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# REFRAMING SUSTAINABLE TRANSPORT: EXPLORING HYDROGEN STRATEGIES USING INTEGRATED SUSTAINABILITY ASSESSMENT (ISA)

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MATISSE Methods and Tools for Integrated Sustainability Assessment

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**MATISSE** (Methods and Tools for Integrated Sustainability Assessment) aims to achieve a step-wise advance in the science and application of Integrated Sustainability Assessment (ISA) of EU policies. In order to reach this objective the core activity of the MATISSE project is to improve the tools available for conducting Integrated Sustainability Assessments.

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The MATISSE Working Papers can be downloaded at http://www.matisse-project.net/.

# Preface

### About the MATISSE project

The MATISSE (Methods and Tools for Integrated Sustainability Assessment) project is funded by the European Commission, DG Research, within the 6th Framework Programme. The project is interested in the role that Integrated Sustainability Assessment (ISA) could play in the process of developing and implementing policies capable of addressing persistent problems of unsustainable development and supporting transitions to a more sustainable future in Europe. The core activity of MATISSE is to develop, test and demonstrate new and improved methods and tools for conducting ISA.

This work is carried out through developing and applying a conceptual framework for ISA, looking at the linkages to other sustainability assessment processes, linking existing tools to make them more useable for ISA, developing new tools to address transitions to sustainable development and applying the new and improved tools within an ISA process through a series of case studies.

The extent to which the case studies are carrying out a complete ISA for their area of focus varies between attempts to cover all phases of an ISA process to partial implementation of the process. Equally, different case studies are oriented to developing and testing tools and approaches to some, but not all, of the methodological challenges of ISA. The case studies are complementary, however, and the set of cases offers the opportunity to address a wide range of methodological challenges and to explore linkages between cases. An evaluation of practical experiences with ISA implementation in the case studies will provide guidance on the further improvement of methods and tools. Results will also contribute to more informed policy advice.

## What is ISA?

Within the MATISSE project, Integrated Sustainability Assessment (ISA) has been defined as a cyclical, participatory process of scoping, envisioning, experimenting, and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner, in order to explore solutions to persistent problems of unsustainable development. ISA is conceptualised as a complement to other forms of sustainability assessment, such as Sustainability Impact Assessment, Integrated Assessment and Regulatory Impact Assessment. Whereas these other forms of assessment fulfil the pragmatic need for *ex ante* screening of incremental sectoral policies that are developed within the prevailing policy regime, ISA is conceptualised as a support to longer-term and more strategic policy processes, where the objective is to explore persistent problems of unsustainable development that have a systemic pathology and possible solutions to these. ISA is therefore oriented toward supporting the development of cross-sectoral policies that specifically address sustainable development and at exploring enabling policy regimes and institutional arrangements.

### MATISSE Working Papers

Matisse Working Papers are interim reports of project activities that are published in order to illustrate ongoing work and some provisional conclusions, as well as providing the opportunity for discussion of the approaches taken by the project and interim results. This discussion should be both within the project and between project members and the broader scientific and policy communities. Readers are encouraged to contact the authors to discuss the content of MATISSE Working Papers.

Jill Jäger and Paul Weaver

Editors of the MATISSE Working Paper Series

# ABSTRACT

The paper reports a case study of induced innovation, sustainable technology and transition management. The case study concerns the role of hydrogen in sustainable transport in Europe and uses a novel assessment process, Integrated Sustainability Assessment (ISA). ISA is a cyclical, participatory process of scoping, envisioning, experimenting and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner to explore solutions to persistent problems. ISA is strategic, constructive and potentially transformative. Its key role is to explore the problem-solving potential of framing conditions other than those in place, such as alternative technologies, institutions and policy regimes. The case study uses stakeholder workshops to obtain different perspectives on sustainable transport. It uses the ASTRA model to explore impacts and trade-offs implied by alternative transition strategies. Results reveal wide consensus that sustainable transport requires a diversified and renewable primary energy supply and diversified delivery of mobility solutions. International competitiveness is a serious economic/social concern. Hydrogen fuels and electrochemical conversion technologies could contribute to sustainability, but outcomes depend on how and where hydrogen is produced, the cost and technical performances of technologies, how these are improved, and whether the technologies induce new resource/sustainability constraints.

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# REFRAMING SUSTAINABLE TRANSPORT: EXPLORING HYDROGEN STRATEGIES USING INTEGRATED SUSTAINABILITY ASSESSMENT (ISA)

## 1 Introduction

The use of hydrogen as an energy carrier for the transport system has been discussed and tested in research niches for many years. High oil prices, the growing awareness that this will not be a temporary but a permanent situation and the strong dependency (more than 97%) of the European transport system on fossil fuels, 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.

In addition the strong dependency on fossil fuels of today's transport system is causing a number of important adverse environmental impacts. Energy consumption and associated greenhouse gas emissions of transport grew in the past decade by more than 20% in the EU15 countries. Some reductions in emissions have been achieved for air pollutants from transport (e.g. VOC, CO), while for others the emission levels remain high causing health and environmental damages (e.g. particulate matter, NOx) (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 that could help tackle most of the aforementioned problems would be hydrogen. It can be generated from a number of different primary energies, both fossil and non-fossil, which would improve the security of energy supply for transport due to the diversity of potential feedstocks and geographical sources. Depending on the production pathway of hydrogen the emission of greenhouse gases can be reduced or completely eliminated. It is also conceivable to develop production pathways that would contribute to reducing atmospheric carbon concentrations (Weaver et al 2000). 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 could be solved by hydrogen. For example, 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 increase in nuclear waste, increase in the problems associated with producing platinum-group metals, or increase in competition for land between production of energy crops and food). Considering these newly-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 convincing enough that in all world regions stakeholder networks and research programmes have been set up to promote and work on this shift. In Europe there is the European Hydrogen and Fuel Cell Technology Platform (https://www.hfpeurope.org/), in the US, for example, the California Fuel Cell Partnership (http://www.fuelcellpartnership.org/), in Japan, for example, the Hydrogen and Fuel Cell Demonstration Project (http://www.jhfc.jp/ e/index.html) and on the 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. For instance, 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 according to the plans of the Japanese METI would imply zero CO2 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 system (fuel cell, storage, system integration) is still too costly to introduce them into a mass market for vehicles and their durability is not sufficient; second, not all technical problems have been solved yet (e.g., cold start, for liquid hydrogen the boil-off effects, for gaseous hydrogen the tank size issue).

