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Conditions for market penetration of hydrogen fuel cell cars in the transportation sector

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I dedicate this work to my aunt Ewa.

Abstract

The transportation sector, similarly to other large-scale systems like heat or electricity networks, carries numerous benefits and burdens. In the case of the transportation sector the benefits comprise of the support of the economical development as well as mobility for citizens. Nevertheless it also carries heavy environmental and climate burdens (local pollutants and CO_2), and dependency on oil, which often has unstable prices and lacks security of supply. In the light of the mentioned disadvantages, it is claimed by many that by mid century we could be considering alternatives.

In this study an assessment of the potential conditions which would need to be fulfilled in order for hydrogen to substitute the conventional oil-based transportation system, has been presented.

The research has been carried out using three different optimization models, which focused on different time frames (2000-2050/2100), world regions (from single to global scale) and sub-sectors of the transportation sector (from passenger vehicles, buses to road freight and other aggregated modes). All of the models employed were equipped with state of the art Endogenous Technological Learning, which allows for cost reduction of selected technologies, as function of increasing cumulative capacity. The primary execution of the analysis employed extensive sensitivity analysis of various factors which could have potential impacts on market penetration of hydrogen fuelled fuel cell vehicles. The tested factors included: fuel cell prices, their respective learning rates (as element of the introduced endogenous technological learning), initial number of vehicles launched to the market, trends in oil prices, dynamics of hydrogen infrastructure build-up, internalisation of external costs of local pollutants (NOx, SOx) and global greenhouse gases (CO_2) as well as government supportive policies for fuel cell vehicles (cash-back promotions, preferential crediting options and "demonstration vehicle" projects).

The results of the study suggest that the two most crucial elements are the price of fuel cells (price ought to be in the range of 600 US$/kW by the time the fuel cells are ready from market deployment) and their potential to further reduce costs as function of growing market popularity (learning rate of 15% or more). Further, the results of the study suggest that the development of the infrastructure may be of lesser importance in the early years of the switch to hydrogen based mobility. However, this importance should not be omitted in long term planning. The results further suggest that in the case when the fuel cells are on a break-even point, the governments may have numerous policy measures as to initiate the switch. Such policy measures may include internalisation of externalities (negative impacts of pollution coming from the transportation sector), demonstration and deployment tactics as well as direct subsidies to fuel cells in form of cash-back promotions for the purchase of fuel cell vehicles as well as preferential credits for projects which contribute to the build-up of the hydrogen infrastructure.

Results of the study suggest that short term policy instruments, which could aid the transition to hydrogen based transportation sector, ought to be targeted at the fuel cell vehicles themselves (especially the fuel cells stack) as their cost is the most significant obstacle. Moreover, promoting the fuel cell vehicles may be a very promising policy tool. This may increase the popularity of fuel cell vehicles, triggering the demand for this type of cars. Furthermore, promotion of hydrogen fuel cell vehicles could contribute to the number of vehicles in service, which in turn would contribute to the cost reduction of fuel cells (expressed in the modelling framework as Endogenous Technological Learning). Further, the results suggest that long run policy instruments target the build-up of fully fledged hydrogen infrastructure, which could prove to be a bottle neck for the development of hydrogen based transportation in a long timeframe. Moreover, long term policy options could target penalisation of emissions (such as CO_2, NOx and SOx) which originate from technologies generating fuels as well as vehicles themselves. Such policy option could impose more pressure and cause a more dynamic shift to hydrogen option.

The study, apart from bringing results suggesting condition for possible market penetration of hydrogen fuel cell vehicles, contributed also to the extension of the modelling framework of the GMM (Global Markal Model) in terms of more explicit representation of the global transportation sector. GMM is widely used by numerous research and governmental institutions, which can benefit from the expansion. The expansion makes GMM a more robust tool for designing and evaluation of environmental policies.

Kurzfassung

Der Verkehrssektor bietet der Gesellschaft verschiedene Formen von Nutzen, bringt aber auch, ähnlich wie bei anderen grossräumigen Systemen wie dem Wärme- oder Elektrizitätssektor, verschiedene Belastungen mit sich. Im Falle des Verkehrssektors liegt der gesellschaftliche Nutzen insbesondere in der Unterstützung von wirtschaftlicher Entwicklung sowie in der Mobilität der Bürger. Die einhergehende Umwelt- und Klimabelastung durch CO2 und lokale Luftschadstoffe sowie die Abhängigkeit von Öl, welches Preisschwankungen unterliegt und Probleme der Versorgungssicherheit aufwirft, sind jedoch zwangsläufige unerwünschte Belastungen. Angesichts dieser Nachteile könnte die Suche nach Alternativen zur Mitte dieses Jahrhunderts nötig sein.

In dieser Arbeit wird eine Einschätzung der nötigen Bedingungen vorgenommen, unter denen Wasserstoff das konventionelle ölabhängige Transportsystem ersetzen könnte.

Die Untersuchung wurde mittels dreier verschiedener Optimierungsmodelle vorgenommen, die verschiedene zeitliche Rahmen (2000-2050/2100), Weltregionen (Einzelregionen bis ganze Welt) und Unter-Bereiche des Verkehrssektors (von Individualverkehr und Bussen bis Güterverkehr und sonstigen Möglichkeiten) beleuchten. Alle Modelle verwendeten Endogenes Technisches Lernen (ETL) nach Stand der Technik, das Reduktion der Kosten einzelner Technologien in Abhängigkeit steigender kumulierter Kapazität gestattet.

In der Hauptsache wurde eine ausführliche Analyse der Sensitivität verschiedener Faktoren vorgenommen, die Einfluss auf die Marktdurchdringung von Wasserstofffahrzeugen haben könnten. Dabei wurden nachfolgende Faktoren untersucht: Kosten von Brennstoffzellen, ihre jeweilige Möglichkeit technologischen Lernens (als Teil der Verwendung endogenen technologischen Lernens), Anzahl der Fahrzeuge bei Markteinführung, Ölpreistrends, Dynamik des Aufbaus eines Infrastruktur für Wasserstoff, Internalisierung externer Kosten lokaler Luftschadstoffe (NOx, SOx) und globaler Klimagase (CO2) sowie politische Rahmenbedingungen zur Unterstützung von Brennstoffzellenfahrzeugen (cash-back Unterstützung, Vorzugskredite und „Demonstrationsfahrzeug‟-Projekte).

Die Ergebnisse dieser Arbeit legen nahe, dass die zwei wesentlichen Einflussfaktoren der Preis der Brennstoffzelle (der Preis sollte bei Markteinführung im Bereich von US$ 600/kW liegen) und ihr Potenzial zu weiterer Kostenreduktion bei steigendem Marktanteil sind (Lernrate von 15% oder mehr). Desweiteren legen die Ergebnisse dieser Arbeit nahe, dass die Entwicklung der Wasserstoff-Infrastruktur in den ersten Jahren einer Wasserstoff-basierten Mobilität von untergeordneter Bedeutung ist. Nichtsdestotrotz sollte die Wichtigkeit der Infrastruktur bei vorausschauender Langzeitplanung nicht unterschätzt werden. Die Ergebnisse dieser Arbeit zeigen weiterhin, dass zum Zeitpunkt des Erreichens der Rentabilitätsgrenze von Brennstoffzellenfahrzeugen regierungsseitig verschiedenste Policy-Instrumente zur Unterstützung des Umstiegs zur Verfügung stehen. Diese Instrumente umfassen die Internalisierung externer Kosten (nachteilige Auswirkungen der Verschmutzung durch den Verkehrssektor), Strategien der Demonstration und Entwicklung sowie direkte Subventionen von Brennstoffzellen durch cash-back Unterstützung beim Kauf eines Brennstoffzellenfahrzeugs oder Vorzugskredite für Projekte die zum Aufbau einer Wasserstoff-Infrastruktur beitragen.

Ferner legt diese Arbeit nahe, dass kurzfristig wirksame Policy-Instrumente, die den Übergang zu einem wasserstoffbasierten Transport-Sektor unterstützen sollen, sich die Brennstoffzellenfahrzeuge selbst (und hier speziell die Brennstoffzellen) zum Ziel setzen sollten, da deren Kosten das hauptsächliche Hindernis darstellen. Auch die Verkaufsförderung von Brennstoffzellenfahrzeugen könnte ein vielversprechendes Policy-Werkzeug sein. Dies könnte die Popularität dieser Fahrzeuge steigern und damit die Nachfrage ankurbeln. Zudem würden verkaufsfördernde Massnahmen die Anzahl der Fahrzeugen auf dem Markt erhöhen, und damit zur Reduktion der Kosten für Brennstoffzellen beitragen (im Modell ausgedrückt mittels endogenen technologischen Lernens).

Gleichzeitig zeigen die Ergebnisse dieser Arbeit, dass langfristig wirksame Policy-Instrumente den Aufbau einer Wasserstoffinfrastruktur zum Ziel haben, da es sonst zu Engpässen in der Entwicklung eines wasserstoffbasierten Transportsektors kommen könnte. Langfristig wirksame Policy-Optionen könnten beispielsweise Emissionen (wie CO2, NOx und SOx) sowohl aus der Herstellung von Treibstoffen als auch aus ihrer Verwendung zum Ziel haben. Eine solche Policy Option könnte den Druck und damit die Dynamik einer Umstellung auf Wasserstoff erhöhen.

Die vorliegende Studie hat neben den Analysen zu Rahmenbedingungen für die Marktdurchdringung von Brennstoffzellenfahrzeugen auch zur Erweiterung des Modells GMM (Global Markal Model) beigetragen, indem der globale Transportsektor detailliert erweitert wurde. GMM wird von zahlreichen Forschungs- und Regierungsorganisationen genutzt, sie von dieser Erweiterung profitieren können. Die Erweiterung des Transportsektors macht GMM zu einem robusteren Werkzeug für das Design und die Bewertung von Umweltpolitischen Massnahmen.

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List of abbreviations

AFR	**Afr**ica Region made up of all the countries on the African continent
ASIA	Centrally planned **Asia**, South **Asia** and Pacific **Asia** Region made up of Asian countries not members of former soviet Union and far east countries (Koreas, Vietnam, Malaysia, etc.)
BBL	Price of crude oil
CC	**C**umulative **C**apacity The cumulative capacity is the sum of all the capacities installed (delivered to the market) in the timeframe from the moment a technology started 'producing' to the given time (for example the end of the time horizon of the analysis)
CCo	Initial **C**umulative **C**apacity
CCo_{H2FC}	Initial number of hydrogen fuelled fuel cell vehicles launched to the market
CCoH2FC	Initial **C**umulative **C**apacity of Hydrogen (**H2**) **F**uel **C**ell Vehicles
CDA	**C**ausal **D**iagram **A**nalysis
CPA	**C**entrally **P**lanned **A**sia Region made up of such centrally planned countries as China, Mongolia and Nepal
crf	**C**apital **R**ecovery **F**actor This factor allows for discounting of investments costs of a given technology over it's technological lifetime
EEFSU	**E**astern **E**urope and **F**ormer **S**oviet **U**nion Region made up of former Soviet Union and Eastern Block countries (Slovakia, Hungary, Romania, Poland, etc.)
EEU	**E**astern **Eu**rope Region made up from the former Eastern Block countries (Slovakia, Hungary, Romania, Poland, etc.)
ETL	**E**ndogenous **T**echnological **L**earning
ETL investment	**Inv**estment Costs, which undergo **E**ndogenous **T**echnological **L**earning

etlcost	**Inv**estment Costs, which undergo **E**ndogenous **T**echnological **L**earning, specified for passenger cars specific to each particular vehicle type. This cost covers such items as for example the fuel cells which are an essential element of the hydrogen fuel cell car. The given parameter may be directly read from the data tables
EXT	EXT region externality internalisation scaling factor
FIXOM	**Fix**ed **O**perations **M**aintenance Costs Costs related to operation of a technology, independent if the technology is being used or not; such costs are accounted if a technology is on the market and may be operational. FIXOMs usually include such elements as insurance costs, operating personnel, etc.
FSU	**F**ormer **S**oviet **U**nion Region made up from the former Soviet Union (currently Russian Federation, Belarus, Lithuania, Ukraine, etc.)
Gasoline	**Gasoline** passenger car
Gasoline-electric hybrid	**Gasoline-electric hybrid** passenger car
GDP	**G**ross **D**omestic **P**roduct
GDP ppp	Gross Domestic Product referred in Purchase Power Parity
GDP/capita	Ratio of **GDP** to **capita** (population) economic indicator
H2	Final price of hydrogen
H2FC	Hydrogen (**H2**) **F**uel **C**ell Vehicle
H2FC initial cost	Initial cost of the Hydrogen (**H2**) **F**uel **C**ell
H2FC-kW	Cost of 1kW of fuel cell stack used in a hydrogen fuelled fuel cell vehicle
H2FC-kW Floor	Hydrogen (**H2**) **F**uel **C**ell price **Floor** Cost
H2FC-LRN	Hydrogen (**H2**) **F**uel **C**ell **L**earning **R**ate
H2kW	Hydrogen (**H2**) **F**uel **C**ell price
HST	**H**igh **S**peed **T**ransport
LAFM	**L**atin America, **Af**rica and **M**iddle East

	Region comprised of Latin America (from Mexico south), Africa (whole continent) and Middle East (Saudi Arabia, Kuwait, Iraq, Iran, etc.)
LAM	**L**atin **Am**erica Region made up of counties south of Mexico (including Mexico)
LRN	**L**ea**rn**ing rate
MEA	**M**iddle **Ea**st Region made up of Middle East countries (Saudi Arabia, Kuwait, Iraq, Iran, etc.)
MIP	**M**ixed **I**nteger **P**rogramming
NAM	**N**orth **Am**erica Region of North America, made up of USA and Canada
non-ETL	**Non**-**E**ndogenous **T**echnological **L**earning index; this index indicates that the discussed costs do not undergo the Endogenous Technological Learning costs reduction mechanism
OOECD	Western Europe and Pacific **OECD** Original European Union (EU 15 countries), Switzerland, Turkey, Norway, Australia, New Zealand, Japan
PAO	OECD countries in the **Pa**cific **O**cean Region made up of pacific OECD countries like Australia, Japan and New Zealand
PAS	Other **P**acific **As**ia Other countries in the Asian region which did not fit in to other divisions
PPL-GR	Hydrogen **P**i**p**e**l**ine **G**rowth **R**ate
pr	**P**rogress **R**atio
PV	**P**resent **V**alue the parameter is calculated as $1/(1+DR)^t$ where DR is the **D**iscount **R**ate, and serves the purpose of discounting the investment costs
PVC	**P**resent **V**alue of **C**osts The main variable which contains the lowest possible cost of the combination of activities of vehicles, generation technologies, as

	well as including their individual, technology specific costs
SC	**S**pecific **c**ost (at given cumulative capacity)
SCo	Initial **s**pecific **c**osts of the first unit of production at given initial cumulative capacity
VAROM	**Var**iable **O**perations **M**aintenance Costs Costs directly related to the operation of a given technology. Using an example of a personal car, such costs usually accounts for engine oil, tyres, break pads, etc. In the case of for example hydrogen generation technologies these costs would include lubricants used for hardware, cleaning of the equipment, production related checkups, etc.
v-km	**V**ehicle **km** 1 km travelled by a road vehicle
WesternEurope	Index designating the West European countries (equivalent to the WEU region)
WEU	**W**estern **Eu**rope Region made up from the former Western European Block countries (EU 15 with Switzerland and Turkey)

1 Introduction

1.1 The transportation sector – benefits and burdens

In modern societies, almost every form of human activity is accompanied by energy consumption. This resulting energy demand may be associated with direct application of energy (in form of heat or electricity) or other application such as transportation allowing for mobility. While the heat and electricity sectors have been broadly discussed by numerous researchers, the transportation sector still provides much space for exploration as to suggest pathways for development, which may improve its operation. Today transportation is one of the indispensable elements of every countries economy. From moving people, animals, materials to transportation of final end products, the transportation sector has a major impact on how citizens and goods reach their destinations. As economies develop, so does the demand for transportation which allows further development and well being of societies. Therefore, over the past century one may notice a strong bond and dependency of nations on their transportation sectors (BP 2005).

However, since the developments of the gasoline and diesel engines, most of the transportation systems have started depending on these two technological solutions. This has created a dependency between the ever needed transportation and oil, which is the primary source for creating gasoline and diesel. This dependency has created in many regions of the world a "supply security" problem, which is vital for effective and undisturbed functioning of the transportation sector. Moreover, increased activity during the last century has placed the transportation sector among one of the main emitters of CO_2 and local pollutants. The resulting combination of oil security supplies, increasing price of oil and the environmental burdens have imposed a question if oil based transportation should be altered. If possible, this change would allow for such improvements so that security of fuel supply could be maintained, while at the same time the environmental soundness and fuel price stability were secured. Many options which are discussed broadly on scientific and political levels include switching to more advanced vehicle technologies (like gasoline/diesel-electric hybrids) and a possible switch to other alternative fuels (Keith and Farell 2003; Kröger, Fergusson et al. 2003). The first discussed option is already being implemented today; this may be observed in the fact that many vehicle manufacturers include in their vehicle portfolio cars with low fuel consumption (like the "Lupo 3L" from VW) or cars with hybrid power trains (like "Prius" from Toyota, "Insight" from Honda or "Ram Diesel Hybrid" from Dodge). Nevertheless, the hybrid vehicles and highly efficient diesels are dependant on gasoline and diesel, and still pollute the environment. Therefore, one may perceive this strategy as a time 'buyer', leaving the mentioned problems with the need to be solved eventually.

In terms of alternative fuels the discussions point to numerous choices (methanol or bio-diesel to mention the two), however one of them in particular seems quite promising. It is claimed by many, that hydrogen could be such an alternative fuel (Fergusson 2001; Farrel, Keith et al. 2003; Hekkert, Faaij et al. 2004; Service 2004; Wokaun, Baltensperger et al. 2004).

Hydrogen based transportation could bring numerous benefits and prove far superior of a solution than the currently existing oil dependant transportation system. Firstly, hydrogen as fuel is a cleaner, in terms of environmental concerns, as compared to gasoline or diesel. Secondly, if hydrogen based mobility would become a reality one may think of fuel cell vehicles; this means, vehicles with a fuel cell stack and an electric motor, which have a much higher efficiency than cars equipped with conventional internal combustion engines. Thirdly, hydrogen may be generated locally from numerous primary energy sources (conventional as well as renewable), which could secure generation and supply of fuel and additionally stimulate local economy. Experts point to many more arguments in favour of hydrogen based mobility, such as lower noise levels coming from fuel cell vehicles as compared to conventional cars, hydrogen is a safer fuel as compared to gasoline – both in terms of human impacts (safety) as well as the natural environment (emissions, leakages, etc.).

Nevertheless, today the hydrogen based mobility is still a concept. This is mainly due to technical and economical reasons. Currently fuel cells are still under development, while with still significant deficiencies (for example the lifetime of the membranes) they are priced above any level of competitiveness. Moreover, the hydrogen infrastructure is basically inexistent. Nevertheless, numerous business enterprises as well as scientific institutions and governments are intensively working on the hardware and conditions essential for the hydrogen based mobility. Looking at the progress which has been achieved over the past decades, one may picture that in the coming 30 years a transition to hydrogen based mobility may become a reality (Pridmore and Bristow 2002).

1.2 Research scope

In this research the main stress has been placed on analysis of the conditions which would need to be met in order to allow the hydrogen based mobility to become a reality. The analysis of the issue has been initiated by defining research questions which would need to be addressed in order to suggest an answer to the main question of the analysis. Among numerous research and methodological questions, the following have been outlined:

- Can, and under which conditions, hydrogen transportation replace the oil based transportation sector?
- Which elements of the transportation and energy sector would need to be considered to resolve the issue?
- Which technological options are/will be there, which could facilitate hydrogen based transportation?
- What are the critical elements of technologies supporting hydrogen based transportation?
- What are the strengths/weaknesses and thresholds characteristics of technologies supporting hydrogen based transportation?
- What methodological framework would be necessary to draw a guide path for addressing the issue of potential future developments of hydrogen based mobility?
- What methodological tools would be required for the analysis?

Later, having defined the research and preliminary methodological questions which would need to be addressed, a methodological framework was established as to outline the steps which would need to be carried out as to facilitate the analysis for answering of the research issues. The diagram, in form of a goal tree, illustrates the methodological framework (conceptual approach) to the analysis of the issue (**Figure 1**).

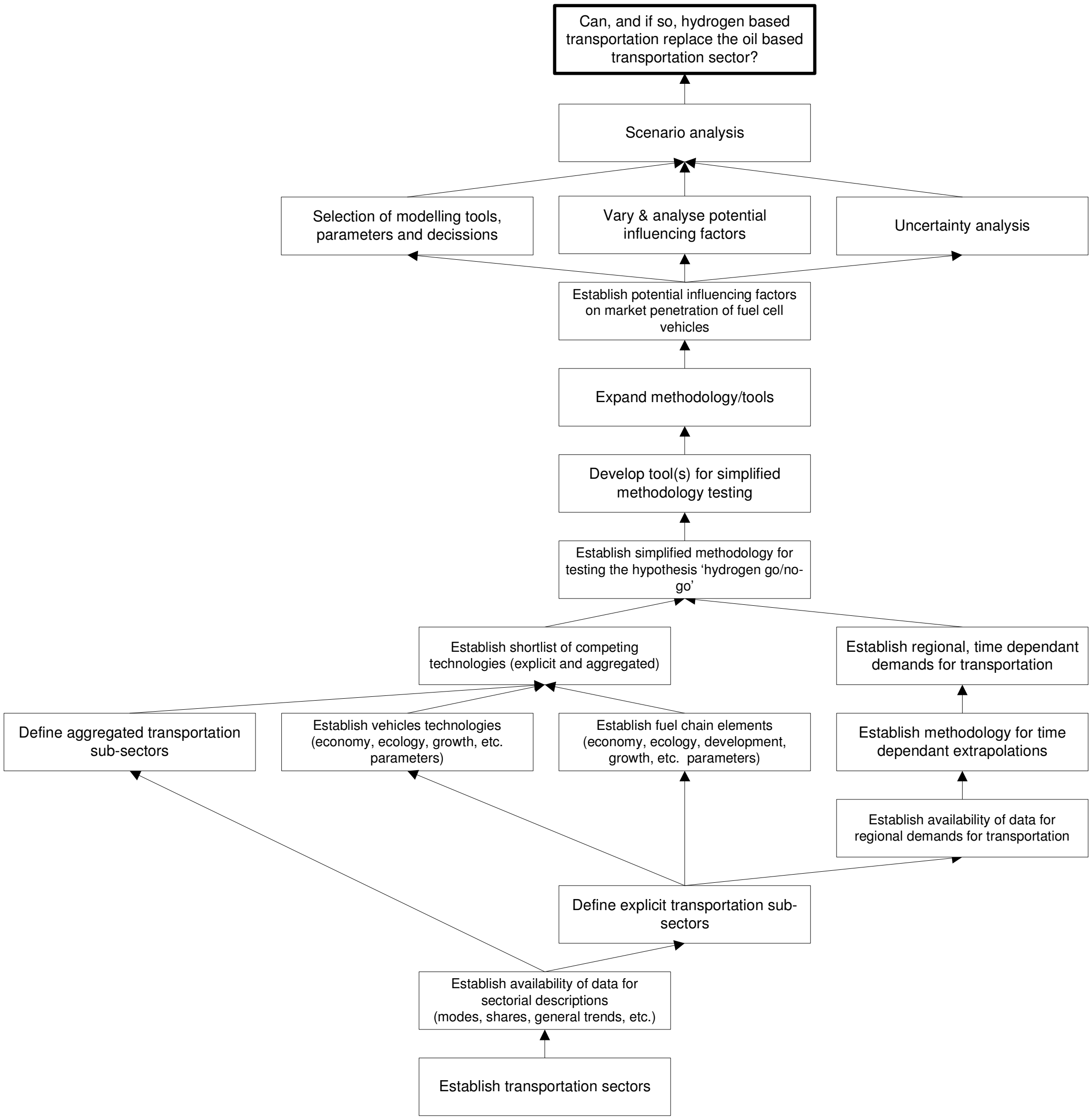

Figure 1 Schematic diagram of methodological approach within the research framework of the dissertation

Next, after having prepared the main methodological framework, a task was established to develop methodological tools which would directly facilitate the analysis.

1.3 Methodology

On the basis of the established research questions, assumed methodological approach, in-house[1] knowledge and experience from other researchers (Barreto and Kypreos 1999; Babiker, Reilly et al. 2001; Breugem, van Vuuren et al. 2002), it has been decided that the most appropriate way of tackling the issue of the future potential for hydrogen to become the core of the transportation sector would be using an optimisation modelling framework.

Due to the complex nature of the system analysed, the analysis would be carried out step wise. Firstly, using crude and general assumptions as to outline the corner stones of the system and its potential behaviour. Later, expanding the modelling framework as to include a more detailed characterisation of the transportation sector. Lastly, the findings from the first two parts would be tested in a full scale energy model.

In terms of tool development for each step of the analysis the following tools have been developed:

Step 1 General assumptions modelling and evaluation

In the first phase, a stand-alone optimisation model was created. Using a simplified market conditions, the results were to show if the "hydrogen transportation" is at all a realistic possibility. This analysis was carried out using a model called FinalTRA, which analysed the sub-sector of personal vehicles, in a single world region in a timeframe of 100 years (2000-2100).

Step 2 Extended analysis of the transportation sector

Achieving positive results, that indeed, the "hydrogen transportation" is a realistic option, the analysis was deepened by substituting several of the exogenous inputs (like the price of hydrogen) to the model, with endogenous ones. This approach resulted in a more realistic representation of the analysed system in a model called CUBE. The modelling framework of CUBE was, similarly to FinalTRA, restricted to one world region, and a timeframe of 100 years (2000-2100).

Step 3 Full scale energy systems analysis

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[1] of the Paul Scherrer Institute, Energy Economics Modelling Group

Lastly, the hydrogen transportation was placed in a global level, within the framework of the GMM model (Kypreos 1996; Loulou, Goldstein et al. 2004).

More detailed description of each of the models used has been presented in the following chapters (Chapters: 3.1 Introduction to FinalTRA – H_2FC in "laboratory" market conditions, 4.1 Introduction to CUBE – the complexity of full hydrogen fuel chains, 5.1 Introduction to GMM – broad scale market entrance of advanced technologies).

The following diagram illustrates the application of the methodological framework and tools developed as to facilitate an environment for tackling the research questions (**Figure 2**).

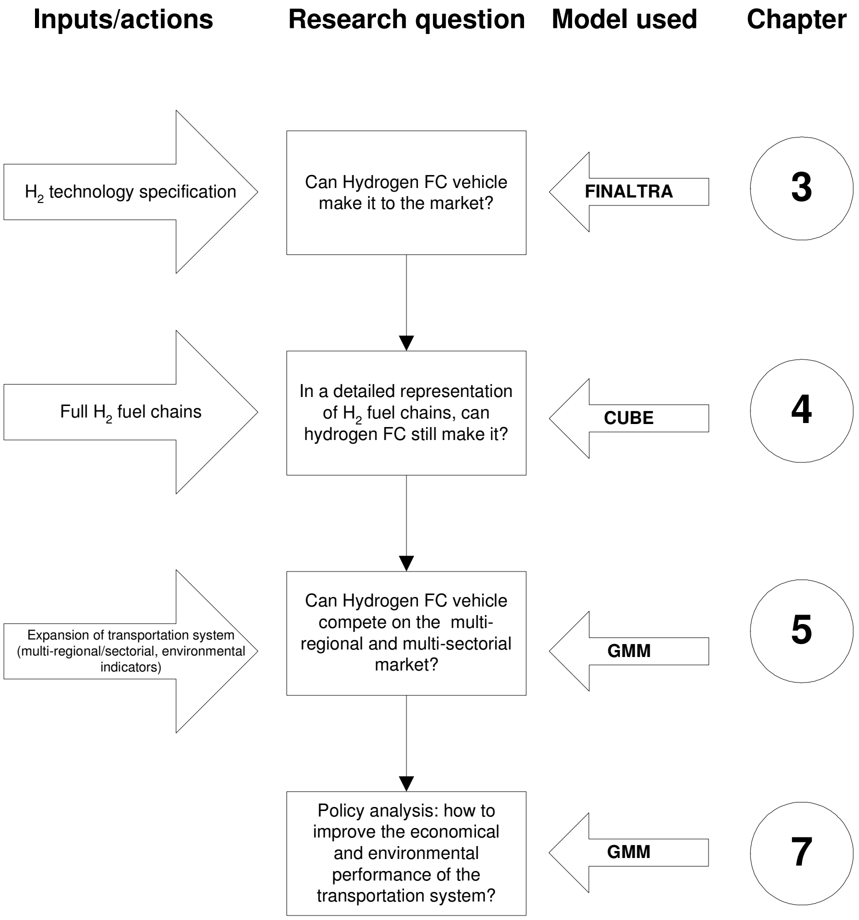

Figure 2 Schematic diagram illustrating steps carried out within the research framework of the dissertation

1.4 Structure

The rest of the document has been organised as follows. In Chapter 2 (Description of tools and inputs) the input data for the modelling framework is presented. Here the reader will find a detailed description of technologies used for transportation (vehicles), generation, transmission and distribution of fuels, as well demands for transportation. In the following part, Chapter 3 (Does the hydrogen fuelled FC vehicle stand a chance? Analysis conducted with FinalTRA) the inputs are put together in a simplified market allocation model called FinalTRA, with the aim of addressing the question if hydrogen transportation is a feasible option. The results include first sensitivity analyses, pointing to relevant factors, which may have a substantial influence on the market diffusion of the hydrogen transportation sector. Later, in Chapter 4 (Market penetration of advanced transportation technologies. Analysis conducted with CUBE), the modelling framework was expanded in a model called CUBE with the aim of addressing the question of how the chances of hydrogen based transportation could change in a more realistic representation of the transportation sector with a significantly higher number of endogenous parameters. The results contain more information of the factors promoting and/or limiting the development of hydrogen based transportation system. Next, in Chapter 5 (Market penetration of advanced technologies on global scale. Analysis conducted with GMM) the hydrogen option is introduced into the global transportation, modelled using an optimisation model called GMM (Kypreos 1996; Loulou, Goldstein et al. 2004). Later, in Chapter 6 (Consistency across model results) a methodological assessment of the consistency of the results coming from all three models is presented. Following this, in Chapter 7 (Global impacts of advanced transportation technologies) the results of policy analysis, aiming at introduction of sustainable alternatives to the current oil-based transportation system, are presented. In final part of this document, Chapter 8 (Conclusions) conclusions from all phases of the analysis are drawn and recommendations for policy analysis are presented.

2 Description of tools and inputs

The modelling framework of the transportation sector, in this analysis, concentrates on a global scale, with the world divided into 5 main regions (GMM-model type division); this has been illustrated below (**Figure 3**).

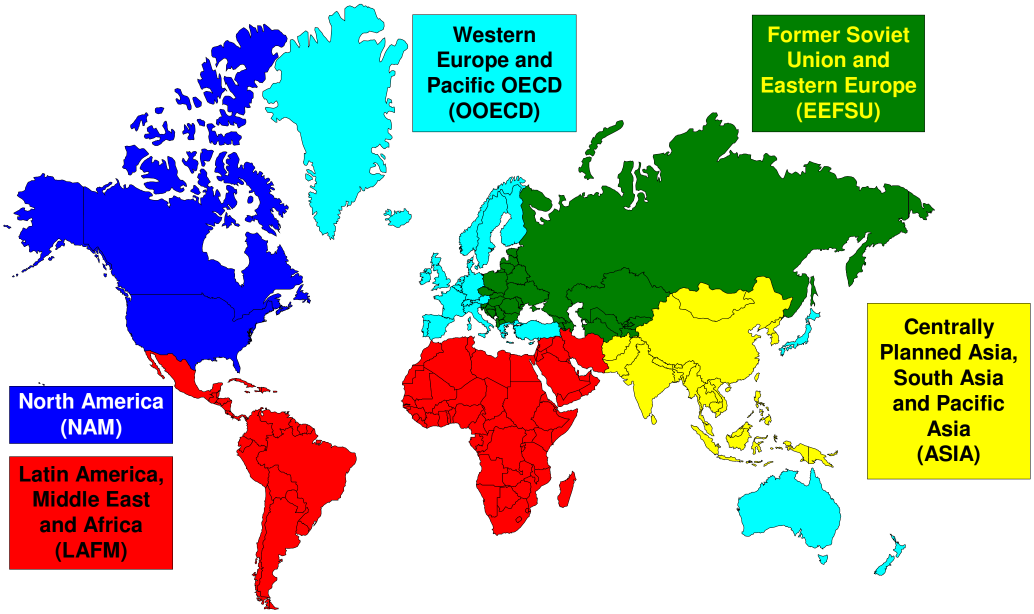

Figure 3 Division of the world into regions, as used in FinalTRA, CUBE and GMM

The timeframes used for the analysis consisted of two: one being a short-range (2000-2050, used in GMM) and one being a long-range (2000-2100, used in FinalTRA and CUBE).

The transportation sector consists of many modes, like personal vehicles, buses, passenger railroad, airplanes, etc. For the analysis presented in this document, three modes have been selected, being Personal Vehicles, Buses and Road Fright Transportation[2]. The choices of different modes and timeframes for models used have been illustrated on the following diagram (**Figure 4**). A more detailed description of the specific modes and transportation technologies has been presented in the descriptive part of each of the models used in the analysis.

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[2] Freight trucks, with a pay load of 35-40 tonnes (similar to the U.S. class 8 trucks)

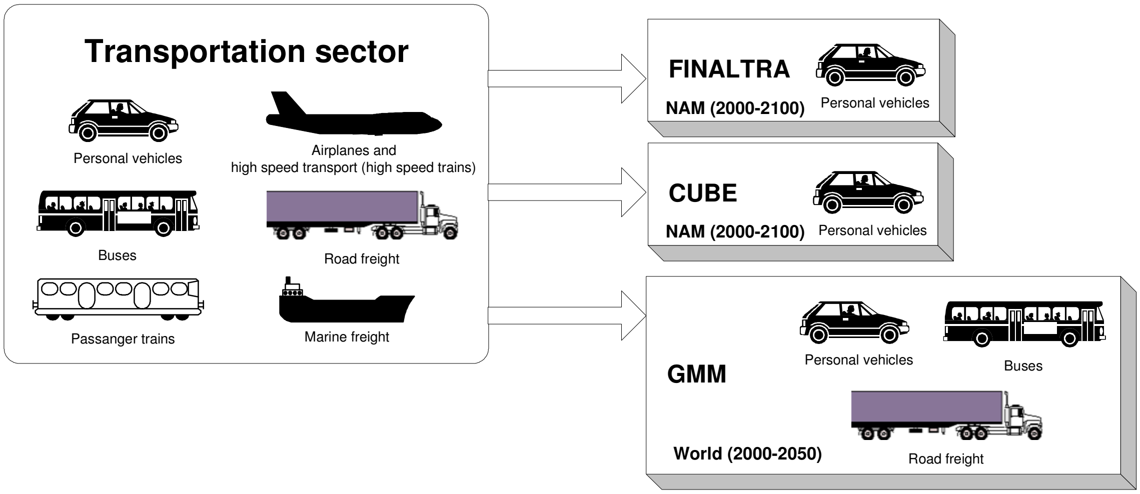

Figure 4 Illustration of modes and timeframes used in FinalTRA, CUBE and GMM

2.1 Vehicle technologies

One of the main constituents of the transportation sector are the vehicles in operation. For the analysis with the first two models (FinalTRA and CUBE) only the personal vehicles have been selected as to allow flexibility and reduce the calculation time of the models. In GMM however, this has been expanded as to include apart from personal vehicles also buses and heavy road freight. Each of the models has used the same technological description of the included vehicles (**Table 1**).

Each of the vehicle technologies representing vehicles for a given sub-sector has been selected in such way as to allow for comparability. Therefore for Personal Vehicles the representative car is a 5-seater, with a weight of ~1,350kg and an engine capacity ~2 l (gasoline) or 1.9 (diesel). The illustrative vehicle may be compared to Audi A4 or Honda Accord. The annual mileage has been assumed to be 17,000 km/year (Roder 2001; Breugem, van Vuuren et al. 2002; Pridmore and Bristow 2002; Ogden, Williams et al. 2004).

In the sub-sector of buses, the buses have been described on the basis of a model bus which is an average city bus with 45 passenger seats; the annual mileage has been assumed to be 45,500 km/year (Pelkmans, De Keukeleere et al. 2001; Brager 2003). In the road freight sub-sector the trucks selected are the represented by a 19 ton pay load truck (US Class 8) with an annual mileage of 134,000 km/year (DaimlerChrysler 2003; Ergudenler and Jennejohn 2005).

Table 1 Description of vehicle technologies as used in the analysis with FinalTRA, CUBE and GMM models (Austin, Dulla et al. 1999; Contadini 2000; Weiss, Heywood et al. 2000; Metschies 2001; Pelkmans, De Keukeleere et al. 2001; Roder 2001; L-B-Systemtechnik 2002; Brager 2003; DaimlerChrysler 2003; Litman 2003; Toyota 2003; Hekkert, Faaij et al. 2004; Ogden, Williams et al. 2004)

Vehicle type	Year of availability	Purchase price	Fixed costs	Variable costs	Fuel efficiency[3]	ETL		Market share in 2000
						Learning rate	ETL costs	
		[US$]	[US$/1k v-km]		[k v-km/GJ]	[%]	[US$]	[%]
Gasoline	2000	18,600	70	8.1	0.3502	Non-ETL technology		75%
Diesel	2000	20,500	70	8.1	0.4081	Non-ETL technology		25%
Gasoline-electric hybrid	2000	22,000	70	8.1	0.7648	10	2,000[4]	<0.1%
Electric	2050	22,500	100	8.1	1.7800	10	2,000[5]	-
Hydrogen fuel cell	2030[6]	20,000[7]	50	8.1	1.2000	5-20	10,000-50,000[8]	-

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[3] "Non-ETL technologies" are subject to time-dependant improvement of fuel efficiency, which is 7.5% per decade. Because of the assumption on the high efficiency of the "ETL technologies" they are not subject to time dependent improvement of fuel efficiency. The competitive position of the ETL technologies, despite lack of improvement on fuel efficiency may be sustained by ETL cost reduction mechanism of the ETL part of the costs (more description on ETL has been presented in Chapter 2.4 Learning-by-doing, the costs reduction mechanism)

[4] Cost related to the ETL of the battery

[5] Cost related to the ETL of the battery

[6] First year when the vehicles are available to be launched onto the market, however, despite the fact they are available, the optimisation system is free to do the market launch at later time

Bus – Diesel	2000	250,000	3000	653	0.0495	Non-ETL technology		~60%
Bus – CNG	2000	320,000	3000	653	0.0286	Non-ETL technology		~40%
Bus – Electric	2000	350,000	3000	653	0.0856	10	150,000	<0.1%
Bus – H_2 Fuel Cell	2010	850,000	3000	653	0.0750	5-20	50,000-250,000	-
Truck – Diesel	2000	167,000	20	146	0.0732	Non-ETL technology		100%
Truck – Diesel-electric hybrid	2010	170,000	20	146	0.0682	10	35,000	-

---

[7] Hydrogen fuel cell vehicle consists of a base personal car chassis with an electric motor, control devices, an onboard hydrogen storage (worth 15,000 US$) and a 50kW fuel cell stack (worth 5000 US$); this price is the floor cost; during market penetration the price of the fuel stack is increased with the ETL element (it's value is related to the cumulative market penetration and resulting reduction of price)

[8] Full price of a 50kW fuel cell stack; the ranges covers the prices of fuel cells from 200-1000 US$/kW

2.2 Fuel generation technologies

In all models the transportation sector description also includes the specification of fuels which are used for vehicles; the complexity of the descriptions varies however from model to model. This description defines steps from the extraction/generation of primary fuels, through conversion, transmission and final distribution to appropriate types of vehicles. An illustrative diagram has been presented below (**Figure 5**).

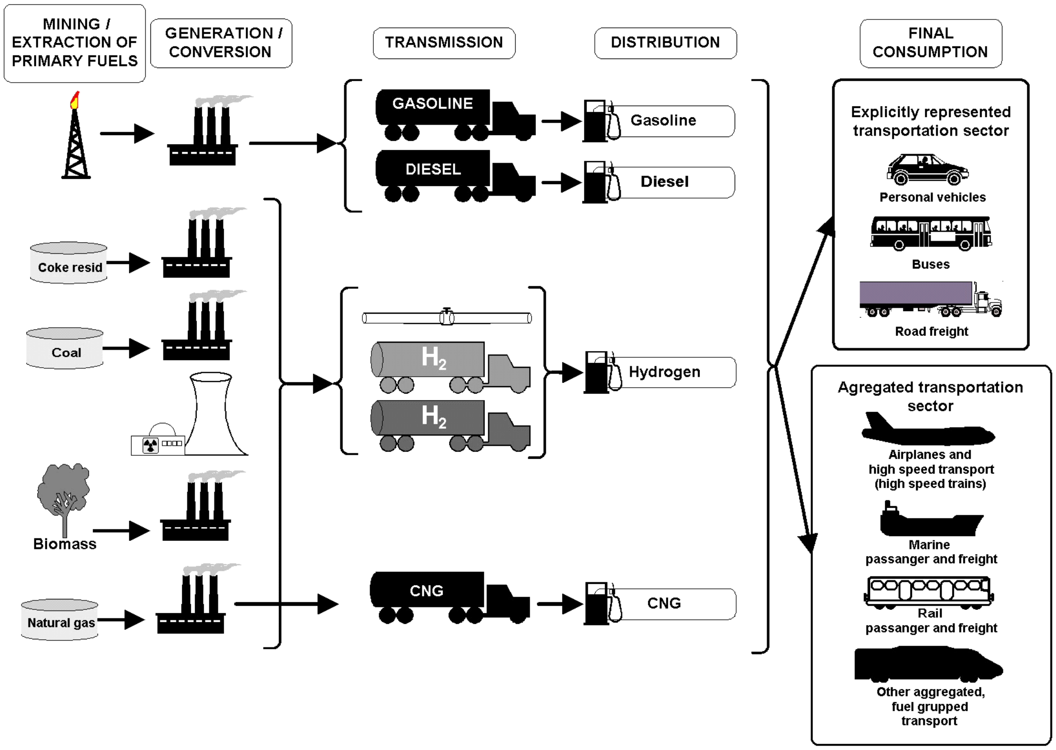

Figure 5 Illustrative representation of fuel chains as used in GMM

The specific elements included in each analysis have been specified in later parts describing each of the models in more detail.

