H2 consumption between 2010 and 2050 by -30%.

The calculated demand for hydrogen can be satisfied by ten different production pathways in ASTRA: five renewable pathways (biomass, wind, solar-thermal, geothermal and hydro) and five other pathways (natural gas, coal, electrolysis with electricity from average grid mix, nuclear, by-product). For a number of countries a specific mix of pathways is developed in HyWays based on potentials for renewables and policy approaches (e.g. high share of nuclear in France, high share of CCS in Poland). These mixes are transferred to the remaining EU25 member states according to similarities to countries analysed in HyWays. Based on the demand and the strategies of the individual countries for considering renewable pathways the required investments into additional capacity for renewables is derived using the following conversion factors for full load hours of the different renewable technologies:

Table 1: Conversion factors from kWh into required capacities of renewables

	biomass	wind on-shore	wind off-shore	solar-thermal	geothermal	hydro
hour	8000	2000	3800	3000	8000	6000

This means, that a growing demand for hydrogen also leads to growth in investments for renewable technologies. The investment costs depend for each technology on the already installed capacity reflecting a learning curve effect. With the average learning curves shown in Table 2 the investments into the six renewable technologies are calculated endogenously.

Table 2: Broad learning curve for renewable investments

MW already installed	MW	0	1	100	1000	10000	1.00E+06
Installation cost per new MW	Mio*EURO / MW	2	2	0.5	0.25	0.15	0.1

The resulting investment by renewables technology then have to be distributed onto the different economic sectors to become effective as demand within the input-output-table calculations of ASTRA.

Table 3: Assignment of technologies to economic sectors to satisfy investments into additional renewable capacities

[%] economic sectors renewables technologies	Metal Products	Industrial Machines	Electronics	Construction	Trade	Transport Inland	Other Market Services	Non Market Services
Biomass	5	35	23	10	16	4	6	1
Geothermal	5	45	10	15	15	4	5	1
Hydro	5	29	16	27	4	0	15	4
Solarthermal	10	61	10	0	16	0	3	0
Wind off-shore	23	45	8	15	2	2	4	1
Wind on-shore	25	50	8	10	2	1	3	1

Source: derived from Nathani 2003

3.3 Sustainability impact assessment of the scenario

Based on the framework of economic development, energy prices, hydrogen car penetration and structure of renewable hydrogen production described in the previous section 3.2 the scenario is simulated with the ASTRA model and the results are compared to the BAU scenario. Figure 4 presents the changes of the major economic variables for the EU25. Overall, the economic development proves to be positive with a growth of close to +0.5% of GDP in 2030, a growth of +0.3% of employment and a stronger increase of investment by +2.4%. This increase of investment has several reasons: first the above explained additional investment into H2 production and fuelling infrastructure as well as for the additional renewable capacities required to produce 'renewable' H2 (see also Figure 8) both funded by revenues of selling H2 as a fuel, and, second the wider economic effects following these additional investments i.e. effects like increased employment and income leading to higher GDP leading to increased demand and hence more investment in the second round.