However, shifting transport to hydrogen is not only a technical issue. It would induce structural economic changes through developing a large-scale industry producing and distributing hydrogen, trade-flow changes through reducing trade of fossil fuels and increasing trade of feedstock for hydrogen production, and through changes in employment opportunities.

This paper draws on work currently undertaken in a number of European research projects including TRIAS (http://www.isi.fhg.de/TRIAS/) and MATISSE (http://www.matisse-project.net/projectcomm/) that are exploring possible hydrogen futures. The latter project is concerned with implementing a novel sustainability assessment process, Integrated Sustainability Assessment (ISA) and is taking hydrogen mobility as one of its test cases. After briefly explaining the concept of ISA, this 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 Integrated Sustainability Assessment (ISA): the case of a hydrogen transition

The paper reports methods and findings from a case study of sustainable technology and transition management. The case study looks at the role and potentials of hydrogen in sustainable transport in Europe and pioneers the use of Integrated Sustainability Assessment (ISA). ISA is a novel assessment process that is being developed and tested in the EC MATISSE project (Framework VI http://www.matisse-project.net/projectcomm/). ISA is defined in MATISSE as a cyclical, participatory process of (1) scoping, (2) envisioning, (3) experimenting and (4) learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner in order to explore solutions to persistent problems of unsustainable development. ISA is strategic, constructive and potentially transformative. Its key role is to explore the problem-solving potential of framing conditions other than those now in place, such as would be represented by alternative technologies, institutions, spatial arrangements, market conditions, and policy regimes, etc. ISA takes a broad systems view and seeks simultaneously to explore acceptable solutions to problems and the framing conditions that would be consistent with these.

ISA is appropriate for exploring and reframing persistent problems of unsustainable development, which have a systemic pathology, which are complex and where solutions are likely to depend upon cross-sectoral, inter-disciplinary approaches and upon coordinating agency across multiple levels. ISA is therefore distinguished from more routinely-used forms of ex ante sustainability assessment, such as sustainability impact assessment (SIA) and Impact Assessment (IA), which accept the existing framing conditions and whose purpose is to screen policies for unintended impacts. By contrast, ISA is concerned with the process of transition and with how path-dependence, lock-in, power inequalities and related phenomena might be analysed and addressed. It is concerned with understanding how stakeholders, agents and actors perceive their own self-interests and with understanding their behaviours, their capacities for social learning and the possibilities for transformation, empowerment and regime change. Exploring strategies and handling agency involves modulation between levels and scales within the same ISA process.

Unsustainable patterns and trends in transport, mobility and accessibility typify persistent, multi-faceted, cross-sectoral problems. Equally, solution possibilities based upon induced, co-evolutionary innovation of hydrogen technologies, institutions and behaviours depend upon contextual reframing and paradigm change. ISA is therefore an appropriate process for exploring problems of (un)sustainable patterns and trends in transport and mobility and possible solutions.

The case study uses stakeholder workshops in the scoping and envisioning phase to obtain alternative perspectives on the problem of sustainable transport in Europe and to develop interpretations of and criteria for sustainability. The ASTRA model is then used in the experimenting phase of the ISA process to explore the relationships, impacts and trade-offs implied by a selected hydrogen strategy for transport, alternative strategies and transition pathways. The work is ongoing. The purpose of the present paper is to report the status as we come to the end of the full iteration of the first ISA process cycle. The following sections report on the first stakeholder involvement and the quantitative results of the first experimenting phase. The work so far reveals a wide consensus among stakeholders that sustainable transport depends upon a diversified and renewable primary energy supply and also upon more diversified and context-specific transport and mobility solutions. Sustainable transport and renewable energy are inextricably linked. Competitiveness is also a serious concern.

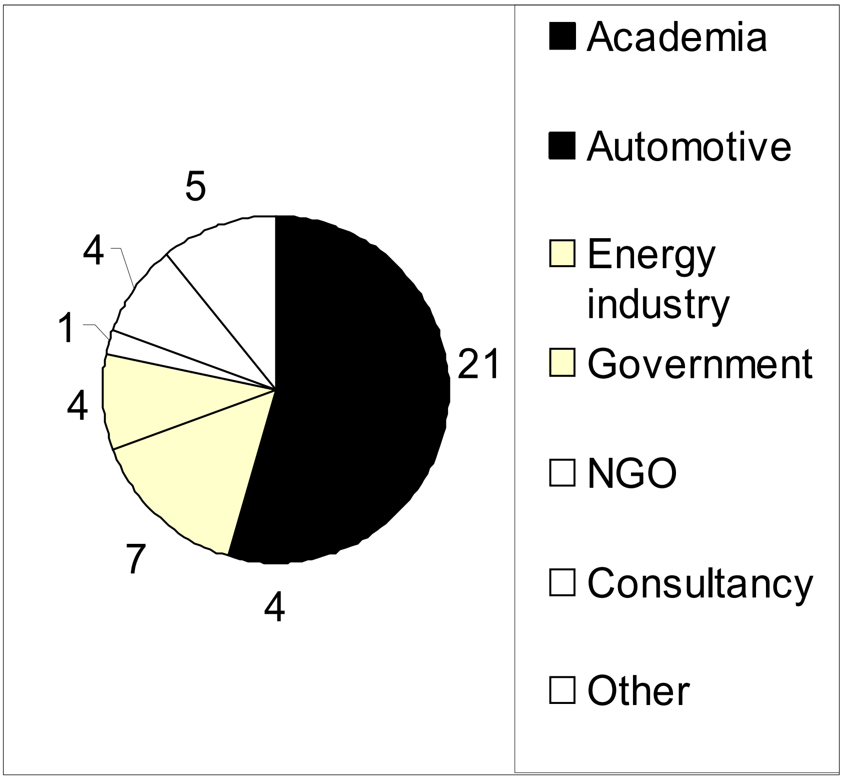
# 3 Sustainability implications of hydrogen: stakeholder view