The following tables present the specifications of the hydrogen fuel chains characteristics which have been used in the analysis with the three models (**Table 2** through **Table 4**).

The remaining description of the fuel chains as used in GMM may be found in the MARKAL Family of Models documentation (Loulou, Goldstein et al. 2004).

Table 2 Description of hydrogen generation technologies as used in the analysis with CUBE and GMM models (Simbeck and Chang 2002)

Technology	Investment costs[9]	FIXOM	VAROM	Feedstock		Operation fuel		Lifetime
				Type	Efficiency	Type	Efficiency	
	[US$/GJ H_2]				[GJ/GJ H_2]		[GJ/GJ H_2]	[years]
Natural gas reforming with compression (215 atm)	38.73	1.94	4.56	Natural gas	1.3123	Electricity	0.053	20
Natural gas reforming with pipeline compression (75 atm)	13.30	0.67	0.40	Natural gas	1.3123		0.022	20
Natural gas reforming with liquefaction	22.40	1.11	0.88	Natural gas	1.3123		0.337	20
Resid with pipeline compression (75 atm)	31.16	1.55	1.28	Residuals from oil refining	1.3157		0.077	20
Coal reforming with compression (215 atm)	75.46	3.77	6.37	Hard coal	1.4409		0.158	20
Coal reforming with pipeline compression (75 atm)	43.62	2.17	1.79	Hard coal	1.4409		0.108	20
Coal reforming with liquefaction	57.10	2.86	2.54	Hard coal	1.4409		0.450	20

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[9] The investment costs presented here have not been annualised; therefore in order to obtain the annualised value of the investment costs one needs to multiply the presented investment cost with CRF (Capital Recovery Factor). For technologies which have a technical lifetime of 20 years, with a discount rate of 5% the CRF ≅ 0.08 (EQ. 28)

Biomass with compression (215 atm)	76.13	3.81	6.48	Biomass	1.3157		0.189	20
Biomass with pipeline compression (75 atm)	49.69	2.48	2.29	Biomass	1.3157		0.145	20
Biomass with liquefaction	60.97	3.05	2.96	Biomass	1.3157		0.460	20
Electrolysis with compression (215 atm)	115.88	5.79	0.49	Water	1.5748		1.634	20
Electrolysis with pipeline compression (75 atm)	95.33	4.77	0.29	Water	1.5748		1.634	20
Electrolysis with liquefaction	101.40	5.07	0.35	Water	1.5748		1.935	20

For the analysis three types of transmission modes were selected. Firstly, a low pressure diesel truck delivery. Secondly, pipeline which could deliver hydrogen from the centralised generation sites to the fuelling station. The pipeline contrary to other two modes may not be created quickly, however once constructed allows for large thru-outputs ensuring reliability of deliveries. Lastly, a diesel truck carrying liquefied hydrogen. The last option, although flexible, requires hydrogen to be liquefied at the generation plant, which in turn involves demand for electricity for the operation of compressors (**Table 3**).

Table 3 Description of hydrogen transmission technologies as used in the analysis with CUBE and GMM models (Simbeck and Chang 2002)

Technology	Investment costs[10]			FIXOM + VAROM	Input/output efficiency of H_2 transmission	Operation fuel		Lifetime
	Non-ETL costs	ETL costs	Learning rate			Type	Efficiency	
	[US\$/GJ H_2]		[%]	[US\$/GJ H_2]	[%]		[GJ/GJ H_2]	[years]
Truck (215 atm compression)	23.75	Non-ETL technology		13.08	0.997	Diesel	0.099	10
Pipeline (215 atm)	101.57	13.73	10	6.14	0.997	Electricity	0.006	20
Truck (liquefied)	2.19	Non-ETL technology		1.12	0.997	Diesel	0.006	10

For the distribution of hydrogen to end consumers three types of fuelling stations have been selected. In order to match the three pressures in the delivery chains (75 atm, 215 atm and liquefied) the stations have been specified accordingly. For the end consumer the stations would provide the same service, however because of the predeceasing fuel chain their overall financial and technical performance varies (**Table 4**).

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[10] The investment costs presented here have not been annualised; therefore in order to obtain the actual value of the investment costs one needs to multiply the presented investment cost with CRF (Capital Recovery Factor) which allows for annualisation. For technologies which have a technical lifetime of 20 years, with a discount rate of 5% the CRF ≅ 0.08, while for technologies with a 10 year technical lifetime (also 5% of discount rate) CRF ≅ 0.13 (EQ. 28)

Table 4 Description of hydrogen distribution technologies as used in the analysis with CUBE and GMM models (Simbeck and Chang 2002)

Technology	Investment costs[11]			FIXOM+ VAROM	Input/output efficiency of H_2 distribution	Operation fuel		Lifetime
	Non-ETL costs	ETL costs	Learning rate			Type	Efficiency	
	[US$/GJ H_2]		[%]	[US$/GJ H_2]	[%]		[GJ/GJ H_2]	[years]
Low pressure (75atm)	35.71	2.58	10	2.49	0.997	Electricity	0.017	20
High pressure (215atm)	35.71	3.39	10	2.17	0.997		0.008	20
Liquefied	46.99	2.58	10	1.82	0.997		0.007	20

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[11] The investment costs presented here have not been annualised; therefore in order to obtain the actual value of the investment costs one needs to multiply the presented investment cost with CRF (Capital Recovery Factor) which allows for annualisation. For technologies which have a technical lifetime of 20 years, with a discount rate of 5% the CRF ≅ 0.08 (EQ. 28)

2.3 Demands for transportation

2.3.1 Demands for personal transportation (Personal vehicles and Buses)

The demand for personal transportation, which includes: Personal Vehicles (personal cars) and Buses have been calculated using the approach suggested by Schafer and Victor (Schafer and Victor 2000).

This approach is based on the concept of Travel Time Budget (TTB), which indicates that world-wide, citizens spend an average, fixed amount of around 1 hour a day for commuting. This includes work-office travel, as well as vacational travel, household trips, etc. The estimated TTB includes travel by different modes of transport – ranging from bipeds, personal automobiles to public transport and airplanes. Additionally, it has been noticed that the preference of citizens to travel with specific modes of transport is dependant on the income measurement (GDP/capita). Hence, citizens of countries with high GDP/capita level tend to use faster and more expensive modes of transport (for example airplanes), while citizens from lower-income countries, with low GDP/capita, tend to use slower modes.

The above mentioned observations have been described using mathematical equations, which allow the implementation into a modelling framework. In this study, a modified version of Schafer and Victor equations was applied as to more effectively work within the modelling environment. In what follows, the equations used have been presented. More information on TTB and the estimates on the dependency between preferences for mode transportation and shift to faster modes, is available elsewhere (Schafer and Victor 2000).

The overall demand for transportation, as a function of GDP/capita is defined as presented in EQ. 1 (Schafer and Victor 2000), where the demand for a given time period is directly derived from the GDP/Capita index for a given time period and region.

EQ. 1

$$TV(t) = Log\left(\frac{GDP(t)}{G} - H\right) * GDP(t)^{E*F}$$

Where:

TV	Overall demand for passenger transportation [passenger km]
t	Time index
GDP	GDP/capita, expressed in USD [USD'95]
G,H,E,F	constants (Schafer and Victor 2000) adopted for the GAMS code[12]

Further, out of the overall demand for transportation demands for specific modes are obtained in forms of shares, which is described in the following equations (EQ. 2 through EQ. 5) (Schafer and Victor 2000). The shares of each mode for a given time period are directly derived form the total demand for a given region and time period.

EQ. 2

$$S_{Rail}(t) = I * \left(\frac{1}{(TV(t)\text{-}J)^{K}} - \frac{1}{(240000 - J)^{K}}\right)$$

Where:

S_{Rail}	Share of railroad transportation [share of 1]
t	Time index
I,J,K	constants (Schafer and Victor 2000) adopted for the GAMS code
TV	Overall demand for passenger transportation [passenger km]

EQ. 3

$$S_{HighSpeed}(t) = S * 10^{e(-T*(TV(t)-U))} + V$$

Where:

$S_{HighSpeed}$	Share of high speed transport (airplanes and ultra fast trains) [share of 1]
t	Time index
T,U,V	constants (Schafer and Victor 2000) adopted for the GAMS code

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[12] Due to the precision limitations of the GAMS software, the constants were recalculated as to include the available precision rate of GAMS, hence the constants presented here are more precise as the ones actually entered to the GAMS code.

TV	Overall demand for passenger transportation [passenger km]

EQ. 4

$$S_{Bus}(t) = \frac{BK}{\left(TV(t) - TV_{Bus}(1990)\right)^{BM}} + BC - S_{Rail}(t)$$

Where:

S_{Bus}	Share of bus transportation [share of 1]
t	Time index
TV	Overall demand for passenger transportation [passenger km]
BK,BM,BC	constants (Schafer and Victor 2000) adopted for the GAMS code

EQ. 5

$$S_{PersonalVehicle}(t) = 1 - S_{Bus}(t) - S_{Rail}(t) - S_{HighSpeed}(t)$$

Where:

$S_{PersonalVehicle}$	Share of personal cars [share of 1]
t	Time index

Addition of all the shares (buses, personal cars, trains and high speed transport) yields 1.

The values of the original constants used for the calculation of the demand projection in the personal transportation sub-sector have been presented below (**Table 5**).

The regional division as proposed in the original source (Schafer and Victor 2000) used an 11-region division, which is different to the GMM 5-region division. The Adjustment of refitting was established by means of adding values of regions which ought to be aggregated according to the GMM world region division.

The illustrative example of the changes for LAFM region, as observed by Schafer and Victor, has been presented below (**Figure 6**). The later diagram (**Figure 7**) illustrates the development of the demand for personal cars across the 5 regions as used in GMM, which has been the primary demand used for the market balances.

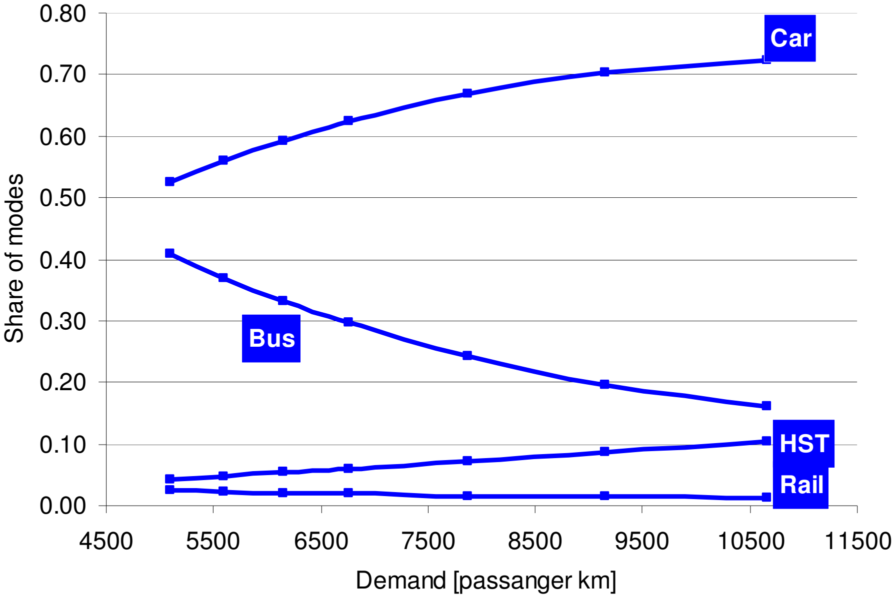

Figure 6 Modal changes in the demand for passenger transportation (LAFM illustrative example)

Observing the following diagram (**Figure 7**) one may notice a decline in the demand for personal vehicle transportation in some of the regions (for example NAM) by the end of the time horizon. This drop in the demand is a result of the modal change – as citizens become wealthier they tend to switch to more expensive modes of transport (namely high speed transport). Therefore, in the long run, the more and the faster economies develop, the more of an abrupt modal switch may be observed, hence reduction in the demand for transportation in given sub-sectors.

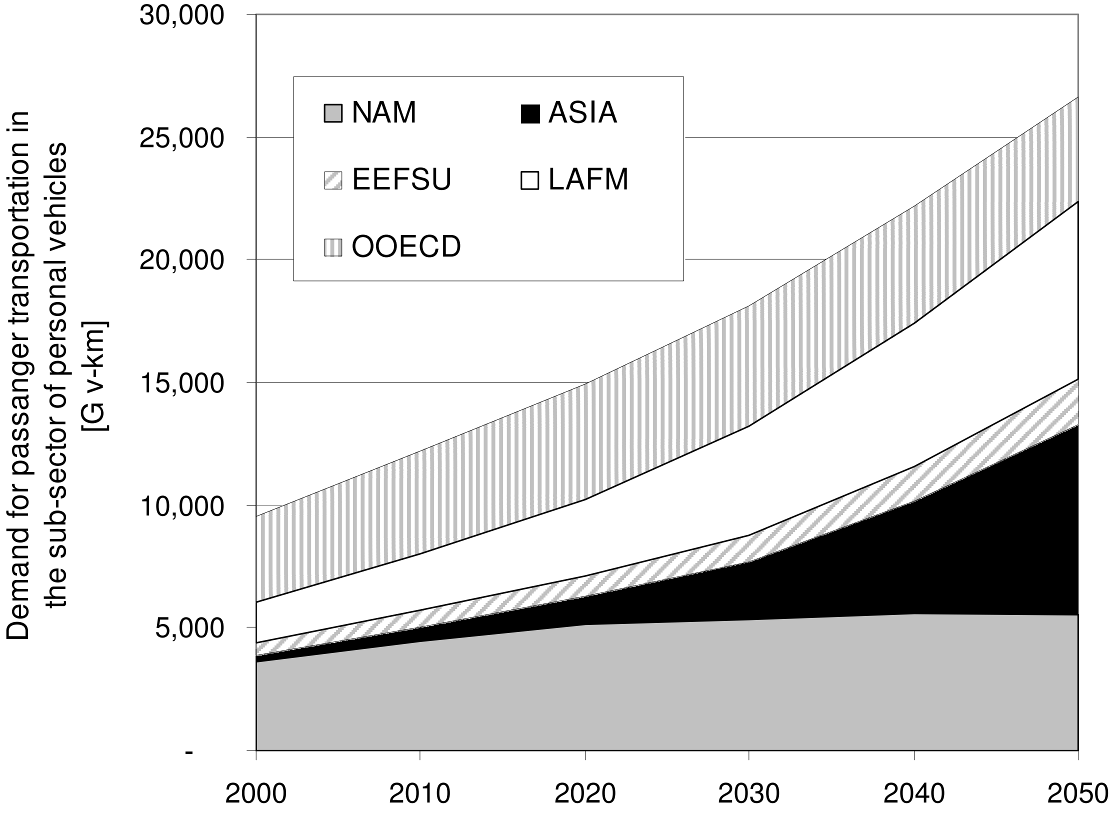

Figure 7 Demand for passenger transportation in the five geographical regions in the sub-sector of personal vehicles

Table 5 Specification of constants (dimensionless) for the estimation of demand projections for personal transportation (Schafer and Victor 2000)

Parameter	Region										
	NAM	LAM	WEU	EEU	FSU	MEA	AFR	CPA	SAS	PAS	PAO
E	0.766	0.946	0.720	0.401	1.095	0.913	0.910	0.598	0.769	0.746	0.930
G	40.2	-	1053	1.3e4	1.1e5	-	-	4202	13.2	202.5	5493
H	61.19	1.960	1.981	-1.061	-610.6	2.931	3.044	-.0931	54.95	0.041	-9.180
I	122.7	10.10	8.63	170.9	42.71	0.20	2.8e4	1068	12.09	0.558	3.1106
J	6262	1431	1991	417	42	1124	-1985	-2234	-39.9	363.8	-4632
K	1.00	0.726	0.503	0.767	0.554	0.070	1.610	1.00	0.558	0.262	1.791
L	1195	-	2256	-	-	-	-	-	-	-	3867
M	-3248	-	-2426	-	-	-	-	-	-	-	-1542
N	-	1.120	-	1.070	1.019	1.68	0.776	0.997	0.918	0.967	-
O	-	-1.9e-4	-	-1.2e-4	-8.3e-5	-1.4e-3	-1.5e-4	-5.7e-5	-6.3e-7	-1.8e-4	-
P	-	1.3e-8	-	5.2e-9	2.4e-9	5.57e-7	6.4e-9	-5.8e-9	9.0e-9	5.2e-8	-
Q	-	-3.1e-13	-	-7.6e-14	-2.4e-14	-9.2e-11	-	-	-6.4e12	-6.8e-12	-
R	-	-	-	-	-	5.1e-15	-	-	-	-	-
S	1.009	1.086	1.011	1.016	3199	1.357	707	7981	1.098	-9.719	1.206
V	-0.009	-0.086	-0.011	-0.016	-3198	-0.354	-706	-7980	-0.097	1.00	-0.206
T_{Vo}	-	1.4e4	-	2.2e4	3.3e4	7152	1763	4440	3374	4454	-

2.3.2 Demands for freight transportation (Trucks)

Of the date this work is prepared, no comprehensive studies have been found which were carried out in order to establish the projections for freight transportation on a world scale[13]. Therefore, for the purpose of the presented in the further parts analysis, a set of projections of freight demands for 5 world regions (according to GMM division) have been established. The data which has been used for calculating the projections originated from various sources like governmental agencies and statistical offices (National Bureau of Statistics of China 1997; World Energy Council 1998;

World Energy Council and International Institute for Applied Systems Analysis (IIASA) 1998; BTS 2000; U.S. Department of Transportation 2000; Luxembourg Office for Official Publications of the European Communities 2001; Davis and Diegel 2002; Government of India Planning Comission 2002; Landwehr and Marie-Lilliu 2002; Nguyen 2002; U.S. Department of Transportation 2002; Ergudenler and Jennejohn 2005; Gerilla, Teknomo et al. 2005).

In order to find satisfying projections on the development in the demand for freight transportation, the collected historical data has been correlated with different economic parameters (like GDP, population, GDP expressed in PPP, etc.). Having established the correlations, it has turned out that the best correlation has been established when relating the demand for freight transportation and GDP/capita index (R^2 in the range of 0.95). Then, using the correlation to GDP/capita, the demands for freight transportation have been extrapolated until the year 2050.

Due to the availability of data, the initial calculations have been done using the 11-region division (Schafer and Victor 2000), which at later stage were aggregated. The extrapolations of the demand for road freight have been conducted manually (manual fitting) using in-house knowledge. During the fitting it has been observed that several regions followed similar fitting patterns. Therefore, EQ. 6 illustrates the fitting in the regions of NAM and WEU while the remaining regions have been described using EQ. 7.

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[13] Only partial and regional demands have been found, which later have been used in the long term demand projections as presented in this work

EQ. 6

$$DfF_{Reg}(t) = A_{Reg} + B_{Reg} * 10^{(GDP/Capita)_{Reg} * C_{Reg}}$$

EQ. 7

$$DfF_{Reg}(t) = A_{Reg} * (GDP/Capita)_{Reg}^{B_{Reg}}$$

Where:

DfF	Demand for freight transportation [G T-km]
Reg	Region indicating index
t	Time index
A,B,C	Manual fitting coefficients
GDP/Capita	GDP/Capita index, according to IIASA B2 scenario (World Energy Council and International Institute for Applied Systems Analysis (IIASA) 1998)

In the following table, the respective manual fitting coefficients have been presented (**Table 6**).

Table 6 Manual fitting coefficients (dimensionless) for the estimation of freight demand

	Parameter			
Region	A	B	C	R^2
NAM	4.5326	2.0000	1.5274	0.9730
LAM	678.3021	0.4816	-	1.0000
WEU	3.3199	2.0000	1.3276	0.9827
EEU	23.0964	0.8466	-	0.9984
FSU	320.1963	0.1263	-	0.9997
MEA	419.3916	0.4422	-	0.9997
AFR	101.7454	0.8033	-	0.9999
CPA	345.2089	0.7682	-	0.9872
SAS	262.0416	0.7585	-	1.0000
PAS	439.8483	0.6734	-	1.0000
PAO	216.6110	0.6564	-	1.0000

In order to provide the projections according to GMM 5-region division, the values of the calculated demands were added accordingly. The results have been presented below (**Figure 8** and **Table 7**).

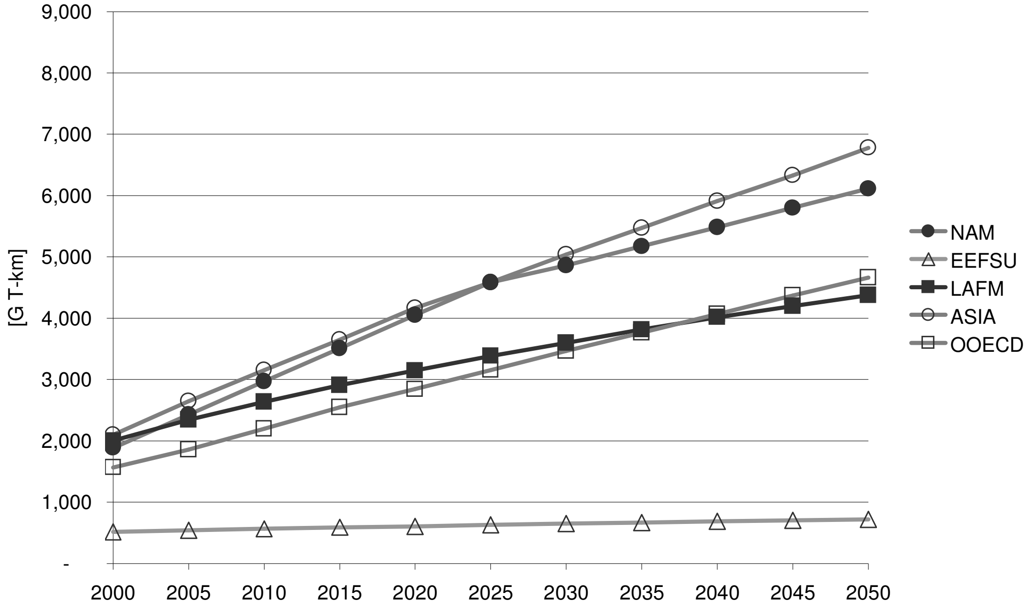

Figure 8 Demands for freight transportation for 5 world regions

Table 7 Demands for freight transportation for 5 world regions [G T km]

Year	World region				
	NAM	EEFSU	LAFM	ASIA	OOECD
2000	1,887	517	2,005	2,100	1,570
2005	2,428	542	2,345	2,650	1,860
2010	2,969	568	2,640	3,155	2,199
2015	3,510	593	2,908	3,650	2,550
2020	4,051	606	3,149	4,168	2,844
2025	4,584	631	3,387	4,585	3,159
2030	4,861	653	3,600	5,040	3,467
2035	5,174	669	3,815	5,472	3,765
2040	5,487	689	4,018	5,914	4,069
2045	5,800	704	4,199	6,330	4,371
2050	6,112	722	4,379	6,780	4,665

2.4 Learning-by-doing, the costs reduction mechanism

A learning, or experience, curve shows how experience improves performance in a given activity. Thus, a generic learning curve relates a certain performance index to a quantity measuring cumulated experience (Wright 1936; Robinson 1980; Laitner and Sanstad 2004). The most common specification (and the one applied here), describes the specific investment cost of a given technology as a function of the cumulative capacity, which is used as a proxy for the cumulated knowledge. The curve reflects the fact that some technologies may experience declining costs as a result of increasing adoption into the society, due to the accumulation of market penetration (Manne and Barreto 2004).

The customary form to express an experience curve (learning-by-doing) is using an exponential regression is presented below EQ. 8 (Argote and Epple 1990) and on the following diagram (**Figure 9**).

EQ. 8

$$SC(C) = SC_0 \cdot CC^{-b}$$

Where:

SC	Specific cost (e.g. US$/kW for electricity generation technologies)
CC	Cumulative capacity
b	Learning index
SC_0	Specific cost of the first unit

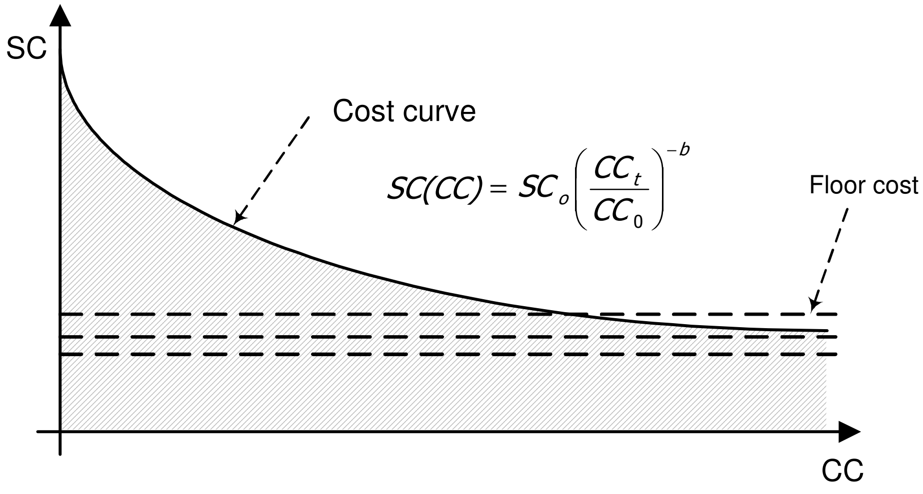

Figure 9 Graphical illustration of learning curve

The learning index *b* defines the effectiveness with which the learning process takes place.

It constitutes one of the key parameters in the expression above. Usually, for simplicity its value is not given but the progress ratio (or the learning rate) is specified instead. The progress ratio (pr) is the rate at which the cost declines each time the cumulative production doubles. For instance, a progress ratio of 80% implies that the costs are reduced to 80% when the cumulative capacity is doubled. The relation between the progress ratio and the learning index can be expressed as presented in EQ. 9.

EQ. 9

$$pr = 2^{-b}$$

An alternative is to specify the learning rate (lr) defined as presented in EQ. 10.

EQ. 10

$$lr = 1 - pr$$

The parameter *a* may be computed using one given point of the curve (usually the starting point SC_0, C_0 is specified) as presented in EQ. 11.

EQ. 11

$$SC(CC) = \frac{SC_0}{(C_0)^{-b}}$$

The curve is very sensitive to the progress ratio specified and to the starting point (SC_0,CC_0). The future progress ratio of a given technology can be uncertain. Also, the definition of the starting point may pose difficulties for future, or currently in the pre-commercial stage, technologies for which data concerning actual cumulative capacity or costs may not be available or reliable (Mattsson and Wene 1997; McDonald and Schrattenholzer 2001).

As an illustration of the sensitivity to its defining parameters, **Figure 10** presents a hypothetical learning curve with different values of the progress ratio (0.81, 0.85, 0.90) with a common starting point (SC_0=5000 US$/kW, CC_0 = 0.5 GW). An additional curve with pr=0.85 but a different starting point (SC_0=5000 US$/kW, CC_0=2 GW) is also presented in this figure.

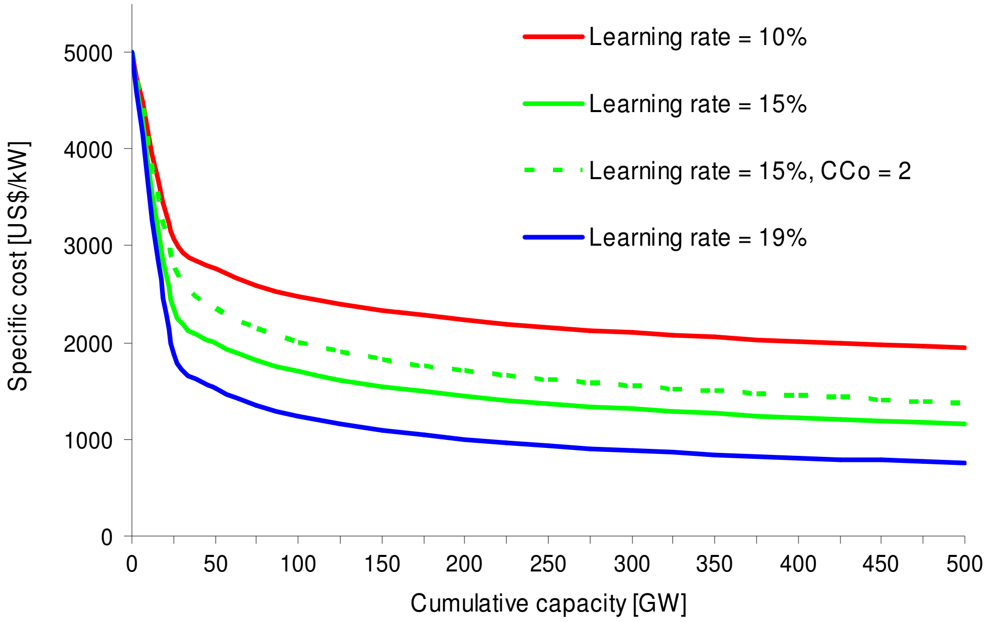

Figure 10 Learning curves for different learning rates

The linear form in the logarithmic scale should not drive to the interpretation that ever decreasing costs can be expected. In fact, with each consecutive cumulative capacity doubling, the absolute cost reduction obtained is smaller than in the previous one. In addition, every new capacity doubling is more difficult to obtain over time - this means that eventually a high level of penetration is needed to double the capacity. Therefore, one may notice that as the cumulative capacity grows, the specific cost tends to a "boundary" value, below which it shall not fall. The "floor cost" reflects the cost which the specialists believe to be a pragmatic expectation of the actual costs of a given technology at the time (and capacity installed) it reached its full maturity (Messner 1997). Graphical illustration of the learning curve as presented above (**Figure 9**) indicates the discussed floor cost level. The floor cost may however be placed below, above or at the point to which the cost curve tends to (as denoted on the mentioned diagram). As the floor cost defines a 'theoretical' level, it does not need to be related to the dynamics of the cost curve.

For commercial technologies such as wind turbines, gas turbines or photovoltaics it is usually possible to extract learning curves from historical data. It is, however, very difficult to make estimations of cost trends for technologies which are at the edge of market introduction such as fuel cell applications in the transport sector. Mostly, only researchers working for private companies have estimates on expected cost reductions due to research and development. These companies and research centres are very reluctant to disclose cost data, since those might allow for drawing conclusions on company strategies. On rare occasions however such data is disclosed. An example of such data for innovative powertrain technologies is displayed in **Figure 11** (Cisternino 2002). They correspond to the sum of target cost for each of the fuel cell powertrain components such as reformer, processor and fuel cell stack. The diagram also shows the price evolution of the mass produced internal combustion engine powertrain baseline technology, which price increases from € 2,000 in 1995 to € 2,500 in 2025. It can be assumed that the cost for this baseline powertrain could be an indicative floor cost for the innovative technologies which undergo the learning-by-doing (endogenous technological learning, ETL) cost reduction. One should therefore understand by this, that the alternative technology, which undergoes "learning" costs reduction, once introduced on the market starts with a price of the powertrain higher then the one of the conventional technologies. As the popularity of the alternative technology increases, its price decreases as function of market penetration. The price of the alternative powertrain reduces from the base price, until it reaches a competitive level to the conventional powertrain (the floor cost of the alternative powertrain). As the definite lower bound of the costs reduction may not be precisely estimated at the current level of knowledge, an assumption is made how far the alternative powertrain cost can be reduced. Therefore, the price of conventional powertrain indicates what could or should be the floor cost for the "learning" technologies, as at this level, if the floor costs is at the level of conventional technologies, it is possible for the "learning" technologies to be competitive in terms of costs. This however does not take into consideration fuel price and customer preferences, which could consider other factors (for example prestige image of new technology or environmental considerations) for deciding which technological option to purchase.

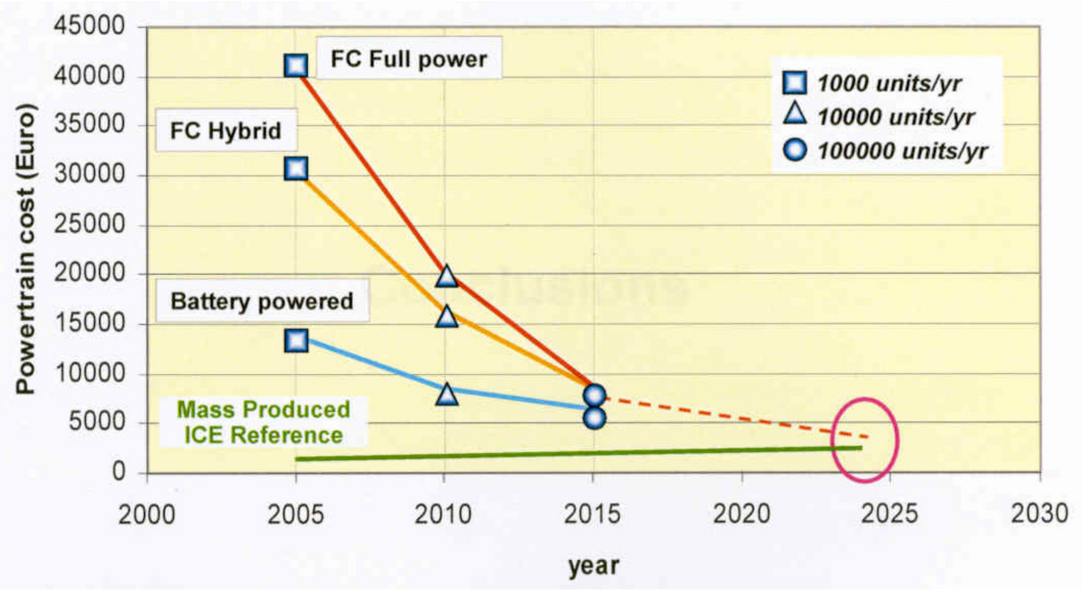

Figure 11 Projected cost reduction for innovative powertrain technologies. Full power fuel cell (FC) and internal combustion engine (ICE) powertrains have 40 kW power. The hybrid fuel cell configuration has 20 kW continuous from the FC and 20 kW peak from a battery pack, and the battery powered has 40 kW peak power with 18 kWh storage capacity (Cisternino 2002).

Figure 12 shows the learning curve (cost vs. cumulative capacity) extracted from the data by Fiat in a log-log presentation in order to determine the progress ratio and the initial investment costs. The initial investment costs are taken from **Figure 11** and correspond to the ones at 1,000 produced units per year, which seems to be lowest realistic number for mass production of powertrains. With help of the fit in **Figure 12**, the initial investment cost for even lower production numbers could be extrapolated.

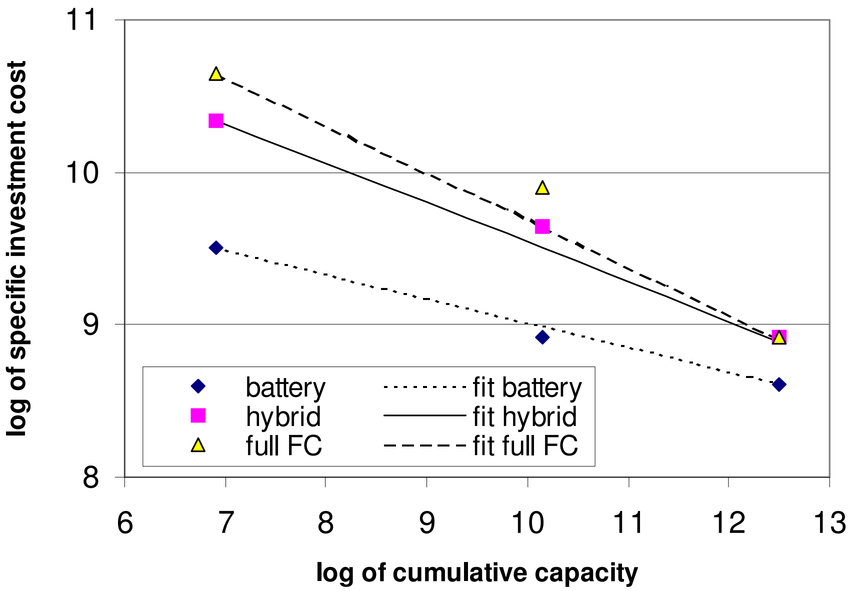

Figure 12 Learning curve of Figure 11 in the log-log representation in order to determine the progress ratios

2.5 Sensitivity analysis assumptions

Design of policies targeted at achieving a specified goal, ought to aim at such elements of the overall system which, when influenced, would produce a favourable change in the system. However, influence of such points should, apart from providing a plausible influence on the system, be cost attractive, technically and administratively feasible. Therefore the analysis of the transportation system ought to be linked with understanding of factors influencing the system. This understanding of the transportation sector may be achieved by using a technique, commonly used in System Dynamics modelling and Policy Analysis, called the "causal diagram analysis" (CDA). The CDA is based on construction of a network of factors influencing the system. Creation of a CDA allows for pin-pointing of factors, which may be influenced. Later translation of CDA into a mathematically expressed model, allows observation of how the analysed system changes depending on the different values of influenced factors. Therefore, the more detailed the description, hence the number of factors, of the system is, the closer to the real-life conditions the modelled system shall be. However, it is advisable to keep in mind that in such complex systems as the transportation sector, the number of factors may be extensive.

Capturing of all the factors may in many cases impose a serious time and computational constraints. In this analysis an attempt has been made to capture the most important factors, from the perspective of technological description of the system. Many factors however have been put aside, and not included in the analysis due to such reasons as limited data availability or significant difficulties to express them in an optimisation modelling framework.

For the purpose of analysing the transportation sector and answering the question of its potential developments, a CDA diagram has been created (Appendix A: Causal diagram for establishing sensitivity analysis factors).

Having created a CDA, the recognised factors were quantified and described in more detail. The table below contains the description of the influencing factors (**Table 8**).

Table 8 Causal Diagram Analysis – specification of factors

Factor	Unit	Description / Comment
Vehicle related		
Price of variable operations & maintenance costs	[US$/v-km]	Cost of expenditures which are directly proportional to the operation of the vehicle (tyres, oil, etc.)
Price of fixed operations & maintenance costs	[US$/v-km]	Cost of expenditures which are independent of vehicle operation (insurance, etc.)
Cost of 1km travel non-ETL	[US$/v-km]	Part of the overall cost of travelling related to the non-ETL part of the investment costs
Cost of 1km travel ETL	[US$/v-km]	Part of the overall cost of travelling related to the ETL part of the investment costs
Demand section		
Demand for mobility by trains	[G v-km]	Externally derived from Travel time Budget and GDP/Capita, as specified in Chapter 2.3.1
Demand for mobility by HST	[G v-km]	Externally derived from Travel time Budget and GDP/Capita, as specified in Chapter 2.3.1
Demand for mobility by personal cars	[G v-km]	Externally derived from Travel time Budget and GDP/Capita, as specified in Chapter 2.3.1
Demand for mobility by buses	[G v-km]	Externally derived from Travel time Budget and GDP/Capita, as specified in Chapter 2.3.1
Modal substitution factor	Dimensionless	Externally derived from Travel time Budget and GDP/Capita, as specified in

		Chapter 2.3.1
Demand for freight transportation	[G v-km]	Own estimates, as specified in Chapter 2.3.2
GDP/Capita	[US$/capita]	On the basis of IIASA B2 scenario (World Energy Council and International Institute for Applied Systems Analysis (IIASA) 1998; Heston, Summers et al. 2002)
Fuel section		
Needed fuel price	[US$/GJ]	Derived from the final price of fuel and vehicle efficiency
Final fuel price	[US$/GJ]	Sum of costs related to generation, transmission and distribution
Fuel tax	[US$/GJ]	Governmental, region and time specific fuel tax
Price of fuel generation	[US$/GJ]	Sum of costs related to fuel generation
Price of fuel transmission	[US$/GJ]	Sum of costs related to fuel transmission
Price of fuel distribution	[US$/GJ]	Sum of costs related to fuel distribution
Efficiency of fuel generation	[GJ_{IN} / GJ_{OUT}]	Ration between input and output in terms of energy value flows
Efficiency of fuel transmission	[GJ_{IN} / GJ_{OUT}]	Ration between input and output in terms of energy value flows
Efficiency of fuel distribution	[GJ_{IN} / GJ_{OUT}]	Ration between input and output in terms of energy value flows
Price of feedstock	[US$/GJ]	Region and time specific price of materials (primary fuels) used for generation of fuel
FIXOM & VAROM	[US$/GJ]	Additional costs related to operation of infrastructure (insurance, staff, rent, etc.)
Investment costs	[US$/GJ]	Investment capital needed to establish given element of infrastructure
Price of operations fuel	[US$/GJ]	Fuel used for running stage of the fuel can (f.eg. diesel for trucks moving fuels)

Vehicle-technology section		
Fuel efficiency	[v-km/GJ]	Efficiency of the overall vehicle (power train and road efficiency)
Final price of vehicle	[US$]	Showroom price for the end customer
Price of non-ETL component	[US$]	Cost of vehicle elements not subject to ETL costs reduction
Price of ETL component	[US$]	Cost of vehicle elements subject to ETL costs reduction
Learning rate	[%]	
Size of initial launch	[Number of vehicles]	Number of vehicles entering the market as the first batch

On the basis of the constraints of the modelling framework, results of the initial runs and the availability of data, the following factors have been selected for the sensitivity analysis runs:

- Price of fuel cells
- Learning rates of fuel cells
- Trends in oil price changes
- Dynamics of infrastructure

The ranges for which the mentioned factors were tested have been specified in each of the sections corresponding to specific models used.

2.6 Interpretation of sensitivity analysis runs

The results of the sensitivity analysis have been presented from the perspective of a given technological option (f.eg. the hydrogen fuel cell vehicle) as a percentage of overall market penetration. The following explanatory diagram and interpretation illustrate the specification (**Figure 13**).

