Impact on resource use and emissions of transport by using renewable energy and hydrogen as transport fuel

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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 feedstocks including both fossil and non-fossil sources. This paper presents a model-based analysis of resource use for transport as part of an overall sustainability impact assessment of a scenario to introduce hydrogen for transport. The analysis draws inputs from a number of European projects (e.g. HyWays, MATISSE, TRIAS) Overall, the introduction of hydrogen into transport seems to be promising for sustainable development, though there is a risk of shortages of precious metals like platinum and of exporting adverse environmental impacts upstream outside Europe.

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: renewable energies 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.

The most prominent indicator where the energy system and the transport system are connected is the energy efficiency of vehicles. Though energy efficiency of fossil fuel based cars is improving since the late 1980ies and is expected to increase further their well-to-wheel energy consumption in comparison to hydrogen fuel cell cars will be about two to three times higher, if one takes into account the more energy efficient production pathways for hydrogen (CONCAWE et al. 2006).

Overall, 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.[1] 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, and it would offer new employment opportunities.

This paper draws on work currently undertaken in a number of European research projects like TRIAS and MATISSE.[2] It combines results of these projects with stakeholder scenarios on the development of hydrogen use for transport of the HyWays project (HyWays 2006). Quantification and impact assessment of the scenario results is undertaken with the ASTRA model.

The paper is structured into four main sections after this introduction. First, the applied ASTRA model is briefly explained. Second, the scenario parameters feeding the model are presented, which includes penetration rates for hydrogen vehicles and renewable technologies. Third, the results of the model-based scenario analysis are shown and fourth conlusions of the analysis are drawn.

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[1] Europe: European Hydrogen and Fuel Cell Technology Platform (https://www.hfpeurope.org/); US e.g. California Fuel Cell Partnership (http://www.fuelcellpartnership.org/); Japan e.g. Hydrogen and Fuel Cell Demonstration Project (http://www.jhfc.jp/ e/index.html); International the International Partnership for the Hydrogen Economy (http://www.iphe.net/).

[2] TRIAS http://www.isi.fhg.de/TRIAS/, MATISSE http://www.matisse-project.net/projectcomm/