Stakeholder engagement is relevant to the issue of shifting transport to hydrogen use given the complexity, ambiguity and subjectivity that surround questions concerning how best to approach persistent problems of unsustainability, such as those of transport. In such cases, where stakes are high, where views and values differ across stakeholders, and where agency and power are dispersed, sustainability assessment is most usefully undertaken using a participatory approach that engages with stakeholders and actors (see Weaver/Rotmans 2006, Gibson et al. 2005). The participatory approach prescribed for ISA in the MATISSE project was implemented in the hydrogen transport case study.

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.

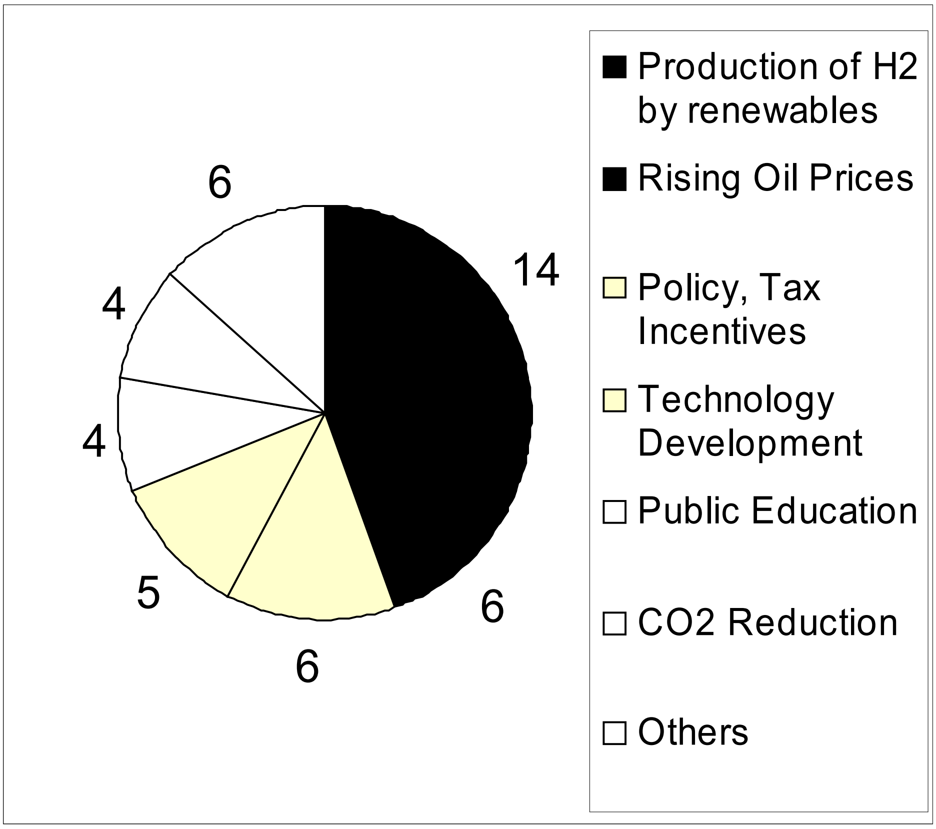
Participants at the cluster workshop included researchers and consultants, an NGO representative, policy-makers, and members of the automotive and energy industries from across Europe, with interests and expertise in hydrogen and transport technologies (see Figure 1). More information on the workshop 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 a 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 that 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 and habitat/biodiversity protection).

*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 Carbon Capture and Storage (CCS) are 'sustainable'. For a number of participants, sustainability was equated with zero emissions or 'CO2 free'. These feedstocks fulfil this criterion and, additionally, many stakeholders felt these are necessary to achieve energy security and a diversified, flexible supply. However other participants pointed 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 has 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 CO2-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).

# 4 Sustainability implications of hydrogen: model results

The results presented in this paper combine transition scenarios on the development of hydrogen use for transport from the HyWays project (HyWays 2006) with inputs and model calculations undertaken in the MATISSE project. Quantification and impact assessment of the scenario results as part of the experimenting stage of an ISA is undertaken with the ASTRA model.

An extended analysis will follow in later stages of the TRIAS project, where ASTRA will be linked with an energy system model (POLES,), a transport network model (VACLAV), and a model to calculate regional environmental impacts, in particular concentrations of air pollutants (Regio-SUSTAIN) (see Fiorello et al. 2005), and the second phase of the MATISSE project.

### Brief description of the ASTRA model

ASTRA (Assessment of Transport Strategies) is a system dynamics model that generates 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 basis of existing models that were converted into a dynamic formulation that could be implemented in system dynamics. These models included 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 stem from various sources with the bulk of data coming from EUROSTAT (2005) and the OECD online databases (2005).