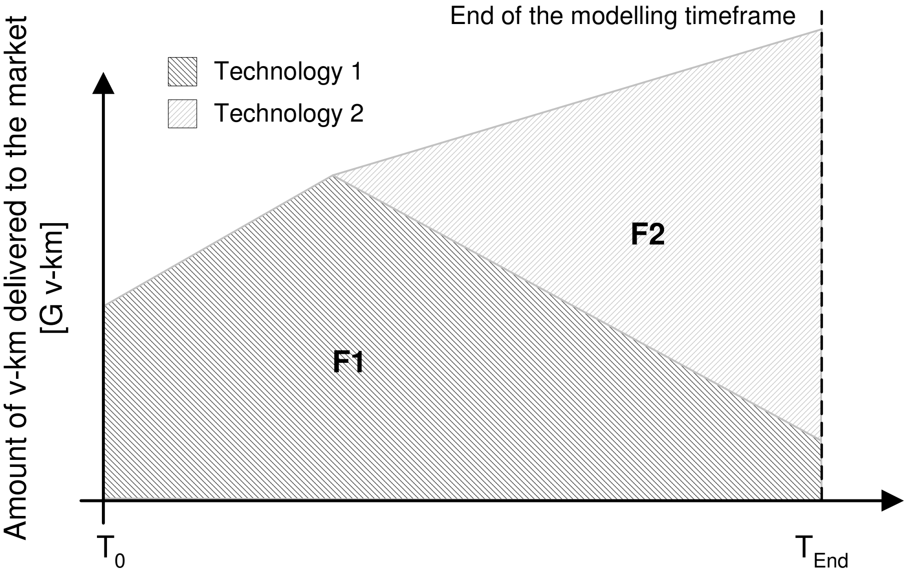

Figure 13 Explanatory illustration of "Cumulative amount of v-km delivered"

The “Cumulative amount of v-km delivered” is therefore expressed as presented in EQ. 12.

EQ. 12

$$CA_{T1} = \frac{F_{T1}}{F_{T1} + F_{T2}}$$

$$CA_{T2} = \frac{F_{T2}}{F_{T1} + F_{T2}}$$

Where:

CA	Cumulative amount of v-km delivered by given technology [%]
T1	“Technology 1” designating index
F	Cumulative amount of v-km delivered by given technology [v-km]

3 Does the hydrogen fuelled FC vehicle stand a chance? Analysis conducted with FinalTRA

3.1 Introduction to FinalTRA – H_2FC in "laboratory" market conditions

One of the first questions which needed to be addressed was if the hydrogen fuel cell vehicle, using simple and generalised assumptions, could be a competitor on the transportation market. In order to answer this question a simple optimisation model was created. The model has been named FinalTRA, created during the first period of the research by Socrates Kypreos, and facilitated the first element of the analysis.

3.2 FinalTRA – model description

The non-ETL part of the costs of transportation by various technologies which have been used in the model have been calculated according to the following equation, which has been developed using in-house knowledge (EQ. 13).

EQ. 13

$$C_{NonETL} = \left(\frac{crf * P_{Tech} + FIXOM_{Tech} + VAROM_{Tech}}{AM_{Tech}} + \frac{F_{Tech}}{E_{Tech}} \right) * 1000$$

Where:

C_{NonETL}	Cost of travelling with a technology which does not undergo learning [\$/k v-km]
crf	Capital recovery factor: $crf = \frac{DR * (1+DR)^{TL_{tech}}}{(1+DR)^{TL_{tech}} - 1}$, where DR is the discount rate of 5%, and TL the technical lifetime of a given technology
Tech	Technology designating index
P_{Tech}	Technology specific vehicle purchase price [US\$]
AM_{Tech}	Technology specific annual mileage travelled [k v-km]
$FIXOM_{Tech}$	Technology specific annual fixed costs (insurance, road tax, etc.) [US\$/year]

$VAROM_{Tech}$	Technology specific annual variable maintenance costs associated with travelling of the annual mileage (service repairs, maintenance checks, tires, etc.) [US$/year]
F_{Tech}	Technology specific costs of technology specific fuel [US$]
E_{Tech}	Technology specific fuel efficiency [%]

The formulation of the learning part of the costs, associated with the reduction of costs as function of cumulative installed capacity has been done using the Mixed Integer Programming (FinalTRA and GMM). The equations below illustrate this procedure (EQ. 14 through EQ. 21) (Barreto 2001), additionally a set of graphs illustrates the approach (**Figure 14** and **Figure 15**).

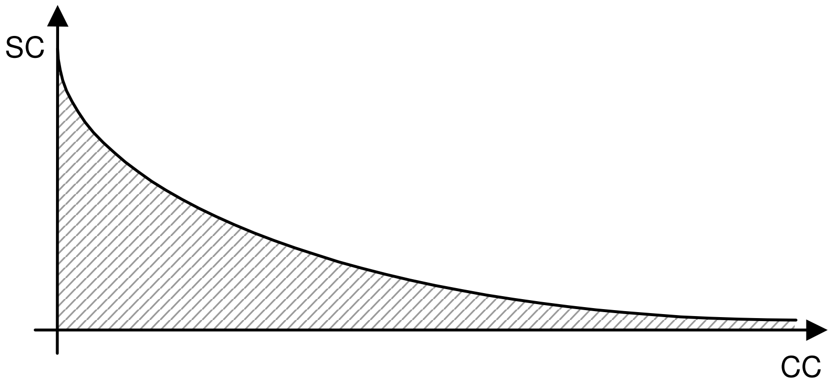

Figure 14 Representation of costs reduction according to the "learning" approach: specific cost (SC) as function of cumulative capacity (CC)

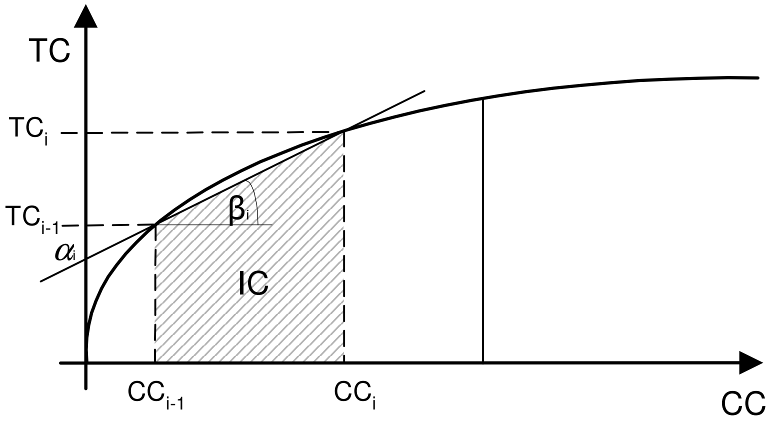

Figure 15 Representation of costs reduction according to the "learning" approach: cumulative capacity (CC) vs. total cost (TC) with indication of MIP coefficients

The cumulative capacity is expressed as a summation of continuous lambda variables (EQ. 14) (Barreto 2001).

EQ. 14

$$CC_{Tech,t} = \sum_{i=1}^{N} \lambda_{Tech,i,t}$$

The cumulative cost is expressed as a linear combination of segments expressed in terms of the continuous lambda and binary delta variables (EQ. 15 through EQ. 17)(Barreto 2001).

EQ. 15

$$TC_{Tech,t} = \sum_{i=1}^{N} \alpha_{i,Tech} * \delta_{Tech,i,t} + \beta_{i,Tech} * \lambda_{Tech,i,t}$$

With:

EQ. 16

$$\beta_{i,Tech} = \frac{TC_{i,Tech} - TC_{i-1,Tech}}{CC_{i,Tech} - CC_{i-1,Tech}}$$

EQ. 17

$$\alpha_{i,Tech} = TC_{i-1,Tech} - \beta_{i,Tech} CC_{i-1,Tech}$$

The reader should note that, for each learning technology, one delta variable is defined for each segment of the piecewise learning curve and time period. When this segment of the learning curve becomes active, this delta variable is set to one while the delta variables associated to the other segments are set to zero.

The logical conditions to control the active segment of the cumulative curve are as follows (EQ. 18 and EQ. 19)(Barreto 2001).

EQ. 18

$$\lambda_{Tech,i,t} \geq CC_{i,Tech} * \delta_{Tech,i,t}, \quad \lambda_{Tech,i,t} \leq CC_{i+1,Tech} * \delta_{Tech,i,t}$$

The sum of delta binary variables is forced to one (EQ. 19)(Barreto 2001).

EQ. 19

$$\sum_{i=1}^{N} \delta_{Tech,\ i,t} = 1$$

Using the fact that experience must grow or at least remain at the same level, additional constraints are added to the basic formulation, helping to reduce the solution time (EQ. 20)(Barreto 2001).

For t=1,...T, te=1, ...TE, i=1,...N

EQ. 20

$$\sum_{P=1}^{i} \delta_{Tech,P,t} \geq \sum_{P=1}^{i} \delta_{Tech,P,t+1} \quad , \quad \sum_{P=i}^{N} \delta_{Tech,P,t} \leq \sum_{P=i}^{N} \delta_{Tech,P,t+1}$$

The investment cost $IC_{Tech,t}$ associated to the investments in learning technologies is computed as described below (EQ. 21)(Barreto 2001).

EQ. 21

$$IC_{Tech,t} = TC_{Tech,t} - TC_{Tech,t-1}$$

Having established the costs of the technologies, their activity is matched with the externally defined demand. The match has been obtained using the following equation (EQ. 22), which has been developed using in-house knowledge.

EQ. 22

$$X_{gen,t} * \eta_{gen} \geq X_{car(H2FC),t} / \eta_{car}$$
$$X_{car,t} / \eta_{car} \geq Demand_t$$

Where:

X	Activity of technology
gen	Hydrogen generation technology index
η	Efficiency
car	Personal vehicle technology index
t	Time index
Demand	Demand for passenger car transportation

Having established the supply/demand balance, in the next step the objective function has been prepared using in-house knowledge, which links the activity of technologies with the appropriate costs and the demand (EQ. 23).

EQ. 23

$$\mathrm{PVC} = \sum_{t=2000}^{t=2100} \sum_{\mathrm{Tech}} \mathrm{PV}_t * \mathrm{DISPP} * \mathrm{X}_{\mathrm{Tech}} * \left(\mathrm{C}_{\mathrm{Non-ETL}} + \mathrm{IC}_{\mathrm{Tech},t}\right)$$

Where:

PVC	Present value of costs, subject to minimisation by optimisation
PV	Present value factor, where $\mathrm{PV}=(1/(1+\mathrm{DR}))^t$ and DR being the discount rate
DISPP	Discounting to present period factor (DISPP=7.722 as $\mathrm{DISPP} = \sum_{2000}^{2100} (1+\mathrm{DR})^t$ and DR being the discount rate)
X	Activity of technology
Tech	Technology designating index
$\mathrm{C}_{\mathrm{Non-ETL}}$	Cost of travelling with a technology which does not undergo learning
$\mathrm{IC}_{\mathrm{Tech},t}$	Integral of costs related to the learning component of travelling by a specific technology

In further parts of this work, the reader may find the source code of FinalTRA with the mentioned formulation as used in GAMS code (Appendix A: Causal diagram for establishing sensitivity analysis factors).

3.3 FinalTRA - assumptions on data input

Similarly to the models which follow (CUBE and GMM) FinalTRA uses the same input data. Due to the simplicity of the initial modelling framework of FinalTRA the model, on contrary to later models, has many factors which are externally defined. The table below specifies the parameters which are endogenous and exogenous (**Table 9**).

Table 9 FinalTRA – specification of exogenous and endogenous parameters (U.S. Department of Energy 2003; Energy Information Administration 2004; IFTA 2004)

Parameter	Endogenous	Exogenous
ETL	Cost of fuel cell stack for the hydrogen fuel cell vehicle [US$/kW]	
Oil price		28 US$/bbl (2000) 55 US$/bbl (2010) increase of +5%/decade after 2010
Other primary fuels		Electricity: 12 US$/GJ Natural gas: 6 US$/GJ Hard coal: 2 US/$GJ Biomass: 4 US$/GJ Gasoline: linear relation to price of oil Diesel: linear relation to price of oil
Hydrogen fuel chain		Fixed price for hydrogen at fuelling station
Other fuel chains		Fuels for transportation provided as fuel price at fuelling station
Upper limit for vehicle penetration		+10%/year
Lower limit for vehicle penetration		- 10%/year

3.4 FinalTRA – sensitivity analysis

In the designing of the "base case", conducted using FinalTRA, an assumption has been made that there shall be no governmental initiative for imposing a CO_2 tax on the emissions coming from utilisation of fuels in the transportation sector. The new, alternative technologies are developing at quite dynamic learning rates (15% decrease of costs with the doubling of the installed capacity). One may observe that the market structure does not change over time, as the predominant role in the Personal Vehicle sector is still played by the gasoline-fuelled engines with a similar share of the diesel fuelled vehicles as in the year 2000 (**Figure 16**). However one may notice a shift towards advanced technologies such as the Advanced Gasoline or the gasoline-electric hybrid. By 2050 one may observe first appearance of H2FCs. The learning rate and relatively high to hydrogen prices of conventional fuels allow for successful market penetration of H2FC. By the end of the modelling timeframe (2100) H2FC capture much of the market share.

FinalTRA which operates under numerous generalised assumptions has the "advanced" versions of gasoline and diesel vehicles. Both of the vehicles differ from the "base" cars as defined in the input table (**Table 1**) in that their fuel efficiency is increased by 10%, while all other parameters are kept at the same values.

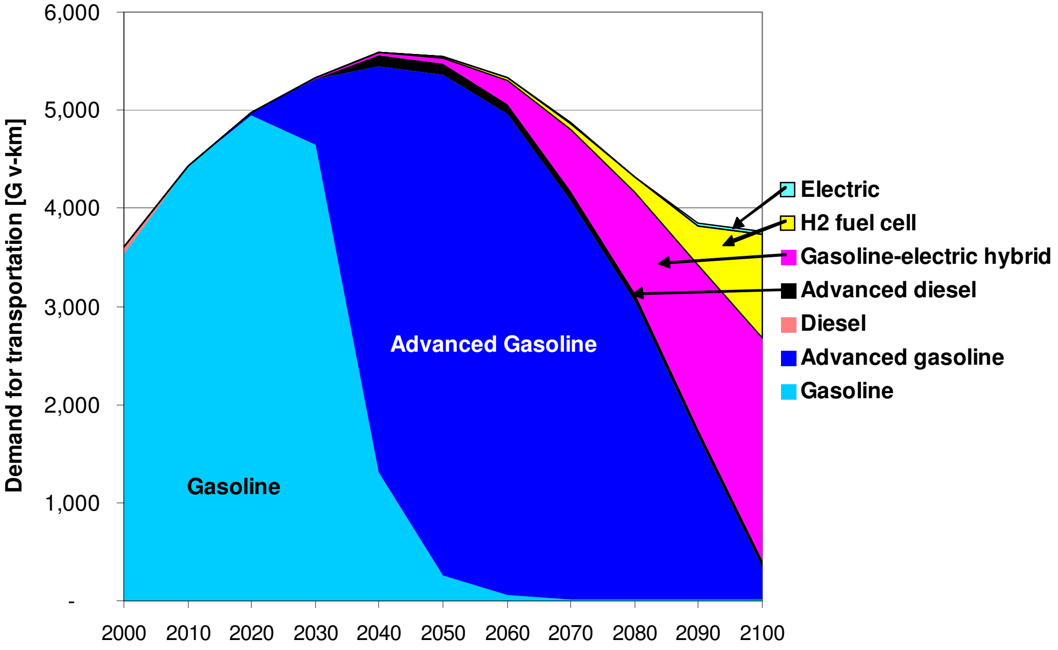

Figure 16 FinalTRA: "Base Case" of distribution of market shares for different types of vehicles (hydrogen fuel cell stack price: 600$/kW, hydrogen learning rate: 15%)

Next, a set of factors was chosen for testing using FinalTRA for the potential influence on the market penetration of hydrogen fuel cell vehicles (**Table 10**).

Table 10 Specification of factors used in the sensitivity analysis (FinalTRA)

Factor	Value	State
H_2FC-LRN	2.5 … 20%	Variable
	15%	Constant
H_2FC-kW	200 … 1000 $/kW	Variable
	600 $/kW	Constant
H_2FC-kW Floor	100 $/kW	Constant
BBL	-5 … +5% / decade	Variable
	+5% / decade	Constant
PPL-GR	+2.5 … 17.5% / year	Variable
	10% / year	Constant
CCo_{H2FC}	75,000…700,000 vehicles	Variable
	75,000 vehicles	Constant

Later, the selected factors were paired (**Table 11**) and the runs were conducted. The list of abbreviations and a more detailed explanation of the selected factors which were used the reader may find in the earlier parts of this work (Section "List of abbreviations" and Chapter 2.6 Interpretation of sensitivity analysis runs).

Table 11 FinalTRA: Combination of pairs of influential factors used in the sensitivity analysis

		1st Factor				
		H_2FC-LRN	H_2FC-kW	CCo_{H2FC}	BBL	PPL-GR
2nd Factor	H_2FC-LRN	☒		☑		
	H_2FC-kW	☑	☒		☑	
	CCo_{H2FC}		☑	☒		
	BBL			☑	☒	
	PPL-GR	☑				☒

3.4.1 Price of fuel cells vs. fuel cell learning rates

The first pair of factors which have been considered is composed of the learning rate and the price of the fuel cell used for the fuel cell stack as presented below (**Figure 17**).

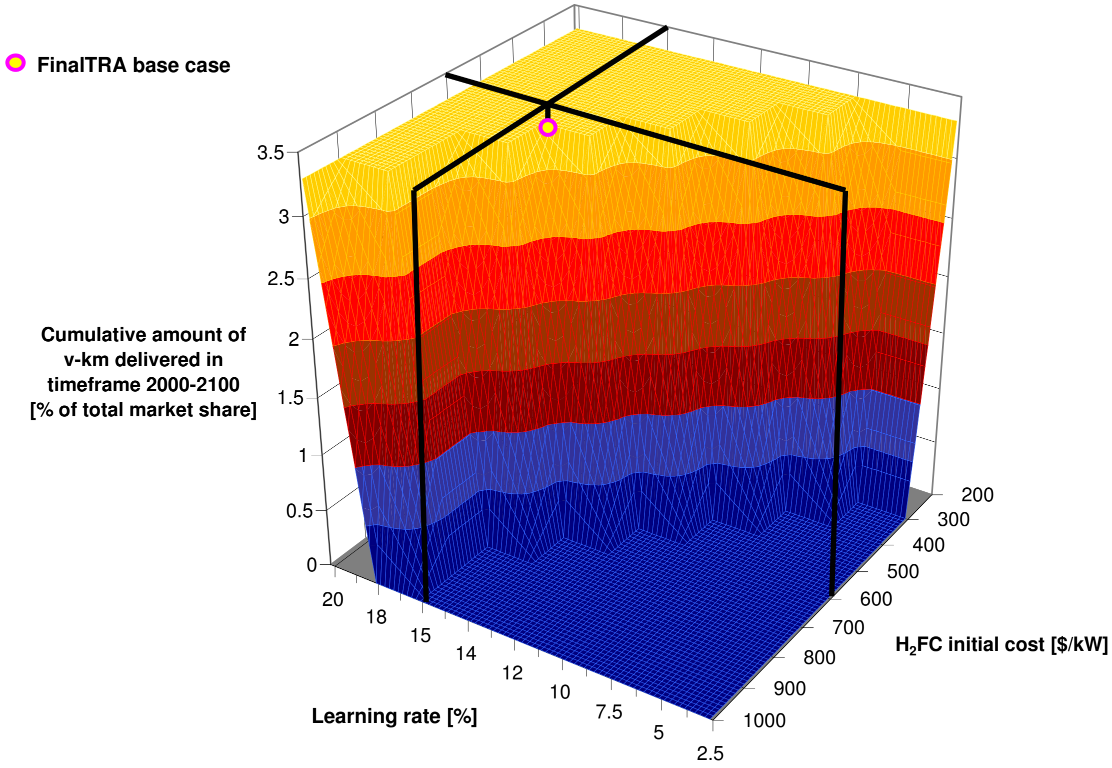

Figure 17 FinalTRA: Graphical illustration of market penetration of H_2FC in the context of variable H2kW and H2FC-LRN factors (with all other factors constant, hydrogen price: 26 USD/GJ, oil price growth: +5%/decade, hydrogen fuel cell floor cost 100 $/kW)

Examination of the graph above indicates that even at relatively high prices of fuel cells (in the range of more than 400 USD/kW[14]) market penetration of hydrogen fuelled vehicles is possible. However, the learning rate is an equally important factor. At low learning rates (less than 10%) penetration is possible if fuel cell are at a price of around 400 US$/kW. The results of this analysis suggest that there is a synergetic and complementary effect. The synergy may be observed by considering that if

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[14] The value of 400 USD/kW is in comparison to current fuel cell prices in the range of one fifth. Keeping in mind that fuel cell vehicles shall not be available in the next 5-6 years, and the current reduction of prices, one may hope that by the time fuel cell vehicles are introduced to the market, the price of the fuel cells may already be in the range as considered in this analysis.

learning rates are high enough (10% or more) and the price of the fuel cell is in the range of 500 US$/kW the combined effect allows for successful market penetration under the assumptions of FinalTRA modelling framework. The complementary effect may be observed, by analysing a case where the initial price of the fuel cell is high (more than 700US$/kW) however for a long term market penetration this can be reduced by presence of high learning rates (18% or more). The results of the analysis suggest that the price of the fuel cells and their potential to reduce cost as function of market penetration are a significant factor influencing the possible market penetration of hydrogen fuel cell vehicles. The availability of market share which can be taken over by the fuel cell vehicles is limited by the externally implied bounds (growth rates). Therefore, in long run as the fuel cell powertrain becomes competitive the market share won by fuel cell vehicles, independent of the economical performance, may not reach a higher level than the technology specific growth rate.

3.4.2 Price of fuel cells vs. change in oil price

The second pair of factors which have been analysed in terms of influence on the penetration of hydrogen fuelled fuel cell vehicles was the price of fuel cells and the of price oil (**Figure 18**).

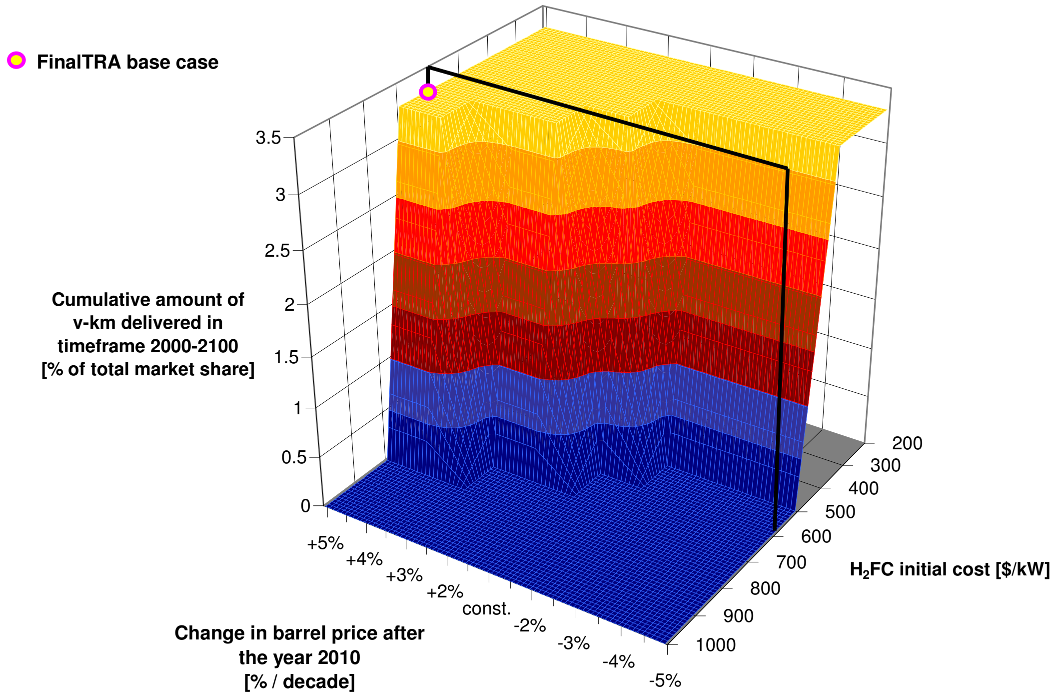

Figure 18 FinalTRA: Graphical illustration of market penetration of H_2FC in the context of variable H2kW and BBL factors (with all other factors constant, hydrogen price: 26 USD/GJ, hydrogen fuel cell floor cost: 100 $/kW, hydrogen fuel cell learning rate: 15%)

The results of this analysis indicate that, assuming the conditions of FinalTRA, oil price which is already at a high level, may cast a shadow on the competitors of hydrogen vehicles – the conventional cars. This fact has a direct translation to gasoline and diesel prices, which in turn have a major impact on conventional vehicles as well as the more advanced hybrid technologies. However, the simplified approach used in FinalTRA does not consider if an increase in oil price could have an impact on final price of hydrogen, as very likely in the first phase of the hydrogen economy transition, hydrogen could be delivered by trucks. This issue shall be elaborated in further parts of this analysis with CUBE and GMM models.

Nevertheless, keeping in mind general assumptions of FinalTRA one may draw a conclusion that oil prices at the levels as assumed in FinalTRA or higher most probably shall aid in the possible transition to hydrogen based transportation.

3.4.3 Price of fuel cells vs. initial number of vehicles

The following pair which has been tested for the potential influence on the market penetration of fuel cell vehicles was the initial number of vehicles launched to the market and the price of fuel cells (**Figure 19**). Similarly to the previous parts of the analysis, the results of this analysis point to the fact that the more influential factor is the price of the fuel cells. The initial number of vehicles seems to be influencing only the extent of the penetration, which results in a higher market share by the end of the modelling timeframe. FinalTRA with a time frame of 100 years allows for many potential doublings of the amount of vehicles which enter the market, hence penetration may be observed. The initial number of vehicles serves only as a seed value for the deployment.

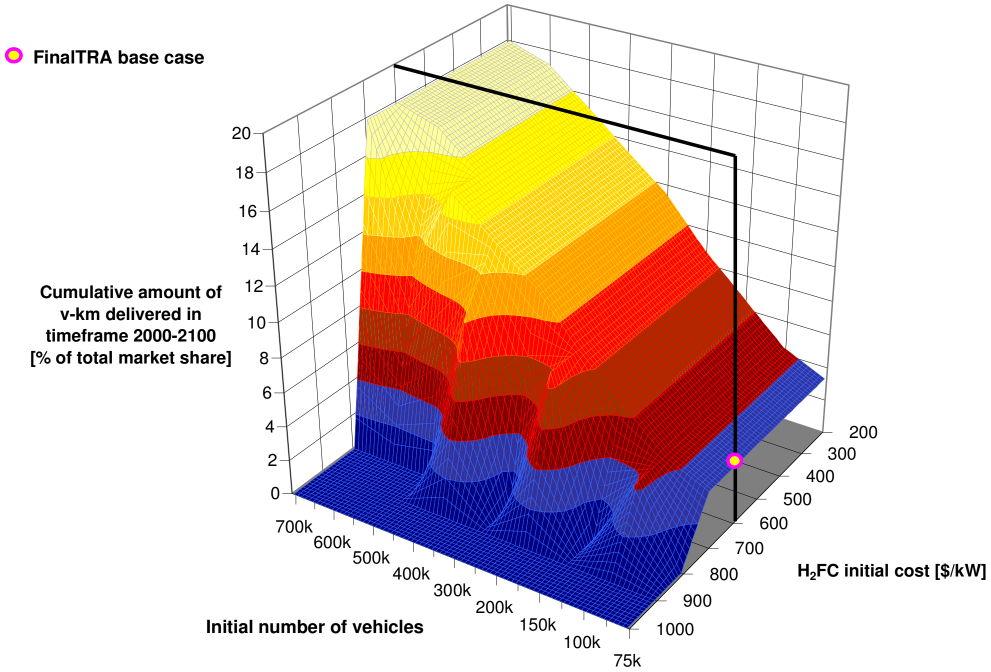

Figure 19 FinalTRA: Graphical illustration of market penetration of H_2FC in the context of variable H2kW and CCo_{H2FC} factors (with all other factors constant, hydrogen price: 26 USD/GJ, hydrogen fuel cell floor cost: 100 $/kW, hydrogen fuel cell learning rate: 15%)

3.4.4 Learning rates vs. initial number of vehicles

Next, the initial number of vehicles has been paired with learning rates as to determine the potential influence on the market penetration of fuel cell vehicles (**Figure 20**).

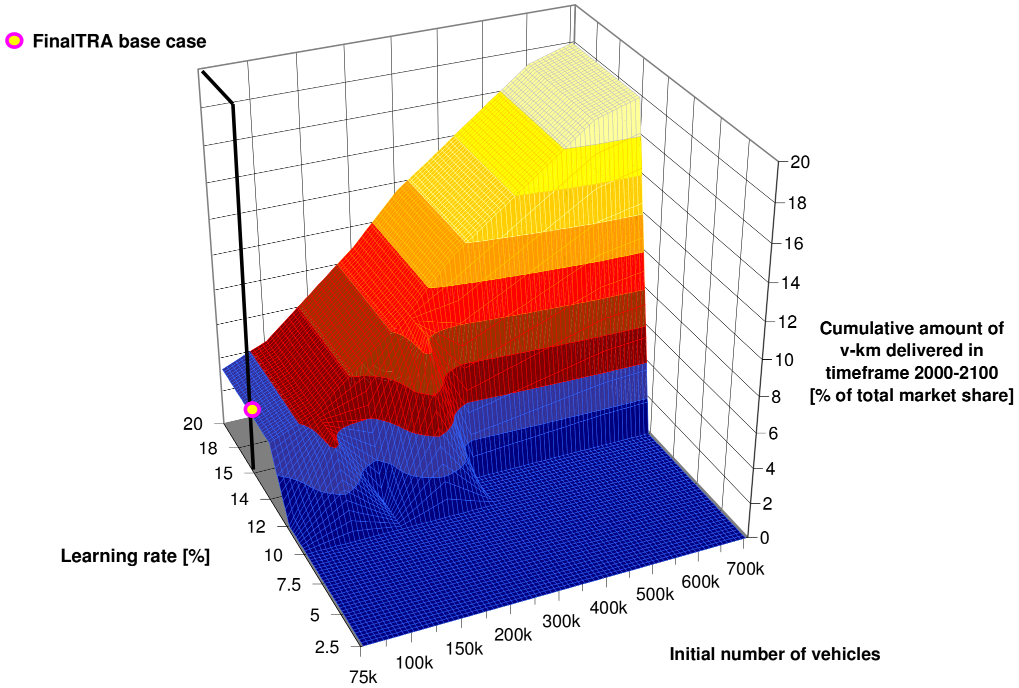

Figure 20 FinalTRA: Graphical illustration of market penetration of H_2FC in the context of variable H2FC-LRN and CCo_{H2FC} factors (with all other factors constant, hydrogen price: 26 USD/GJ, hydrogen fuel cell floor cost: 100 $/kW, hydrogen fuel cell learning rate: 15%)

Similarly to the analysis in which the price of fuel cells was paired with the initial number of vehicles launched to the market, also the learning rates seems to display similar influence as the initial price of the fuel cells. Mainly, due to the amount of time which FinalTRA may use for the allocation of fuel cell vehicles, by the end of the time horizon, there has been enough room as to provide doublings which make the fuel cells competitive. The initial number of vehicles launched to the market in combination with high potential to further reduce the price of the fuel cells (learning rates of more than 10%) allows for successful market penetration. In the case when the learning rates provide a very prospective reduction of costs (learning rates of more than 10%) there is enough time in the modelling framework as to achieve a substantial number of doublings and increase the overall market share which could be taken by the fuel cell vehicles.

3.4.5 Learning rates vs. hydrogen pipeline growth rates

Lastly, the learning rates of the fuel cells have been paired with the growth rate at which the hydrogen pipeline network can develop (**Figure 21**).

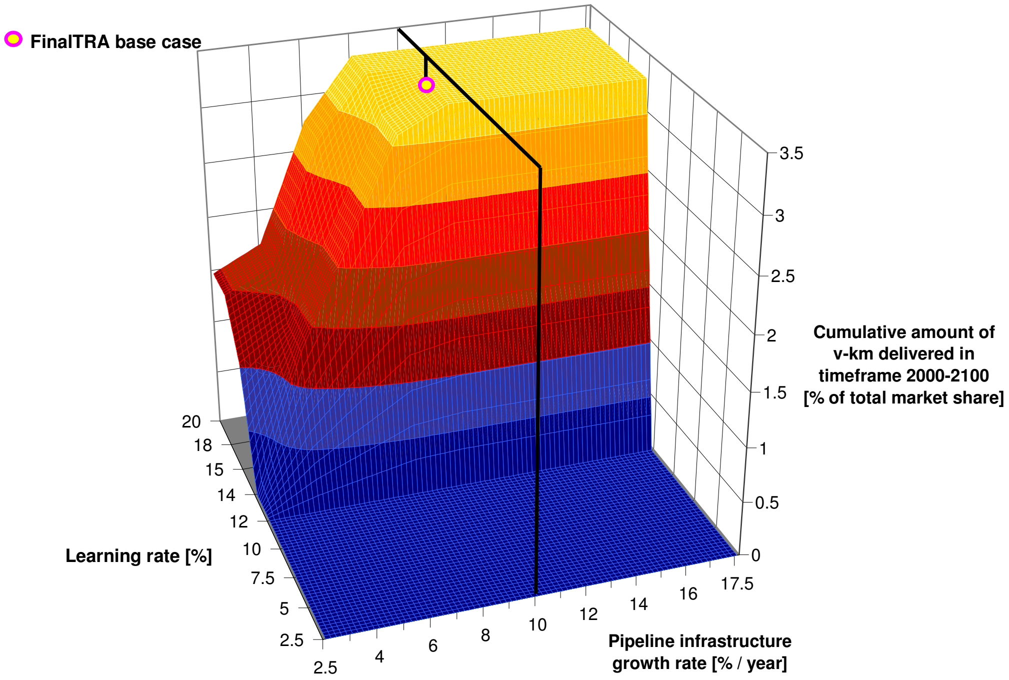

Figure 21 FinalTRA: Graphical illustration of market penetration of H_2FC in the context of variable H2FC-LRN and PPL-GR factors (with all other factors constant, hydrogen price: 26 USD/GJ, hydrogen fuel cell floor cost: 100 $/kW, hydrogen fuel cell learning rate: 15%)

The results of this analysis suggest that there is an impact of the development rate at which the pipelines are set up. This is due to the fact, that in long range planning once could foresee that the hydrogen infrastructure would be based on pipelines (length around 150-300km) which deliver the hydrogen from the generation plants to fuelling station. In the cases when the fuelling stations are remotely localised, one could foresee delivery by trucks or local generation of hydrogen. However, in the case of large suburban areas citizens might find it troublesome when the city roads would be congested by trucks delivering the fuel. Increased traffic could increase the fuel consumption of delivery trucks, which would result in an increase of price of hydrogen delivered to the end consumer. Therefore, the growth rates of the pipeline infrastructure, although not so relevant in short term, for a long term planning of the hydrogen based transportation could be a crucial influencing factor (Ogden 1999; Schoenung 2002).

3.5 FinalTRA – conclusions from the analysis

The first part of the analysis, which was aimed at establishing the conditions under which hydrogen based transportation, could be a feasible and cost attractive option was initiated by developing a simple costs optimisation model called FinalTRA. The working area of the model was a single world region made up of USA and Canada, where in the timeframe 2000-2100 the personal passenger car sector was analysed. Most of the assumption in the model, except the endogenous technological learning has been introduced externally – from demands for passenger transportation, vehicle efficiencies to prices of primary and final fuels.

The analysis with FinalTRA was to deliver an answer to the first of the research questions which was "is hydrogen based transportation a feasible option?". Despite many general assumptions and uncertainties in respect to the future potential performance of hydrogen based mobility, the results coming from the runs with FinalTRA have suggested, that indeed hydrogen based transportation is a feasible option. The uncertainties on many parameters have been assessed in FinalTRA by means of extensive sensitivity analysis, in which key factors were varied during the model runs and their potential impact on the future market penetration of hydrogen fuelled fuel cell vehicles was observed. The results of the analysis with FinalTRA have suggest the following conclusions.

Hydrogen based transportation is a feasible option, especially in the light of growing oil prices. The most crucial element which probably shall be decisive for the future of fuel cell vehicles is the **price of the fuel cell** element. However, provided that the price of **fuel cells would be in the range of 600 US$/kW or less** there is a high possibility that fuel cells vehicles shall become strong competitors for the conventional technologies like gasoline or diesel cars. The gasoline-electric hybrid vehicles seem to be a competition to the fuel cell cars, however with the rising prices of oil their distant future may be questionable as they too depend on gasoline. Nevertheless, the hybrids may provide a bridge towards the fully mature advanced technologies like the fuel cell or electric vehicles. Another factor which may have a strong influence on market penetration of future fuel cell cars is the potential to further reduce the price of the fuel cell stack as market penetration progresses. Therefore, the results suggest that a **learning rate in the range of 12% or more** could provide prospective background for successful deployments. Results of the analysis with FinalTRA further suggest that the **initial number of vehicles as well as growing prices of oil do not have a strong influence** on the potential market penetration of fuel cell vehicles. Today's price of oil has past 50US$/bbl, which already puts the hydrogen based transportation in a favourable position in terms of fuel costs. Any more rises in the oil price may therefore only increase the benefits of hydrogen based mobility.

In respect to the hydrogen infrastructure, the results obtained from the analysis with FinalTRA suggest that the **growth rates of hydrogen pipelines have a large impact only in long term perspective**. This is due to the fact that very likely, at the time when there is little demand for hydrogen, the fuel shall be distributed by trucks or shall be generated locally. Because pipelines are a long term investment, one could foresee their creation after a large demand for hydrogen emerges, as a result of increased number of fuel cell vehicles on the roads.

4 Market penetration of advanced transportation technologies. Analysis conducted with CUBE

4.1 Introduction to CUBE – the complexity of full hydrogen fuel chains

As described in the previous section, the results of the analysis using FinalTRA have showed that hydrogen fuelled fuel cell vehicle could become a market player, under specific conditions. However, the earlier model (FinalTRA) contained a generalised description of one of the crucial elements of the hydrogen based transportation, namely the hydrogen fuel chains. Parts of the analysis conducted using FinalTRA have suggested that for a more precise evaluation of the potential of hydrogen fuelled vehicles to penetrate the transportation market, a more insightful look in the light of detailed description of the hydrogen fuel chains would be required. To address this, a new model based on similar assumption as FinalTRA was created. The expanded framework was fitted into a new model, designed especially for this stage of the analysis called CUBE[15]. CUBE is a non-linear (NLP formulation), optimisation model, which similarly to FinalTRA, focuses on one world region (NAM) in a timeframe from 2000 to 2100. Similarly to FinalTRA, CUBE includes the learning-by-doing cost reduction mechanism (ETL), which has been described in more detail earlier (Chapter 2.4 Learning-by-doing, the costs reduction mechanism). As compared to FinalTRA, CUBE contained the following extensions of the modelling framework:

- full representation the hydrogen prices, expressed as so called "fuel chains"[16],
- application of advanced tools for sensitivity analysis[17].

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[15] The name "CUBE" originates from the possibility of carrying out sensitivity analysis with the transportation model, and the results are presented in 3D graphs, which have a *cubical* shape

[16] By fuel chains, one should understand a total pathway of the fuel before reaching the final consumer, and these are generation, transmission and final distribution at fuelling stations

[17] From the historical perspective how the analysis was conducted, CUBE was the first model which was able to produce extensive sensitivity analysis. At a later stage, a step back was taken in order to apply the developed tools also for the runs with FinalTRA. Later, the tools which came from the research conducted with CUBE were also introduced to the analysis conducted using the GMM model.

4.2 CUBE – model description

The basic principle, which is the backbone for CUBE calculations, is that the computation framework is based on activities of elements of fuel chains and vehicles competing on the transportation market. Each element of the fuel chain is linked with the 'next-in-line'. This linking includes all step (technology and economy) related characteristics. The principle has been illustrated in a simplified way on the figure below (**Figure 22**).

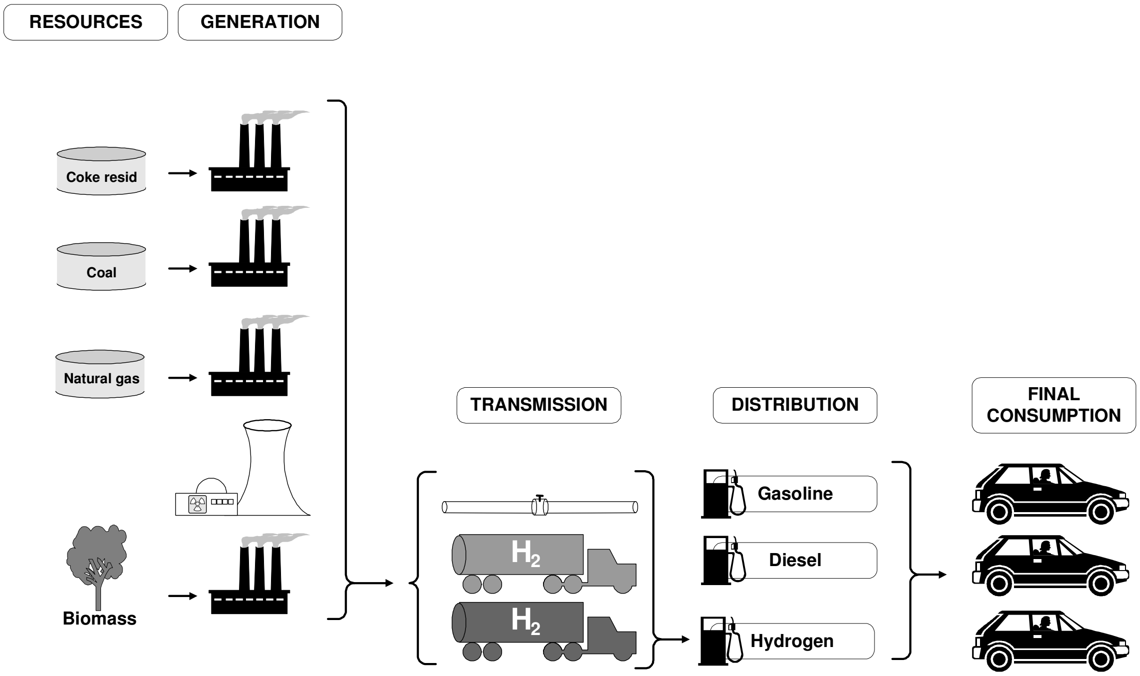

Figure 22 Schematic illustration of activity match as used in CUBE

The intermediary steps of generation, transmission, distribution and final activity of vehicles are further lined up, as to specify exact fuel chains (for example: linking of biomass with biomass gasification plant generating hydrogen, transport of hydrogen by trucks, distribution from fuelling stations, and finally, consumption by H2FC, which complete the illustrative fuel chain). A more detailed diagram illustrating all the chains present in CUBE is presented in the Appendix (Appendix B: CUBE and GMM: Hydrogen full fuel chain diagram).