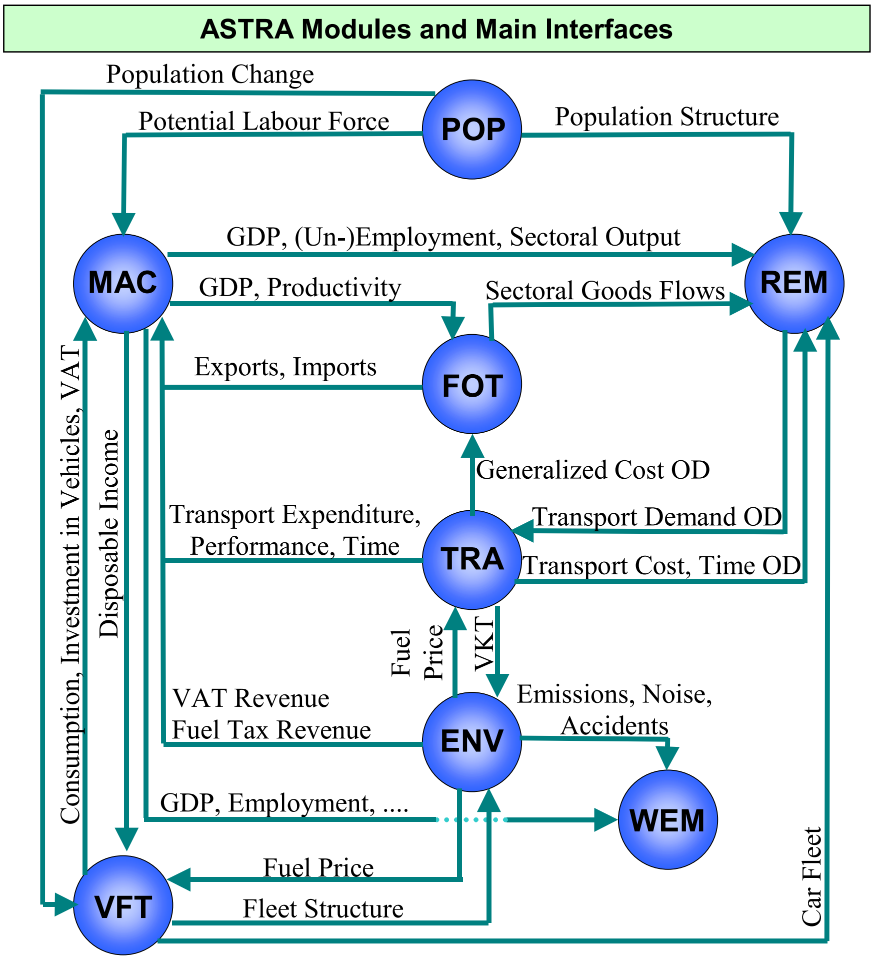
Brief description of the ASTRA model

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 1*. Purposes of the modules are:

- Population module (POP) calculates the population development and population structure for the EU29 countries with one-year age cohorts.
- Macroeconomics module (MAC) provides the national economic framework. The MAC combines different theoretical concepts as it incorporates neo-classical elements, Keynesian elements and elements of endogenous growth theory. Of particular relevance for this paper is the sectoral structure of investments and consumption within the MAC enabling detailed consideration of changes due to penetration of hydrogen vehicles and renewable energies.
- Regional economics module (REM) describes spatial changes and the generation of transport on the level of sub-national functional zones.
- Foreign trade module (FOT) estimates trade flows by sector by country combination e.g. trade of vehicles from Sweden to Spain etc.
- Transport module (TRA) provides the modal-split of transport demand and calculates the transport performance by mode for passenger and freight transport as well as vehicle kilometres travelled.
- Vehicle fleet module (VFT) delivers the composition of the road vehicle fleets differentiated into different vehicle sizes, engine types and emission standards.
- Environment module (ENV) calculates the fuel consumption for the different fuels and the emissions of transport. Based on the fuel consumption also fuel tax revenues are calculated.
- Welfare measurement module (WEM) provides aggregate indicators like transport intensity, investment multipliers or cost-benefit ratios of policies.

The strength of the ASTRA model is that the eight modules are not connected in a linear way e.g. the economy drives transport and this leads to emissions, but that various feedbacks are implemented between the modules, such that inventions in the vehicle fleet (e.g. hydrogen cars) or new energy supply systems (e.g. renewables) feed back into the economic system through changes of investments or cost changes.



Abbreviations:

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

Figure 1: Overview on the ASTRA model

The scenario definition for this paper follows the business-as-usual (BAU) scenario of the ASTRA model as applied in the first phase of the MATISSE project, which for a number of variables followed a rather optimistic path e.g. for the GDP growth between 2005 and 2030.

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 2*.

Some further variables that determine a scenario are taken exogenously. This includes the energy prices for oil (see *Figure 2*) and gas that are taken from the WETO-H2 reference case (World Energy Technology Outlook-2050), which is an extended project of the first WETO study providing an outlook until 2030 (EC 2003b).

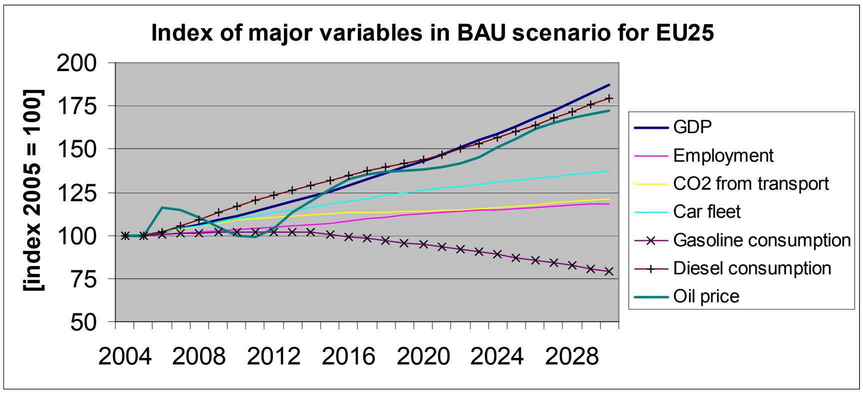


Figure 2: Overview on the trends in the BAU scenario

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 car purchase of these categories is shown in *Figure 3*. 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 a structural identity scenario is taken implying that H2 cars are manufactured with the same spatial distribution as currently conventional cars.