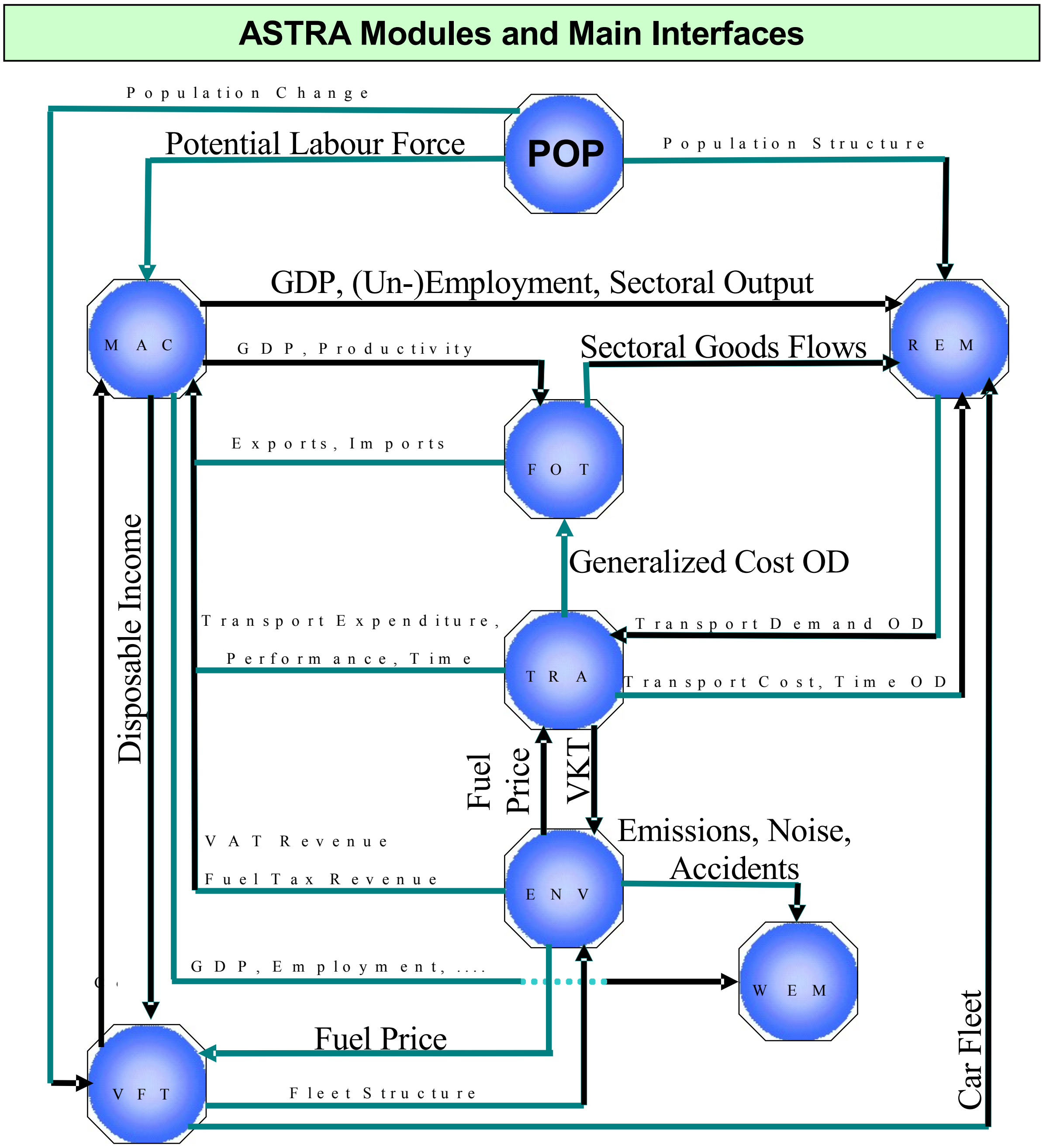
The ASTRA model consists of eight modules and the version presented in this paper covers the 25 Western European Union countries (EU25) plus Norway, Switzerland, Bulgaria and Romania (EU29). The major interlinkages between the eight modules are shown in Figure 3.

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, such as the number of persons of 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; and elements of endogenous growth theory, like the implementation of endogenous technical progress as one important driver for the long-term economic development.

The macroeconomics module has six major elements. 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: private consumption, investments, exports-imports and 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.

*Figure 3: Overview of the ASTRA model*




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** |

The fourth element is 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 in order to reflect the growing importance of part-time employment. Unemployment can be estimated in combination with the population module. 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.

The sixth element of 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 the calculation of 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, which. influences trade flows between the European countries. Employment and unemployment are two influencing factors for passenger transport generation. The sectoral production value drives national freight transport generation. Disposable income exerts a major influence on car purchases, which affects the vehicle fleet module including the introduction of new vehicle types like hydrogen fuel cell vehicles. By changing the vehicle fleet structure the passenger transport emissions are also changed.

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 the employment situation, car-ownership development and the 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 the sectoral production value of the 15 goods-producing sectors, where the monetary output of the input-output table calculations are transferred into volume of tonnes 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 last of these 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 inputs to the Transport Module (TRA) are the demand for passenger and freight transport that is provided by the REM in the form of OD-matrices. Using transport cost and transport time matrices the transport module uses a logit-function to calculate 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 outputs 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 calculates the emissions from transport. In addition to 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.

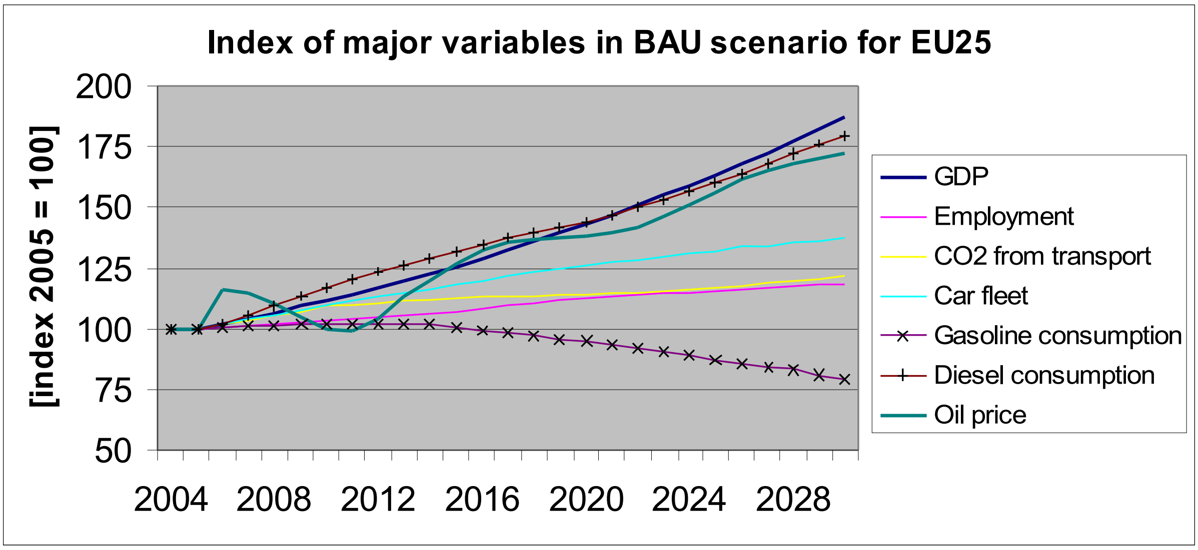
The Vehicle Fleet Module (VFT) describes the vehicle fleet composition for all road modes. Vehicle fleets are differentiated into age classes based on one-year-age cohorts and into emission-standard categories. Additionally, the car vehicle fleet is differentiated into gasoline and diesel powered cars of different cubic capacity and into hybrid vehicles, hydrogen internal combustion engine (H2-ICE) vehicles and hydrogen fuel cell vehicles (H2-FC). The car vehicle fleet develops during model runs according to income changes, development of population and development 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 to the economic sectors in the MAC that cover vehicle production.