The equations below describe in more detail the relations between activities on intermediary steps (EQ. 24 through EQ. 28). One should keep in mind when considering the following equations, that general variables have been used. Therefore, activity (denoted by "XE") or cumulative activity (denoted by "YE") of any technology is distinguished by using appropriate indexes. In the modelling framework, however, dependant on the type of technology, the units used are appropriate for the outcome. Hence, the activity of vehicles is given in [G v-km] while for the fuel generation and handling technologies it is expressed in [GJ].

All of the equations which follow, describing the activity links, have been developed according to in-house knowledge (EQ. 24 through EQ. 27).

In the first step, the generation of fuels is linked to their appropriate transmission modes (EQ. 24).

EQ. 24

$$XE_{gen,t} * \eta_{gen,t} \geq XE_{tran,t}$$

Where:

XE	Activity of a given technology (for gen, tran and dis [GJ]; for vehicle technologies [G v-km])
gen	Generation of fuel index
tran	Transmission of fuel index
t	Time index
η	Input/output process efficiency

Next, the transmission of fuel is linked to their respective distribution (EQ. 25).

EQ. 25

$$XE_{tran,t} * \eta_{tran,t} \geq XE_{dis,t}$$

Where:

XE	Activity of a given technology (for gen, tran and dis [GJ]; for vehicle technologies [G v-km])
tran	Transmission of fuel index
dis	Distribution of fuel index
t	Time index
η	Input/output process efficiency

After this step, the distribution of fuels is linked with appropriate activity of vehicles (EQ. 26).

EQ. 26

$$XE_{dis,t} * \eta_{dis,t} \geq XE_{car,t} \;/\; \eta_{car,t}$$

Where:

XE	Activity of a given technology (for gen, tran and dis [GJ]; for vehicle technologies [G v-km])
dis	Distribution of fuel index
t	Time index
η	Input/output process efficiency
car	Personal car vehicle index

Then, the activity of vehicles is matched with the overall demand for transportation by personal vehicles (EQ. 27).

EQ. 27

$$\sum_{car,t} XE_{car,t} \geq Demand_t$$

Where:

XE	Activity of a given technology (for gen, tran and dis [GJ]; for vehicle technologies [G v-km])
car	Personal car vehicle index
t	Time index
Demand	demand for activity of vehicles [G v-km]

Finally, the linked activities are associated with respective costs in the objective function, and made subject to optimisation procedure with the aim of finding the least total discounted system cost (EQ. 28). The objective function has been established using in-house knowledge. The optimisation aims at such composition of the market as to obtain overall least cost (with respective constraints like growth and decline rates).

EQ. 28

$$OBJF = PV * DISCPP * \sum_{t}^{t\_max} \sum_{tech} XE_{tech,t} * \left(\begin{array}{l} crf * \left(inv_{tech,t} + linv_{tech,t} * \left(\frac{YE_{tech}}{YEo_{tech}} \right)^{lrn_{tech}} \right) \\ + fixom_{tech,t} \\ + varom_{tech,t} \\ + feedstock_{gen,t} * \eta_{gen,t}^{nfeedstock} \\ + fuel_{gen,\, tran,\, dis\, ,t} * \eta_{gen,tran,dis,t}^{nfuel} \\ + fuel_{convcar,t} * \eta_{convcar,t}^{nfuel} \end{array} \right)$$

Where:

OBJF	Objective function value
PV	Present value factor: $pv = \left(\frac{1}{1+DR} \right)^{tp}$, where DR is the discount rate
DISCPP	Discounting to present period factor (DISPP=7.722 as $DISPP = \sum_{2000}^{2100} (1+DR)^{t}$ and DR being the discount rate)
t	Time index
t_max	Last period of the timeframe
tech	General technology designating index (comprised of gen, trans, dis and car)
crf	Capital recovery factor: $crf = \frac{DR * (1+DR)^{TL_{tech}}}{(1+DR)^{TL_{tech}} - 1}$, where DR is the discount rate of 5%, and TL the technical lifetime of a given technology
inv	Technology specific, non-learning investment costs [\$/v-km] or [\$/GJ] – dependant on the output
linv	Technology specific, learning investment costs [\$/v-km] or [\$/GJ] – dependant on the output
YE	Technology specific cumulative capacity
YE_0	Starting (at market launch, or already present on the market) technology specific cumulative capacity
lrn	Learning rate [%]

fixom	Fixed operation and maintenance costs [$/v-km] or [$/GJ] – dependant on the output
varom	Variable operation and maintenance costs [$/v-km] or [$/GJ] – dependant on the output
fuel	Running fuel costs, necessary for operation of a given technology [$/GJ]
feedstock	Input fuel costs, necessary for operation of a given technology [$/GJ]
convcar	Subset of the personal vehicles, which comprises of all vehicles apart form the hydrogen fuel cell personal car
η	Technology specific efficiency
nfeedstock	Feedstock designating index
nfuel	Fuel designating index

While the data for generation, transmission and distribution technologies may be directly introduced as presented earlier (**Table 1**), the data for vehicles needs to have the annual mileage included. Therefore, the INV and LINV parameters in EQ. 28 for personal vehicles are expressed as described below (EQ. 29).

EQ. 29

$$inv_{car,t} = \frac{purchaseprice_{car}}{am_{car}} \qquad linv_{car,t} = \frac{etlcost_{car}}{am_{car}}$$

Where

inv	Technology specific, non-learning investment costs [$/v-km] or [$/GJ] – dependant on the output
linv	Technology specific, learning investment costs [$/v-km] or [$/GJ] – dependant on the output
t	Time index
purchaseprice	Purchase price of a vehicle (**Table 1**)
car	Personal vehicle technology index
am	Annual mileage of a vehicle (17,000 km/year)
etlcost	Cost of the ETL element (**Table 1**)

In further parts of this work, the reader may find the source code of CUBE with the mentioned formulation as used in GAMS code (Appendix D: CUBE source code).

4.3 CUBE – assumptions on data input

The data, which has been used in analysis with CUBE, is the same as the one used in the analysis conducted with FinalTRA, as well as the analysis which has been conducted with GMM[18]. The data applied has been presented in the earlier chapters (Chapter 2, Description of tools and inputs) as well as on the following diagrams (**Figure 23** and **Figure 24**).

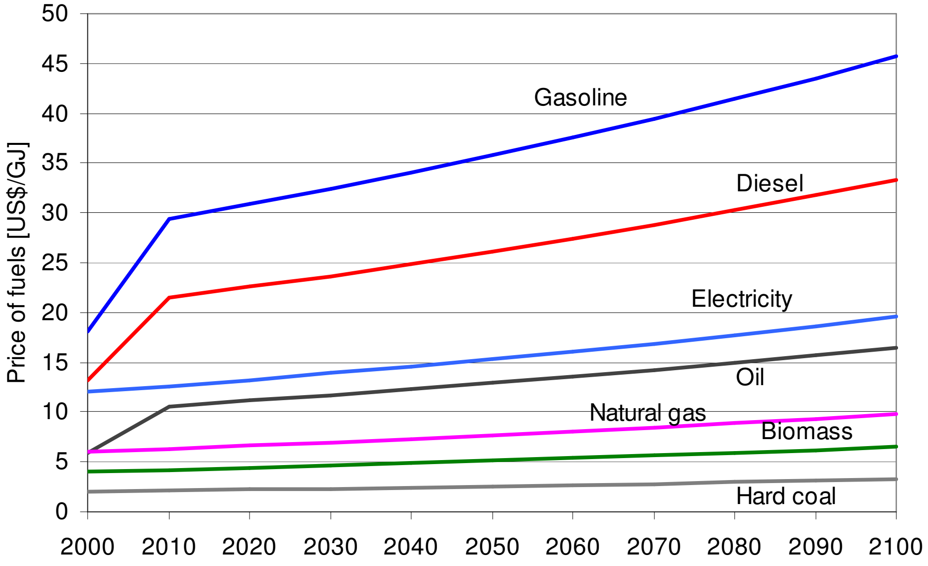

Figure 23 Prices of fuels as used in CUBE

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[18] Chapter 5 - Market penetration of advanced technologies on global scale. Analysis conducted with GMM

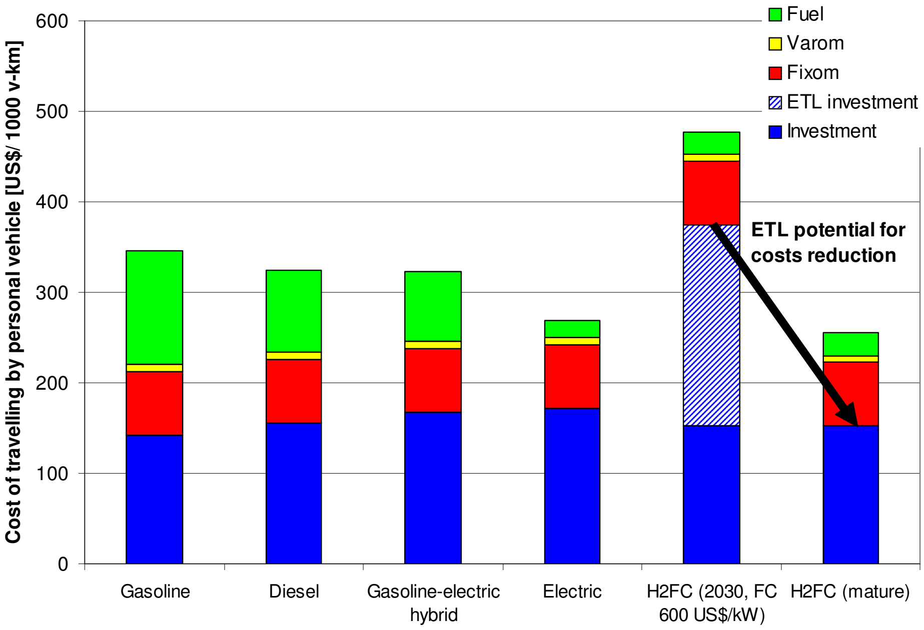

Figure 24 Price of travelling by personal vehicles as used in CUBE; the diagram illustrates the potential reduction in the price of travelling with H2FC, which could be reached if H2FC would penetrate the market. The case of the hydrogen fuel cell vehicle has an illustrative example of the most cost attractive hydrogen cost share – hydrogen generated from natural gas and transported liquefied by trucks. (CUBE Base case: H2FC-kW: 600$/kW; H2FC-LRN: 15%)

4.4 CUBE – sensitivity analysis

The work conducted using the model CUBE, similarly to the analysis conducted with other models, was initiated by developing a "base case" – a scenario where the model is free to allocate technologies according to the least cost optimisation algorithm. The result of this step has been presented below (**Figure 25**).

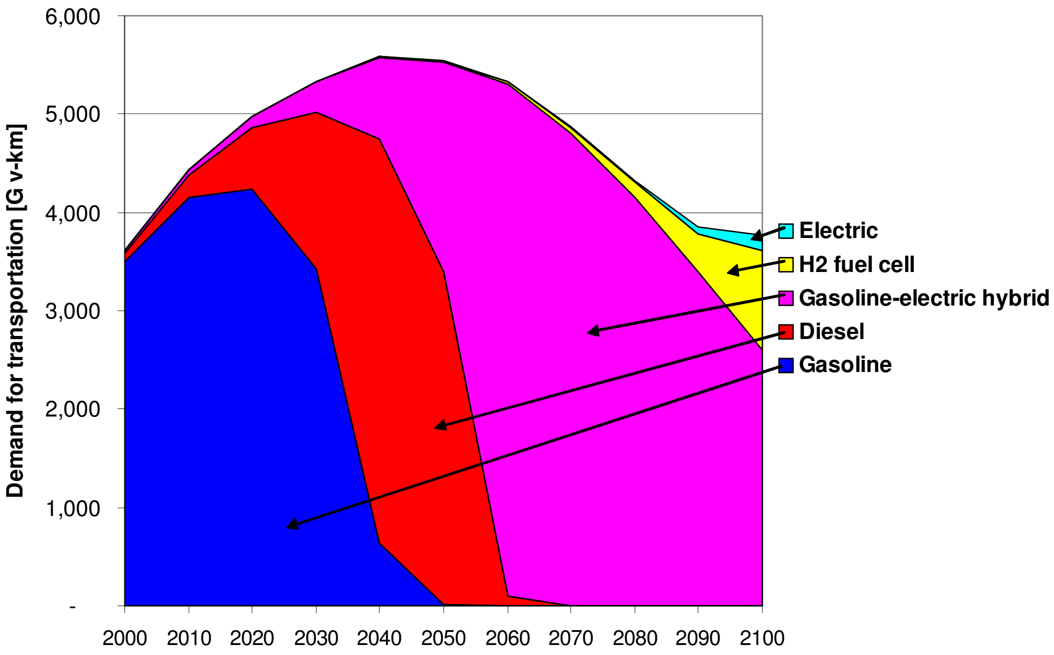

Figure 25 CUBE: "Base Case" of distribution of market shares for different types of vehicles (hydrogen fuel cell stack price: 600$/kW, hydrogen learning rate: 15%)

In CUBE base case, the beginning of the century is dominated by the gasoline vehicles. Later, as the hybrid technologies have not yet matured enough, the dominating position is played by the diesel vehicles. However, this domination is rapidly ended by mid century when the gasoline-electric hybrids penetrate at maximal rates. However, as the fuel prices grow, so does the competitiveness of the hydrogen fuel cell vehicles. The H2FC's start to steadily push away the gasoline-electric hybrids and establish their market position quite firmly in the last decade of this century. However, starting from their introduction in 2050, electric vehicles also emerge. Due to the significant market penetration of gasoline-electric hybrids and H2FC's they keep a marginal share of the market. Nevertheless, by the end of the century, alike the H2FC's they begin to establish a firm market position. One could stipulate, that if the analysis time frame would be longer, one could observe a competition between the two (H2FC and electric vehicles) in the next century.

Comparing the results of the base case obtained from the analysis with CUBE and the earlier results obtained with the analysis conducted with FinalTRA (**Figure 16**) one may observe that the market share which in the results from FinalTRA was taken by advanced gasoline cars, in the results from CUBE were taken by the diesel and the gasoline-electric hybrid cars. The reason for this lays in the fact that FinalTRA, on contrary to all the other models, did not contain time-dependant fuel efficiency improvement of the vehicles (the time dependant improvement of fuel efficiency was captured by means on introducing an "advanced" version of the gasoline and diesel vehicles which were able to penetrate the market in 2010). In the specification used in CUBE, such time-dependant efficiency improvement is present (all types of vehicles, except for the fuel cells and electric cars). Therefore, by the time the gasoline vehicles (CUBE) could reach a level of time-dependant efficiency as to be competitive against other types of vehicles (diesels and gasoline-electric hybrids), the overall costs optimisation algorithm has found that the more efficient way of allocating the market shares would be to favour diesels and gasoline-electric hybrids, which resulted in the diminishing share of gasoline cars in favour of other types of vehicles. Moreover, one should bear in mind the growing prices of oil, which are unfavourable for the gasoline and diesel vehicles. The oil price to a much lesser extend influences the market penetration of gasoline-electric hybrids, which are far superior in terms of fuel efficiency to the portrayed gasoline and diesel cars. All of the models (FinalTRA, CUBE and GMM) are perfect foresight models; therefore the optimisation algorithm "foresees" all possible end-solutions and picks the one with the lowest overall cost. In the case of the market take-over by gasoline and advanced gasoline vehicles (FinalTRA) and later entrance of gasoline-electric hybrids and fuel cell vehicles, one should bear in mind that the algorithm sees that the hydrogen fuel cell vehicles shall have the lowest cost (once enough doublings according to the ETL costs reduction mechanism occur). Therefore, the main market allocation occurs in the time prior to the market penetration of hydrogen fuel cell vehicles, which penetrate at maximal rates. The algorithm employed in FinalTRA henceforth sees the best allocation by favouring the gasoline and advanced gasoline cars, while in the case of CUBE – the algorithm opts for quench the market penetration of gasoline cars and favouring the diesels and the gasoline-electric hybrids.

As mentioned earlier (Chapter 2.5 Sensitivity analysis assumptions), selected factors have been tested for their influence on the market penetration of the advanced vehicles, namely the hydrogen fuel cell vehicles. The modelling framework of CUBE, for the purpose of the sensitivity analysis and later presentation of the results, has been prepared in such way that during a single sensitivity analysis run a pair of factors is varied, as presented below (**Table 12**). The results of the analysis are therefore presented on three-dimensional graphs, which have allowed for establishing of general trends, and in many cases, also threshold values for selected factors. The analysis, including the variations of pairs, has been conducted maintaining the remaining model parameters constant. These parameters have been specified below (**Table 13**).

Due to the overwhelming amount of results, obtained in the course of the analysis, the following parts have been structured as follows. In the first part, a detailed presentation of a single sensitivity run has been presented from the perspective of the H2FC. Later, the same case is analysed from the perspective of other vehicles present on the market (gasoline, diesel, gasoline-electric hybrid and electric vehicles). Lastly, a summary of the full set of runs is presented and conclusions from the whole analysis are drawn. In the later parts of this document, a comparison between the results obtained from all the models shall be presented (Chapter 6, Consistency across model results).

Table 12 Combination of pairs of influential factors used in the sensitivity analysis (CUBE)

		1st Factor				
		H_2FC-LRN	H_2FC-kW	CCo_{H2FC}	BBL	PPL-GR
2nd Factor	H_2FC-LRN	☒		☑		
	H_2FC-kW	☑	☒		☑	
	CCo_{H2FC}		☑	☒		
	BBL			☑	☒	
	PPL-GR	☑				☒

Table 13 Specification of factors used in the sensitivity analysis (CUBE)

Factor	Value	State
H_2FC-LRN	2.5 … 20%	Variable
	15%	Constant
H_2FC-kW	200 … 1000 $/kW	Variable
	600 $/kW	Constant
H_2FC-kW Floor	100 $/kW	Constant
BBL	-5 … +5% / decade	Variable
	+5% / decade	Constant
PPL-GR	+2.5 … 17.5% / year	Variable
	10% / year	Constant
CCo_{H2FC}	75,000…700,000 vehicles	Variable
	75,000 vehicles	Constant

The list of abbreviations and a more detailed explanation of the selected factors which were used the reader may find in the earlier parts of this work (Section "List of abbreviations" and Chapter 2.6 Interpretation of sensitivity analysis runs).

4.4.1 Price of fuel cells vs. fuel cell learning rate (H2FC penetration)

Similarly to the analysis conducted with FinalTRA, the results of runs carried out with CUBE show similar tendencies (**Figure 26**). There is a strong relationship between the learning rate and the initial price of fuel cells. The results suggest that a higher learning rate allows for market penetration staring from a higher initial cost. A learning rate of 15% allows for successful market deployment when the price of the fuel cells is in the range of 600 US$/kW. In the case the fuel cells are above this value, more dynamic learning rates would be expected in order to provide grounds for market penetration.

In the most favourable conditions when the fuel cell vehicles penetrate the market, by the end of the modelling timeframe they reach an overall market share of slightly more than 3%. This is independent on the degree of favourability of the conditions. This is due to the fact, that in the modelling framework the competing technologies may penetrate at a given, externally fixed growth rate. In reality however one could expect the growth rate to depend on the market performance.

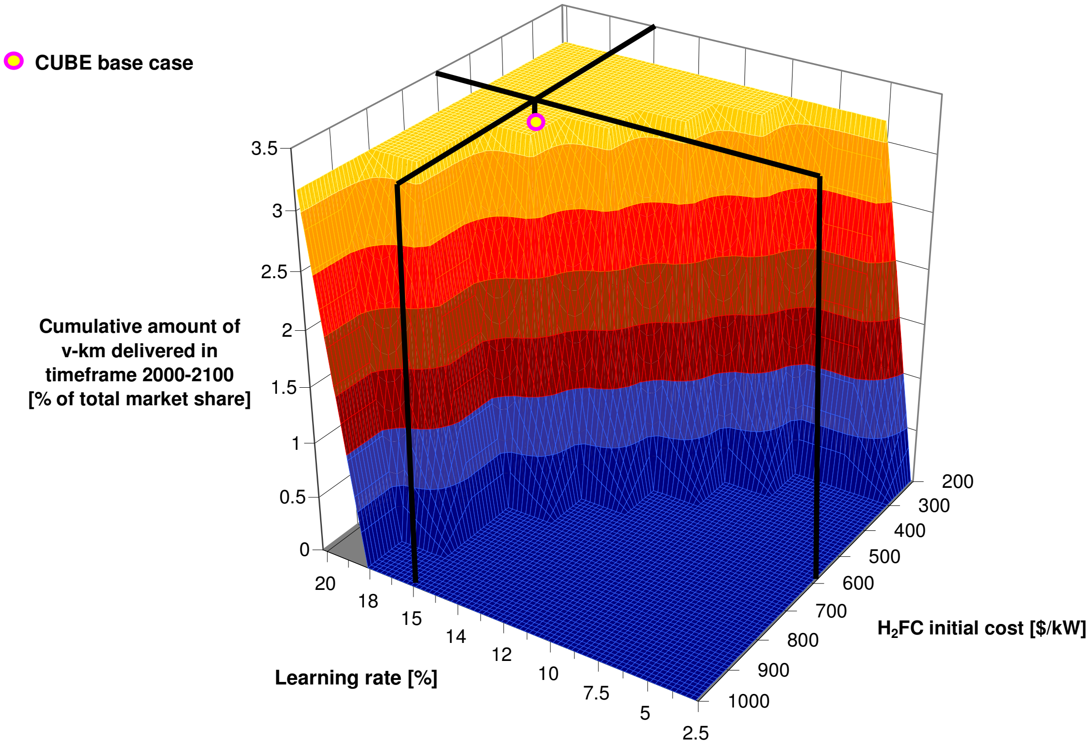

Figure 26 CUBE: Graphical illustration of market penetration of H_2FC in the context of variable H2kW and H2FC-LRN factors (with all other factors constant, oil price growth: +5%/decade, hydrogen fuel cell floor cost 100 $/kW)

4.4.2 Price of fuel cells vs. fuel cell learning rate (penetration of other technologies)

The availability of market share which can be taken over by hydrogen fuel cell vehicles is limited by the externally implied bounds (growth rates). Therefore, in long run as the fuel cell powertrain becomes competitive the market share won by fuel cell vehicles, independent of the economical performance, may not reach a higher level than the technology specific growth rate. A similar constraint is bounding also the other types of vehicles.

Nevertheless, as long as the competitive technologies do not enter the market (for example in the first periods of the analysis timeframe) the position of most widely spread technologies is dominant. Due to the fact that the advanced technologies have a low initial capacity (75,000 vehicles per region) and there is a limited time to build up capacity, their share in the cumulative amount of vehicle-kilometres is significantly smaller than the ones of technologies which are already present on the market. Nonetheless, the results of the sensitivity analysis indicate conditions (in this case different learning rates and initial prices of fuel cells) at which the advanced technologies are able to push out the technologies already present on the market. In the case of gasoline vehicles (**Figure 27**) one may observe a similar pattern to the one of H2FC (**Figure 26**), which shows that the higher the learning rate and the lower the initial price of fuel cells, the more penetration of H2FC vehicle penetration may be observed, hence a decrease in penetration of gasoline vehicles.

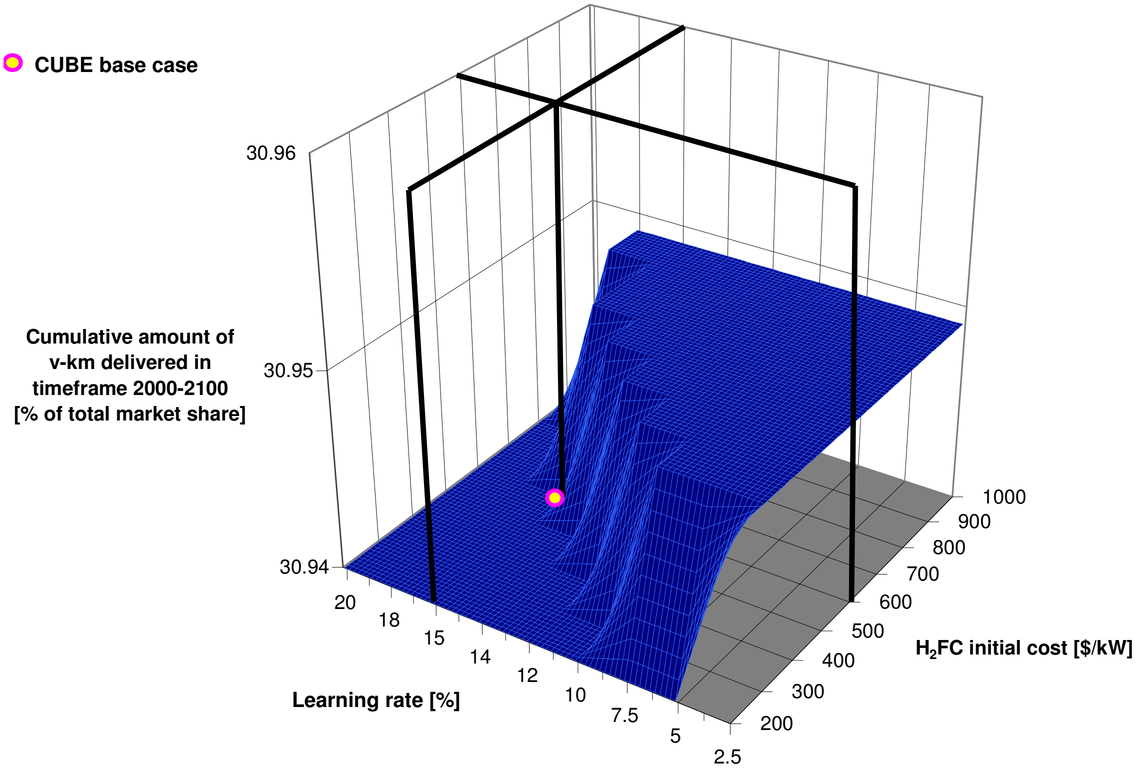

Figure 27 CUBE: Graphical illustration of market penetration of gasoline vehicles in the context of variable H2kW and H2FC-LRN factors (with all other factors constant, oil price growth: +5%/decade, hydrogen fuel cell floor cost 100 $/kW)

The penetration of diesel vehicles (**Figure 28**) and gasoline-electric hybrids (**Figure 29**) exhibit similar patterns as the ones described earlier. Provided that the learning rates and initial price of the fuel cells are competitive all three technologies (gasoline, gasoline-electric hybrid and diesel) give room to advanced technology of fuel cells. One should bear in mind that the changes are in the range of 1/10 of a percent; this is due to the fact that in the 70 years (2030-2100) when the fuel cell vehicles are available to penetrate the market, within externally imposed market expansion rates, they can conquer at maximum ~3% of the total market share.

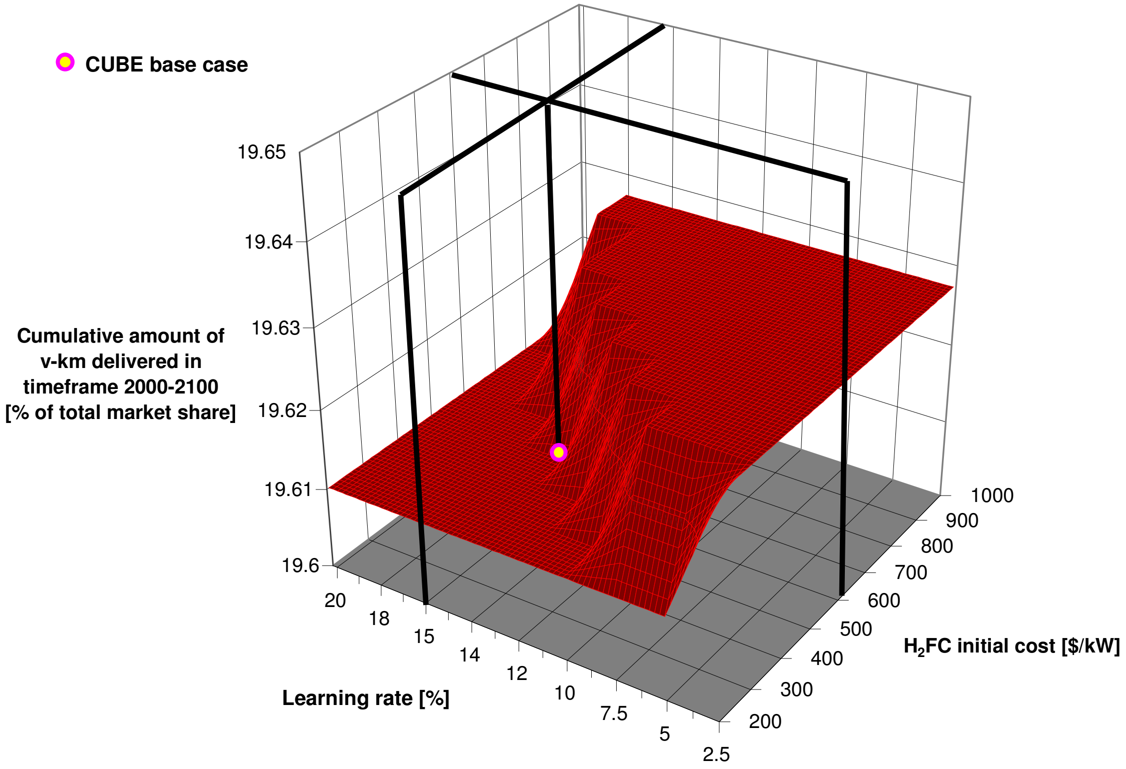

Figure 28 CUBE: Graphical illustration of market penetration of diesel vehicles in the context of variable H2kW and H2FC-LRN factors (with all other factors constant, oil price growth: +5%/decade, hydrogen fuel cell floor cost 100 $/kW)

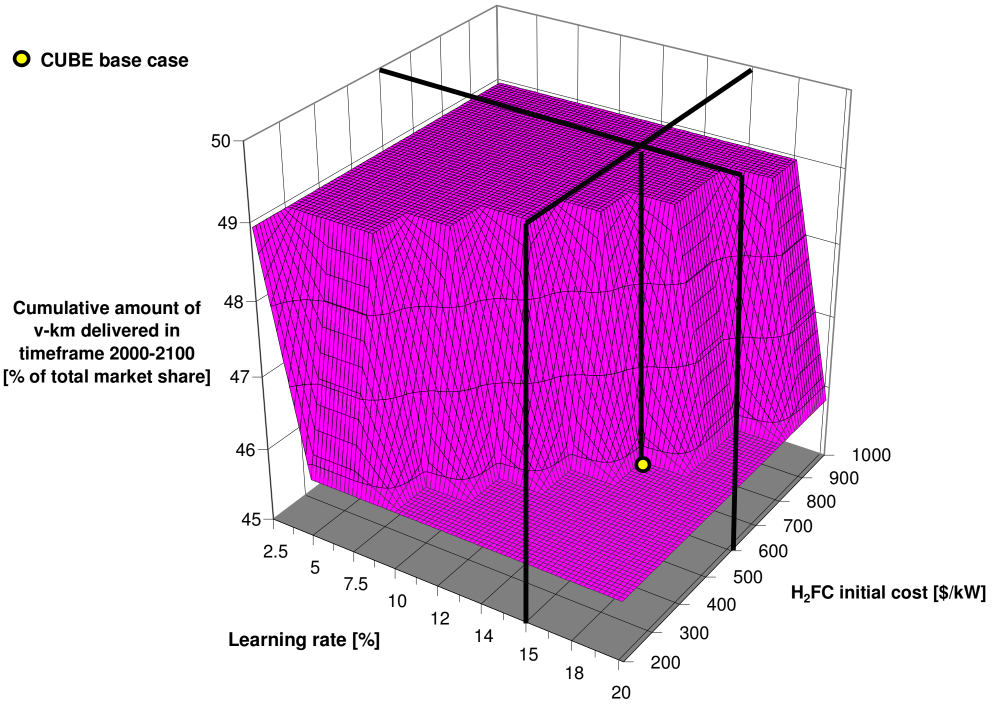

Figure 29 CUBE: Graphical illustration of market penetration of gasoline-electric hybrid vehicles in the context of variable H2kW and H2FC-LRN factors (with all other factors constant, oil price growth: +5%/decade, hydrogen fuel cell floor cost 100 $/kW)

Market positioning of the electric vehicles does not impose any challenges for the penetration of the fuel cell vehicles. On the basis of the technological and economical performance as described earlier (**Table 1**), the electric vehicles may be considered as the next stage for the development of the transportation sector. As of the time the electric vehicles are introduced (2050) they slowly penetrate the market at an even pace independent on the market performance of other competing technologies (**Figure 30**). The equally flat plain is the result of the fact that the electric vehicle penetrates at maximum growth rate allowed in the constraints of the modelling framework, while its penetration is undisturbed by the competition independent of market conditions.

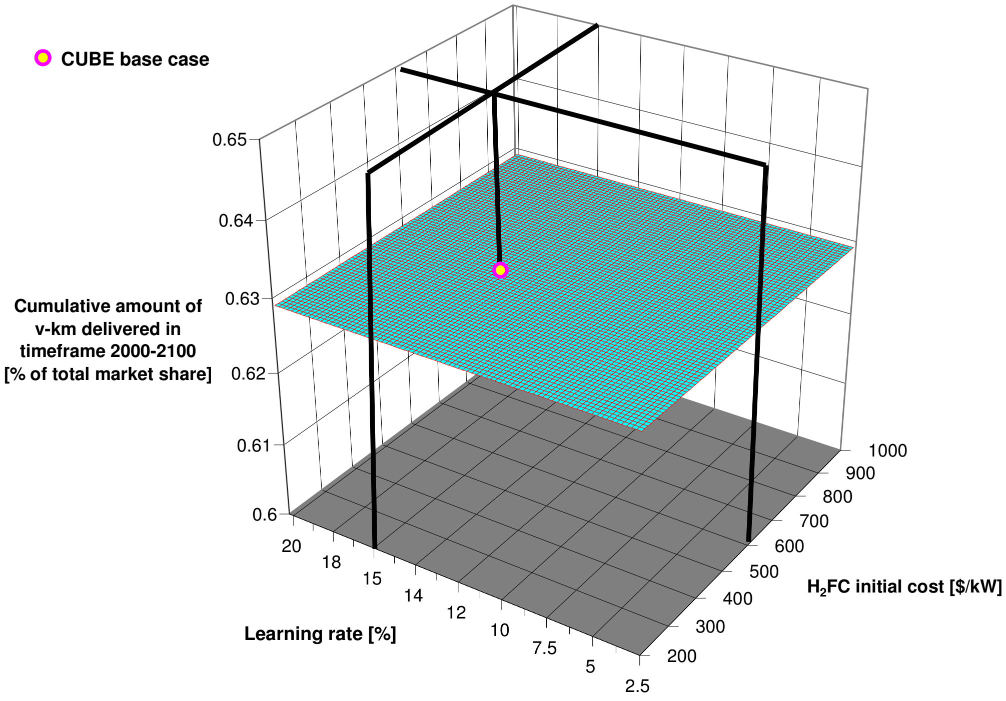

Figure 30 CUBE: Graphical illustration of market penetration of electric vehicles in the context of variable H2kW and H2FC-LRN factors (with all other factors constant, oil price growth: +5%/decade, hydrogen fuel cell floor cost 100 $/kW)

4.5 CUBE – conclusions from the analysis

The results of the analysis conducted with CUBE, a non-linear optimisation algorithm (NLP) model, brought similar conclusions as the ones which came from the earlier analysis with FinalTRA. Within a more detailed, than the one of FinalTRA, modelling framework the results of the analysis conducted with CUBE confirm that hydrogen based transportation system has a significant potential to become a feasible option. Nevertheless, the results show that one of the **critical elements might be the price of the fuel cells**, which constitute the major element of the overall cost structure of travelling with fuel cell vehicles (**Figure 22**).

Further the results confirmed the conclusions which have been drawn after the analysis conducted with FinalTRA:

– In order to provide a successful possibility for fuel cell vehicles to penetrate the market, the **fuel cell price ought to be in the range of 600 US$/kW** by the time the vehicles are introduced to the market.

- Moreover, a potential for **costs reduction in at the level of 14%** would be a benefit which could strengthen the potential for the development of hydrogen based mobility.
- The current and future projections of oil prices provide a favourable position for hydrogen as fuel; nevertheless the **price of oil** is already so high that the further possible growth of prices **may even more strengthen** the financial benefit of hydrogen over oil-based fuels.
- The growth rate, at which the hydrogen **pipeline infrastructure** may grow **has a moderate impact** on the development of the hydrogen based mobility.

Due to the fact that with both models (FinalTRA and CUBE) similar runs have been conducted, in the later part an overview and comparison of the results shall be presented (Chapter 6 Consistency across model results).

5 Market penetration of advanced technologies on global scale. Analysis conducted with GMM

The third, and the last, model used in this analysis was GMM. GMM is a global edition of the full energy system model MARKAL. GMM, similarly to the two earlier used models (FinalTRA and CUBE) is a perfect foresight, costs optimisation model which uses a MIP optimization algorithm.

GMM shares the following items with the simplistic models used in the first two parts of the analysis.

- Technological database
- External demand for transportation
- External prices of oil (defined on purpose to reproduce recent price changes)
- Endogenous technological learning for selected technologies

The advantage of GMM modelling framework is that it provides a picture of the whole of the energy system, including industry, households and transportation (Loulou, Goldstein et al. 2004). This allows for better evaluation of policy measures, as GMM is able to picture the overall impact of policies. This allows for observing if any feedback loops exists, once transport specific policies are introduced. Due to the fact that GMM is a more complex model containing much more detail, than the two remaining ones (FinalTRA and CUBE), the modelling timeframe is 50 years (2000-2050). GMM, similarly to other models used in this research, is a perfect foresight model, therefore the calculations algorithm is able to "knows" the potential effects at the end of the timeframe already in the moment when the conditions of the first period are analysed.

5.1 Introduction to GMM – broad scale market entrance of advanced technologies

GMM, an advanced edition of the MARKAL model (Fishbone and Abilock 1981), is equipped with the state of the art endogenous technological learning. The implementation of this feature to GMM has been carried out by Barreto (Barreto 2001) using the Mixed Integer Programming (MIP) technique. MIP approach allows linearization of otherwise non-linear, non-convex problems. A simplified introduction of ETL using MIP has also been introduced in FinalTRA; therefore the mathematical description used in FinalTRA (as described in Chapter 3.2 FinalTRA – model description) reflects the methodology which has been introduced in GMM.

5.2 GMM - assumptions on data input

The data, which has been used in analysis with GMM, is the same as the one used in the analysis conducted with FinalTRA, as well as the analysis which has been conducted with CUBE. The data applied has been presented in the earlier chapters (Chapter 2, Description of tools and inputs).

5.3 GMM – sensitivity analysis

The starting point of the analysis was the development of the "base case" which was a basic scenario where the model is free to allocate the technology mix according to overall, least-cost optimization algorithm. The base case is therefore free of any external interventions like governmental subsidies or extra taxation. In the base case of GMM, as illustrated below (**Figure 31**), the first 30 years of this century are primarily dominated by two types of vehicles, namely with gasoline and diesel power trains. Later, as the hybrid technology has matured more, it is the gasoline-electric hybrid that begins to dominate the market. In the first quarter of the century, major fuel cell producers and developers were able to solve technical problems related to the operation of fuel cells (like limited life time of membranes) (Bruijn de 2005), and by the time the fuel cells are ready for preliminary market launch, their price is at the level of 600 US$/kW. Moreover, manufacturers of fuel cell see possibilities for further costs reduction, provided that a significant demand for fuel cells would appear (fuel cell learning rate 15%). Additionally, steadily growing oil prices (oil price reaches an average of around 70 US$/bbl by the end of the modelling timeframe) which are unfavourable for vehicles based on conventional fuels, suggest that a change to an alternative transportation option could be feasible. Despite all of the favourable for hydrogen based mobility conditions, the hydrogen transportation does not lift off. This is mainly due to the fact, that fuel cells are still too expensive for potential customers; additionally the potential customer is faced with a problem of limited access to the fuelling network. The lack of fuelling facilities is in a way a "chicken&egg" problem. Fully fledge fuelling infrastructure is not constructed, as no noticeable demand exists; while on the other hand, no demand can be triggered as the potential buyers see a significant drawbacks in the possibilities of fuelling their hydrogen fuel cell vehicles. In order to break this "chicken&egg" problem, an external incentive is required. The fuel cell developers and manufacturers have invested significant sums during the first quarter of the century and could be reluctant to continue investments at such pace (mobile fuel cell would remain as back-stop technology, with perspective of launching at later time) while only a marginal share of individual users would be willing to commit themselves to investments into vehicles with majorly limited access to fuelling network. Therefore, the remaining potential body which could provide the initiative for the switch to hydrogen based mobility is the government. The possible directions of governmental support have been presented in the further parts of this document (Chapter 7 Global impacts of advanced transportation technologies).