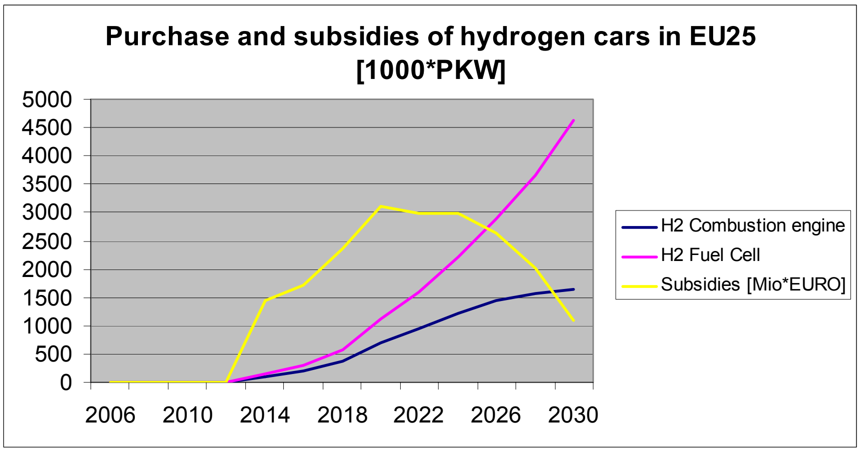


Figure 3: Subsidies and diffusion of hydrogen cars into car fleet of EU25

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 3*).

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 investments into renewable energies

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. The split for the different technologies onto eight of the 25 economic sectors of ASTRA is shown in *Table 3*.

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

[%] economic sectors	Metal Products	Machinery	Electronics	Construction	Trade	Transport Inland	Other Market Services	Non Market Services
renewables technology								
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

The presented potentials for renewables, the learning curves and the technology split of investments onto different economic sectors lead to aggregate figures for the EU25 on installed renewables capacity to produce hydrogen for transport and related investments as presented in *Figure 4*.

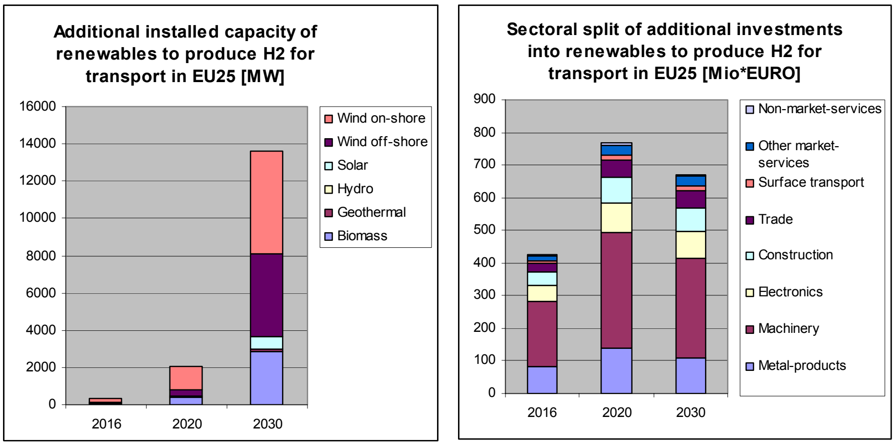


Figure 4: Additional installed capacity and investments into renewables to produce hydrogen for transport in the EU25

Source: ASTRA results based on HyWays country approaches to apply renewable technologies.

Based on the framework of economic development, energy prices, hydrogen car penetration and structure of renewable hydrogen production described in the previous section the scenario is simulated with the ASTRA model and the results are compared to the BAU scenario. *Figure 5* 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 7*) 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.