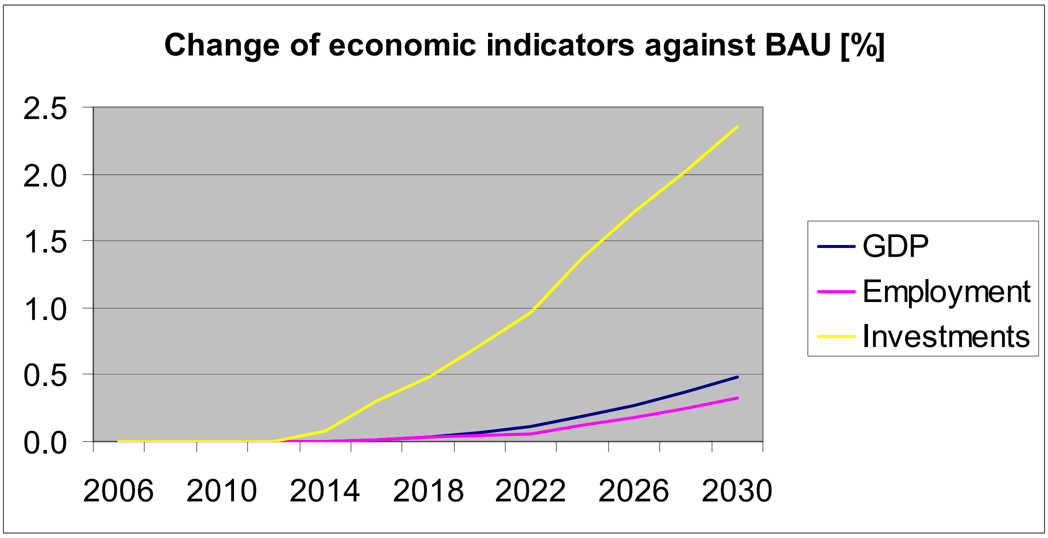


Figure 6: Impact on economic indicators through H2-cars introduction for EU25

As expected in the initial discussion, major environmental indicators are affected positively by the introduction of the H2 cars. Demand for gasoline drops by more than 13% until 2030 compared to BAU and demand for diesel by about 2%. The difference is that significant as in this scenario only cars are equipped with fuel cells and H2-ICE engines, but neither buses or light duty vehicles for which it is also expected that they will be equipped with FCs. This means only a small share of diesel fuel consumers is affected, i.e. the diesel cars, while buses, light and heavy duty vehicles (LDV, HDV) continue to run on diesel. Also, as GDP grows a bit stronger, freight transport will be increasing thus raising demand for diesel from freight transport compared to BAU.

Total CO_2 emissions from transport are reduced by about -3.5% in 2030. However, emissions from the driving activity decrease by -4.6% (CO2 Hot in Figure 7), 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 H2 is produced by non-renewables e.g. gas or by-product H2 some upstream emissions occur such that the change of CO_2 emissions while driving and of total CO_2 emissions differ.

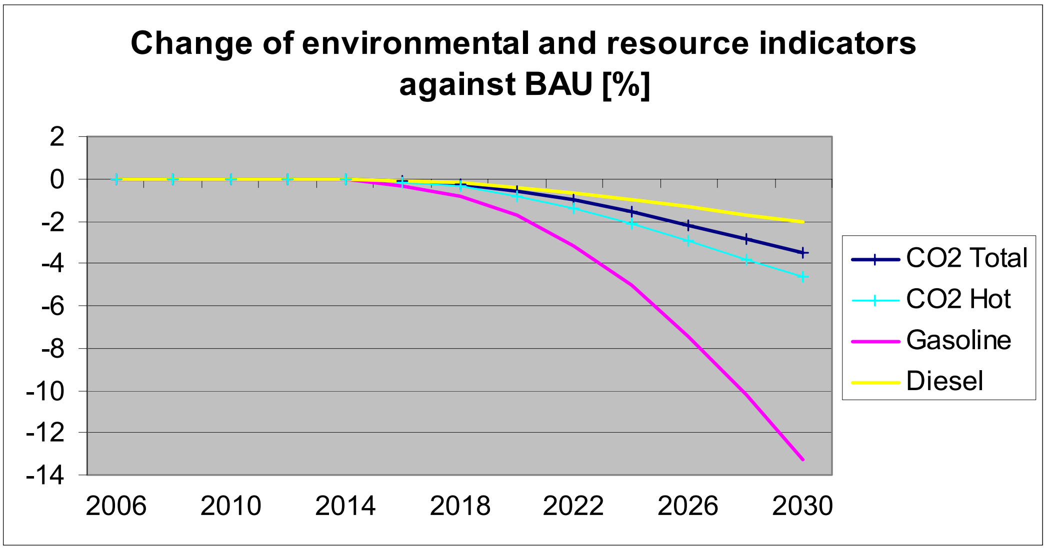


Figure 7: Impact on environmental indicators through H2-cars introduction for EU25

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 12 Bio EURO of savings in the year 2030 with a minor compensation of increased imports of natural gas reaching more than 1 Bio EURO in 2030 (see Figure 8).