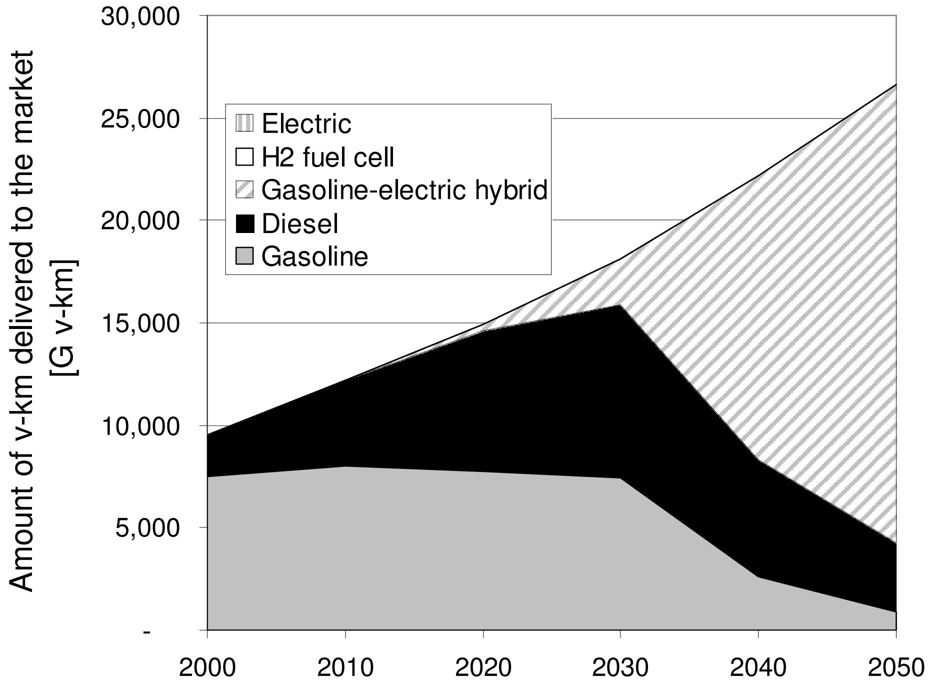

Figure 31 GMM: "Base Case" of distribution of market shares for different types of vehicles

Similarly to the presentation of the results in the earlier chapters (Chapter 4.4 CUBE – sensitivity analysis) in what follows a single illustrative case of sensitivity analysis has been presented in more detail. Due to the multitude of results obtained, the full range of results acquired has been presented in a concise way and compared with the results obtained from the analysis using the remaining two models in the further parts of this work (Chapter 6 Consistency across model results).

The illustrative example of the exercises carried out using GMM covers a sensitivity analysis which was focused on analysing the potential influence on the future market penetration of hydrogen fuel cell vehicles analysing two factors, namely the change in oil price and the learning rate of the fuel cells. The graphical illustration of the results has been presented below (**Figure 32**).

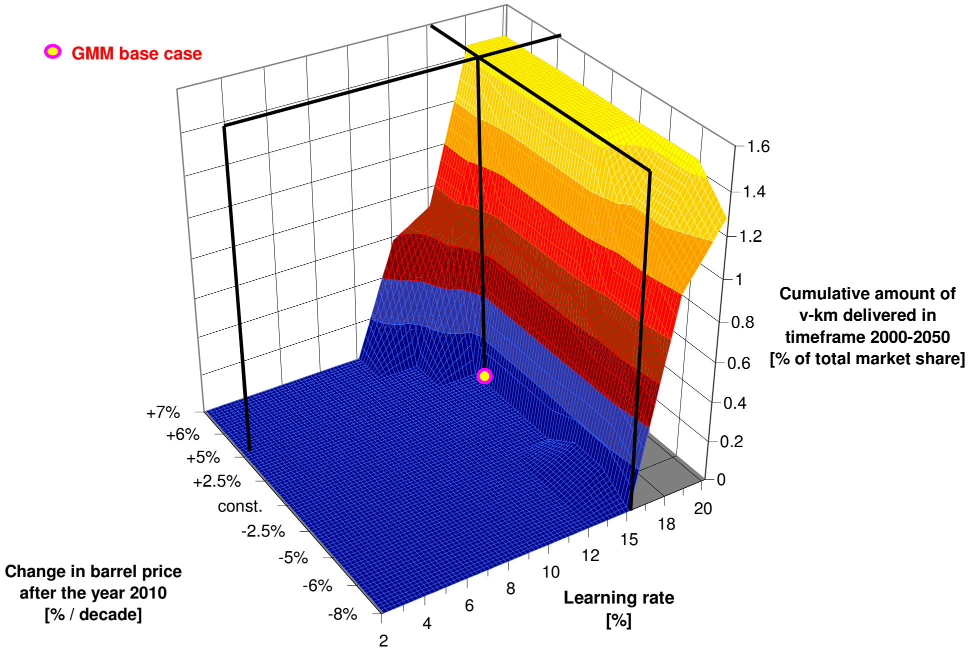

Figure 32 GMM: Graphical illustration of market penetration of H_2FC in the context of variable LRN and BBL factors (with all other factors constant, hydrogen fuel cell floor cost: 100 $/kW)

The results of this part of the analysis suggest that the determining factor, considering the pair learning rate and change in oil price, is the learning rate. Earlier trail runs, which have not been reported here, suggested that the oil price already at a level of more than 30 US$/bbl is high enough to support the possible market penetration of the fuel cell vehicles. Nevertheless, comparing the overall costs of travelling by different types of vehicles, the investment costs related to the fuel cell vehicle (car body as well as the fuel cell stack) play a dominating role in respect to the competitiveness of the hydrogen car (**Figure 24**). Reduction of this cost by means of the considered learning rate seems to be crucial. Even if the assumed prices of oil would increase even more, they would improve the market competitiveness of fuel cell vehicles, however most probably would not be able to outbalance the investment costs of the fuel cell cars and the necessary need for further costs reduction of fuel cells. On the other hand, the learning rate of the fuel cells has a significant potential to reduce the learning part of the investment costs and in result allowing fuel cell vehicles to be much more competitive. The results of this analysis, in reference to learning rates, suggest that above 15% there is enough potential to reduce the price of the fuel cell stack to the level where successful market penetration of hydrogen fuelled vehicles could be possible.

5.4 GMM – conclusions from the analysis

The analysis conducted with GMM allowed the examination of the influence of selected factors on possible market penetration of hydrogen fuelled fuel cell vehicles. Despite numerous similarities in the approach which was applied while using the earlier two models, analysis with GMM provided more benefits in terms of the overall view on the possible developments in the transportation sector. The benefits of using GMM over the two previous models (FinalTRA and CUBE) included among others:

- possibility to observe the potential market penetration of fuel cell vehicles in the full frame of the energy system in more than one part of the transportation sector (FinalTRA and CUBE contained only passenger vehicles, while GMM contained also specific data related to heavy road freight and buses as well as generalised data for other, fuel-specific, aggregated modes of transport),
- possibility of including in the analysis cluster learning factors; in GMM the key component used in fuel cell vehicles (fuel cells) as well as batteries used in the hybrid-electric vehicles profited in terms of ETL performance from all technologies which employed the mentioned technological elements (for example, the ‘learning’ of the fuel cells in personal vehicles benefits from

market penetration from other types of vehicles like fuel cell buses, and *vice versa*) (Seebregts, Bos et al. 2000),

- possibility of analysing the impact of environmental policies applied not only to the end-of-pipe emissions of pollutants (strictly originating from vehicles themselves), but also emissions originating from other fuel chains (natural gas, coal, biomass, etc.),
- possibility to broaden the geographical area to global scale, allowing the incorporation of region specific data; the two earlier models (FinalTRA and CUBE) focused only on the highly developed region of North America, which due to high GDP/capita may more easily accept more expensive technologies.

The results of the analysis with GMM in principle confirmed the findings from the exercises with two simplified models, suggesting that the potential to further reduce the costs of the fuel cells **(learning rates) as well as the price of fuel cells are the key elements** which may stand in the way of successful market penetration of hydrogen fuel cell vehicles. This part of the analysis, with the comparison to the results coming from the two prior models, has been presented in the following part of this work (Chapter 6 Consistency across model results).

Nevertheless, the broadness of the model in terms of numerous fuel chains and related characteristics has shown that the **possibility of switching to hydrogen based transportation sector is a much more complex issue** than the one pictured in the 'small' models. However, this complexity has indicated numerous areas which could be influenced as to promote the switch to hydrogen based mobility. The results of this specific policy analysis have been presented in more detail in the later parts of this work (Chapter 7 Global impacts of advanced transportation technologies).

6 Consistency across model results

The three models (FinalTRA, CUBE and GMM) which have been used in the analysis of the possible development in the transportation sector have been all focused on the same target issue, which was possible market penetration of hydrogen fuel cell vehicles under different market conditions. However, the three models differ in the extend of their complexity, in terms of representation of the transportation sector, time frame as well as the algorithm which was used to perform the calculations. The table below presents major differences across the models (**Table 14**).

Table 14 Specification of main differences between FinalTRA, CUBE and GMM

Element	**FinalTRA**	**CUBE**	**GMM**
Algorithm	MIP	NLP	MIP
Timeframe	2000-2100	2000-2100	2000-2050
Single run calculation time	<5 sec	<5 sec	15-55 min
Regions	NAM	NAM	NAM, OOECD, ASIA, LAFM, EEFSU
Energy sectors	Transportation	Transportation	Full energy system
Transportation modes	Personal cars	Personal cars	Personal cars, Buses, Trucks, other[19]
ETL technologies	Fuel cells	Fuel cells	Fuel cells, batteries, other[20]
Fuel chains	Hydrogen (aggregated)	Hydrogen (full specification)	All fuels
Energy prices	External with fuel specific +1..+5%/decade increase	External with fuel specific +1..+5%/decade increase	Internal and external, with global +1 to +5%/decade increase with

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[19] Aggregated according to fuel type

[20] in different energy sectors – like solar panels

			region specific initial prices
Emissions	CO_2	CO_2	CO_2, NOx, SOx
Environmental pollutants specified for	Personal vehicles, aggregated hydrogen fuel chain	Personal vehicles, hydrogen fuel chain	Full energy system

Despite the mentioned differences, one could expect that the results ought to allow for drawing conclusions which are consistent across models. One could expect small differences in the results from all three models, nevertheless these should not indicate significant discrepancies, which would question the integrity of the whole multi-step analysis process. To address the issue of the consistency across the results coming from all three models, in the following a comparison between the results of the runs which were carried out for all three models has been presented (**Figure 33** through **Figure 42**).

6.1 Consistency: H2FC-kW vs. H2FC-LRN

The first pair of factors which has been tested for the influence using all three models was the initial price of fuel cells and the fuel cell learning rate (**Figure 33** through **Figure 35**).

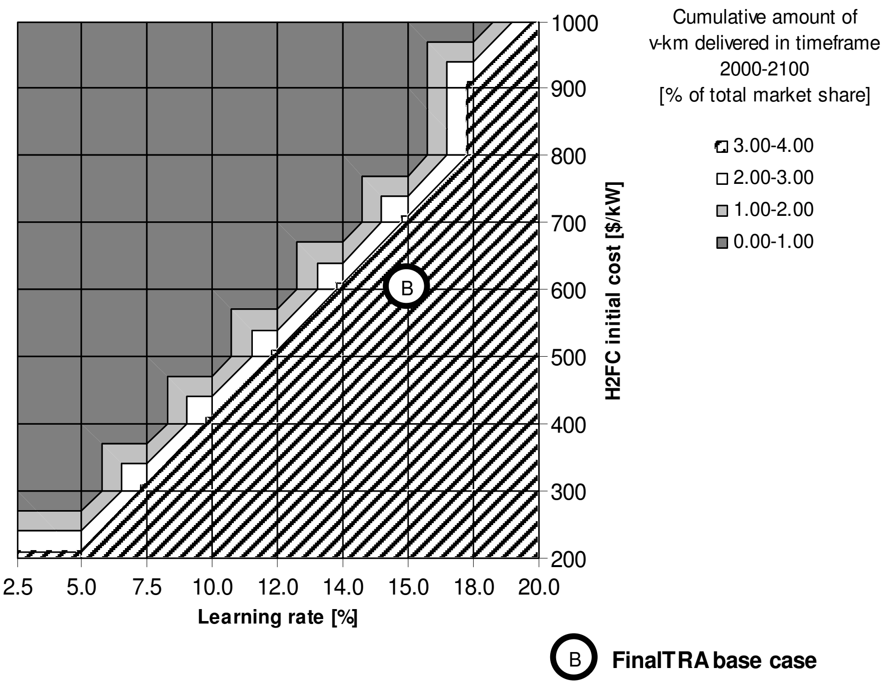

Figure 33 Consistency across models (FinalTRA): H2FC-kW vs. H2FC-LRN

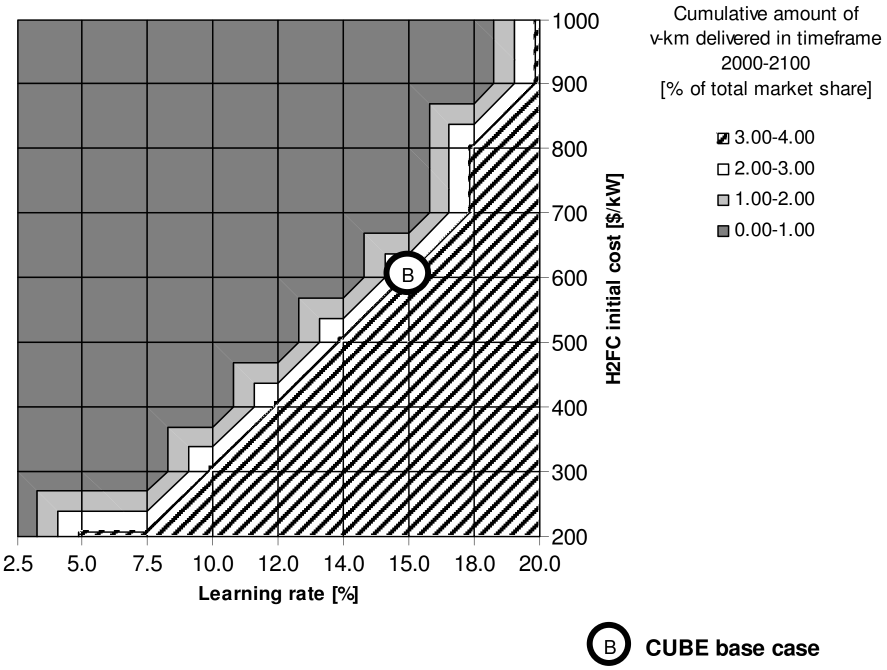

Figure 34 Consistency across models (CUBE): H2FC-kW vs. H2FC-LRN

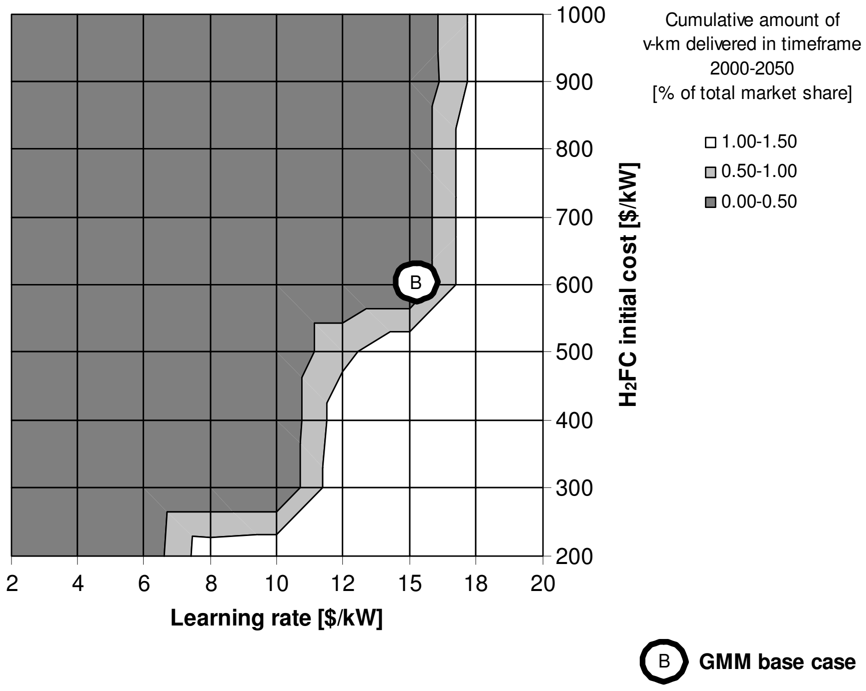

Figure 35 Consistency across models (GMM): H2FC-kW vs. H2FC-LRN

The results of this set of runs suggest, considering results from all three models, that both parameters are equally important for the penetration of fuel cell vehicles. All results suggest that the higher the learning rate and the lower the initial cost of fuel cells, the more prospective is the market penetration. Comparing results from all models one may notice that the results from FinalTRA and CUBE suggest a cumulative market share or around 3-4% (at full market penetration), while in the case of the results from GMM this value is in the range of 1-1.5%. The explanation for this is that GMM uses a shorter timeframe as the remaining models; therefore if fuel cell vehicles are able to penetrate they may not reach such penetration as in the case of FinalTRA or CUBE, because in GMM the fuel cell vehicles have 'only' 20 years for penetration, while in the case of the other models the available time is 70 years.

Comparing the results originating from FinalTRA and CUBE, one may notice that the FinalTRA results tend to be more optimistic – a lower learning rate and a higher initial price of fuel cells allows for market penetration. The reason for this is that FinalTRA uses aggregated fuel chains, which implies hydrogen to be slightly cheaper as in the case of CUBE. Example of such aggregation may be the lack of fuel cost needed for the trucks to deliver hydrogen. This number may be small at first glance, however considering a large scale, long time frame and growing prices of oil, this element is able to influence the overall results.

Moreover, one may observe that despite the fact that all models used the same setting for the base case, in the case of FinalTRA and CUBE, the fuel cells penetrate the market. However, looking at the results from GMM it may be noted that in the base case the fuel cells do not penetrate the market. The reason for this is quite similar to the already mentioned one about the time frame. All of the optimisation models are perfect foresight, therefore the model 'sees' the potential evolution of technologies in a given timeframe. As the price of fuel cells is linked to the ETL costs reduction mechanism, which in turn is dependant on the cumulative number of vehicles present on the market, in the case of the GMM base case the model has calculated that the fuel cell vehicles may not become competitive, under the base case assumptions, within the given timeframe. Therefore, the model 'decides' not to go for the fuel cell vehicle option, as not enough time space is available for fuel cells to develop in terms of ETL cost reduction (not enough cumulative capacity may be build up in the given timeframe with implied growth rates). Nevertheless, the results from the other models suggest that if the timeframe is longer (50 years longer as compared to the timeframe of GMM), the fuel cell vehicles have enough time to accumulate the necessary capacity as to allow promising cost reduction.

The results from GMM do not display such linearity as the results from the remaining models. The reason for this lays in the complexity of the interactions in GMM which portrays the whole of the energy system. Nevertheless, the results from GMM confirm the general tendency that higher learning rates and lower initial cost of fuel cell benefit the market propagation of fuel cell vehicles.

6.2 Consistency: H2FC-LRN vs. CCo_{H2FC}

The next pair of factors which potentially may influence market penetration of fuel cell vehicles was made up from the fuel cell learning rate and the initial number of vehicles launched to the market. The comparison of the results from all three models has been presented on the following diagrams (**Figure 36** through **Figure 38**).

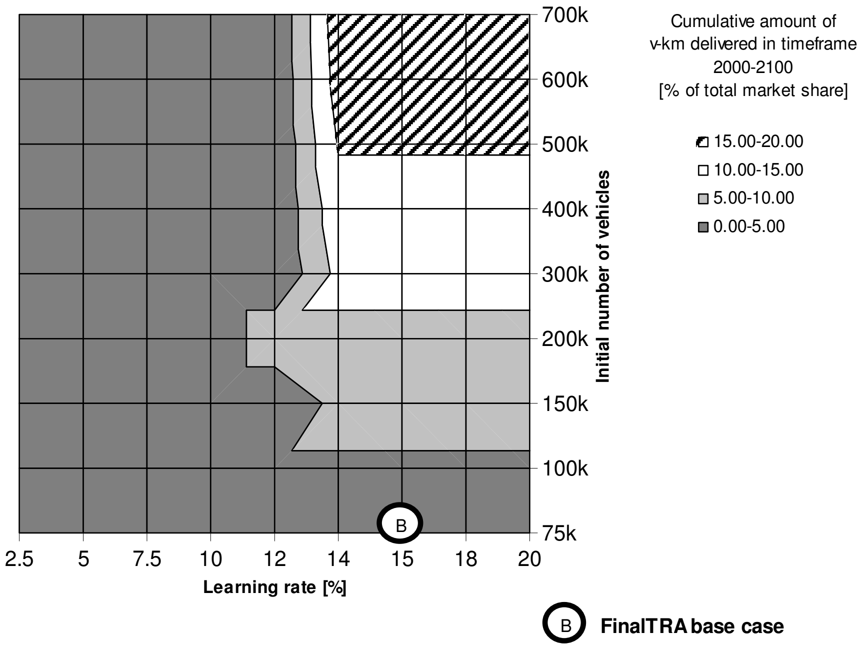

Figure 36 Consistency across models (FinalTRA): H2FC-LRN vs. CCo_{H2FC}

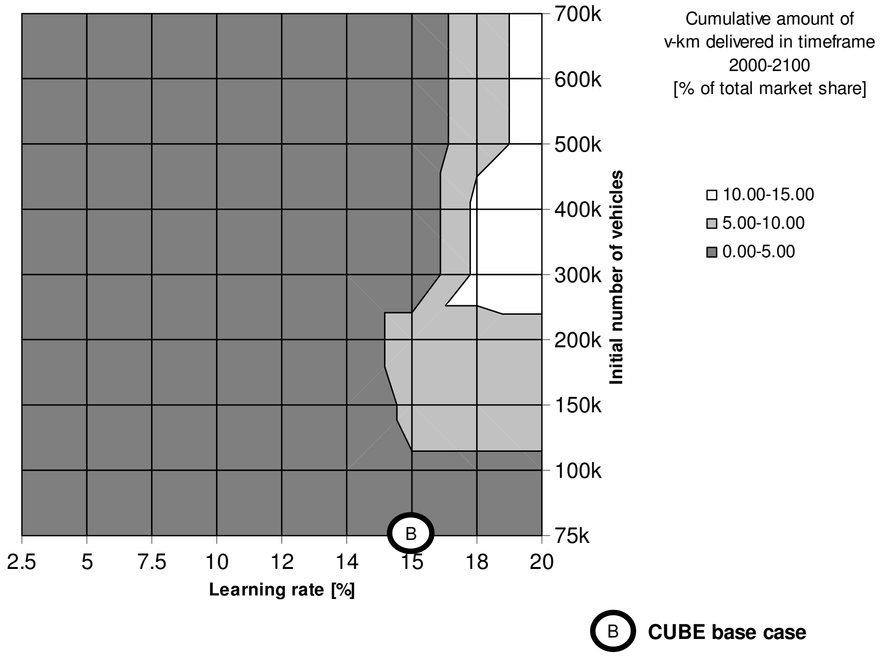

Figure 37 Consistency across models (CUBE): H2FC-LRN vs. CCo_{H2FC}

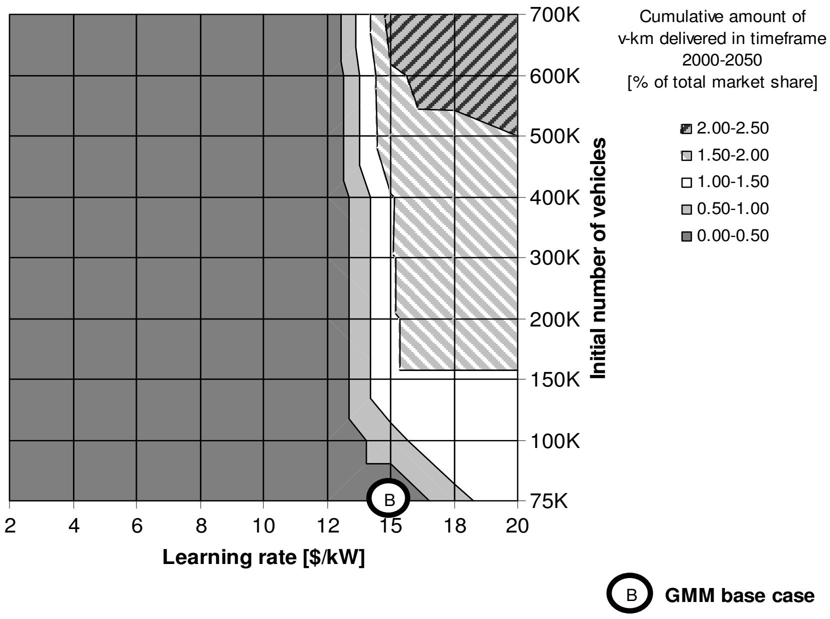

Figure 38 Consistency across models (GMM): H2FC-LRN vs. CCo_{H2FC}

All of the results of this part of the analysis, originating from the three models, point to the same conclusion, which is – the higher the initial number of vehicles launched to the market, the higher is the share they may take over, in the model specific time frame. Similarly to the results of the previous analysis (Chapter 6.1 Consistency: H2FC-kW vs. H2FC-LRN) the results of this one suggest that the picture drawn by FinalTRA is more optimistic than the one coming from CUBE. While the results of FinalTRA indicate that there is no matter how large the starting capacity is a learning rate of more than ~12% allows for full market penetration, the results from CUBE suggest that at higher initial starting capacities (more than 300,000 vehicles) more dynamic learning rates would be required (14% or more). The explanation for this lays in the differences which the models 'see' at the end of the time analysis frame, which is directly related to the algorithm used (MIP in the case of FinalTRA and LP in the case of CUBE). The tendency of the results coming from the analysis done with GMM suggest similar conclusions as the ones originating from FinalTRA – a learning rate of more than 15% is able to facilitate such cost reduction, independent on the starting capacity, as to allow successful market penetration of fuel cell vehicles. One should bear in mind, that the results of GMM consider only a starting capacity of personal vehicles; nevertheless the fuel cells are also used in buses (cluster learning component for both types of vehicles) which also contribute to the starting amount of fuel cells used on the market.

Looking at the results coming from all three models one may notice a consistent conclusion, which is that with the increased (as compared to the base case, which for all models was 75,000 vehicles) starting capacity, a learning rate of 15% may allows for successful market penetration of fuel cell vehicles.

6.3 Consistency: H2FC-kW vs. CCo$_{H2FC}$

Nextly, the pair made up from the initial cost of fuel cells and the initial number of vehicles launched to the market was considered for consistency across the three models. The results of the runs carried with the three models have been presented below (**Figure 39** through **Figure 41**).

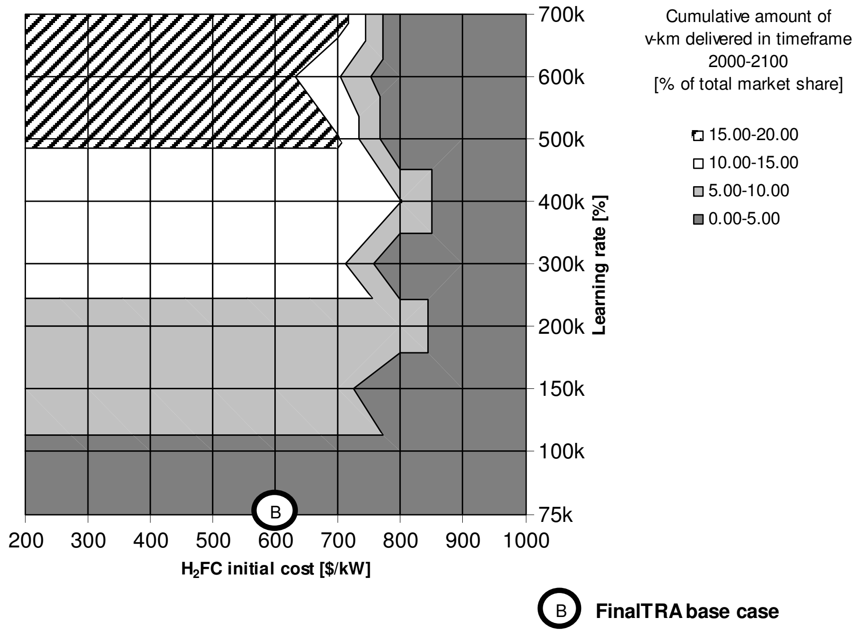

Figure 39 Consistency across models (FinalTRA): H2FC-kW vs. CCo$_{H2FC}$

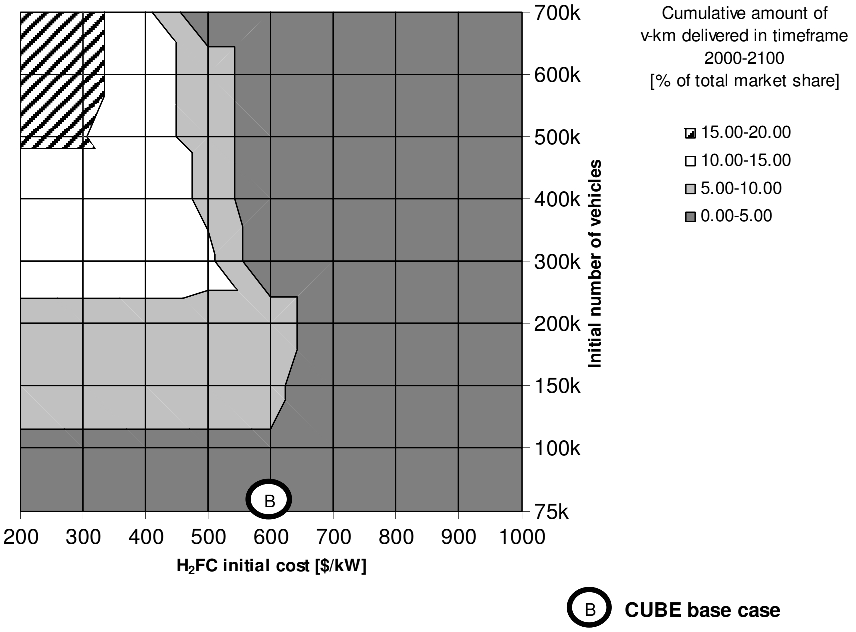

Figure 40 Consistency across models (CUBE): H2FC-kW vs. CCo_{H2FC}

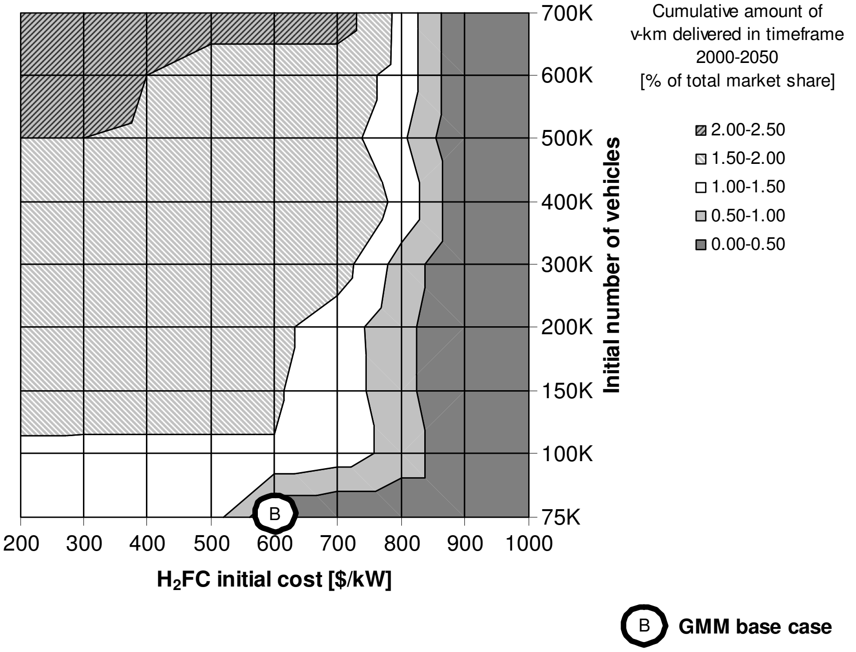

Figure 41 Consistency across models (GMM): H2FC-kW vs. CCo_{H2FC}

The results of FinalTRA and CUBE show similarities when considering the price of fuel cells to be lower than 700 US$/kW. Above this threshold, the results of FinalTRA tend to be more optimistic, as compared to the ones from CUBE, suggesting that even at higher prices of fuel cells the penetration is possible. Nevertheless, one should bear the notion in mind while examining these results, that the representation of hydrogen price is limited in FinalTRA as compared to CUBE. This results in the fact, that in FinalTRA the overall cost of travelling with a fuel cell vehicles is slightly lower as the ones in CUBE or GMM.

The results originating from the analysis with GMM show similar trends and conclusions as the results coming from the remaining two models. All the results suggest that the starting capacity has preliminary influence on the final, overall market share which may be captured. This is a result that in all models, the potential to penetrate the market (assuming a technology is competitive) is governed by the initial number of vehicles launched to the market and a growth rate. Therefore, as in all the cases the growth rates were constant, the initial number of vehicles was decisive. Nevertheless, the results suggest that market penetration may be achieved, under the assumption of all other factor constant, if the price of the fuel cells shall be lower than 850 US$/kW and the initial market launch shall be considerable (more than 100,000 vehicles).

6.4 Consistency: H2FC-kW vs. BBL

The last pair of factors, which was tested using all three models, was the pair made up of the initial price of the fuel cells and the possible trends in the price of oil. The results of the runs conducted with FinalTRA, CUBE and GMM have been presented below (**Figure 42** through **Figure 44**).

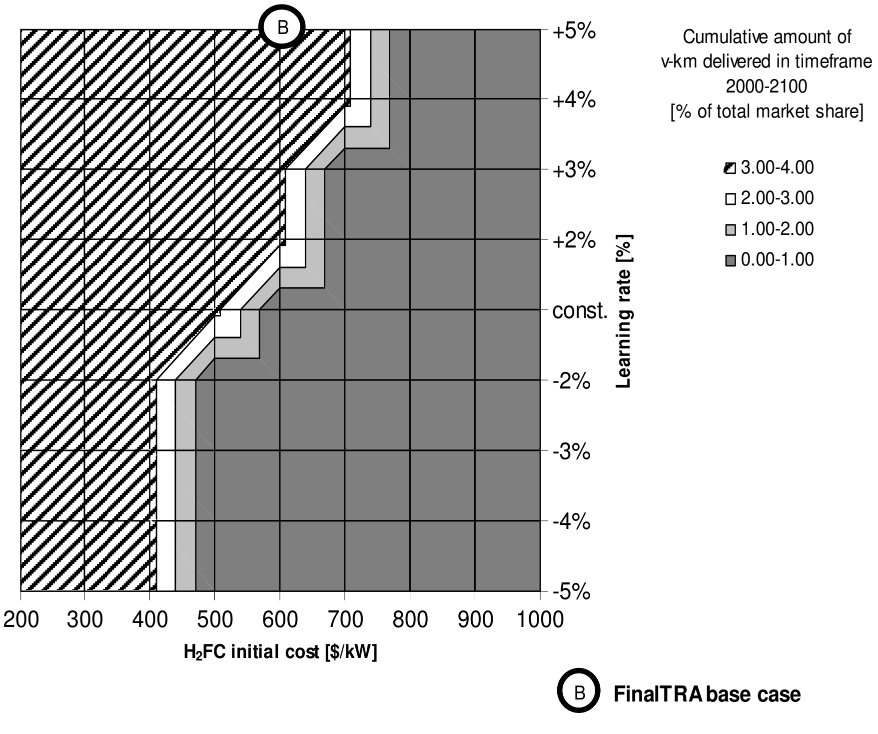

Figure 42 Consistency across models (FinalTRA): H2FC-kW vs. BBL

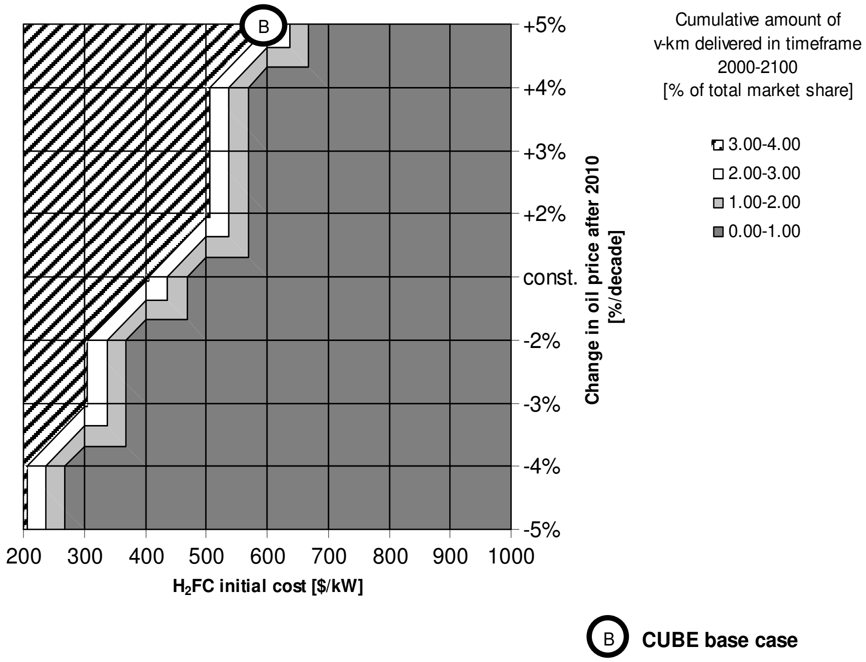

Figure 43 Consistency across models (CUBE): H2FC-kW vs. BBL

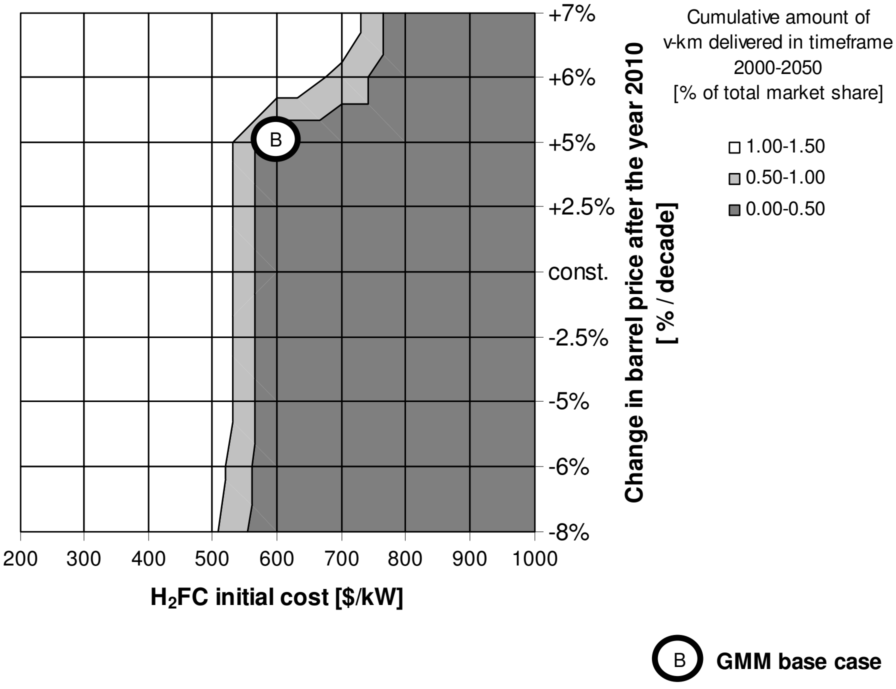

Figure 44 Consistency across models (GMM): H2FC-kW vs. BBL

The results of all three models suggest that the oil price is already high, and does not have a significant influence. The results confirmed preliminary trial runs which suggested that a price of over 30 US$/bbl is already giving hydrogen an advantage over oil based fuels. Considering the most preferable scenario for conventional vehicles, the results of the three models suggest that a reduction in the overall price trend of 5%/decade still keeps the oil prices at a considerably high level[21].

Nevertheless, any increase in the price of oil may only improve the position of hydrogen as fuel. What has not been taken under consideration in this work, mainly due to the limitations of the modelling framework, is the possible response of countries to extreme high prices of oil. In reality if the oil price continues to rise so significantly, one could be expecting in the coming years governmental interventions to promote alternative fuels as to counterbalance the negative impacts of the oil price trends.

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[21] The price of oil of 55 US$/bbl (2010) with a decrease of 5%/decade results in ~47US$/bbl (2050) and ~38 US$/bbl (2100)

7 Global impacts of advanced transportation technologies

The transportation sector is an all present and vital part of every county's economy. It serves for the commuting of citizens and moving of goods and at the same time supports the economical development. As the economies develop, there is an observable increase in the demand for transportation – both in the passenger and freight sub-sectors. This increase for transportation demand has many, long term implications such as depletion of primary resources (fuels), on which transportation is very dependant, and an increase in carbon dioxide and local pollutants emissions, originating primarily from road vehicles.

In the past years, the environmental concern for the sustainable development and functioning of the transportation sector has been broadly discussed especially in highly industrialized regions like Europe or North America. The environmental burdens carried by the currently functioning oil-based transportation system, to a significant extent, contribute to the emissions of CO_2 as well as nitrogen and sulphur oxides. These environmental pollutants have a major, negative impact on the well being of societies. As reported by the European Commissions Project ExternE "[…]*the vast majority (over 95%) of the total damage costs is due to health impacts, and among health costs the dominant item is reduced life expectancy. Chronic bronchitis is also important, and so are impacts for asthmatics. Cancers have also been quantified, but their contribution to the total cost is very small.*" (Rabl and Spadaro 2000). To address this issue, estimates have been prepared on the financial impacts of externalities (negative effects of pollutants emissions). The analysis results suggest that in order to accurately asses the performance of the transportation system, these externalities ought to be accounted for (McCubbin and Delucchi 1999; Rabl and Spadaro 2000; Ogden, Williams et al. 2001).

Therefore, in the light of the constantly growing demand for transportation and its resulting side effects, many claim that by mid century mankind might be looking for other options as to mitigate the negative impacts of the current transportation system. These options might include changing to more efficient, but still petroleum based, technologies or switching to a different, more environmentally friendly fuel. One of such options which is broadly discussed is hydrogen based mobility and hydrogen fuel cell vehicles (Wokaun, Baltensperger et al. 2004).