### 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.

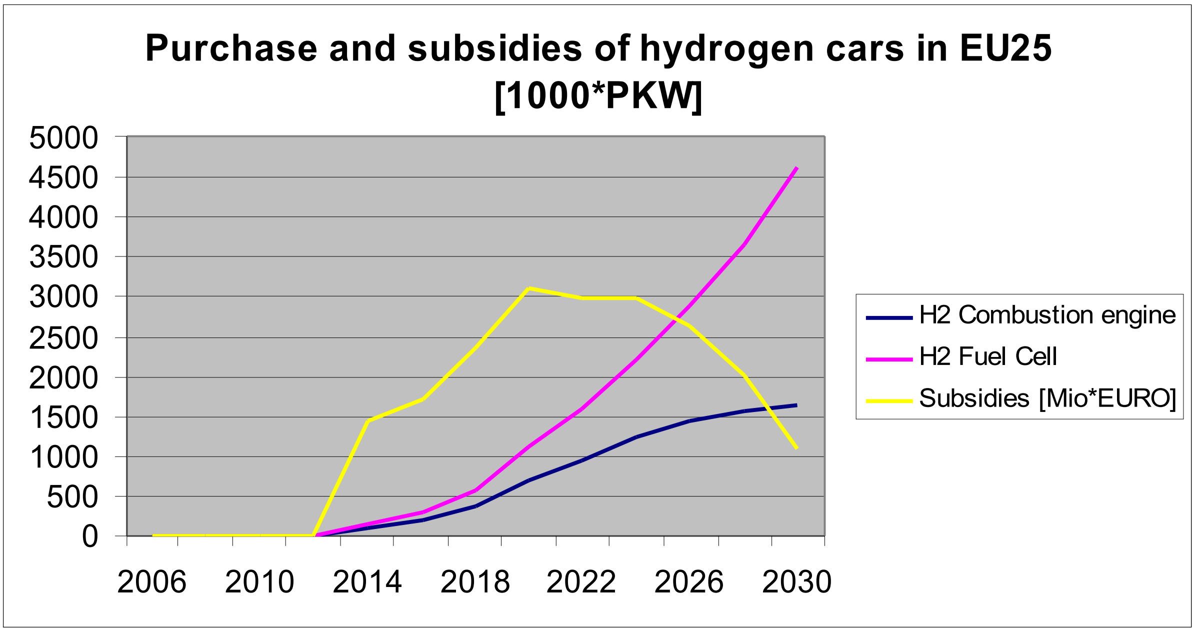
Some further variables that determine a scenario are taken exogenously. This includes the prices for oil (see Figure 4) and gas that are taken from the WETO-H2 reference case (World Energy Technology Outlook-2050, not published, yet), which is an extended project of the first WETO study providing an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

*Figure 4: Overview of the trends in the BAU scenario*



Market entrance 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 per car by the government have to be provided due to the high cost of the fuel cells. These subsidies per car diminish over time such that the peak of total 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 parts of the fuel cell also benefit. HyWays estimates that about one third of a car's price is related to the drive-train. For H2 fuel cell cars about 30% of this one third 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 corresponding 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 of the cost of producing hydrogen conclude that some production pathways are competitive even today compared with fossil fuels for transport (Hilkert 2003). Taking this hypothesis it is feasible to build-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., a 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 in 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 for each renewables technology then has 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*