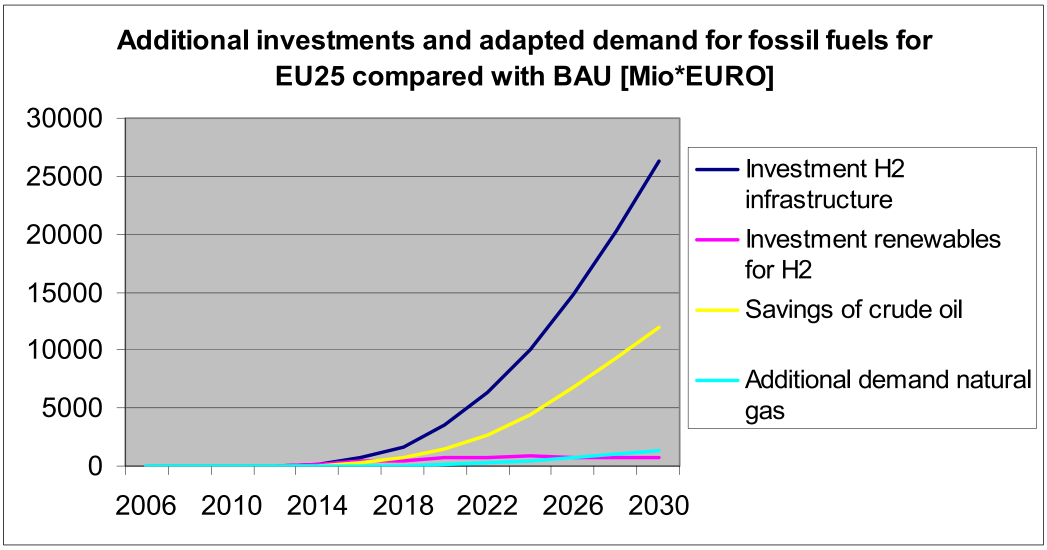


Figure 8: Investments and resource demand for EU25

Another environmental impact of accelerated diffusion of fuel cell vehicles into the fleet should not be neglected. Hydrogen Fuel Cells contain a small quantity of platinum group metals (PGM, platinum, palladium and rhodium). Mining and extraction of these metals is very energy consuming and releases a significant quantity of CO_2 emissions, which also depends on the countries of extraction due to technology and energy production methods in the different countries. For our analysis of the impacts of PGM use in FCs we concentrate on Platinum as the most important metal that is also relevant for use in catalytic converters and diesel particle filters. The Platinum content of the following three technologies is relevant for the calculation: catalytic converters and diesel filters (see Table 4), fuel cells (see Figure 9).

Table 4: Platinum (PGM) content of different technologies

[g Pt/vhc]	Euro1	Euro2	Euro3	Euro4	Euro5
Gasoline catalytic converters	2.0	2.7	3.5	4.0	4.1
Diesel filters	0.0	1.4	4.1	4.8	5.0

Source: Saurat (2006); EURO 5 own assumptions; for catalytic converters aggregated PGM content.

For Fuel Cells the Platinum content depends on three parameters: the power of the Fuel Cells (kW), the power density (kW/m²) and the Platinum load (g Pt/m²). All parameters develop over time either due to consumer preferences (power of cars) or due to learning curve effects (power density and Pt load) resulting into the learning curve for the Pt content of a fuel cell in cars (see Figure 9).

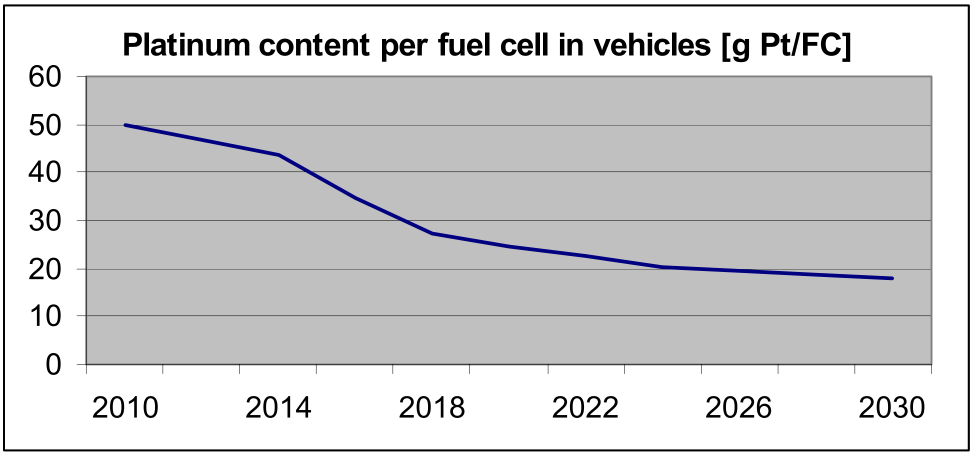


Figure 9: development of Platinum content per fuel cell (ASTRA results based on Saurat 2006)

Based on the material input figures above the Platinum demand for production of new cars can be calculated by multiplying the demand for cars equipped with different technologies from the ASTRA scenario with the material input numbers. This shows, that even though the Platinum content in fuel cells is subject to a significant learning process and hence is strongly reduced it can be expected that with the accelerated diffusion of FC vehicles into the fleet after 2020 the Pt demand increases over levels than current demand reaching close to 150 tons in the year 2030 (see Figure 10). This would cause concerns about environmental impacts associated with extraction and also about scarcity of the metal resource. One option to take into account to mitigate these problems is to develop strategies for recycling and reusing the Pt, when cars are scrapped.