Today, vehicles based on fuel cells and fuel cells themselves are still in experimental phase, commercially not available, while the hydrogen infrastructure is, in essence, non-existent. Nevertheless, considering the progress which has been achieved in the fuel cell technology during the last 10 years, one could imagine that in the coming 25 years (by the year 2030) it could be possible that the research in fuel cell technology overcomes technical and economical difficulties and allows for preliminary, mass scale, market deployment. Nevertheless, one could foresee that if major technical and economical difficulties are resolved, there still might be a need for additional support as to allow the beginning of the transition to a hydrogen based transportation.

In this chapter, the work has been focused on assessing potential governmental policy instruments which could aid successful market penetration of hydrogen fuel cell vehicles.

7.1 GMM: 2000-2050 Base-case

The starting point of the analysis was the development of the "base case" which was a basic scenario where the model is free to allocate the technology mix according to overall, least-cost optimization algorithm. The base case is therefore free of any external interventions like governmental support or extra fiscal burdens. In the base case of GMM, as illustrated below (**Figure 31**), the first 30 years of this century are primarily dominated by two types of vehicles, namely the gasoline and diesel engine powered. Later, as the hybrid technology has matured more, it is the gasoline-electric hybrid that begins to dominate the market. In the first quarter of the century, major fuel cell producers and developers were able to solve technical problems related to the operation of fuel cells (like limited life time of membranes), and by the time the fuel cells are ready for preliminary market launch, their price is at the level of 600 US$/kW. Moreover, manufacturers of fuel cell see possibilities for further costs reduction, provided that a significant demand for fuel cells would appear (fuel cell learning rate 15%). Additionally, steadily growing oil prices (oil price reaches an average of around 70 US$/bbl by the end of the modelling timeframe) which are unfavourable for vehicles based on conventional fuels, suggest that a change to an alternative transportation option could be feasible (O'Driscoll 2005). Despite all of the favourable for hydrogen based mobility conditions, the hydrogen transportation does not lift off. This is mainly due to the fact, that fuel cells are still too expensive for potential customers; additionally the potential customer is faced with a problem of limited access to the fuelling network. The lack of fuelling facilities is in a way a "chicken&egg" problem. Fully fledge fuelling infrastructure is not constructed, as no noticeable demand exists; while on the other hand, no demand can be triggered as the potential buyers see a significant drawbacks in the possibilities of fuelling their hydrogen fuel cell vehicles. In order to break this "chicken&egg" problem, an external incentive is required. The fuel cell developers and manufacturers have invested significant sums during the first quarter of the century and could be reluctant to continue investments at such pace (mobile fuel cell would remain as back-stop technology, with perspective of launching at later time) while only a marginal share of individual users would be willing to commit themselves to investments into vehicles with majorly limited access to fuelling network. Therefore, the remaining potential body which could provide the initiative for the switch to hydrogen based mobility is the government (L-B-Systemtechnik 2002; Litman 2003).

7.2 The catalyst role of the Government

As a result of numerous relations with other sectors of the economy, high dependency on the services provided to other sectors and citizens as well as with impact on the environment, the transportation sector is a very complex system. One of the challenges is to establish such conditions, so that the services provided by the transportation sector may allow for continuity in terms of service delivery (reliability), cost optimal allocation of technology and fuel mix (cost optimal) as well as causing least possible environmental impact (environmental soundness).

One of the numerous issues, which is often discussed, is the **security of fuel supplies**. In respect to the transportation sector, it is security of deliveries of oil on which a significant part of the transportation system is based. Last years have proven many times that due to the conflicts in the Middle East and natural disasters the continuity of this delivery may be threatened. A possible initiation of the switch towards hydrogen based transportation could allow for limiting the dependency on imported fuels (Grant 2003; Talhelm 2005).

However, dependency on oil deliveries also carries another burden, namely the **variability of price** (Talhelm 2005). Transportation is an indispensable element of every countries economy; therefore the demand for fuels like gasoline or diesel is very inelastic. Moreover, the fuels may not be easily substituted due to the technologies (types of vehicles) present on the streets. This fact has a strong implication on the economical development. A rise of fuel prices causes an increase in the price of all articles, hence escalates the overall cost of final products for local markets and export.

A possible switch to a hydrogen based transportation system in many ways is able to provide improvements over the current, oil-based transportation system. However, this switch would require long term planning and consistent persuasion of strategies despite possible lack of popularity in the first phases of the introduction (Greene 2004).

The transportation sector, similarly to other areas like the energy sector, has a large inertia which implies significant amount of time and investments to be made before relevant changes may take place. Therefore, changes which could take place as to improve the performance of the transportation sector are usually long term oriented. These changes however, in the first phases of their introduction, may not always be popular as usually they involve extra costs, efforts and changes in the current functioning of the system. Therefore, despite long term potential beneficial effects, such changes are prone to **technology lock-out**. This mechanism inclines that a given solution may be "locked out" as a result of unfavourable perception at the time it is introduced. An example of such lock-out could be the case of fuel cell vehicles. In the first period of market introduction their high cost discourages potential buyers. This in turns results in lack of sales, which eventually hinders the costs reduction (as function of increasing installed capacity). The potential buyers are usually unable to perceive the long term benefits such as costs reduction as market penetration evolves, improvement of air quality or overall running costs of operating a fuel cell vehicle. Nevertheless, the technology lock-out could be overcome through external support, such as governmental demonstration, R&D and propagation programs.

A possible switch to a hydrogen based transportation sector could well address the mentioned concerns as well as brining additional benefits.

- Hydrogen could be generated locally (national level), which could allow for independence on oil imports.
- Local (national) generation of hydrogen could serve as a mechanism to promote local entrepreneurs.
- A broad range of primary sources which can be used for generation of hydrogen could allow for securing a wide primary resource mix for the generation of hydrogen.
- Overall cost of hydrogen at a retail station in combination with high efficiency of fuel cell vehicles could provide a lower cost-benefit of hydrogen based transportation over currently functioning oil based transportation.
- Focus on hydrogen based transportation may boost the research&development of technologies contributing to realizing the hydrogen based mobility. This research could result in numerous technological spillover effects.
- Introduction of hydrogen based transportation could allow for limitation of emissions of CO_2 and local pollutants, hence mitigating climate change.

Nevertheless, the mentioned benefits may be reached if long term planning is taken under consideration, despite high initial costs which would be required. A significant part of the funds needed for such action plans could be resourced from complementary policies. For example: on one hand penalization of CO_2 polluters, while on the other hand supporting (with the acquired funds from penalization) zero-emission technologies.

7.3 Environmental burdens of the transportation sector

As the economies develop, so does the demand for transportation and the amounts of emissions coming from road vehicles. Due to the nature of the fuels like gasoline and diesel, the functioning of the oil-based transportation sector is strongly bound to **externalities** (side effects) originating from the emissions of carbon dioxide and local pollutants. These pollutants carry with them a potential of deteriorating health of humans in terms of increasing acute morbidity, chronic morbidity, mortality and cancer. Therefore, the emissions ought to have a cost associated, related to the damage they impose (Greene and Schafer 2003). Evaluation of the value of associating costs to the negative effects of air pollution is a complex task as it is necessary to combine the relationships between the epidemiological data, which links to illness, with the results form the economic data, which allows placing monetary value on illness. As the difficulty of this task is extensive, this research has been resourced to the studies which have already been carried out in the field of valuing of externalities (McCubbin and Delucchi 1999). Considering policy measures which aim at improving the functioning and the performance of the transportation system one should bear the facts of externalities in mind.

To address this issue of assigning costs related to the negative impacts of externalities, an analysis was conducted in which the costs of the harmful impacts of CO_2, NOx and SOx emissions coming from the transportation sector were included. As the basis for the analysis the estimated values for external costs of the mentioned pollutants originating from the transportation sector were used. The indicative values which have been elaborated by many unfortunately have two main short comings. Firstly, they display quite a broad range of estimated costs (a range between 25-650 US$/ton for CO_2 and in the range of 520 to over 70,000 US$/ton for SOx and NOx emitted; the price ranges for SOx and NOx are separate, however they lay in a similar cost range) and secondly are limited to only few world regions (mainly Western Europe and the State of California in USA) (McCubbin and Delucchi 1999; Ogden, Williams et al. 2001). Therefore, following the available studies targeting the estimation of externalities, to allow for introduction into the GMM modelling framework average values for the externalities associated with selected pollutants have been calculated and scaled to fit the GMM regional division. The average values have been calculated on the basis of the data as presented in the results of the Externe Project (McCubbin and Delucchi 1999; Ogden, Williams et al. 2001).The scaling has been done using a developed methodology of relating the mitigation costs of a given pollutant to GDP_{PPP}/capita index of selected regions (Markandya and Boyd 1999; Hirschberg, Heck et al. 2003; Hischberg, Heck et al. 2003; Rafaj 2005).

The mentioned scaling approach as first step assumes of linking between population density of a given region, with the population density of a region which the reference studies cover (f.ex. population density between Western Europe (member of OOECD) and Asia). This scaling link has been presented below (**Table 15**)(Rafaj 2005).

Table 15 Scaling of externalities – population density factors

Determinant for scaling		SOx	NOx	Region
Population density factor	High	1.5	1.5	OOECD, ASIA
	Moderate	1.0	1.0	NAM, EEFSU, LAFM
	Low	0.75	0.75	-

Next, in order to capture the differences in the regional economic development level and allow for linking to the reference value of externalities for Western Europe, an equation is established (EQ. 30) (Markandya and Boyd 1999; Hirschberg, Heck et al. 2003; Hischberg, Heck et al. 2003; Rafaj 2005) which references the GDP_{PPP}/capita of the analyzed region to the reference region (Western Europe).

EQ. 30

$$EXT_{region,time} = EXT^{reference\_value}_{WesternEurope,2000} * \frac{GDP^{region}_{ppp,time}}{GDP^{WesternEurope}_{ppp,2000}}$$

Having established the relationship between the population density scaling (**Table 15**) and a relationship between the economic developments in terms of GDP_{PPP}/capita the scaling factors are calculated (**Table 16**). Using the IIASA B2 economic development scenario (World Energy Council and International Institute for Applied Systems Analysis (IIASA) 1998) for GDP_{PPP} the externality scaling factors are calculated for the consecutive time periods and regions as used in GMM (**Figure 45**).

Table 16 Values of external costs and regions specific scaling factors

Region	Time period				
	2010	2020	2030	2040	2050
NAM	2.0	2.2	2.3	2.5	2.8
OOECD	1.3	1.5	1.6	1.7	1.8
EEFSU	0.4	0.5	0.7	0.9	1.1
ASIA	0.3	0.4	0.5	0.6	0.7
LAFM	0.2	0.2	0.3	0.4	0.5
Reference values:					
CO_2:	25 US$/ton[22]				
NOx:	6,500 US$/ton				
SOx:	9,300 US$/ton				

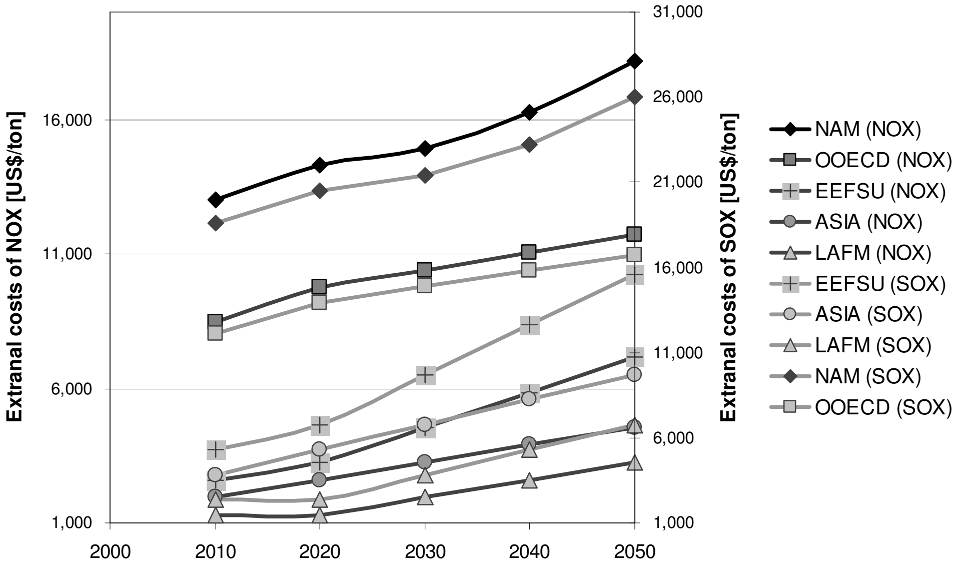

Figure 45 Value of externalities (SOx, NOx) for GMM with world region and time scaling

The mentioned external costs have been introduced into to GMM which provided a scenario in which the negative impacts of emissions originating from the transportation sector are charged as to balance out the effect. The results have been presented below (**Figure 46**).

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[22] CO2 is a global pollutant, hence it does not undergo scaling

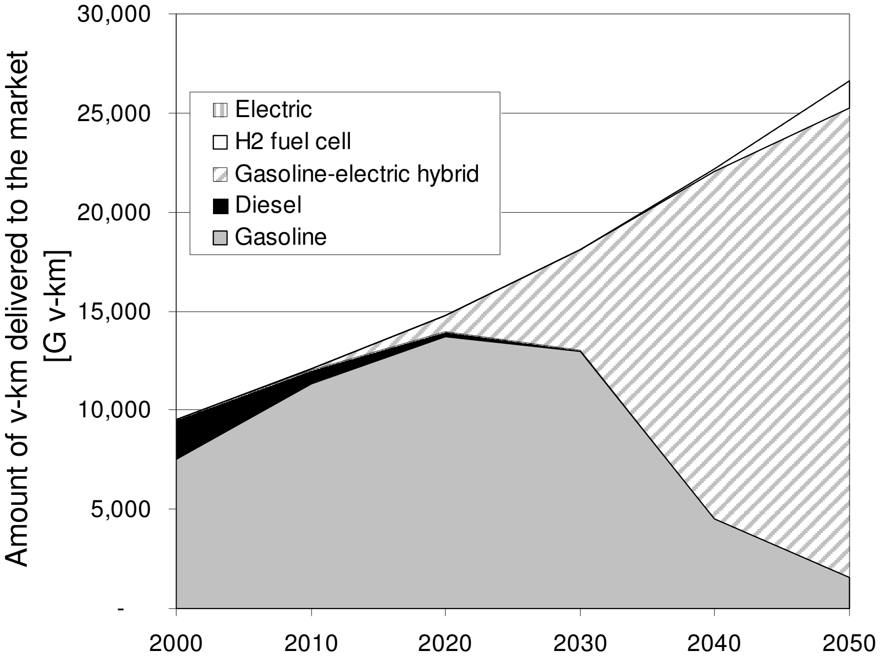

Figure 46 GMM externality case

The results of the case suggest that if the external costs are internalized, the dominating role in the later part of the analysis timeframe would be played by the gasoline-electric hybrid vehicles. This is due to the fact that gasoline-electric hybrid vehicles, despite being based on gasoline, display much better fuel and environmental performances as compared to gasoline or diesel vehicles. Later, as the fuel cell vehicles develop enough, one can observe the beginning of the switch towards hydrogen in the last decade of the analysis timeframe.

Nevertheless, introduction of measures which would fully cover the estimated damages (**Figure 45**) caused by the pollution coming from the transportation sector could require very harsh fiscal measures. Therefore, in the later parts of this work less drastic measures have been described, which would allow for improvement of the performance of the transportation sector.

7.4 Selective internalization of external costs

In the light increasing environmental pollution coming from oil-based transportation sector and semi-favourable conditions to initiate the transition to hydrogen based transportation, governments world-wide could start the initiative by internalizing external costs. The imposed costs apart from bringing the benefit of delivering extra funds to compensate for environmental damage caused by the transportation sector, could also serve as a trigger for the transition to hydrogen based mobility. In the analyzed cases is has been assumed that governments are willing to initiate the switch. Therefore, in this part of the analysis, the governments have two possibilities to penalize for the environmental impacts. Firstly by internalizing the external costs related to the CO_2 emissions coming from generation of fuels as well as emissions coming from vehicle themselves (additional taxation of the fuel) (Azar, Lindgren et al. 2003). Secondly, using the same assumptions as above, but by penalizing the emissions of local pollutants (sulphur and nitrogen oxides). While the first option can be quite easily introduced, the second one is more difficult to capture. This is mainly due to the fact that already in earlier years strict environmental standards on NOx/SOx emissions have been imposed which covered the issue (examples of this can be the European EURO or the American CAFE emissions standards) (U.S. Department of Transportation 2000). Therefore, in this analysis the NOx/SOx internalization was considered as a distant alternative which could serve as an additional measure provided that the effects of all the other policy measures are insufficient (IEA (International Energy Agency) 2002a; IEA (International Energy Agency) 2002b; IEA (International Energy Agency) 2004). The level of NOx/SOx penalization is incomparably higher (per unit of pollutant emitted) than the one of carbon dioxide; this is due to the fact that NOx/SOx emissions are significantly lower in quantity than carbon dioxide emissions (comparison: a conventional family car emits ~220 g CO_2/km travelled, while simultaneously, the same vehicle emits only 0.05 g NOx/ km travelled and no SOx emissions). Therefore, to impose any noticeable effect of NOx/SOx external costs internalization, one should expect penalization of three orders of magnitude higher than as the one for carbon dioxide emissions (Choudhury, Weber et al. 2004).

In this part of the analysis a series of runs with variable levels of both internalization pathways was carried out. The results have been presented below (**Figure 47**).

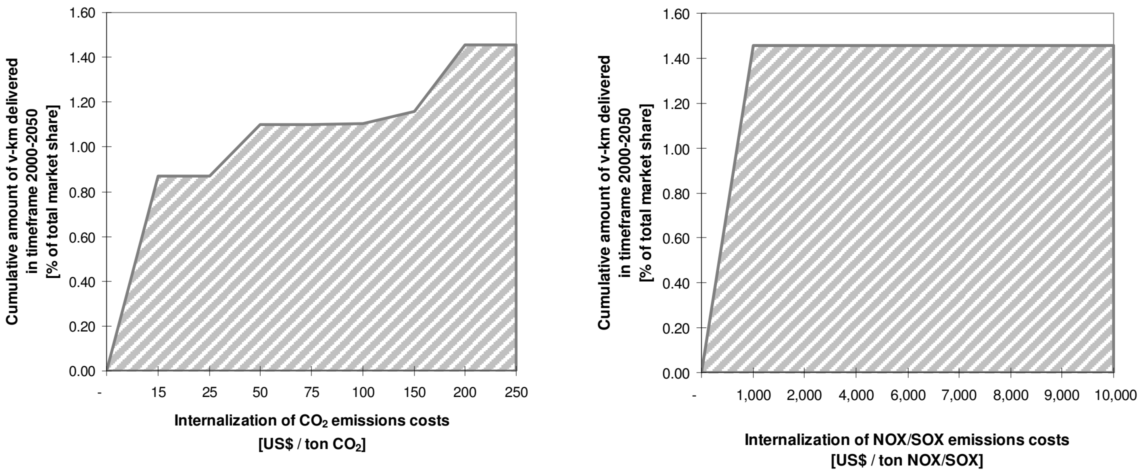

Figure 47 Sensitivity analysis of the potential impact of CO_2 and local pollutants internalization, on the market penetration of hydrogen fuel cell vehicles

These tactics, despite not being particularly targeted at the promotion of the hydrogen based mobility, apart from penalizing the emitters also provide the indirect influence of putting fuel cell vehicles in a more favourable light as compared to the conventional, more polluting technologies. Nevertheless, without the environmental initiatives, the level of fuel cell prices, producer’s potential to further reduce their price and steadily growing prices of primary fuels, place the hydrogen based transportation on a break even point. The results of this analysis suggest that even a minor intervention in form of emissions internalization is, apart from internalizing the cost of externalities, also sufficient to trigger the change towards hydrogen based mobility. Nevertheless, one should bear in mind that environmental penalization influences hydrogen based transportation too, as only generation of hydrogen through carbon-free primary sources like electrolysis, with electricity coming from a non-emitting source (for example solar energy or nuclear power plants to mention the two) and transmitting the hydrogen via pipelines does not produce any “penalisable” emissions. In any other case, the price of hydrogen rises as a result of the internalization of external costs. However, despite the additional costs related to externalities, the final price of hydrogen can still be attractive for hydrogen based transportation sector. This is due to the fact that the price of hydrogen rises significantly less than the price of oil-based fuels which emit much more "penalisable" emissions. Overall, these tactics result in a general rise of fuel prices, however creating the hydrogen based mobility to be more economically attractive as compared to conventional mobility.

7.5 Governmental support

Despite the growing global environmental concerns, one could imagine a situation where the emissions are controlled, capture, storage and mitigation options are in operation and governments do not wish to further emphasize the path of penalizing polluters. Considering such case, the possibilities of promoting fuel cell vehicles by other means, namely financial benefits, have been considered.

For this policy two strategies were analysed: to directly influence the market price by means of demonstration project support, and another strategy to directly influence the market price of fuel cells by creating favourable conditions.

To begin with, the first strategy of supporting the demonstration projects has been presented, and in the later part the direct marketing influence.

The "demonstration project" strategy assumes promoting fuel cell vehicles by means of pilot, demonstration cars at more favourable prices to the end consumer. In real terms this leads to a preliminary market launch of fuel cell vehicles at prices lower than their actual value. This demonstration project approach allows increasing of the installed capacity (an increase of market popularity) and secondly allows for price reduction. The resulting increase in market penetration and potential for further price reduction may be later utilized by means of the endogenous technological learning, which permits costs reduction as function of increasing cumulative capacity. The demonstration launches could be pictured in the following, illustrative way. At the time the fuel cell vehicles are ready to enter the market, they are still at an uncompetitive level. Therefore, an initiative could be formed to support first 60,000 vehicles. Therefore, the initial 60,000 'demonstration' vehicles may be purchased at a discount of 100US$/kW (giving a benefit of 5,000US$/vehicle). However, as soon as customers are willing to purchase more than the demonstration launch pack, the favorable 100US/kW bonus is raised. The prices of vehicles free of the bonus are at the level the price level of the demonstration with what they were able to 'learn' during the preferential deployment less the bonus. The following diagram illustrates this strategy (Figure 48).

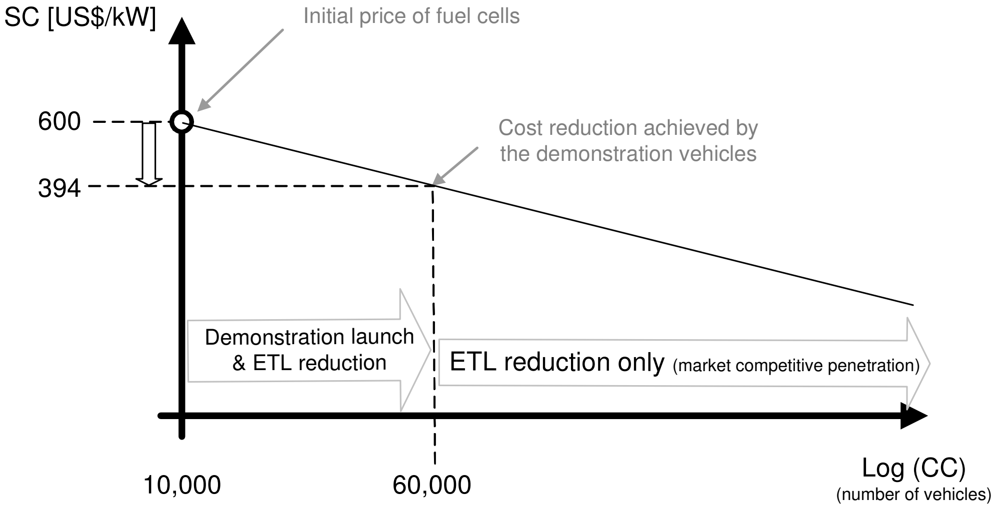

Figure 48 Demonstration projects – graphical illustration of costs reduction

Reading the presented above diagram (**Figure 48**) and considering the mathematical expression of ETL costs reduction (Chapter 2.4 Learning-by-doing, the costs reduction mechanism) one may read, how the initial cost of the fuel cells change (**Table 17**).

Table 17 Change of the specific cost of fuel cells as result of demonstration projects

Learning rate	15%					
SC_0	600 US$/kW					
CC_0	10,000					
CC[23]	None	12,500	20,000	50,000	75,000	150,000
SC	600	569	510	411	374	318

The illustrative values have been introduced into GMM as to probe what is the potential influence of this strategy. The diagram below illustrates the outcomes of this strategy (**Figure 49**).

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[23] Number of vehicles in the demonstration project

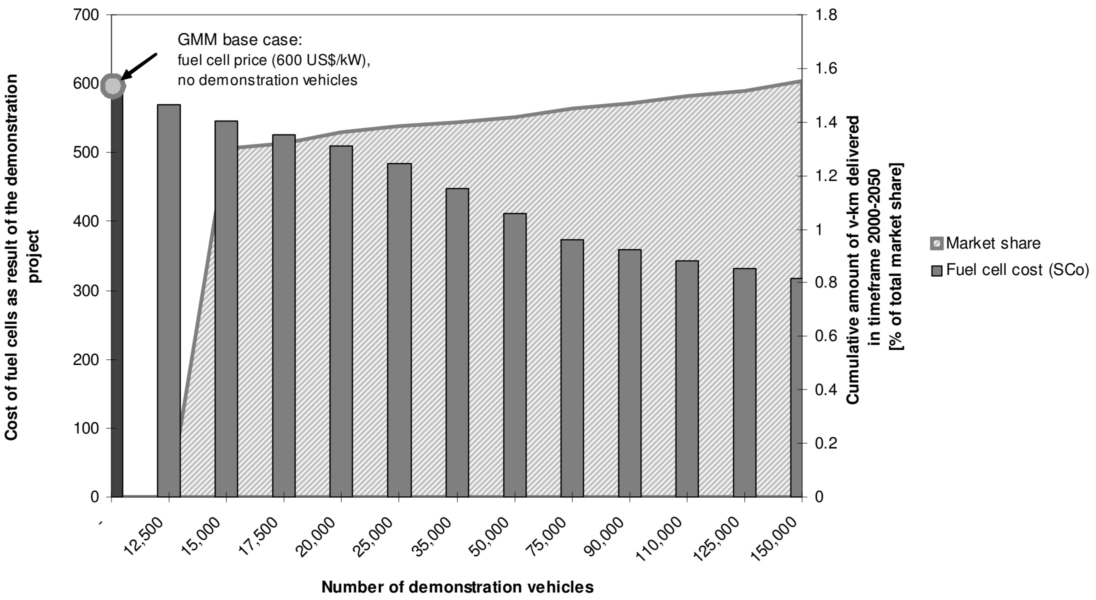

Figure 49 Demonstration projects – graphical illustration of market penetration

In the direct market influence strategy three tactics were analysed. The proposed tactics are as follows. Firstly to directly support fuel cells, by means of compensating mobile fuel cell vehicle customers with a fixed reimbursement for every kW of fuel cells purchased. This type of tactic has been already applied in many countries over the past years and has proven to be successful – both in terms of effects, as well as in terms customer satisfaction (Katz and Payne 2000; Payne and Katz 2000; Somasundaram 2004).

Secondly, the tactic in which the government by means of support may allow for preferential credits for hydrogen infrastructure buildup projects (lower discount rates for infrastructure) has been considered.

Lastly, a combined strategy with two tactics: internalization of externalities (CO_2, NOx and SOx) and 100,000 demonstration vehicles has been presented.

The selected tactics were entered into GMM and a series of runs was conducted. The results have been presented below (**Figure 50** and **Figure 51**).

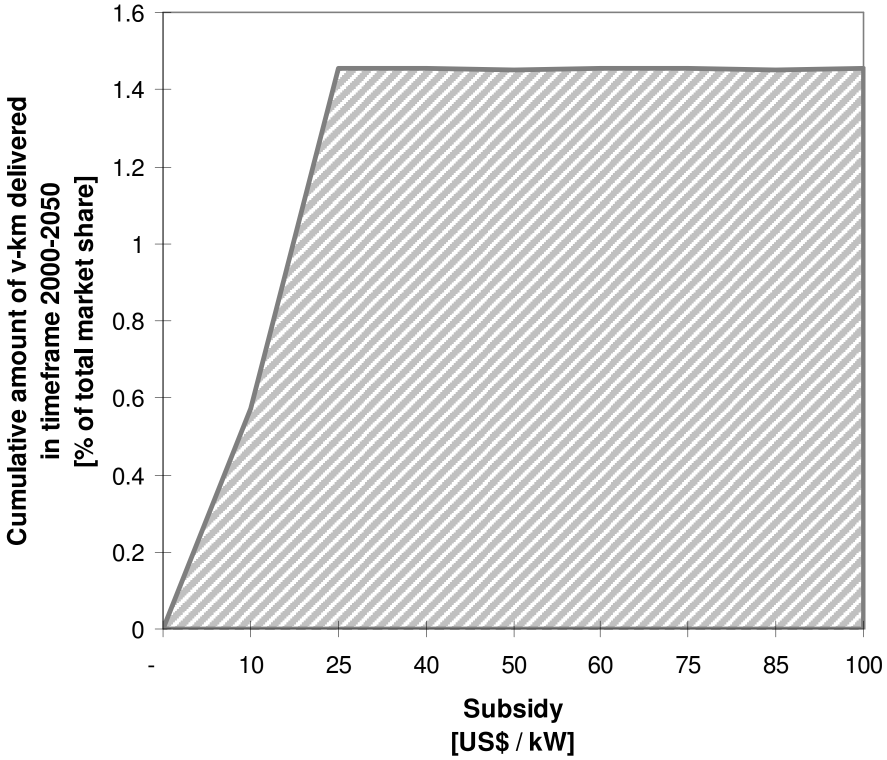

Figure 50 Sensitivity analysis of the potential impact of support to fuel cells on the market penetration of hydrogen fuel cell vehicles

The hydrogen based transportation, despite growing prices of oil and preliminary stage of competitiveness of the fuel cell technology, is on the break-even point. The results of the first analysis, in which the potential influence of direct governmental support to fuel cells was evaluated, suggest that even with minor governmental support, the break-even point can be surmounted. This is due to the fact that the most decisive element of the fuel cell technology, and the hydrogen based mobility, is the price of the fuel cells.

Next, the potential for the impact of preferential credits for projects which result in development of hydrogen infrastructure (fuelling stations, pipelines, local and central generation plants, etc.) has been considered. The results of the analysis have been presented below (**Figure 51**).

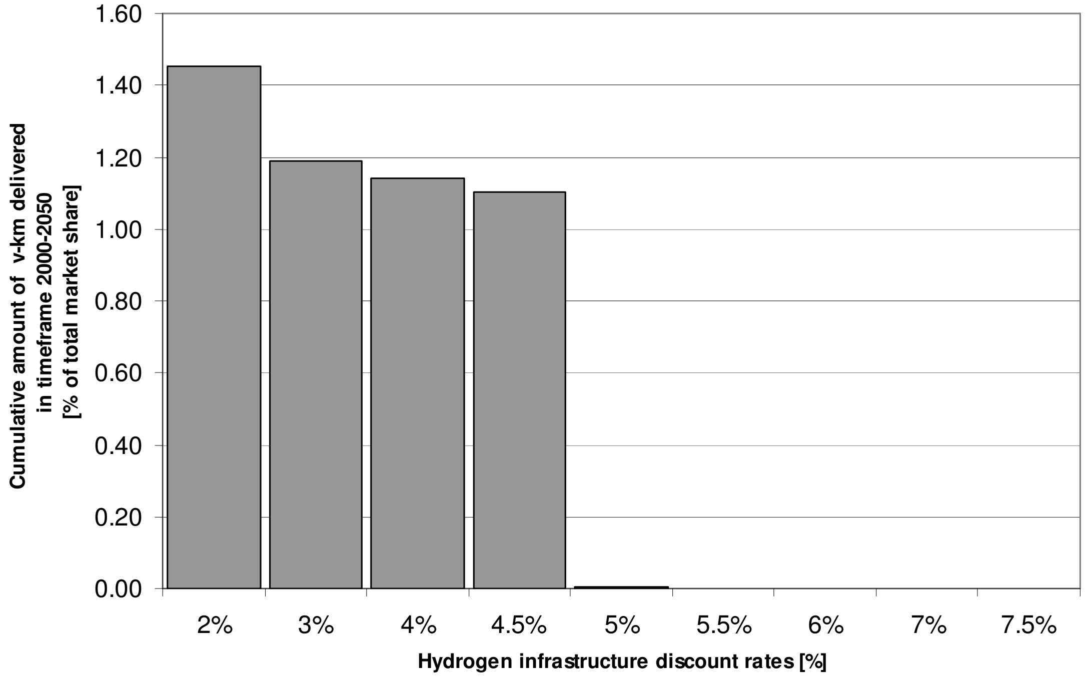

Figure 51 Sensitivity analysis of the potential impact of preferential discount rates for hydrogen infrastructure build up on the market penetration of hydrogen fuel cell vehicles

The results of the analysis suggest that the average discount rates which have been assumed for the runs with GMM (5%) keep the hydrogen based mobility on a go/no-go break-even point. Outcomes of the sensitivity runs suggest that there is a potential of promoting hydrogen based mobility, using the tactic of preferential credits for hydrogen infrastructure projects (Ogden 1999). The existence of this threshold is related to the nature of GMM. GMM is a perfect foresight model, which in many cases uses an "all or nothing approach", moreover the algorithm used in GMM is very sensitive to small changes in parameters, which result in thresholds (which is the case in this example). Observing the presented graph (Figure 51) one may notice different levels of overall market share which is captured by fuel cell vehicles (~1.1% in case of a 4.5% discount rate and over 1.4% in the case of a 2% discount rate). The reason for this outcome is that the altered discount rates allow technologies (in this case hydrogen infrastructure) to become competitive, however at different time periods. In case the discount rates are low, hydrogen infrastructure becomes cheaper 'earlier' thus giving a green light to the market launch of vehicles. This results in more vehicles present on the market, hence a larger market share during the analyzed period of time. On the other hand, if the discount rates would be higher than the base case assumption (5%), hydrogen delivered is more expensive, hence eliminating the possibility of successful market penetration by fuel cell vehicles.

Lastly, on the basis of the findings from the earlier parts of this analysis, a case in which two tactics are simultaneously introduced was considered. The first tactic selected was to charge the external costs (NOx, SOx and CO_2) and second tactic was the introduction of the 100,000 demonstration vehicles promotion project. The graphical illustration of results of this part of the analysis has been presented below (**Figure 52**).

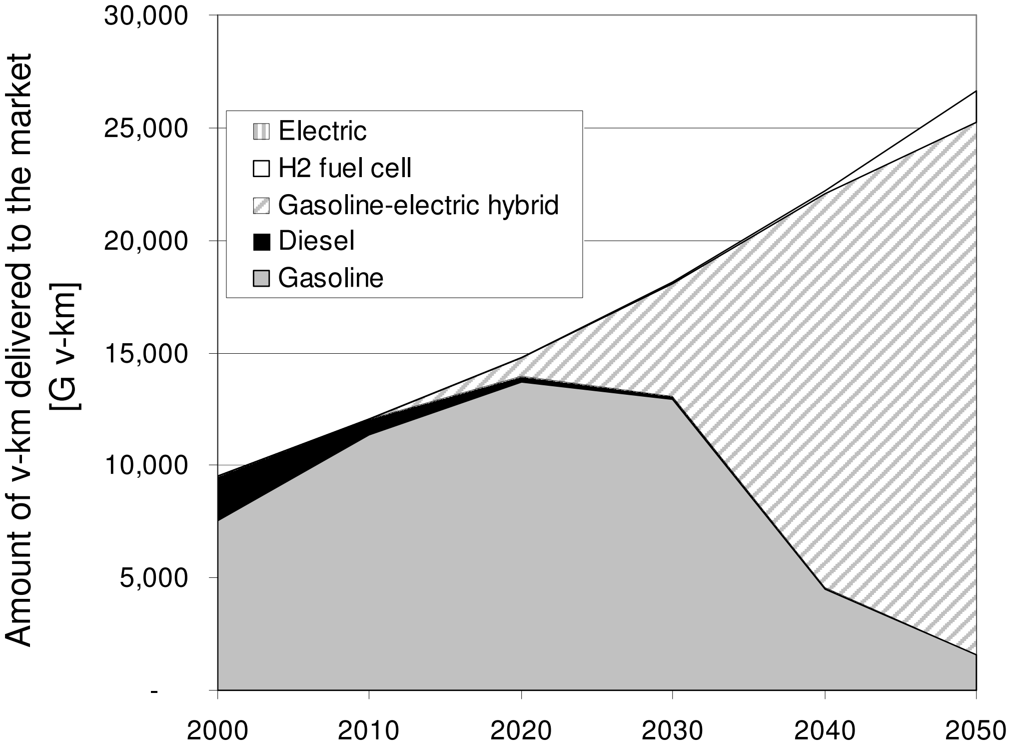

Figure 52 Combined effect of two tactics - internalization of external costs and the 100,000 demonstration vehicles project

The results of this part of the analysis display similarities with the case in which only the externalities were accounted for. As a result of the combination of the two mentioned tactics technologies which show higher emission rates (lower environmental performance) are penalized and hydrogen fuel cell vehicles are given an opportunity of more favourable market conditions as they display much sounder environmental performance. Moreover, the demonstration projects of 100,000 supported vehicles allow for a reduction of fuel cell prices, which in turn could provide promising conditions for a broad scale market penetration of fuel cell vehicles.

One should bear in mind that the mentioned tactics of fuel cell support in terms of cash-back promotions may be questioned from the perspective of who should actually cover the difference between the favourable and actual market price. Therefore, the presented results ought to be taken more as a result of sensitivity analysis, rather than real life policy measures.

7.6 Conclusions from the analysis of global impacts, conducted with GMM

In this part of the research the results of analysis which has been aimed at establishing potential ways for supporting a transition towards hydrogen based transportation has been presented. It may be stated that a transition to a more sustainable fuel is quite likely to happen as currently the transportation system carries numerous burdens with it – such as steadily growing prices of fuels and increasing emissions of CO_2 and local pollutants.

The results of this analysis suggest, assuming the current state of the transportation sector, trends in oil prices, ambitions of fuel cell manufactures and numerous hydrogen fuel cell demonstration projects, that the transition to hydrogen based mobility could be the choice for the future. However, the results point to the fact that the transition might need additional measures for initiation. This is due to the fact, that hydrogen based mobility is a "chicken&egg" problem. With no demand for hydrogen, there are no incentives to create the necessary infrastructure, while with no infrastructure available – there is no apparent demand for hydrogen. However, this loop could be broken. It is quite likely that the governments may have a significant influence in this matter. Using various fiscal instruments, the governments could be able to influence the improvement of climate protection and simultaneously stimulate the beginning of a transition towards hydrogen based mobility.

In this part of the research few of such instruments, which are targeted at improving the negative impacts and characteristics of oil-based transportation and at the same time promoting hydrogen fuel cell vehicles, have been presented. Firstly analyzed the potential influence of internalization of external costs related to the environmental emissions has been considered. The results of this part of the analysis suggest that, assuming long term strategic planning, penalization of emitters of carbon dioxide and/or local pollutants such as nitrogen and sulphur oxides may serve as a tool to initiate a switch towards hydrogen and provide the possibility of charging the polluters for the negative impacts of externalities. Penalisation of emitters of environmental pollutants punishes both the conventional fuels (like gasoline and diesel) as well as hydrogen. However in the case of hydrogen this penalization is less apparent. This is due to two facts. Firstly, production of gasoline and diesel is, in terms of total fuel chains performance, more polluting than comparable fuel chains for hydrogen. Secondly, the efficiency of vehicles using conventional fuels is significantly lower than the one of fuel cell vehicles. These two facts result in a combined effect – conventional vehicles consume more fuel, which additionally is fiscally burdened with external costs (overall cost higher than hydrogen), hence their economic performance is considerable reduced as compared to the case with no environmental "taxation". The results suggest that CO_2 penalization of already 50 US$/ton CO_2 would shift the overall benefit towards hydrogen based mobility. In respect to local pollutants penalization, current trends suggest that this issue is addressed by means of emissions standards. Therefore, in the analysis this potential policy instrument has been approached in a methodological way. Nevertheless this policy instrument could be an option which could bring a 'double' benefit. Firstly, by redeeming the costs of externalities from the polluters; secondly, by creating new fuel price structure which could support the transition to hydrogen based mobility. Keeping in mind however that the mentioned pollutant emissions are regulated by means of standards, one ought to consider this policy tool to be applied provided other measures would not be sufficient.

Next, a case in which the policy instruments would be targeted specifically at the costs related with the transportation sector has been elaborated. Following known examples of direct support to new, emerging technologies, the extent of potential influence of direct support to fuel cells in terms of "cash-back" promotions has been researched. As seen in **Figure 24**, the significant share of the overall costs of travelling using hydrogen fuel cell vehicles are the investment costs related to the stack. However, there is a large potential to reduce this cost, provided that fuel cells would broadly enter the market (as function of ETL – costs reduction related to an increase of market penetration). Nevertheless, the fuel cell vehicles, on the basis of the assumptions used in GMM, are on the verge of being cost competitive. Therefore, an initiative is needed to promote this change. Aiming at the most expensive element of the cost structure (costs related to the fuel cell stack) could result in a successful transition towards hydrogen based mobility. The results of this analysis suggest that a support of 50US$/kW or more would be fully sufficient to provide a successful outcome (50 US$/kW would provide the customer with some 2,500 US$ of cash return upon a purchase of a vehicle with a 50kW stack).

A tactic, which is primarily aimed at promoting fuel cell vehicles has been also analysed. The tactic assumes that a certain number of initial vehicles is sold to final consumers at preferential prices. However, as soon as the preferential quota is exhausted, the consumers are resourced to purchases at market price. This tactic has shown that during the demonstration phase of hydrogen switch, the demo-vehicles contribute to the increased popularity of vehicles (increased cumulative capacity) as well as allow for costs reduction by means of ETL.

Next, a tactic, which aims at promoting the hydrogen infrastructure has been analysed. The results of the analysis suggest that in the first period when the fuel cell vehicles start to penetrate the market, because of the small scale, hydrogen may be delivered by trucks or generated locally. However, at later time, when a substantial demand for hydrogen exists, a stable delivery of hydrogen could be supported by a pipeline infrastructure and large scale hydrogen generation plants. Allowing preferential credits for hydrogen pipeline projects may give an initiative to develop a fully fledged hydrogen economy. In this analysis a constant discount rate has been assumed, however in reality one could rather opt for much higher reductions (discount rates at a level of 2% or even lower) in the first periods when the infrastructure is created, and gradually bringing the interest rates back to the base level of 5% by the time the hydrogen based mobility gained a larger market share.