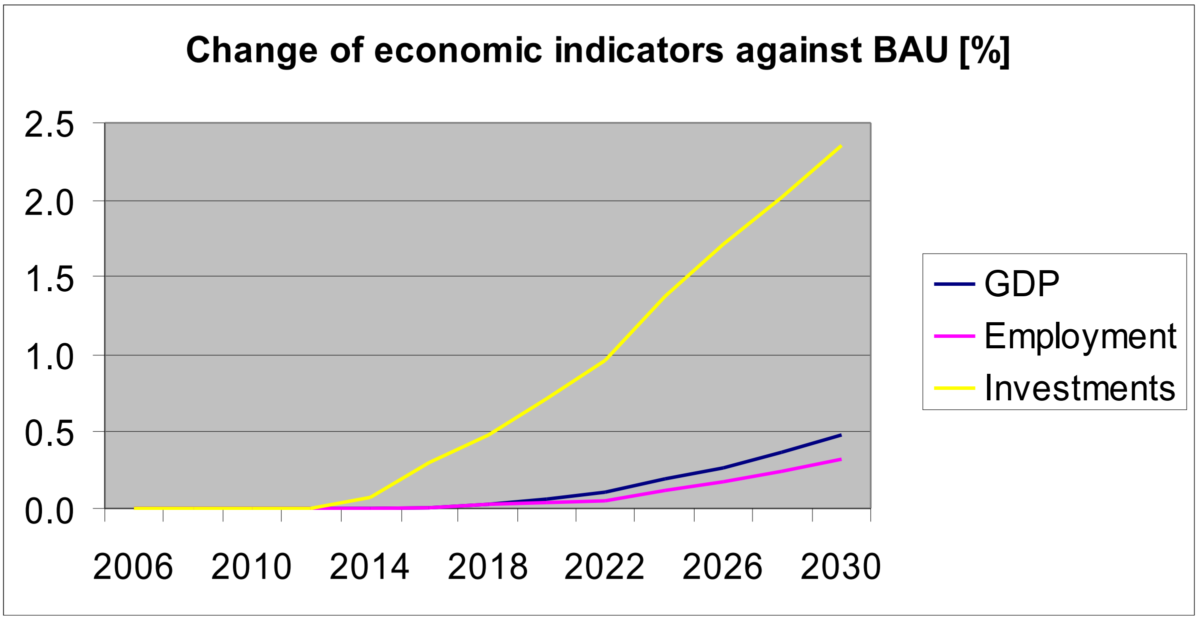
| **[%]** economic sectors / renewables technologies | Metal Products | Industrial Machines | Electronics | Construction | Trade | Transport Inland | Other Market Services | Non Market Services |
|---|---|---|---|---|---|---|---|---|
| Biomass | 5 | 35 | 23 | 10 | 16 | 4 | 6 | 1 |
| Geothermal | 5 | 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

### 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 Section , 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 is 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 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 such as increased employment and income leading to higher GDP leading to increased demand and hence more investment in the second round.

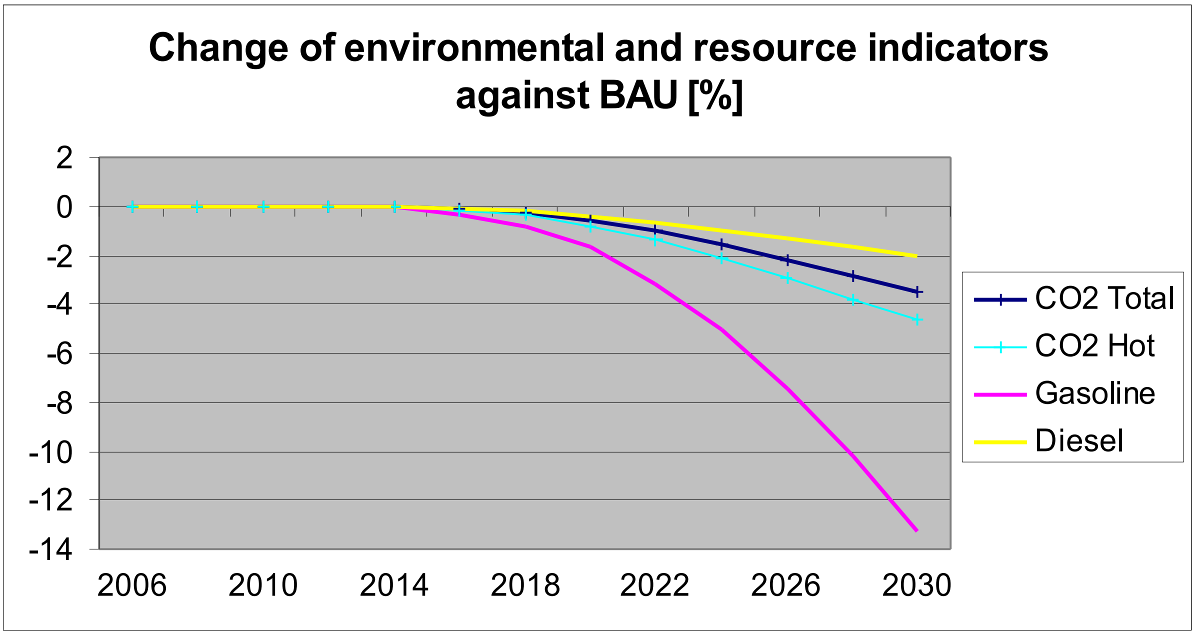
*Figure 6: Impact on economic indicators through H2-cars introduction for EU25*




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%. This difference between gasoline and diesel arises because, in this scenario, only cars are equipped with fuel cells and H2-ICE engines, whereas buses or light duty vehicles are not.. This means that only a small share of diesel fuel consumers is affected, i.e. diesel cars, while buses, light and heavy duty vehicles (LDV, HDV) continue to run on diesel. Also, as GDP grows slightly, freight transport increases, thus raising demand for diesel from freight transport compared to BAU.