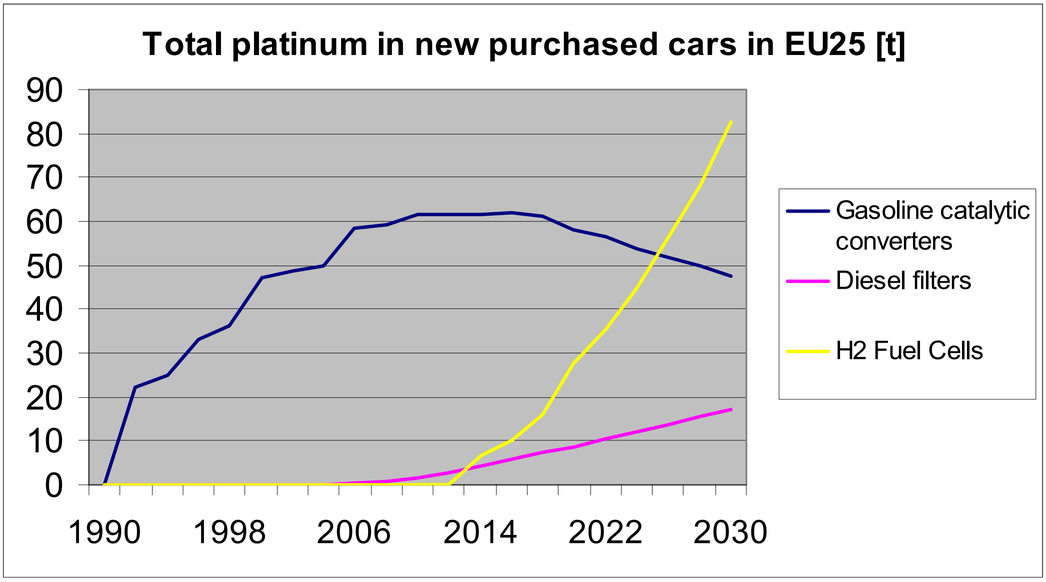


Figure 10: development of Platinum demand for new cars in EU25

Based on Saurat (2006) it can be concluded that mainly three countries produce the Platinum used in the world: South Africa (77%), Russia (13%) and North America (incl. others 10%). Taking into account these market shares and the different CO_2 emission factors of Pt production (see Saurat 2006) ASTRA is calculating the additional CO_2 emissions occurring outside of Europe for the extraction and production of Pt to be used for vehicle production. The numbers are shown in absolute terms in Figure 11. They reveal that both the savings of CO_2 by the shift towards hydrogen while driving and the upstream emissions of H2 production reach higher levels than the CO_2 emitted during Pt production, though with about 3 Mio t CO_2 in 2030 the latter is not negligible.