Lastly, combination of tactics was analysed, which joins two tactics: internalization of external costs and 100,000 demonstration vehicles. This combined tactic has show to have a double benefit. Firstly, it is possible to redeem the costs to cover the environmental burdens of externalities, and secondly to promote the switch towards hydrogen based transportation.

8 Conclusions

8.1 Modelling the transportation sector

The transportation sector is an inseparable element of every economy. Unfortunately, due to technological developments and specific advantages of the gasoline and diesel engines, for the last century the transportation sector has been bound to oil as primary source for gasoline and diesel fuels. Despite providing beneficial services contributing to the development of economies, the transportation sector carries also numerous burdens such as reliability on oil deliveries as well as emission of pollutants which result form combustion of both of the mentioned fuels in conventional engines. The inelasticity of the demand for transportation, dependency on oil and its rising prices over the past years, have increased the cost which needs to be paid in order for the transportation sector to continue its operation. In the light of the environmental burdens, market inelasticity, dependency on oil deliveries as well as the unfavourable rises in the oil price, many claim that if this situation progresses mankind might be searching for an alternative source of fuel for the transportation sector. Out of numerous possible options which are discussed, hydrogen is considered as a prospective candidate.

Hydrogen as fuel when used in vehicles with a fuel cell/electric motor combination does not emit any pollutants. Moreover, hydrogen may be generated from several primary energy sources such as natural gas, coal, biomass or high tech solutions such as solar or nuclear powered electrolysis, which may be set up locally. However, despite many benefits, the prospects for hydrogen based mobility in the nearest future are questionable. This is mainly due to the facts that today there is no infrastructure which could deliver hydrogen to end users, while the key technological component (fuel cells) is still in the development phase. Nevertheless, considering the developments which have been achieved over the past decades in the field of fuel cells, one could picture that around 2030 a switch to hydrogen based transportation could be initiated.

This work has been aimed at addressing the issue of the conditions which would need to be fulfilled in order to provide the grounds for a transition to hydrogen based transportation sector. Large scale introduction of hydrogen to the market could inflict numerous changes in the whole of the energy sector, therefore as to allow grasping of the issue, the analysis for the prospects of hydrogen based transportation has been limited to road vehicles.

As the complexity of the issue is quite significant, the presented analysis has been carried out step wise – from generalised assumptions and their testing to detailed research which employed indications from prior, general steps. The analysis has been primarily done using various (in terms of optimisation algorithm, complexity and detail level of the transportation sector description) optimisation models.

The first step in the presented analysis was resourced to a fairly crude model **FinalTRA**, which was designed as to provide the answer to the question if hydrogen based transportation is a feasible option at all. FinalTRA, a MIP (Mixed Integer Programming) optimisation algorithm model, was focused on the personal vehicle sub-sector in one world region (North America) in the time frame 2000-2100. The pictured sub-sector of the transportation system was represented by 7 types of vehicles (conventional gasoline and diesel, advanced gasoline and diesel, gasoline-electric hybrid, hydrogen fuel cell and electric) which competed in the arena of personal cars. Prices of fuels have been externally introduced, allowing the model for a pure optimisation allocation of the technology mix. The results, despite using generalised assumptions and descriptions, have suggested that indeed, hydrogen based transportation is a feasible option, however under specific conditions. The results suggested that considering the cost structure of transportation, for the advanced technologies the highest significance have the costs directly related to vehicle purchase, while for the conventional technologies it is the price of fuels. For the case of hydrogen fuel cell vehicles the major constituent of the vehicle price (investment cost) is the fuel cell stack, made up of single fuel cell elements. In view of today's prices of fuel cells being in the range of 2,000 US$/kW or more, the price of a vehicle equipped with a 50kW stack would sore above 100,000 US$, which most probably would be restrictive for the majority of potential customers. However, due to progress, this price may be reduced firstly by RD&D (research, development and demonstration), and secondly once the fuel cell vehicles are ready for market deployment by means of costs reduction mechanisms (illustrated in FinalTRA by means of ETL – Endogenous Technological Learning). The results of the analysis conducted with FinalTRA, suggested that if the price of the fuel cells, by the time they are ready for market penetration (assumed in the year 2030), shall be at the level of 600US$/kW or lower, and additionally further potential for price reduction shall exists (learning rate of 12% or more) the hydrogen based transportation system may quite likely be facing very favourable conditions for a widespread. The results suggested that the soaring prices of oil are at the level, which gives hydrogen as fuel, a significant benefit over gasoline or diesel. Therefore, any increases or stable trends in the current price of oil most likely shall be beneficial for the prospects of hydrogen as fuel.

The promising results which originated form the analysis conducted with FinalTRA, gave the signal to further elaborate the issue of the potential for the development of hydrogen based transportation sector. Therefore, the modelling framework was expanded using another optimisation model called **CUBE**. CUBE, on contrary to FinalTRA, employed a different optimisation algorithm (NLP – Non-Linear Programming). Similarly to FinalTRA, the new model was restricted to the same world region (North America), transportation sub-sector (personal vehicles) and timeframe (2000-2100). However, the hydrogen fuel chains were expanded as to include financial and technological details of each of the fuel supply steps. This resulted in a full representation of the fuel chains – from generation, transmission, distribution to final utilisation in personal vehicles. Each of the steps was characterised in terms of technological and financial aspects. Moreover, the technologies which were used in CUBE used a time dependant improvement of fuel efficiency (time dependant fuel improvement reduced the number of vehicles portrayed from 7 to 5, eliminating the advanced versions of gasoline and diesel cars), which in a simplified way captured the developments in the powertrain research. The results from the analysis conducted with CUBE also proved optimistic and confirmed the findings of the earlier analysis with FinalTRA. However, the increase in the complexity of representation of the fuel side, resulted in a slightly less optimistic results as the ones portrayed by FinalTRA. This is due to the fact that FinalTRA employed a generalised end price of hydrogen for the consumer, while the representation in CUBE allowed for much more scrupulous characterisation. The extended representation in CUBE included numerous factors which were omitted earlier. Few of such factors among other were: costs of the fuel needed to deliver hydrogen by trucks in the beginning of the 'hydrogen era' when no pipeline infrastructure is available or limitation on the pipeline network developments while the penetration of fuel cell vehicles is still very limited.

The results coming from the analysis carried out with CUBE suggested that the price of fuel cells would need to be at the level of 600 US$/kW with a further potential to reduce this costs (learning rate of 14% or more). Furthermore, the influence of the pipeline infrastructure may be negligible in the first periods when the fuel cells are only in the early stage of market penetration, however once a larger share of market is captured by fuel cell vehicles the infrastructure may prove to be a bottleneck.

Next, the hydrogen transportation sector was transferred to a full scale energy model. The reason for this transfer laid in the necessity of analysing the case when the fuel cells are not competitive enough, hence needing additional, 3rd party support. This analysis could only be carried out employing a full energy system portraying model, as implementation of 'hydrogen promoting' strategies could influence other sectors of the energy system. The outcomes of such influences could not have been explored using simplified models (FinalTRA and CUBE) as both of them were restricted only to the transportation sector. The model chosen for this part of the analysis was called **GMM** and was a global version of the MARKAL model. GMM used the same optimisation algorithm as FinalTRA (MIP). As compared to the other two models GMM differed in many respects – the model portrayed whole of the energy system (heat and electricity production chains, commercial and domestic utilisation of heat and electricity and also the newly specified transportation sector) on a global scale (5 world regions) in a timeframe 2000-2050. Similarly to other models, GMM was equipped with state of the art formulation of the endogenised technological learning (costs reduction mechanism).

Analysis with GMM was made up of two steps. The first one tested the feasibility of hydrogen transportation sector similarly to the two prior models. The second step tested the supporting policies for the influence, in the case the hydrogen transportation would be on a non-prevailing break-even point.

The results of the first step of the analysis suggested that in the timeframe 2000-2050 the possibility of hydrogen based transportation in becoming a reality could be quite bleak. This finding was contrary to the prior findings originating from FinalTRA and CUBE. The reason for the lack of market penetration in the analysis carried out using GMM, originated from the fact that GMM (similarly to FinalTRA and CUBE) is a perfect foresight model. Therefore, already at the beginning of the calculations the model 'sees' all potential development paths of each individual technology. In the case of fuel cell vehicles, the main costly element is the fuel cell stack. This cost may be reduced, however only in combination with extensive market penetration, which would fulfil the ETL costs reduction formulation. In the case of fuel cells, GMM runs showed that the fuel cells may not reach a competitive level as not enough capacity may be build-up in the analysis timeframe (50 years as compared 100 for the other two models). Nevertheless, further analysis of the results coming from GMM suggested that the fuel cell vehicles are on a break-even point. Therefore, the second step of the analysis was carried out, which aimed at researching the possibilities of overcoming this threshold.

8.2 Long term analysis – future prospects of hydrogen based transportation sector

The results of all the parts of the analysis have show that indeed, hydrogen based transportation is a feasible option for the future. Hydrogen based transportation sector may prove in many ways superior to the currently functioning one which is based on oil. Among the numerous advantages one could name lower pollution (hydrogen is a clean fuel) and lack of dependency on oil mining countries. Nevertheless, before hydrogen lifts off, there is a strong need for improvement. The long-term analysis, which dealt with many uncertainties, was conducted using FinalTRA and CUBE. To address the uncertainties, the analysis was made up of numerous sensitivity runs which tested different levels of potentially influencing factors on the possible market penetration of hydrogen fuel cell vehicles. The factors which were tested comprised of the fuel cell prices (in the range from 200 to 1,000

US$/kW), their learning rates (from 2 to 20%), initial number of vehicles launched to the market (from 75,000 to 700,000 vehicles) and the possible trends of oil prices after the year 2010 (from a decrease of 5%/decade to an increase of 5%/decade). Out of all factors tested, the price of the fuel cells and their learning rates have proved to be of most significance. Based on the results of the analysis carried out, the improvement is especially important in the case of the cost of fuel cells which make the core of the fuel cell vehicle. The results of the analysis carried out suggest that a price of 600 US/kW and further potential to reduce the price (learning rates of more than 14%) would put the hydrogen mobility on the right track.

The transportation sector, similarly to other large systems like the heating or electricity systems, is burdened with large inertia. This means that the results of changes executed today are observable after a long period of time. Moreover, due to the scale of the transportation sector such changes require consequence in execution as well as substantial financial support.

The results of the analysis have suggested that hydrogen based mobility may become a reality, however changes would need to take place. Such changes may include extensive research in fuel cells and promotion of the findings. This approach is already valid, as even today one can be its witness. Fuel cell manufacturers (like Ballard) are already reducing the prices of fuel cells, while large scale vehicle manufacturers (like Daimler-Chrysler or BMW) and governments (like European Commission) support the research, development and deployment of pilot projects (like 'CUTE' - the hydrogen bus demonstration project).

8.3 Hydrogen based transportation by mid century?

The early years of initiating the switch towards hydrogen based transportation may prove to be difficult in terms of finances. One may presume that in the first periods, when the fuel cell vehicles are still a novelty, market penetration may be hindered by the financial aspects. However, results of the analysis presented here suggest that there are numerous policy options which could assist in these difficult periods.

The short term analysis which was carried out using GMM, similarly to the runs with FinalTRA and CUBE, dealt with many uncertainties. Therefore, the short-term response of the transportation sector was tested for the potential influence of the same list of factors which were tested with the two prior models as well as additional ones. The list of potentially influencing factors was expanded by tests of internalisation of CO_2 emissions (from 15 to 250 US$/ton CO_2), internalisation of local pollutants as NOx and SOx (from 1,000 to 10,000 US$/ton of pollutant emitted), introduction of demonstration projects (from 12,500 to 150,000 promotional vehicles), subsidies for purchase of fuel cells in form of 'cash-back promotions' (from 10 to 100 US$/kW) as well as preferential credits for the build-up of hydrogen infrastructure (discount rates from 2 to 7.5%). The factors which were tested could serve as potential mechanisms for policy options.

Some of the mentioned policy instruments despite not being directly targeted at the hydrogen switch, may show to be quite effective in promoting hydrogen fuelled vehicles. Example of such policy measure may be the internalisation of external costs related to the negative impacts of air pollution originating from the combustions of gasoline and diesel. Policies targeted at redeeming the expenses resulting from endangering human life penalise technological options which are environmentally unfriendly, in the result putting the 'friendly' ones in a prospectus position. Such policy measures as internalisation of CO_2, NOx or SOx emissions may therefore bring a double benefit. Firstly by recovering the financial means for the mitigation of negative impacts of externalities, and secondly by promoting the hydrogen based mobility as a more sound option.

Supporting measures in the field or demonstration and deployment may equally bring benefits. Demonstration vehicles on one hand present the new technology to a broader audience while on the other trigger the interest in the new options. Moreover, this measure allows for building up the capacity of fuel cell vehicles (initial, forced market penetration), which on the long run could allow for costs reduction as function of the ETL costs reduction mechanism. An additional measure could be attractive crediting options for fuel cell vehicles. Such combination could attract potential clients. Examples of such joined policies could have been observed in the past in the cases of solar panels as well as the gasoline-electric hybrid vehicles (Hochschild and Hochschild 2002; Solarcentury 2003; Clayton 2005; ACEEE 2006; Energy Saving Trust 2006).

At later periods, when the fuel cell vehicles become more popular and significant demand may be observed, the results of the analysis suggest that stress ought to be placed on the development of a reliable, high thru-output network supplying hydrogen. This may be achieved by developing a pipeline infrastructure. The results of the analysis suggest that despite immediate absence of the necessity in the early phases of transition to hydrogen based transportation, at later stages lack of such infrastructure could be a possible bottleneck for further developments. To overcome this difficulty an effective policy measure could be introduced which would provide preferential crediting options for projects which contribute to the creation of such network. Results of the analysis suggest that interest rates of 3.5% could stimulate the dynamics of pipeline infrastructure developments.

8.4 Possible further steps

The results presented in this work have showed few guidelines on how the switch to hydrogen based mobility could be achieved. However, the results and tools applied here in many respects were generalised, based on assumptions and limited. As the research process indicated, the more detailed description of the system, the more precise advice may be presented. Significant developments may be observed across the presented research, which started off with very general assumption and their representation, and later over numerous sub-steps have been broadened and refined. Still, much improvement may be done as to specify the picture of the transportation sector with the optimisation modelling framework. Expansion of the geographical regions and the region-specific database could allow observing in more detail the potential developments of the system. Furthermore, a more regional description could provide information on region specific policy measures which could be employed. One of major limitations of the GMM modelling framework is the limited timeframe. As of the time the research was conducted it was not possible to expand neither the timeframe nor the technological database of GMM. This was primarily due to the limitations of data availability which would need to be collected, and secondly to the data reliability. Analysis of such complex systems as the transportation sector, due to its inertia, may be better performed if a longer timeframes and extensive databases are available to test the potential changes in the system.

Development of new technologies is to a significant extent related to the research and development, which is one of the shortcomings of the presented modelling framework. Neither of the models contained a module which would allow for assessing the potential of R&D expenditures to promote fuel cells. However, this limitation is not only the problem of the presented here modelling framework, as a very limited number of studies attempts to deal with the issue of R&D in the frame of optimisation models. One of such pioneers could be the study conducted by Kuvoritakis, which employs an extended formulation of ETL (the 2 Factor Learning approach) (Kouvaritakis N., Soria A. et al. 2000). However the mentioned study contains many issues which are questionable from the point of translating the real-life dynamics into the optimisation framework. Development of an effective and realistic translation of the R&D on the development of existing and new technologies could be a very powerful upgrade to the optimisation modelling framework.

The optimisation framework however, has one key element which may be questioned by many. Optimisation models present the ‘plausible’ scenario, however they do not display pathways on how this may be achieved. Therefore, a potential niche which could be to explore the combination of an analysis which in the first step would produce this plausible scenario (application of optimisation models) and later defining the pathways how this scenario could be achieved (this could be done using f.eg. Systems Dynamics modelling framework).

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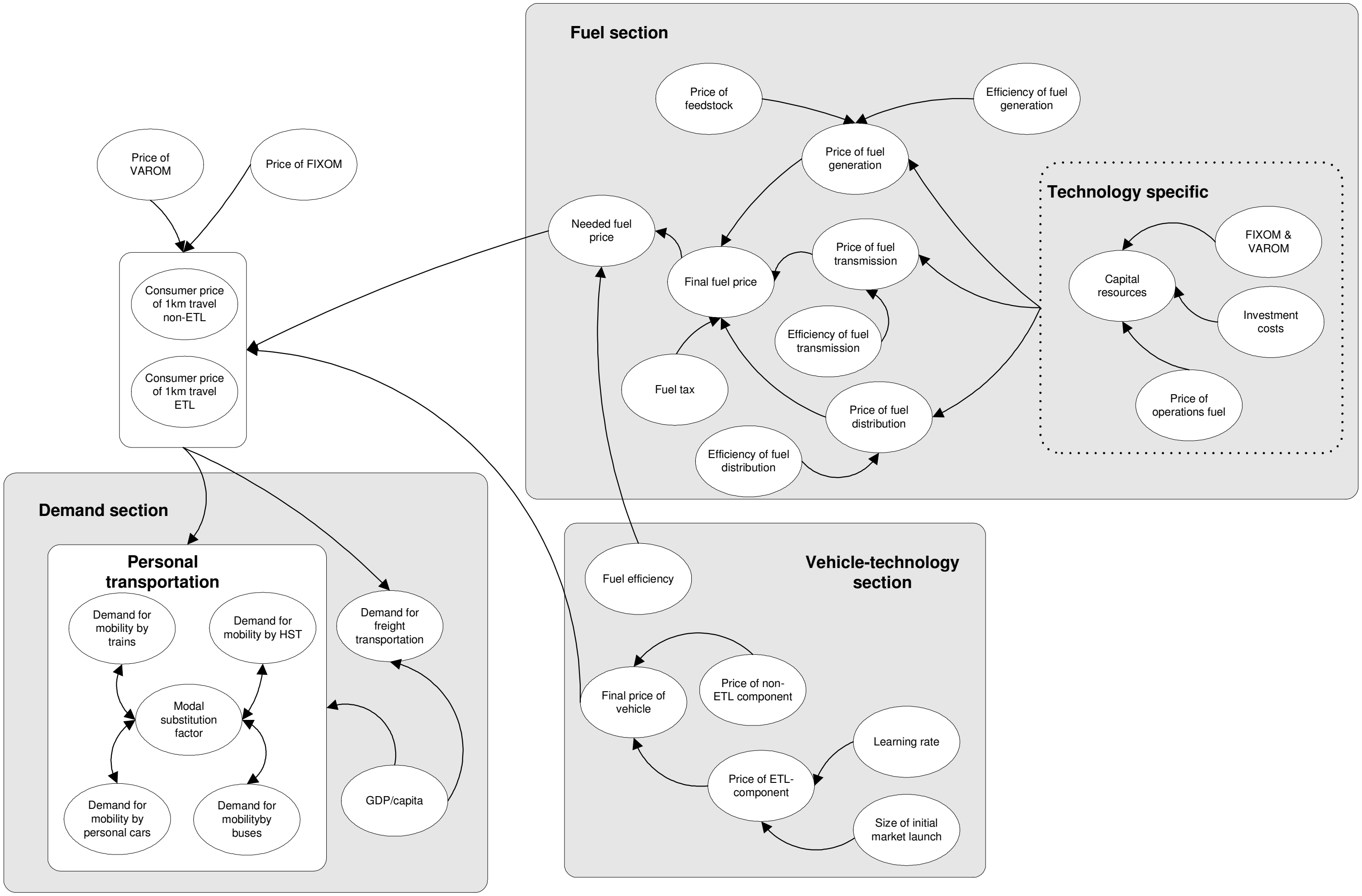
Appendix A: Causal diagram for establishing sensitivity analysis factors



Appendix B: CUBE and GMM: Hydrogen full fuel chain diagram

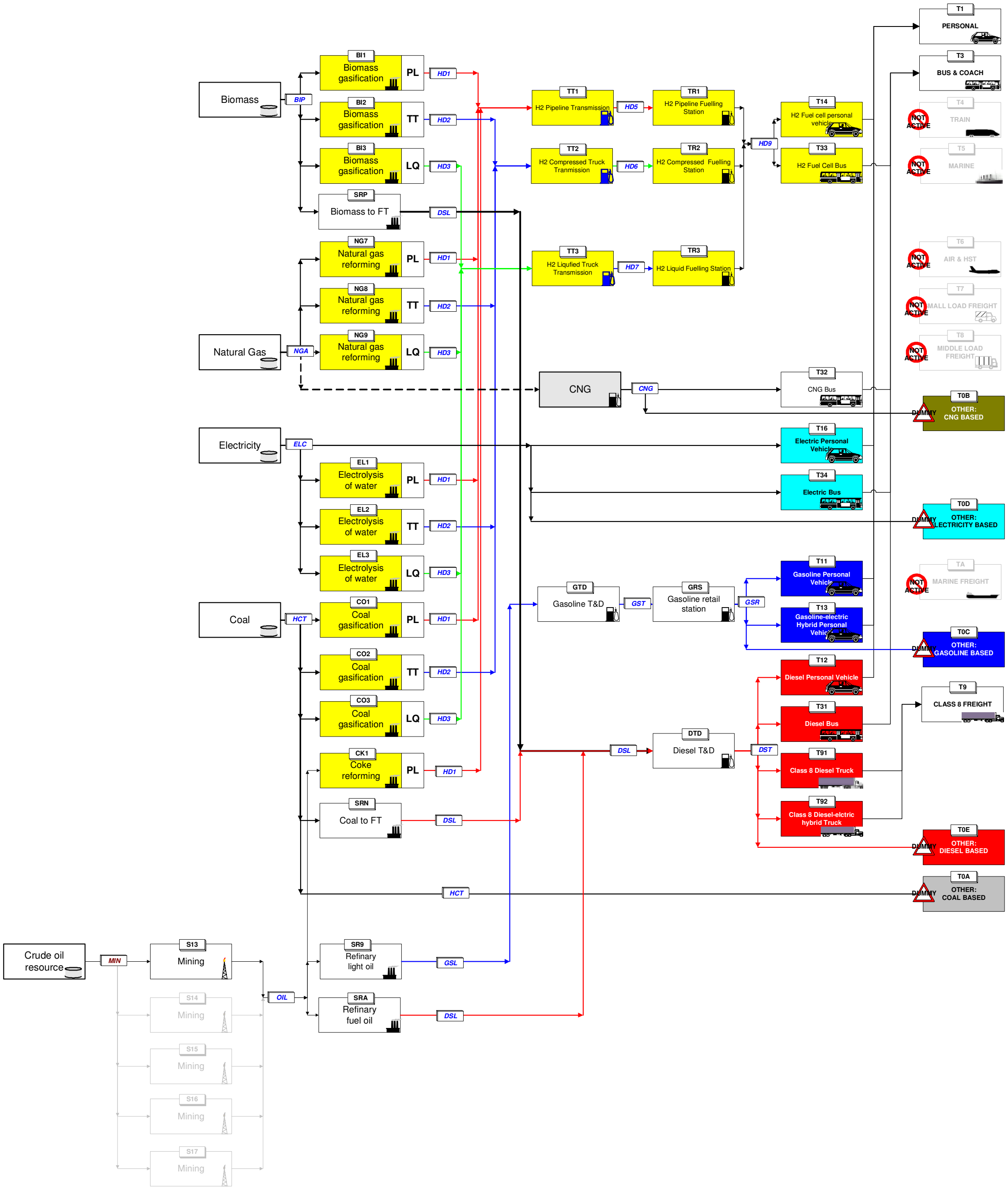


Figure 53 CUBE and GMM: Hydrogen full fuel chain diagram

Appendix C: FinalTRA source code

```
OPTION LIMROW = 1000;
OPTION LIMCOL = 1000;
OPTION SOLPRINT = on;
OPTION SYSOUT = On;
OPTION ITERLIM = 1000000;
OPTION DOMLIM = 1000000;
$OnLISTING

Set reg        /USA/;
set iter       /1*2/;
SET TP         /2000,2010,2020,2030,2040,2050,2060,2070,2080,2090,2100/;

Scalars
Disc           discount rate /0.05/
Period          lenght of time periods /10/;

Alias (tal,tp);
Alias (REG,MREG);

        SET TCH      'TECHNOLOGIES'
         /  TGSL     'Personal - conventional gasoline        '
            TGSA     'Personal - ADV gasoline                '
            TDSL     'Personal - diesel                    '
            TDSA     'Personal - ADV diesel                  '
            THYB     'Personal - hybrid gasoline-electric     '
            THFC     'Personal - H2 FC                      '
            TMFC     'Personal - methanol FC                 '
            TELC    'Personal - electric                   '
            NGLQH2   'Natural gas reforming (liquid)              '
            NGPLH2   'Natural gas reforming (pipeline)        '
            NGTTH2   'Natural gas reforming (tube trailer)    '
            RCPLH2   'Resid (pipeline)                       '
            CRLQH2   'Coal reforming (liquid)                 '
            CRPLH2   'Coal reforming (pipeline)               '
            CRTTH2   'Coal reforming (tube trailer)           '
            BMLQH2   'Biomass (liquid)                       '
            BMPLH2   'Biomass (pipeline)                     '
            BMTTH2   'Biomass (tube trailer)                 '
            ELLQH2   'Electrolysis (liquid)                 '
            ELPLH2   'Electrolysis (pipeline)                '
            ELTTH2   'Electrolysis (tube trailer)             '/

        Set DMD(TCH) 'Automobile technologies'
          / TGSL     'Personal - conventional gasoline        '
            TGSA     'Personal - ADV gasoline                '
            TDSL     'Personal - diesel                    '
            TDSA     'Personal - ADV diesel                  '
            THYB     'Personal - hybrid gasoline-electric     '
            THFC     'Personal - H2 FC                      '
            TMFC     'Personal - methanol FC                 '
            TELC    'Personal - electric                   '  /

       set prc(tch)  ' Processes to generate hydrogen'
          / NGLQH2   'Natural gas reforming (liquid)              '
            NGPLH2   'Natural gas reforming (pipeline)        '
```

```
                NGTTH2   'Natural gas reforming (tube trailer)    '
                RCPLH2   'Resid (pipeline)                         '
                CRLQH2   'Coal reforming (liquid)                  '
                CRPLH2   'Coal reforming (pipeline)                '
                CRTTH2   'Coal reforming (tube trailer)            '
                BMLQH2   'Biomass (liquid)                         '
                BMPLH2   'Biomass (pipeline)                       '
                BMTTH2   'Biomass (tube trailer)                   '
                ELLQH2   'Electrolysis (liquid)                    '
                ELPLH2   'Electrolysis (pipeline)                  '
                ELTTH2   'Electrolysis (tube trailer)              '/

           SET ENC      'ENERGY CARRIERS'
             / GSL      'Gasoline                      '
                DSL      'Diesel                       '
                ELC      'Electric                     '
                MTH      'Methanol                     '
                H2       'Hydrogen                     '
                NGA      'Natural gas                  '
                HCO      'Hard Coal                    '
                BIO      'Biomass                      '
                REN      'Renewables                   '
                NUC      'Nuclear                      '/

           SET ENV      'environmental emissions'
             / CO2      ' Carbon Dioxide                ' /;


$include data.dd

set LL/1*20/;
scalar discpp     discound of annual cost-flow  within  a period to the beginning of the period;
discpp= sum(ll $(ord(ll) LE period), (1+disc)**(- ord(ll) ) );
*                parameter ctax(tp)       time variable carbon tax; specified in data.dd
Parameter tax(tp) Global carbon tax - dollars per ton;
*                ctax=300 ; this is read in from data.dd

tax(tp) = ctax(tp);
*tax(tp) $(ord(tp) gt 2)  = 0.0;

*********************************************************************************
*DK separation of input data for sensitivity analysis runs  (28.07.2005)
*$include techdata.dat
*********************************************************************************

  PARAMETER MA(DMD,ENC)
/
TGSL.GSL        1
TGSA.GSL        1
TDSL.DSL        1
TDSA.DSL        1
THYB.GSL        1
THFC.H2         1
TMFC.MTH        1
TELC.ELC        1
```

```
/;

*PARAMETER FPRICE(ENC,TP);
*calibration for 2000
*FPRICE(ENC,TP)=PRICE(ENC)*(1.+GRPRICE(ENC)/100)**((ORD(TP)-1)*PERIOD);
*    FPrice('GSL','2000') = 5.79;
*    FPrice('DSL','2000') = 5.00  ;
*    FPrice('ELC','2000') = 12          ;
*    FPrice('MTH','2000') = 23          ;
*    FPrice('H2', '2000') = 0           ;
*    FPrice('NGA','2000') = 6           ;
*    FPrice('HCO','2000') = 2           ;
*    FPrice('BIO','2000') = 4           ;
*    FPrice('ren','2000') = 0           ;
*    FPrice('nuc','2000') = 8           ;

*all the next periods
*FPRICE(ENC,TP)$(Ord(tp) GT 1)=PRICE(ENC)*(1.+GRPRICE(ENC)/100)**((ORD(TP)-1)*PERIOD);

display "Fuel prices in USD per GJ ", fprice;

PARAMETER MARKET(DMD,ENC,TP);
MARKET(DMD,ENC,TP) = MA(DMD,ENC);
parameter tpdata(dmd,dat,tp);
tpdata(dmd,dat,tp ) = tchdata(dmd,dat);

*CO2 emmisions for dmd via fuels in [tonnes CO2/PJOF FUEL INPUT]
 parameter  env_tact(env,dmd)    CO2 emissions comming from fuel used by vehicles [tonnes per GJ]
/
   CO2.TGSL          0.071
   CO2.TGSA          0.071
   CO2.TDSL          0.073
   CO2.TDSA          0.073
   CO2.THYB          0.071
   CO2.THFC          0.0
   CO2.TMFC          0.0
   CO2.TELC          0.0
/  ;

 parameter  env_prc(env,prc)     CO2 emissions comming from H2 generation processes [tonnes per GJ]
/
        CO2.NGLQH2        0.0453
        CO2.NGPLH2        0.0453
        CO2.NGTTH2        0.0453
        CO2.RCPLH2        0.0875
        CO2.CRLQH2        0.0906
        CO2.CRPLH2        0.0906
        CO2.CRTTH2        0.0906
        CO2.BMLQH2        0.1169
        CO2.BMPLH2        0.1169
        CO2.BMTTH2        0.1169
        CO2.ELLQH2        0.0
        CO2.ELPLH2        0.0
        CO2.ELTTH2        0.0
```

```
/  ;

SET etl(dmd) ;
  etl(dmd) $ (TCHDATA(DMD,"LR") gt 0) = YES;

SET petl(prc) ;
  petl(prc) $ (DATPRC(prc,"LR") gt 0) = YES;

display etl,petl;

parameter       gencost(prc,tp);
parameter       crfprc(prc);
parameter       lifeprc(prc);
lifeprc(prc)    =DATPRC(PRC,"life")*period;

* Generation cost is given in USD-2000 per GJ

crfprc(prc)=(disc*(1+disc)**(lifeprc(prc)))/((1+disc)**(lifeprc(prc))-1 );
gencost(prc,tp)=
*non-learning part
                          DATPRC(PRC,"INVC")*crfprc(prc)/3.6/8.76/DATPRC(PRC,"af")
                        + DATPRC(PRC,"fixom")+DATPRC(PRC,"varom")
                        + sum(enc,  MAPRC(prc,ENC)*fprice(enc,tp))/DATPRC(prc,"EFF")
*learning part
*                         + DATPRC(PRC,"ILCOST")*crfprc(prc)/3.6/8.76/DATPRC(PRC,"af")
*                           * ( YH.L(prc,tp)/accp0(prc,tp))**lrnp(prc)
;

display   gencost;

PARAMETERS
START(dmd)                  starting year of technology availability
LIFE(dmd)                   life of technology in years
EFF(dmd,tp)                 efficiency   kvkm per GJ
INV_floor(dmd,tp)           specific investments in USD(00) per kvkm travelled per year
ILC(dmd)                    initial learning costs in USD(00) per kvkm travelled per year
FIXOM(dmd,tp)               fix O&M    in USD(00) per kvkm
VAROM(dmd,tp)               var O&M    in USD(00) per kvkm
fuelc(dmd,tp)               fuel cost in USD per 1000vkm
costkmini(dmd,tp)           initial cost per 1000 pkm by ETL cars[$ a 1000 vkm]
costkm_nl(dmd,tp)           non-learning fraction of car costs [$ a 1000 vkm]
costkm_le(dmd,tp)           learning fraction of car costs [$ a 1000 vkm]
crfac(dmd)                  capital recovery factor;

START(dmd) = TCHDATA(DMD,"START");
LIFE(dmd)  = TCHDATA(DMD,"LIFE")*period;
scalar fueleffimp improvement of fuel efficiency in % over decade/7.5/;

Eff(dmd,'2000')=tchdata(dmd,'eff');
Loop (tp$(ord(tp) GT 1),
         eff(dmd,tp) = tchdata(dmd,'eff') * ((1+fueleffimp/100))**((Ord(tp)-1))
     );
*Loop(tp$(ord(tp) GT 1) , EFF(dmd,tp)= (TCHDATA(DMD,'EFF') );
*  ((1+fueleffimp/100)^(Ord(tp))))    );
display 'fuel test', eff;
```

```
INV_floor(dmd,tp)        =TCHDATA(DMD,"Ifloor");
FIXOM(dmd,tp)            =TCHDATA(DMD,"FIXOM");
VAROM(dmd,tp)             =TCHDATA(DMD,"VAROM");
ILC(dmd)                =TCHDATA(dmd,"ILCost");

crfac(dmd)=( disc*(1+disc)**(life(dmd)))/((1+disc)**(life(dmd))-1 );

*     1 GJ fuel makes EFF kvkm and costs  MA(f)*fprice(f) USD;
* ->  1  MA(f)*fprice(f)[USD/GJ]/eff(DMD)[kvkm/GJ]=> [USD/kvkm]
*

FUELC(dmd,tp) = sum(enc,  MARKET(DMD,ENC,tp)*fprice(enc        ,tp))/EFF(dmd,tp);

***********************************************************cost per 1000vkm
*non learning part
SCALAR KMYEAR 1000 KM PER YEAR /17.5/;

  costkm_nl(dmd,tp)=       inv_floor(dmd,tp)*crfac(dmd)/KMYEAR
                         + FIXOM(dmd,tp)
                         + FUELC(dmd,tp)
                         + VAROM(dmd,tp) ;

costkm_le(dmd,tp)=       ILC(dmd)*crfac(dmd)/KMYEAR ;

display "price for travelling:"
         "non-learning:",
         costkm_nl,
         "learning part:",
         costkm_le,
         "CO2 tax:",
         tax;

* for the moment include learning separately in the demand  and cost

Parameter lrn(dmd)   Learning parameter;
Parameter lrnp(prc)  Learning parameter;

lrn(dmd)=log (( 100 - tchdata(dmd,"lr")) / 100) / log(2);
lrnp(prc)=log (( 100 - datprc(prc,"lr")) / 100) / log(2);

parameter prat(dmd);
prat(dmd)=1+lrn(dmd);
parameter pratp(prc);
pratp(prc)=1+lrnp(prc);

display "check lrn", lrn, PRAT, lrnp, pratp;

* 1000 cars times 1 persons times 20000 km per annum makes 20 million  thus one billion p-km
* corresponds to 50000 cars a relatively low and acceptable value to initiate learning ie after
* reaching a stage of commercialization

*Scalar initial cumulative production of starting technologies /5.66/;

parameter dmdtp(dmd,tp);
dmdtp(dmd,tp)=1;
dmdtp(dmd,tp) $(ord(tp) lt start(dmd)) =0;
```

```
display dmdtp;

parameter pdmdtp(prc,tp);
pdmdtp(prc,tp)=1;
pdmdtp(prc,tp) $(ord(tp) lt datprc(prc, "start")) =0;
display pdmdtp;
*$offtext

Parameter accp0(prc,reg) Initial cumulative production - PJ of processes;
*100*initial= 10PJ
*accp0(petl,reg) = 1.1*initial/eff("THFC","2000");
accp0(prc,reg) = 1.1*initial/eff("THFC","2000");

Parameters
decf                          maximum decline factor
expf                          maximum expansion factor
pv(tp)                        present value factor
bb(dmd)                         learning by doing parameter
aa(dmd)                         Coefficient of the learning curve
bbp(prc)                       learning by doing parameter
aap(prc)                       Coefficient of the learning curve
;
pv(tp) = (1/(1+disc))**(period*(ord(tp)-1));

*assignement to calibrate learning by doing
bb(dmd)=-log(prat(dmd))/log(2);
bbp(prc)=-log(pratp(prc))/log(2);

*assignement of coefficient of the learning curve

aa(dmd)=costkm_le(dmd,"2000")*(sum (reg, acc0(dmd,reg)))**bb(dmd);
aap(prc)=gencost(prc,"2000")*(sum (reg, accp0(prc,reg)))**bbp(prc);

* annual growth and declining rates in percent

Parameters
CarExpand(dmd,reg,tp)    expansion constrain for car technologies
GenExpand(prc,reg,tp)    expansion constrain for fuel generation technologies
CarDecline(dmd,reg,tp)   declination constrain for car technologies
decline(tp)              declination constrain for anything else
;

DECLINE(TP)=10;

decline(tp) = (1- decline(tp)/100)**period;
CarExpand(dmd,reg,tp) =  (1+  techexpand(dmd,reg,tp)/100)**period;
CarDecline(dmd,reg,tp) =  (1-  techdecline(dmd,reg,tp)/100)**period;
GenExpand(prc,reg,tp)=  (1+ h2genexpand(prc,reg,tp)/100)**period;

display "decline check", cardecline, carexpand, genexpand;

VARIABLES
COST_NLP                        present value of costs - billion $;

POSITIVE VARIABLES
XE(dmd,reg,tp)                   mobility supplying technology - 10**9 car-km per year
YE(dmd,tp)                      accumulated mobility by technology - 10**9 car-km per year
```

```

XH(prc,reg,tp)                  Hydrogen supply by technology - PJ per year
YH(prc,tp)                      accumulated h2 supply by technology - PJ per year

NTRA(reg,tp)                    non-electric for transport
OILTRA(reg,tp)                  oil for transport
GASTRA(reg,tp)                  gas for transport
H2TRA(reg,tp)                   hydrogen for transport
ETRA(reg,tp)                    electricity for transport
BIOTRA(reg,tp)                  biofuel for transport
HCOTRA(reg,tp)                  hco for H2
RENTRA(reg,tp)                  solar for H2;

Equations

BALTALL(reg,tp)                 fuel balance of transport
BALTOIL(reg,tp)                       balance oil tra
BALTGAS(reg,tp)                 balance gas tra
BALTH2(reg,tp)                  balance hydrogen tra
BALTE(reg,tp)                   balance electricity tra
BALTB(reg,tp)                   balance biofuels tra
BALTHCO(reg,tp)                 coal balance
BALTren(reg,tp)                       renewables balance

DEM(reg,tp)                     mobility supply-demand balance  -  bcarkm
DEC(reg,dmd,tp)                         decline contraints dmd   -  bcarkm
EXP(reg,dmd,tp)                 expansion contraints dmd -  bcarkm
YDF(dmd,tp)                     definition of accumulated  supplies -  bcarkm

DemH2(reg,tp)                         supply-demand balance  for H2  PJ
DECH2(reg,prc,tp)               decline contraints for production of H2   by process
EXPH2(reg,prc,tp)               expansion contraints for production of H2 by process
YDFH2(prc,tp)                   definition of accumulated  supplies of H2 by process

EQ_OBJNLP                       definition of present value of costs - billion

*contrains on the market development region & time specific
EQ_Gasoline_conv(tp,reg)        conventional gasoline should not be produced after 2020
EQ_Diesel_USA(tp)               diesel should not have more then 2% of market share in USA
EQ_Conv_Diesel_fadeout(tp)      conventional diesel fades out
EQ_MeFC_out(tp)                 Methanol FC is not out of the analysis

EQ_H2(tp)                       production of hydrogen in the beggining should trucks
EQ_H2Pipeline(tp)               after reaching a 10% market penetration of h2fc pipeline infrastructure is build

;
*******************************MODEL EQUATIONS

BALTALL(reg,tp) ..              NTRA(reg,tp)   =e= OILTRA(reg,tp)+ GASTRA(reg,tp) + H2TRA(reg,tp) + ETRA(reg,tp)+BIOTRA(reg,tp)
                                         +HCOTRA(reg,tp) + RENTRA(reg,tp);

BALTOIL(reg,tp)        ..              OILTRA(reg,tp) =e=   (1e-3)*sum((dmd), market(dmd,"gsl",tp )/eff(dmd,tp)* XE(dmd,reg,tp) )
                                         + (1e-3)*sum((dmd),  market(dmd,"dsl",tp )/eff(dmd,tp)* XE(dmd,reg,tp) )
```

```
                                                 + (1e-3)*(sum((prc), MAPRC(prc,"gsl")/datprc(prc,'eff')* XH(prc,reg,tp)))
                                                 +  1e-3 *(sum((prc), MAPRC(prc,"dsl")/datprc(prc,'eff')* XH(prc,reg,tp)))   ;

BALTGAS(reg,tp)        ..              GASTRA(reg,tp) =e= (1e-3)*sum((dmd), market(dmd,"nga",tp )/eff(dmd,tp)* XE(dmd,reg,tp) )
                                                 +(1e-3)*(sum((prc), MAPRC(prc,"nga")/datprc(prc,'eff')* XH(prc,reg,tp))) ;

BALTH2(reg,tp)  ..              H2TRA(reg,tp)  =e= (1e-3)*(sum((prc), MAPRC(prc, "h2")/datprc(prc,'eff')* XH(prc,reg,tp))) ;

BALTE(reg,tp)   ..              ETRA(reg,tp)   =e=   (1e-3)*sum((dmd), market(dmd,"elc",tp )/eff(dmd,tp)* XE(dmd,reg,tp) )
                                                  + (1e-3)*(sum((prc), MAPRC(prc,"elc")/datprc(prc,'eff')* XH(prc,reg,tp))) ;

BALTB(reg,tp)   ..              BIOTRA(reg,tp) =e=   (1e-3)*sum((dmd), market(dmd,"bio",tp )/eff(dmd,tp)* XE(dmd,reg,tp) )
                                                   +(1e-3)*sum((dmd), market(dmd,"mth",tp )/eff(dmd,tp)* XE(dmd,reg,tp) )
                                                   + (1e-3)*(sum((prc), MAPRC(prc,"bio")/datprc(prc,'eff')* XH(prc,reg,tp)));

BALTHCO(reg,tp)        ..              HCOTRA(reg,tp) =e=   (1e-3)*(sum((prc), MAPRC(prc,"hco")/datprc(prc,'eff')* XH(prc,reg,tp)));
BALTren(reg,tp)        ..              RENTRA(reg,tp) =e=   (1e-3)*(sum((prc), MAPRC(prc,"ren")/datprc(prc,'eff')* XH(prc,reg,tp)));

*expansion/decline constraints on cars
DEC(reg,dmd,tp+1)$(Ord (tp) GE TchData(dmd,'Start'))..            XE(dmd,reg,tp+1) =g= Cardecline(dmd,reg,tp) *XE(dmd,reg,tp);
*old version:  EXP(reg,dmd,tp+1)  ..          XE(dmd,reg,tp+1) =l= 0.01*demand('2000',reg) + carexpand(dmd,reg,tp)* XE(dmd,reg,tp);
EXP(reg,dmd,tp+1)$(Ord (tp) GE TchData(dmd,'Start'))..            XE(dmd,reg,tp+1) =l= carexpand(dmd,reg,tp)* XE(dmd,reg,tp);

*expansion/decline constraints on H2 generation
DECH2(reg,prc,tp+1)..           XH(prc,reg,tp+1) =g=  decline(tp) * XH(prc,reg,tp);
EXPH2(reg,prc,tp+1)..           XH(prc,reg,tp+1) =l= accp0(prc,reg)  + genexpand(prc,reg,tp)* XH(prc,reg,tp);

*accumulated PRODUCTION

YDF(dmd,tp)    ..               YE(dmd,tp) =e= sum(reg, acc0(dmd,reg))
                                 + sum(tal$(ord(tal) le (ord(tp)-1)), period*sum(reg, XE(dmd,reg,tal)));

YDFH2(prc,tp)  ..               YH(prc,tp) =e= sum(reg, accp0(prc,reg))
                              + sum(tal$(ord(tal) le (ord(tp)-1)), period*sum(reg, XH(prc,reg,tal)));

*supply-demand balances.

DEM(reg, tp) $(demand(tp, reg) GT 0) ..

                           sum (dmd,  XE(dmd,reg,tp))  =g= demand(tp,reg) ;
```

```

DemH2(reg,tp) ..                sum (prc,  XH(prc,reg,tp)* datprc(prc, "EFF"))  =g=

                                        sum((dmd), market(DMD,"H2",tp )/eff(dmd,tp)* XE(dmd,reg,tp)) ;

*contrains on the market development region & time specific**********************
EQ_Gasoline_conv(tp,reg)..       XE('tgsl',reg,tp)$(Ord (TP) GE 8) =l= 10;

EQ_Diesel_USA(tp)..              XE('tdsl','usa',tp) + XE('tdsa','usa',tp) =l= 0.02 * demand(tp,'usa');
EQ_Conv_Diesel_fadeout(tp)
                $(Ord(TP) GE 4)..
                                XE('tdsl','usa',tp) =E= 0;

EQ_H2Pipeline(tp)..
                                 XH('NGPLH2','usa',tp)
                                +XH('RCPLH2','usa',tp)
                                +XH('CRPLH2','usa',tp)
                                +XH('BMPLH2','usa',tp)
                                +xh('ELPLH2','usa',tp)
                                             =L=  5000;

EQ_H2(tp)..
                                 XH('NGLQH2','usa',tp)
                                +XH('NGTTH2','usa',tp)
                                +XH('CRLQH2','usa',tp)
                                +XH('CRTTH2','usa',tp)
                                +XH('BMLQH2','usa',tp)
                                +XH('BMTTH2','usa',tp)
                                +XH('ELLQH2','usa',tp)
                                +XH('ELTTH2','usa',tp)
                                             =L= 500 ;
;

EQ_MeFC_out(tp)..                XE('tmfc','usa',tp) =e= 0;

************************OBJECTIVE FUNCTION FOR NLP*******************************
*present value costs

EQ_OBJNLP..          COST_NLP =e=0.001*sum(reg, sum(tp,pv(tp)*(

*static costs dmds
                     discpp*sum(dmd, costkm_nl(dmd,tp)*XE(dmd,reg,tp))
*static costs prcs
                     + discpp*sum(prc, gencost(prc,tp)*XH(prc,reg,tp))
*dynamic costs dmds
                     + discpp* sum(etl, costkm_le(etl,tp)*XE(etl,reg,tp)*(YE(etl,tp)/sum(Mreg, acc0(etl,reg)))**lrn(etl))
*dynamic costs prcs
                     +discpp* sum(petl, gencost(petl,tp)*XH(petl,reg,tp)*(YH(petl,tp)/sum(Mreg, accp0(petl,reg)))**lrnp(petl))

*carbon taxes  DMD
                 + discpp*tax(tp)*(sum((dmd), env_tact("co2",dmd)/eff(dmd,tp)* XE(dmd,reg,tp)))
*carbon taxes  PRC
```

```
                + discpp*tax(tp)*(sum((prc), env_prc("co2",prc)/datprc(prc,'eff')* XH(prc,reg,tp)))
                )));


********************** bounds  ***********************************

*  bound tch  before start to zero, after bound lo to 4 pc of demand or for etl to acc0, upper to 70 pc of regional demands

*general
XE.fx(dmd,reg,tp) $(dmdtp(dmd,tp) eq 0) = 0.0;
XE.UP(dmd,reg,tp) = 1.01*demand(tp,reg);
xe.fx(dmd,reg,tp)$( ORD(tp) lt Tchdata(dmd,"Start")) = 0;
YE.UP(DMD,tp)$(ord(tp) ge 1) = sum( (REG, tal) $(ord(tal) le ord(tp)), PERIOD*DEMAND(TP,reg));
YE.LO(ETL,tp) = sum(reg, acc0(etl,reg));

*calibration for cars available in 2000
xe.lo(dmd,reg,tp)$( (ORD(tp) eq 1)$
                            (Tchdata(dmd,"Start") eq 1
                            )
                ) = 0.99*acc0(dmd,reg);

xe.up(dmd,reg,tp)$( (ORD(tp) eq 1)$
                            (Tchdata(dmd,"Start") eq 1
                            )
                ) = 1.01*acc0(dmd,reg);

*starting of cars available later then 2000
xe.up(dmd,reg,tp)$(  (ORD(tp) eq Tchdata(dmd,"Start"))$(Ord(tp) GT 1
                                          )
                ) = 1.01*acc0(dmd,reg);


*H2 generation
*XH.LO("b2h",reg,tp)$(pdmdtp("b2h",tp) eq 1)      = accp0("b2h",reg);
*XH.UP(prc,reg,tp) $(ord(tp) ge datprc(prc,"start")) =0.7*demand(tp,reg)/eff("THFC",tp);
YH.LO(prc, TP) =sum(reg, accp0(prc,reg));
XH.fx(prc,reg,tp)$(pdmdtp(prc,tp) eq 0)         = 0.0;
XH.lo(prc,reg,tp)$(pdmdtp(prc,tp) eq 1)         = XE.lo("THFC",reg, tp)/eff("THFC",tp);

***Model segment****************
MODEL LBD_NLP   /
*******************************
               EQ_OBJNLP
               DEM
               DEC
               EXP
               YDF
                  BALTALL
                  BALTOIL
                  BALTGAS
                  BALTH2
                  BALTE
                  BALTB
                  BALTHCO
                  BALTREN
```

```

                 demH2
                 dech2
                 exph2
                 ydfh2
*constrains on market development of technologies
                 EQ_Gasoline_conv
                 EQ_Diesel_USA
*                  EQ_Conv_Diesel_fadeout
                 EQ_H2
                 EQ_H2Pipeline
                 EQ_MeFC_out
                 /;

option nlp = CONOPT3;

Parameters
lrng(dmd,tp)                 learning costs - c$ per car km
xnlp(reg,dmd,tp)               production-nlp
ynlp(dmd,tp)                 cumulative production-nlp
crtx(tp)                    carbon taxes - $ per ton
  demnew(tp,reg)              the numerical value of demand
demexact(tp,reg)              the exact demand function
demratio(tp,reg)             the demand ratio
;

SOLVE LBD_NLP minimizing COST_NLP  using NLP;

* ITERATIVE PARTIAL EQUILIBRIUM PROCEDURE:
* solve first for reference development to define  price0
* solve again with a tax to define new prices
* solve again with adjusted demands

$ontext

parameter priceref(reg,tp);
parameter pricetax(reg,tp);

priceref(reg,tp)= DEM.M(reg, tp)/DISCPP/(1/(1+disc)**(period*(ORD(tp)-1)));
display
"checkpoint 0 - priceref after first run",
priceref;

*INCLUDE NOW A TAX

*tax(tp) $(ord(tp) gt 2)  = ctax;
*the tax is now time variable, so no need for the gt2 condition
tax(tp) = ctax(tp);

* solve again for adjusted carbon taxes

SOLVE LBD_NLP minimizing COST_NLP  using NLP;

pricetax(reg,tp)= DEM.M(reg, tp)/DISCPP/(1/(1+disc)**(period*(ORD(tp)-1)));
display
"checkpoint1",
demand,
```

```
pricetax,
priceref;

demand(tp,reg) $((ord(tp) gt 1)$(pricetax(reg,tp) gt 1)) =demand(tp,reg)*(pricetax(reg,tp)/priceref(reg,tp))**(-.25);

display
"checkpoint2",
demand,
pricetax,
priceref;

SOLVE LBD_NLP minimizing COST_NLP  using NLP;

lrng(etl,tp)=costkm_le(etl,tp)*(YE.L(etl,tp)/sum(reg, acc0(etl,reg)))**lrn(etl)+costkm_nl(etl,tp);
pricetax(reg,tp)= DEM.M(reg, tp)/DISCPP/(1/(1+disc)**(period*(ORD(tp)-1)));

display "check", pricetax;
$offtext
*$include partial.gms

Parameter       costkmetl(dmd,TP)       cost of 1000 vkm by ETL technologies;

costkmetl(dmd,TP)= costkm_nl(dmd,tp) ;

costkmetl(etl,TP)= costkm_nl(etl,tp) + costkm_le(etl,tp)* (
                                                  (YE.l(etl,TP)/sum(reg, acc0(etl,reg)) )**lrn(etl)
                                                 );
*********************************************************** all that for testing purposes

*FUEL BALANCES

PARAMETER
        PRIMARY(ENC,TP)
        CO2(ENC,TP)                     global total co2 emissions as sum of generation of H2 and mobility activity
        co2h2generation(prc,reg,tp)     emissions comming from H2 generating technologies
        realcostkmetl(dmd,tp)           full costs of travelling by a vehicle
        ;
PRIMARY(ENC,TP)= (1e-3)*sum((dmd,REG), market(dmd,enc,tp )/eff(dmd,tp)* XE.L(dmd,reg,tp) )
                      + (1e-6)*(sum((prc,REG), MAPRC(PRC,ENC)/datprc(prc,'eff')* XH.L(prc,reg,tp)));

CO2(ENC,TP)= (1e-3)*12/44* (sum((dmd,REG), env_tact("co2",dmd)*market(dmd,enc,tp )/eff(dmd,tp)* XE.L(dmd,reg,tp)))
        + (sum((prc,REG), env_prc("co2",prc)*MAPRC(PRC,ENC)/datprc(prc,'eff')* XH.L(prc,reg,tp)));

*lll
co2h2generation(prc,reg,tp) = XH.l(prc,reg,tp) * env_prc("co2",prc) ;

* Hydrogen is an secondary energy carrier (only the primary source should be included in the balance)
  PRIMARY("h2",TP)=PRIMARY("H2",TP)-PRIMARY("h2",TP)  ;
```

```

realcostkmetl(dmd,tp) =  costkmetl(dmd,tp)
                          +
tax(tp)*sum(enc,(MARKET(DMD,ENC,TP)*ENV_TACT("CO2",DMD)))/EFF(DMD,TP)

DISPLAY
realcostkmetl,
costkmetl,
tax,
env_tact,
eff;

*DK check on the prices of hydrogen
Parameter h2price(prc,tp)        price of hydrogen from different sources;

h2price(prc,tp) =
*static
*discpp*(gencost(prc,tp));
gencost(prc,tp);
*dynamic
*+discpp* sum(petl, gencost(petl,tp)*XH.l(petl,'usa',tp)*(YH.l(petl,tp)/sum(Mreg,
accp0(petl,'usa')))**lrnp(petl))  ;

display 'XXX', h2price;


*********************************OUTPUT OF RESULTS
Put F1;
Put      '  h2kw=',tchdata('THFC','ILCOST'),
         '  lr=',tchdata('THFC','LR'),
         '  BBL at ', fuelpricegrowth('gsl'), ' % ',
         '  cco cars=', inicar,
         '  pipeline growth=', H2genexpand('NGPLH2','usa','2000')
         /;
Put 'technologies', ';';
Loop (TP, Put TP.tl , ';');
Put /;
*CARS
Loop (DMD,
        put DMD.tl , ';';
        Loop (tp, put xe.l(dmd,'USA',tp), ';');
        put /;
      );
*GENS
Loop (PRC,
        put PRC.tl , ';';
        Loop (tp, put xh.l(prc,'USA',tp), ';');
        put /;
      );

PutClose;
```