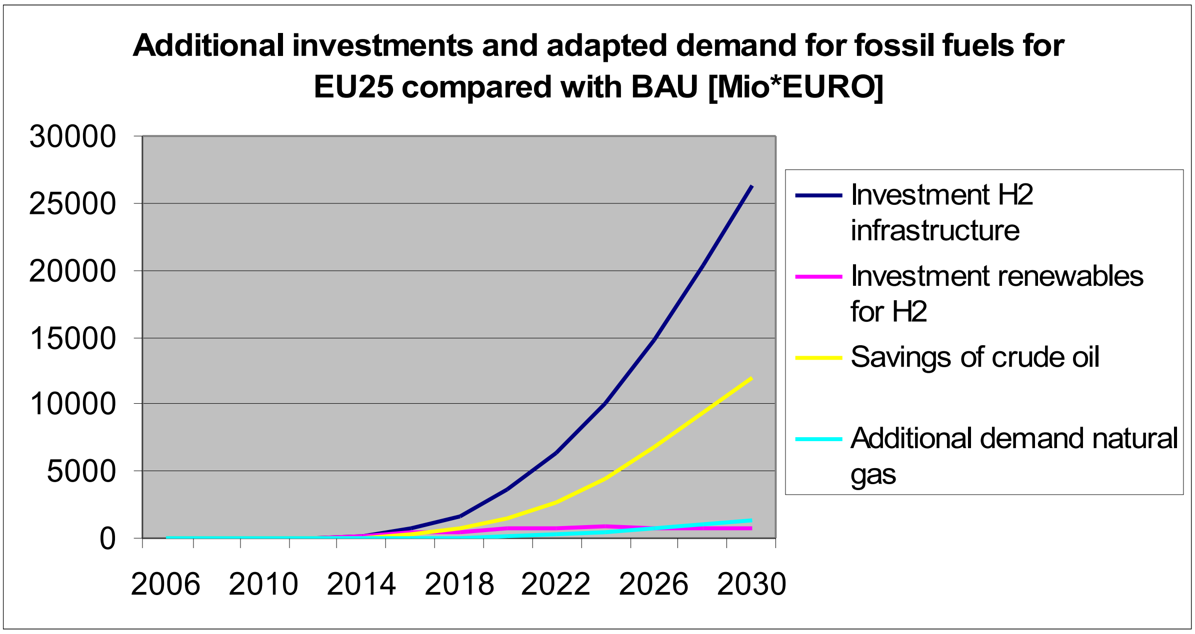
Total CO2 emissions from transport are reduced by about -3.5% in 2030. However, emissions from driving decrease by -4.6% (CO2 Hot in Figure 7), which is significantly stronger than the reduction for total transport CO2. The reason is that ASTRA calculates the life-cycle emissions for the total transport CO2 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, which accounts for this difference.

*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 billion EURO of savings in the year 2030 with a minor compensation of increased imports of natural gas reaching more than 1 billion 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 CO2 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, diesel filters (see Table 4), and fuel cells (see Figure 9).

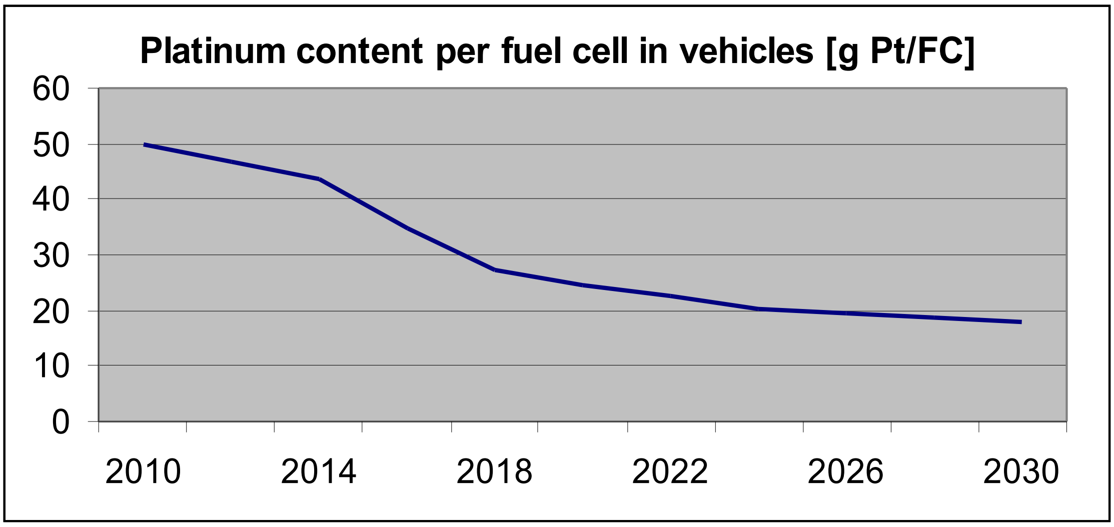
*Table 4: Platinum (PGM) content of different technologies*

| [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.

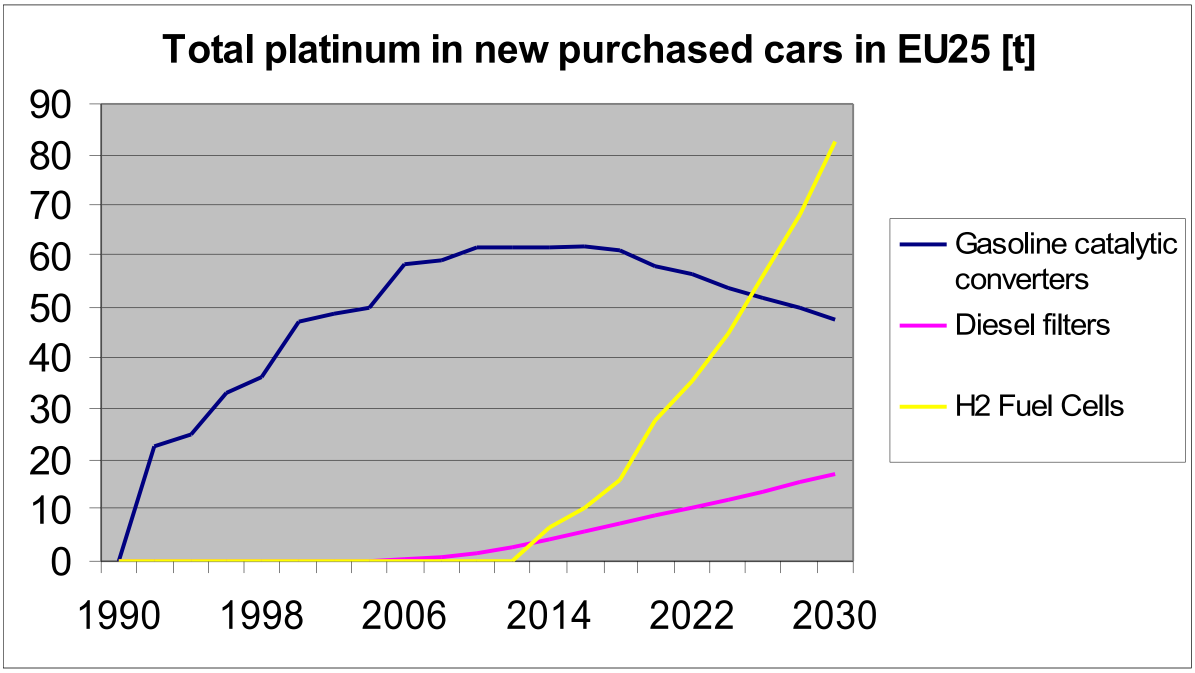
For fuel cells the platinum content depends on three parameters: the power of the fuel cells (kW), the power density (kW/m²) and the platinum load (g Pt/m²). All parameters develop over time either due to consumer preferences (power of cars) or to learning curve effects (power density and Pt load) resulting in 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)*