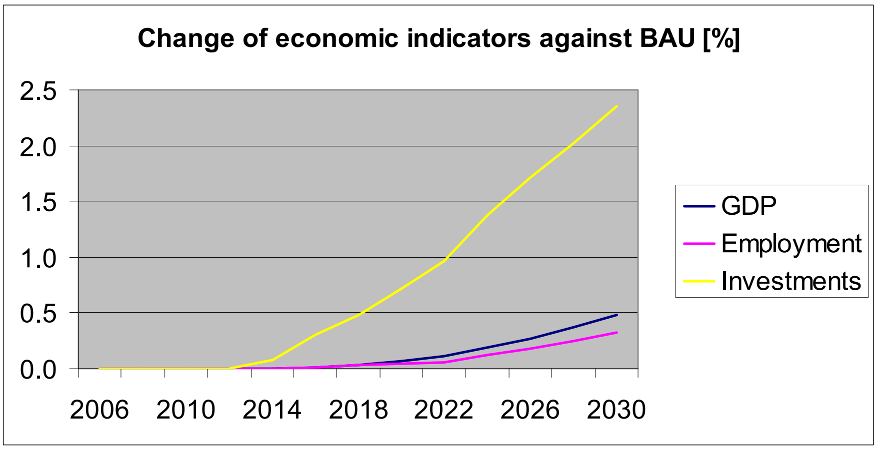


Figure 5: Impact on economic indicators through H2-cars introduction for EU25

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 between gasoline and diesel 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 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 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.

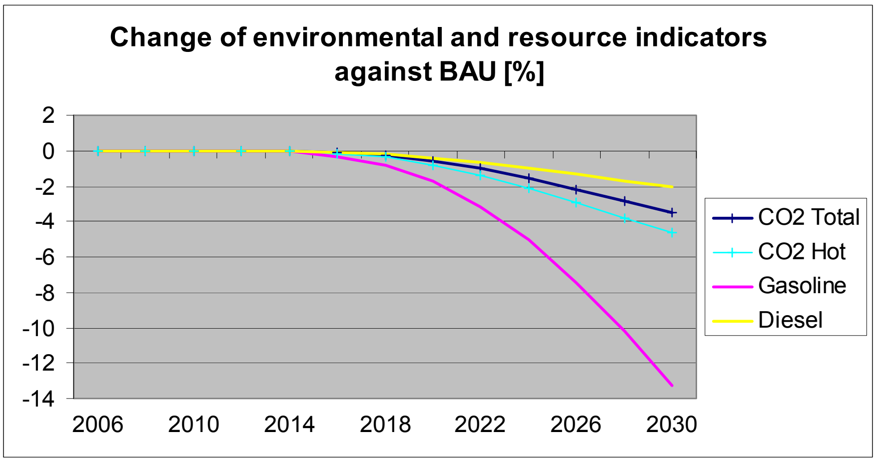


Figure 6: Impact on environmental indicators through H2-cars introduction in EU25

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 7*).

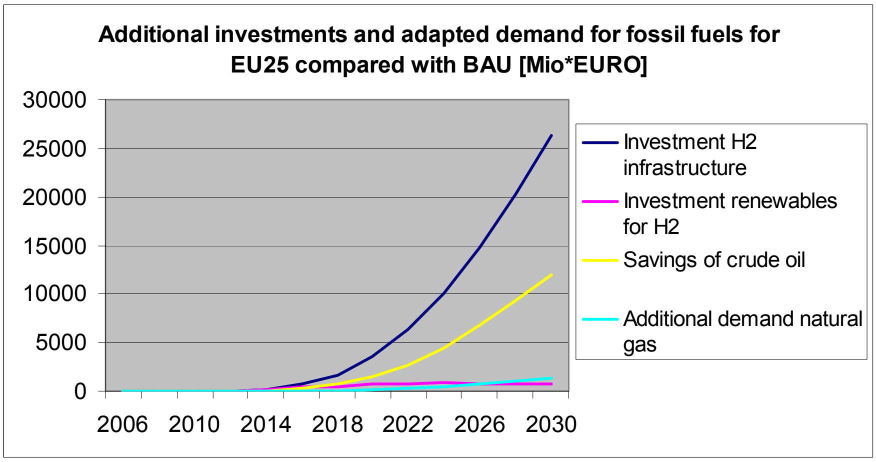


Figure 7: Investments and resource demand for EU25

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 and other air pollutants, 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 8*).

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/m^2) and the Platinum load ($g\ Pt/m^2$). 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 8*).