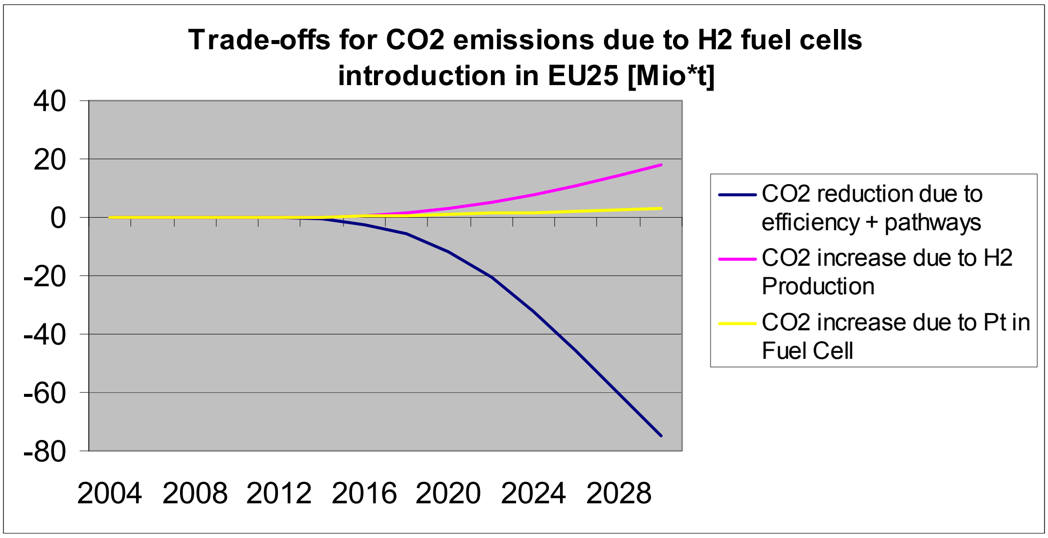


Figure 11: trade-offs between national and 'imported' CO_2 emissions

4 Conclusions

This paper analysed the sustainability of a possible shift of the European transport system towards the use of hydrogen as an energy carrier from two different point of views: first, from a stakeholder perspective, and second, from a model-based perspective using the ASTRA model to implement a scenario of which the exogenous inputs concerning energy prices and technology diffusion are developed in related projects, e.g. in the WETO-H2 and the HyWays projects.

It is obvious that hydrogen provides the potential to develop a more sustainable transport system as its use, in particular in fuel cells, would enable: to diversify the energy supply for transport both in terms of supplier regions and in terms of supply feedstocks; to reduce the emissions of air pollutants and noise during the transport activity, which is particular important for urban areas; and to reduce greenhouse gas emissions, which depends in particular on the feedstocks available to produce hydrogen. Consequently the stakeholders involved in the MATISSE group discussions on the sustainability of a hydrogen transport system suggested 'renewable' hydrogen as the most sustainable solution. However, though this vision was agreed unanimously the opinions differ if it is feasible to become implemented or if e.g. the competition between different sectors for hydrogen (e.g. electricity, heat) and between land for food and land for fuels hinders a sufficient supply of 'renewable' hydrogen for transport.

What became evident is that a sustainable solution for the transport system is getting more and more linked to a sustainable solution for the energy system and both depend on a diversification of energy sources and modes of delivery of final energy services.

The model-based analysis pointed to a number of trade-offs and win-win situations. A win-win situation can be identified that the investments to shift the transport system towards hydrogen, which are partially funded by subsidies and partially by revenues from hydrogen fuel sales, stimulate GDP and employment growth. Such a shift is expected to occur after 2013, presupposing that remaining technological problems have been solved by then such that drive-trains for cars come close to being competitive with internal combustion engines.

Trade-offs can be identified between the CO_2-emissions occurring during the driving activity, which are reduced, and the upstream CO_2 emissions, which are increasing due to the production of a share of the hydrogen from fossil sources. However, the balance of both impacts is positive in terms of sustainability as total life-cycle CO_2 emissions of transport fuel decrease. A further trade-off is identified for the trade balance of fossil energy carriers: crude oil imports of the EU25 are reduced in the hydrogen scenario while imports of natural gas increase, but by a lower value. A final trade-off is observed for the increased usage of PGM metals to produce the fuel cells, as with the extraction and production of PGM significant environmental impacts (e.g. CO_2 emissions, mine spoils) outside Europe are connected. A summary of the quantified impacts is provided in Table 5:

Table 5: Summary of major quantified impacts of introducing H2 cars in the EU25

Economy	GDP	Employment	Investment	
Impact of H2 cars	↑	↑	↑↑	
Resources	Gasoline	Diesel	Import of natural gas	Platinum
Impact of H2 cars	↓↓	↓	↑	↑↑
Transport emissions	CO_2 driving	CO_2 upstream	CO_2 total	NO_x emissions
Impact of H2 cars	↓	↑	↓	↓

Source: ASTRA scenario results

Finally, it should be mentioned that though hydrogen used in fuel cells producing electricity to propel electric engines seems to provide a promising option for a sustainable transport system, it still has to overcome some technological barriers. The same holds for an alternative technology, which is to store electric energy in batteries propelling electric engines of cars. The race is open, which technology will break its barriers faster, but hydrogen currently seems to be in a better position.

Acknowledgements:

We would like to acknowledge the valuable contributions of a number of colleagues from related research projects like MATISSE, TRIAS and PROGRESS. Grateful thanks go to Lorraine Whitmarsh, who is driving the stakeholder involvement in MATISSE, Paul Weaver, who is always a very stimulating contributor to methodological discussions about sustainability assessments, Ulrike Hasenauer, who is providing us with quantifications for the important input data on hydrogen related issues, Michael Krail, who is contributing to the ASTRA development in TRIAS, and Mario Ragwitz, who supplies any kind of required detailed information on renewables.

Of course, any errors and omissions of the paper remain with the two authors.

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