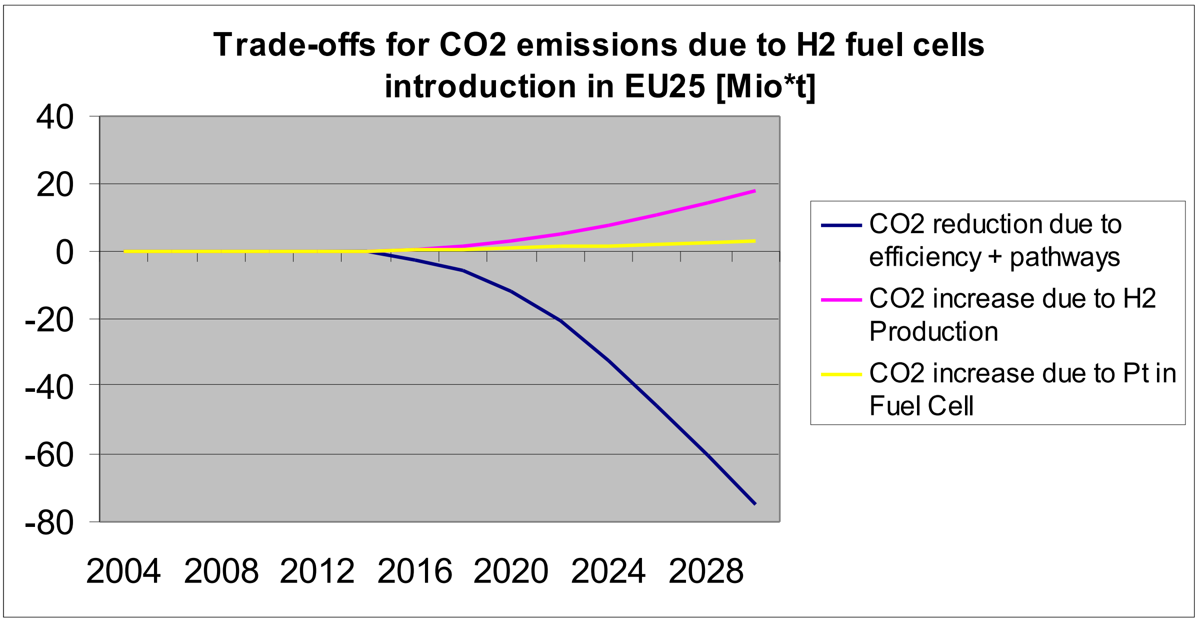

Based on the material input figures above the platinum demand for production of new cars can be calculated by multiplying the demand for cars equipped with different technologies from the ASTRA scenario with the material input co-efficients. This shows, that even though the platinum content in fuel cells 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 to levels higher 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 mitigate these problems is to develop strategies for recycling and reusing the Pt, when cars are scrapped. A second option is to substitute platinum by other substances. This approach is increasingly followed for the production of catalytic converters, but for fuel cells it still requires the identification of suitable substitutes, which is still a matter of research and a technological breakthrough.

*Figure 10: Development of platinum demand for new cars in EU25*




Saurat (2006) reports that three countries produce most of the used platinum: South Africa (77%), Russia (13%) and North America (incl. others 10%). Taking into account these market shares and the different CO2 emission factors of Pt production (see Saurat 2006) ASTRA calculates the additional CO2 emissions occurring outside 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 CO2 by the shift towards hydrogen while driving and the upstream emissions of H2 production reach higher levels than the CO2 emitted during Pt production, though with about 3 Mio t CO2 in 2030 the latter is not negligible.

*Figure 11: Trade-offs between national and 'imported' CO2 emissions*



# 5 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 points of view: first, from a stakeholder perspective, and second, from a model-based perspective using the ASTRA model to implement a scenario for which the exogenous inputs concerning energy prices and technology diffusion are developed in related projects (WETO-H2 and HyWays).

Hydrogen provides the potential to develop a more sustainable transport system as its use, in particular in fuel cells, would enable: a diversification of the energy supply for transport both in terms of supplier regions and in terms of supply feedstocks; a reduction of the emissions of air pollutants and noise during the transport activity, which is particularly important for urban areas; and a reduction of 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 on whether implementation is feasible or if, for example, 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 becoming increasingly 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, in which 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 CO2-emissions occurring during the driving activity, which are reduced, and the upstream CO2 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 for climate change mitigation as total life-cycle CO2 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 the extraction and production of PGM are connected with significant environmental impacts (e.g. CO2 emissions, mine spoils) outside Europe. 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 although hydrogen used in fuel cells producing electricity to propel electric engines appears to provide a promising option for a sustainable transport system, it still has to overcome significant technological barriers and it is in competition with other plausible solutions, which include battery-powered electric vehicles. The same caveat about technological barriers to be overcome applies also to this and other competing technologies and it is unclear yet which technology will break through its barriers faster and how competition between technologies will play out. There is also international competition to consider. An important aspect from a European perspective concerns the economic and trading implications of being (or not being) in the forefront of hydrogen technology development. For these reasons, investing in hydrogen research, technology development and demonstration projects may also be justifiable as a hedging strategy in the event that breakthroughs are achieved in hydrogen energy chains and mobile fuel cell technologies that lead to hydrogen emerging as a dominant technology in the future.

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

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