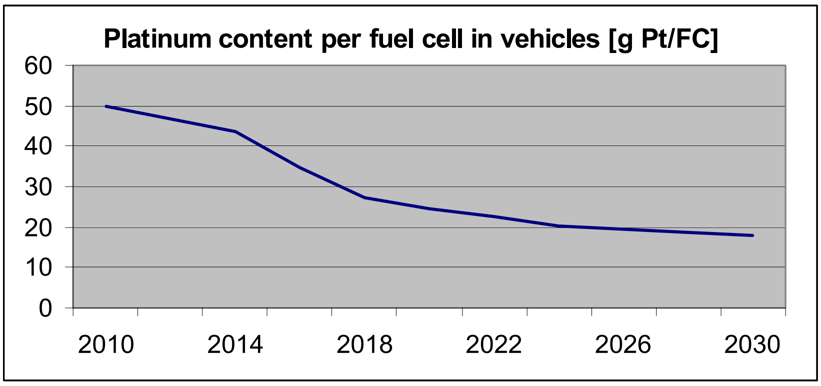


Figure 8: development of Platinum content per fuel cell (ASTRA results based on Saurat 2006)

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 9*). 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.

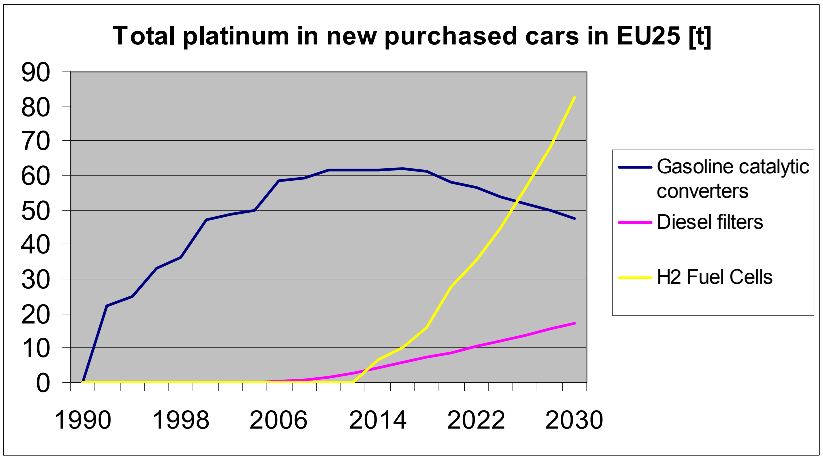


Figure 9: development of Platinum demand for new cars in EU25

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 10*. 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.

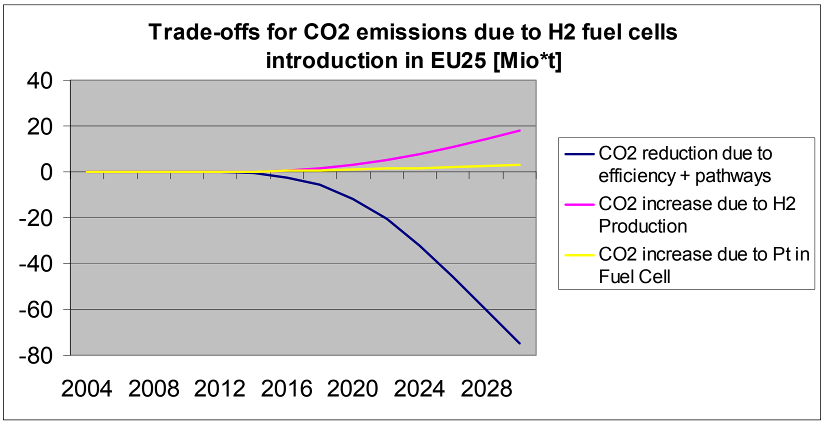


Figure 10: trade-offs between national and 'imported' CO_2 emissions

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 a model-based quantifiable point of view 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.

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. A further link that was not part of the analysis in this paper, but nevertheless is relevant in terms of a sustainable solution, is the potential conflict of food versus biomass for energy uses if hydrogen should be generated to a large extent from biomass instead of from pathways without biomass use.

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 hydrogen fuel cell 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 that has similar positive impacts on sustainability to offer but also faces technological barriers, which is to store electric energy in batteries propelling electric engines of cars. The race is open, which of the two technology lines will break its barriers faster, but hydrogen currently seems to be in a better position.

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

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