File data.dd

```
*****************************************************************
```

```
*CO2 tax
*************************************************************
parameter ctax(tp)       CO2 tax
/
2000     0
2010     0
2020     0
2030     0
2040     0
2050     0
2060     0
2070     0
2080     0
2090     0
2100     0
/;

***************************************************************************
*demand for mobility
***************************************************************************

*PARAMETER demand(*,reg)  demand per category region and year  - reference case;
PARAMETER demand(tp,reg)  demand per category region and year  - reference case;
* in billion Vkm per year

        table rgrowth(reg,tp)

        2000     2010     2020     2030     2040     2050     2060     2070     2080     2090    2100

USA     0.021    0.012    0.007    0.005    0.001    0.0      0.0      0.0      0.0      0.0     0.0
;

TABLE DEMAND(tp,reg)
        USA

 2000   3605.4
 2010   4431.8
 2020   4978.0
 2030   5332.6
 2040   5583.1
 2050   5538.8
 2060   5329.1
 2070   4873.6
 2080   4324.2
 2090   3846.1
 2100   3762.7
 ;

*LOOP (TP,
*demand(tp+1,reg) =demand(tp,reg)*(1+rgrowth(REG,TP))**period ;
*);
display
"checkpoint",
demand;


**************************************************************************
```

```
*expansion constrains for each vehicle type
*************************************************************************
table techexpand(dmd,reg,tp)
              2000   2010   2020   2030   2040   2050   2060   2070   2080   2090   2100
*conventional gasoline
TGSL.USA      8      5      0      0      0      0      0      0      0      0      0
*advanced gasoline
TGSA.USA      0      40     40     20     17     15     15     15     15     15     15
*conventional diesel
TDSL.USA      9      9      5      0      0      0      0      0      0      0      0
*advanced diesel
TDSA.USA      75     75     78     29     26     10     7      0      0      0      0
*hybrid gasoline-electric (prius)
THYB.USA      15     10     10     10     10     15     10     5      5      5      5
*hydrogen fuell cell
THFC.USA      10     10     10     10     10     10     10     10     10     10     10
*methanol fuel cell
TMFC.USA      15     15     15     22     22     17     15     15     15     15     15
*electric
TELC.USA      1      2      6      7      9      9      9      5      5      5      5
;

*************************************************************************
*decline constrains for each vehicle type
*************************************************************************
table techdecline(dmd,reg,tp)
              2000   2010   2020   2030   2040   2050   2060   2070   2080   2090   2100
*conventional gasoline
TGSL.USA      15     15     15     15     15     15     15     15     15     15     15
*advanced gasoline
TGSA.USA      15     15     15     15     15     15     15     15     15     15     15
*conventional diesel
TDSL.USA      25     75     75     75     75     15     15     15     15     15     15
*advanced diesel
TDSA.USA      15     15     15     15     15     15     15     15     15     15     15
*hybrid gasoline-el
THYB.USA      15     15     15     15     15     15     15     15     15     15     15
*hydrogen fuell cel
THFC.USA      15     15     15     15     15     15     15     15     15     15     15
*methanol fuel cell
TMFC.USA      15     15     15     15     15     15     15     15     15     15     15
*electric
TELC.USA      15     15     15     15     15     15     15     15     15     15     15
;

*Prices of fuels

PARAMETER FPRICE(ENC,TP)      price of fuels time depandant;
*calibration for year 2000 (oil is at 28 usd per bbl)
   FPrice('GSL','2000') = 18.07    ;
   FPrice('DSL','2000') = 16.25    ;
   FPrice('ELC','2000') = 12        ;
   FPrice('MTH','2000') = 23        ;
   FPrice('H2', '2000') = 0        ;
   FPrice('NGA','2000') = 2.5       ;
```

```
    FPrice('HCO','2000') = 2          ;
    FPrice('BIO','2000') = 4          ;
    FPrice('ren','2000') = 0          ;
    FPrice('nuc','2000') = 8          ;

*calibration for year 2010 (oil is at 55 usd per bbl)
    FPrice('GSL','2010') = 29.45   ;
    FPrice('DSL','2010') = 21.48   ;
    FPrice('ELC','2010') = 12         ;
    FPrice('MTH','2010') = 23         ;
    FPrice('H2', '2010') = 0          ;
    FPrice('NGA','2010') = 6          ;
    FPrice('HCO','2010') = 2          ;
    FPrice('BIO','2010') = 4          ;
    FPrice('ren','2010') = 0          ;
    FPrice('nuc','2010') = 8          ;

*calibration for all the other years 2020-2100
Parameter          fuelpricegrowth(enc)    increase of primary fuel price per decade
  /
  GSL     5
  DSL     5
  ELC     1
  MTH     1
       H2  1
       NGA         1
       HCO         1
       BIO 1
       ren 1
       nuc 1
       /;

Loop (TP$(ORD(TP) GT 2),
  Fprice(enc,tp) = Fprice(enc,tp-1)*(fuelpricegrowth(enc)/100+1)
     );

*SCENGEN CCo
scalar inicar cumulative production of starting technologies /700.0/;

parameter initial cumulative production of starting technologies;
initial = inicar * 1000 * 17500 / 1e9;
*scalar bblgrowth  growth of oil prices /2.5/;


*processes for H2 production

* set prc(tch)  ' Processes to generate hydrogen' /NGLQH2..... /;
set prdat /eff, af, life, start, invc, fixom, varom, ilcost, lr  /;

       table datprc(prc,prdat)
              start   life    eff     af      invc       fixom       varom   ilcost  lr
*             period  period  -       -       us$/gj     us$/gj      us$/gj  us$/gj  -
NGLQH2         2       2      0.80    0.90    87.91      5.23        4.56    0.00    0
NGPLH2         4       2      0.80    0.90    136.85     9.30        0.40    13.73   10
NGTTH2         2       2      0.80    0.90    81.86      16.01       0.88    0.00    0
RCPLH2         4       2      0.64    0.90    154.71     10.18       1.28    13.73   10
CRLQH2         2       2      0.64    0.90    124.64     7.06        6.37    0.00    0
```

```
CRPLH2        4       2      0.64    0.90    167.17      10.80       1.79    13.73   10
CRTTH2        2       2      0.64    0.90    116.56      17.76       2.54    0.00    0
BMLQH2        2       2      0.67    0.90    125.31      7.10        6.48    0.00    0
BMPLH2        4       2      0.67    0.90    173.24      11.11       2.29    13.73   10
BMTTH2        2       2      0.67    0.90    120.43      17.95       2.96    0.00    0
ELLQH2        2       2      0.75    0.90    165.06      9.08        0.49    0.00    0
ELPLH2        4       2      0.75    0.90    218.88      13.40       0.29    13.73   10
ELTTH2        2       2      0.75    0.90    160.86      19.97       0.35    0.00    0
;

  parameter maprc(prc,enc)
/
NGLQH2.nga       1
NGPLH2.nga       1
NGTTH2.nga       1
RCPLH2.dsl       1
CRLQH2.hco       1
CRPLH2.hco       1
CRTTH2.hco       1
BMLQH2.bio       1
BMPLH2.bio       1
BMTTH2.bio       1
ELLQH2.nuc       1
ELPLH2.nuc       1
ELTTH2.nuc       1
/;

SET DAT /START,LIFE,EFF,Ifloor,FIXOM,VAROM, ILCost, LR/;

*********************************************vehicle technologies
TABLE   TCHDATA(DMD,*)
*                         kvkm/GJ    $95/CAR     $/kvkm    $/kvkm    $/kvkm     -
*                         bvkm/PJ
             START   LIFE    EFF       Ifloor      FIXOM     VAROM      ILCost     LR
TGSL          1       1      10        18600       70.00     8.10       0          0
TGSA          2       1      0.3512    19500       70.00     8.10       0          0
TDSL          1       1      0.4081    20500       70.00     8.10       0          0
TDSA          2       1      0.4693    21500       70.00     8.10       0          0
THYB          2       1      0.7648    22000       70.00     8.10       2000       10
*assuming 50kw stack, with 500USD/kw: 50kw*500usd=25000 usd
*floor cost at 100usd/kw, asuming the base chassis at 15000+50kw stack=20000 for FC vehicles
TMFC          4       1      1.20      25000       50.00     8.10       25000      0
THFC          4       1      1.20      20000       50.00     8.10       30000      20.00
TELC          6       1      1.78      20500       100.0     8.10       2000       10;

***************************************************************************
*expansion constrains for each H2 generation technology
***************************************************************************
table H2genexpand(prc,reg,tp)
            2000     2010     2020     2030     2040     2050     2060     2070     2080     2090     2100
*Natural gas reforming (liquid)
NGLQH2.USA    15       15       15       15       15       1        1        1        1        1        1
*******Natural gas reforming (pipeline)
NGPLH2.USA    10       10       10       10       10       10       10       10       10       10       10
```

```
********Natural gas reforming (tube trailer)
NGTTH2.USA    15    15    15    15    15    1    1    1    1    1    1
********Resid (pipeline)
RCPLH2.USA    10    10    10    10    10    10    10    10    10    10    10
*Coal reforming (liquid)
CRLQH2.USA    15    15    15    15    15    1    1    1    1    1    1
*************Coal reforming (pipeline)
CRPLH2.USA    10    10    10    10    10    10    10    10    10    10    10
*************Coal reforming (tube trailer)
CRTTH2.USA    15    15    15    15    15    1    1    1    1    1    1
*************Biomass (liquid)
BMLQH2.USA    15    15    15    15    15    1    1    1    1    1    1
*************Biomass (pipeline)
BMPLH2.USA    10    10    10    10    10    10    10    10    10    10    10
*************Biomass (tube trailer)
BMTTH2.USA    15    15    15    15    15    1    1    1    1    1    1
****************Electrolysis (liquid)
ELLQH2.USA    15    15    15    15    15    1    1    1    1    1    1
****************Electrolysis (pipeline)
ELPLH2.USA    10    10    10    10    10    10    10    10    10    10    10
****************Electrolysis (tube trailer)
ELTTH2.USA    15    15    15    15    15    1    1    1    1    1    1
;

Parameter acc0(dmd,reg) Initial cumulative production - 10**9 v-km;
acc0('TGSL','USA') = 0.98*Demand('2000','USA')      ;
acc0('TGSA','USA') = Initial                         ;
acc0('TDSL','USA') = 0.02*Demand('2000','USA')      ;
acc0('TDSA','USA') = Initial                         ;
acc0('THYB','USA') = Initial                         ;
acc0('THFC','USA') = Initial                         ;
acc0('TMFC','USA') = Initial                         ;
acc0('TELC','USA') = Initial                         ;

File F1 /out.dk/;
**************
```

Appendix D: CUBE source code

```
OPTION LIMROW = 1000;
OPTION LIMCOL = 1000;
OPTION SOLPRINT = on;
OPTION SYSOUT = On;
OPTION ITERLIM = 1000000;
OPTION DOMLIM = 1000000;
*Option Rtmaxj = 1.00e+7
$OnLISTING

SET TP          /2000,2010,2020,2030,2040,2050,2060,2070,2080,2090,2100/;

Scalars
Disc            discount rate /0.05/
Period          lenght of time periods /10/
faki            scaling factor for OBJ function /1e-2/
;
          SET Tech      'TECHNOLOGIES'
           /
*cars
              TGSL     'Personal - gasoline                    '
              TDSL     'Personal - diesel                      '
              THYB     'Personal - hybrid gasoline-electric    '
              THFC     'Personal - H2 FC                       '
              TMFC     'Personal - methanol FC                 '
              TELC     'Personal - electric                    '
*generation
              H2NGLQ   'Natural gas reforming (liquid)         '
              H2NGPL   'Natural gas reforming (pipeline)       '
              H2NGTT   'Natural gas reforming (tube trailer)   '
              H2RCPL   'Resid (pipeline)                       '
              H2CRLQ   'Coal reforming (liquid)                '
              H2CRPL   'Coal reforming (pipeline)              '
              H2CRTT   'Coal reforming (tube trailer)          '
              H2BMLQ   'Biomass (liquid)                       '
              H2BMPL   'Biomass (pipeline)                     '
              H2BMTT   'Biomass (tube trailer)                 '
              H2ELLQ   'Electrolysis (liquid)                  '
              H2ELPL   'Electrolysis (pipeline)                '
              H2ELTT   'Electrolysis (tube trailer)            '
              MeGSLQ   'Methanol generation - from biomass, see excel for tech description'
              MeARLQ   'Methanol generation - from biomass, see excel for tech description'
              MeSCLQ   'Methanol generation - from biomass, see excel for tech description'
              MeSCMR   'Methanol generation - from biomass, see excel for tech description'
              MeHGAR   'Methanol generation - from biomass, see excel for tech description'
              MESCSR   'Methanol generation - from biomass, see excel for tech description'
*transmission
              H2PL     'H2 transmission by pipeline            '
              H2TT     'H2 transmission by tube trailer        '
              H2LQ     'H2 transmission by liquified           '
              MeTR     'Methanol by truck                      '
*distribution
              H2FSPL   'H2 fuelling station pipeline connected '
              H2FSTT   'H2 fuelling station low pressure       '
              H2FSLQ   'H2 fuelling station high pressure      '
              MeFSNE   'Methanol fuelling station (new)        '
```

```
            MeFSMO   'Methanol fuelling sation (retrofitet)   '
/

Set cars(tech)    'cars'
   /
            TGSL     'Personal - gasoline                    '
            TDSL     'Personal - diesel                      '
            THYB     'Personal - hybrid gasoline-electric    '
            THFC     'Personal - H2 FC                       '
            TMFC     'Personal - methanol FC                 '
            TELC     'Personal - electric                    '
   /

Set fuelchainmember(tech)        'members of the fuel chain'
   /
            H2NGLQ   'Natural gas reforming (liquid)         '
            H2NGPL   'Natural gas reforming (pipeline)       '
            H2NGTT   'Natural gas reforming (tube trailer)   '
            H2RCPL   'Resid (pipeline)                       '
            H2CRLQ   'Coal reforming (liquid)                '
            H2CRPL   'Coal reforming (pipeline)              '
            H2CRTT   'Coal reforming (tube trailer)          '
            H2BMLQ   'Biomass (liquid)                       '
            H2BMPL   'Biomass (pipeline)                     '
            H2BMTT   'Biomass (tube trailer)                 '
            H2ELLQ   'Electrolysis (liquid)                  '
            H2ELPL   'Electrolysis (pipeline)                '
            H2ELTT   'Electrolysis (tube trailer)            '
            MeGSLQ   'Methanol generation - from biomass, see excel for tech description'
            MeARLQ   'Methanol generation - from biomass, see excel for tech description'
            MeSCLQ   'Methanol generation - from biomass, see excel for tech description'
            MeSCMR   'Methanol generation - from biomass, see excel for tech description'
            MeHGAR   'Methanol generation - from biomass, see excel for tech description'
            MESCSR   'Methanol generation - from biomass, see excel for tech description'
            H2PL     'H2 transmission by pipeline            '
            H2TT     'H2 transmission by tube trailer        '
            H2LQ     'H2 transmission by liquified           '
            MeTR     'Methanol by truck                      '
            H2FSPL   'H2 fuelling station pipeline connected  '
            H2FSTT   'H2 fuelling station low pressure       '
            H2FSLQ   'H2 fuelling station high pressure      '
            MeFSNE   'Methanol fuelling station (new)        '
            MeFSMO   'Methanol fuelling sation (retrofitet)   '
   /;

Set chainpath chain paths /H2cpl, H2ctt, H2clq, MeLQ/;

Set gen(fuelchainmember)         'generation technologies'
   /
            H2NGLQ   'Natural gas reforming (liquid)         '
            H2NGPL   'Natural gas reforming (pipeline)       '
            H2NGTT   'Natural gas reforming (tube trailer)   '
            H2RCPL   'Resid (pipeline)                       '
            H2CRLQ   'Coal reforming (liquid)                '
            H2CRPL   'Coal reforming (pipeline)              '
            H2CRTT   'Coal reforming (tube trailer)          '
            H2BMLQ   'Biomass (liquid)                       '
```

```
            H2BMPL   'Biomass (pipeline)                    '
            H2BMTT   'Biomass (tube trailer)                 '
            H2ELLQ   'Electrolysis (liquid)                  '
            H2ELPL   'Electrolysis (pipeline)                '
            H2ELTT   'Electrolysis (tube trailer)            '
            MeGSLQ   'Methanol generation - from biomass, see excel for tech description'
            MeARLQ   'Methanol generation - from biomass, see excel for tech description'
            MeSCLQ   'Methanol generation - from biomass, see excel for tech description'
            MeSCMR   'Methanol generation - from biomass, see excel for tech description'
            MeHGAR   'Methanol generation - from biomass, see excel for tech description'
            MESCSR   'Methanol generation - from biomass, see excel for tech description'
   /

Set tran(fuelchainmember)        'transmission'
   /
            H2PL     'H2 transmission by pipeline             '
            H2TT     'H2 transmission by tube trailer         '
            H2LQ     'H2 transmission by liquified            '
            MeTR     'Methanol by truck                       '
   /
Set dis(fuelchainmember)         'distribution'
   /
            H2FSPL   'H2 fuelling station pipeline connected  '
            H2FSTT   'H2 fuelling station low pressure        '
            H2FSLQ   'H2 fuelling station high pressure       '
            MeFSNE   'Methanol fuelling station (new)         '
            MeFSMO   'Methanol fuelling sation (retrofitet)   '
   /;

Set genmap (gen,chainpath)       'link of generation to fuelchain'
   /
            (H2NGLQ,H2CRLQ,H2BMLQ,H2ELLQ).H2clq,
            (H2NGTT,H2CRTT,H2BMTT,H2ELTT).H2ctt,
            (H2NGPL,H2RCPL,H2CRPL,H2BMPL,H2ELPL).H2cpl,
            (MEGSLQ,MEARLQ,MESCLQ,MESCMR,MEHGAR,MESCSR).MELQ
   /;
Set tranmap (tran,chainpath)     'link of transmission fo fuelchain'
   /
            (H2LQ).H2clq,
            (H2TT).H2ctt,
            (H2PL).H2cpl,
            (METR).MELQ
   /;
Set dismap (dis,chainpath)       link of distribution to fuelchain'
   /
            (H2FSLQ).H2clq,
            (H2FSTT).H2ctt,
            (H2FSPL).H2cpl,
            (MEFSNE,MEFSMO).MELQ
   /;

Set fuels fuels
/
gasoline,
diesel,
hydrogen,
biomass,
```

```
naturalgas,
resid,
coke,
methanol,
electricity,
temp
/;

Set param technology specification parameters /INV,LINV,LR,FIXOM,VAROM,IEFF,FEFF,AF,LIFE,AVA/;

$include techdata.dat

Table effimp(tech,tp)    improvement of technology performance relative to the initial efficiency
                    2000     2010     2020     2030     2040     2050     2060     2070     2080     2090     2100
*cars
            TGSL    1        2        2        3        3        4        4        5        5        6        6
            TDSL    1        3        4        5        6        7        8        9        10       11       12
            THYB    1        2        2        3        3        4        4        5        5        6        6
*            THFC    1        1        1        1        1        5        7        9        11       13       15
            THFC    1        1        1        1        1        1        1        1        1        1        1
            TMFC    1        1        1        1        1        5        7        9        11       13       15
            TELC    1        2        3        4        5        6        7        8        9        10       11
*generation
            H2NGLQ  1        1        1        1        1        1        1        1        1        1        1
            H2NGPL  1        1        1        1        1        1        1        1        1        1        1
            H2NGTT  1        1        1        1        1        1        1        1        1        1        1
            H2RCPL  1        1        1        1        1        1        1        1        1        1        1
            H2CRLQ  1        1        1        1        1        1        1        1        1        1        1
            H2CRPL  1        1        1        1        1        1        1        1        1        1        1
            H2CRTT  1        1        1        1        1        1        1        1        1        1        1
            H2BMLQ  1        1        1        1        1        1        1        1        1        1        1
            H2BMPL  1        1        1        1        1        1        1        1        1        1        1
            H2BMTT  1        1        1        1        1        1        1        1        1        1        1
            H2ELLQ  1        1        1        1        1        1        1        1        1        1        1
            H2ELPL  1        1        1        1        1        1        1        1        1        1        1
```

```
        H2ELTT  1   1   1   1   1   1   1   1   1   1   1
        MeGSLQ  1   1   1   1   1   1   1   1   1   1   1
        MeARLQ  1   1   1   1   1   1   1   1   1   1   1
        MeSCLQ  1   1   1   1   1   1   1   1   1   1   1
        MeSCMR  1   1   1   1   1   1   1   1   1   1   1
        MeHGAR  1   1   1   1   1   1   1   1   1   1   1
        MESCSR  1   1   1   1   1   1   1   1   1   1   1
*transmission
        H2PL    1   1   1   1   2   2   2   3   3   3   1
        H2TT    1   1   1   3   4   5   5   6   6   7   1
        H2LQ    1   1   1   3   4   5   5   6   6   7   1
        METR    1   1   1   3   4   5   5   6   6   7   1
*distribution
        H2FSPL  1   1   1   1   1   1   1   1   1   1   1
        H2FSTT  1   1   1   1   1   1   1   1   1   1   1
        H2FSLQ  1   1   1   1   1   1   1   1   1   1   1
        MEFSNE  1   1   1   1   1   1   1   1   1   1   1
        MEFSMO  1   1   1   1   1   1   1   1   1   1   1
;



table decline(tech,tp)   expand coefs
                2000    2010    2020    2030    2040    2050    2060    2070    2080    2090    2100
*cars
        TGSL    30      30      30      30      30      30      30      30      30      30      30
        TDSL    30      30      30      30      30      30      30      30      30      30      30
        THYB    30      30      30      30      30      30      30      30      30      30      30
        THFC    30      30      30      30      30      30      30      30      30      30      30
        TMFC    30      30      30      30      30      30      30      30      30      30      30
        TELC    30      30      30      30      30      30      30      30      30      30      30
*generation
        H2NGLQ  10      10      10      10      10      10      10      10      10      10      10
```

```
        H2NGPL  10  10  10  10  10  10  10  10  10  10  10
        H2NGTT  10  10  10  10  10  10  10  10  10  10  10
        H2RCPL  10  10  10  10  10  10  10  10  10  10  10
        H2CRLQ  10  10  10  10  10  10  10  10  10  10  10
        H2CRPL  10  10  10  10  10  10  10  10  10  10  10
        H2CRTT  10  10  10  10  10  10  10  10  10  10  10
        H2BMLQ  10  10  10  10  10  10  10  10  10  10  10
        H2BMPL  10  10  10  10  10  10  10  10  10  10  10
        H2BMTT  10  10  10  10  10  10  10  10  10  10  10
        H2ELLQ  10  10  10  10  10  10  10  10  10  10  10
        H2ELPL  10  10  10  10  10  10  10  10  10  10  10
        H2ELTT  10  10  10  10  10  10  10  10  10  10  10
        MeGSLQ  10  10  10  10  10  10  10  10  10  10  10
        MeARLQ  10  10  10  10  10  10  10  10  10  10  10
        MeSCLQ  10  10  10  10  10  10  10  10  10  10  10
        MeSCMR  10  10  10  10  10  10  10  10  10  10  10
        MeHGAR  10  10  10  10  10  10  10  10  10  10  10
        MESCSR  10  10  10  10  10  10  10  10  10  10  10
*transmission
        H2PL    10  10  10  10  10  10  10  10  10  10  10
        H2TT    10  10  10  10  10  10  10  10  10  10  10
        H2LQ    10  10  10  10  10  10  10  10  10  10  10
        METR    10  10  10  10  10  10  10  10  10  10  10
*distribution
        H2FSPL  10  10  10  10  10  10  10  10  10  10  10
        H2FSTT  10  10  10  10  10  10  10  10  10  10  10
        H2FSLQ  10  10  10  10  10  10  10  10  10  10  10
        MEFSNE  10  10  10  10  10  10  10  10  10  10  10
        MEFSMO  10  10  10  10  10  10  10  10  10  10  10

```

```
;

Parameter DEMAND(tp)    demand for transportation
/
 2000   3605.4
 2010   4431.8
 2020   4978.0
 2030   5332.6
 2040   5583.1
 2050   5538.8
 2060   5329.1
 2070   4873.6
 2080   4324.2
 2090   3846.1
 2100   3762.7

/;

YE0('TGSL') = 0.97*Demand('2000');
YE0('TDSL') = 0.025*Demand('2000');
YE0('THYB') = 0.005*Demand('2000');

Parameter mapfuel(tech,fuels)  mapping of fuels
/
*cars
               TGSL.gasoline           1
               TDSL.diesel             1
               THYB.gasoline           1
               THFC.hydrogen           1
               TMFC.methanol           1
               TELC.electricity        1
*generation
               H2NGLQ.electricity      1
               H2NGPL.electricity      1
               H2NGTT.electricity      1
               H2RCPL.electricity      1
               H2CRLQ.electricity      1
               H2CRPL.electricity      1
               H2CRTT.electricity      1
               H2BMLQ.electricity      1
               H2BMPL.electricity      1
               H2BMTT.electricity      1
               H2ELLQ.electricity      1
               H2ELPL.electricity      1
               H2ELTT.electricity      1
               MeGSLQ.temp             1
               MeARLQ.temp             1
               MeSCLQ.temp             1
               MeSCMR.temp             1
               MeHGAR.temp             1
               MESCSR.temp             1
*transmission
               H2PL.temp               1
               H2TT.diesel             1
               H2LQ.diesel             1
               METR.diesel             1
*distribution
```

```
              H2FSPL.electricity      1
              H2FSTT.electricity      1
              H2FSLQ.electricity      1
              MEFSNE.temp             1
              MEFSMO.temp              1
/;

Parameter mapinput(tech,fuels)  mapping of input comodity
/
*cars
              TGSL.temp             1
              TDSL.temp             1
              THYB.temp             1
              THFC.temp             1
              TMFC.temp             1
              TELC.temp             1
*generation
              H2NGLQ.naturalgas       1
              H2NGPL.naturalgas       1
              H2NGTT.naturalgas       1
              H2RCPL.resid          1
              H2CRLQ.coke            1
              H2CRPL.coke            1
              H2CRTT.coke            1
              H2BMLQ.biomass          1
              H2BMPL.biomass          1
              H2BMTT.biomass          1
              H2ELLQ.temp            1
              H2ELPL.temp            1
              H2ELTT.temp            1
              MeGSLQ.biomass          1
              MeARLQ.biomass          1
              MeSCLQ.biomass          1
              MeSCMR.biomass          1
              MeHGAR.biomass          1
              MESCSR.biomass          1
*transmission
              H2PL.temp             1
              H2TT.temp             1
              H2LQ.temp             1
              METR.temp             1
*distribution
              H2FSPL.temp            1
              H2FSTT.temp            1
              H2FSLQ.temp            1
              MEFSNE.temp            1
              MEFSMO.temp             1

/;

*parameter fuelpricegr(fuels,tp)  prices of fuels changeing over time;
*fuelpricegr(fuels,'2000')=1;
*Loop(tp$(Ord(tp) GT 1), fuelpricegr(fuels,tp) =  fuelpricegr(fuels,tp-1)*(fuelgrowthindex(fuels,tp-1)/100+1) );

parameter chain(fuelchainmember,chainpath) mapping of gen-tran-dis to create fuel chains
/
```

```
*generation
        H2NGLQ.h2clq      1
        H2NGPL.h2cpl      1
        H2NGTT.h2ctt      1
        H2RCPL.h2cpl      1
        H2CRLQ.h2clq      1
        H2CRPL.h2cpl      1
        H2CRTT.h2ctt      1
        H2BMLQ.h2clq      1
        H2BMPL.h2cpl      1
        H2BMTT.h2ctt      1
        H2ELLQ.h2clq      1
        H2ELPL.h2cpl      1
        H2ELTT.h2ctt      1
        MeGSLQ.melq       1
        MeARLQ.melq       1
        MeSCLQ.melq       1
        MeSCMR.melq       1
        MeHGAR.melq       1
        MESCSR.melq       1
*transmission
        H2PL.h2cpl        1
        H2TT.h2ctt        1
        H2LQ.h2clq        1
        METR.melq         1
*distribution
        H2FSPL.h2cpl      1
        H2FSTT.h2ctt      1
        H2FSLQ.h2clq      1
        MEFSNE.melq       1
        MEFSMO.melq       1
/;


*final step - maping of fuel chain to a specific vehicle type

Set carfuel set for car-fuelchain link/meoh, h2/;
Set lsfuelchainmember(tech) set of technologies for the last step of the fuel chain
/ thfc,tmfc,
  h2fspl,h2fstt,h2fslq,mefsne,mefsmo/;
Set chaincar(lsfuelchainmember) /thfc,tmfc/;
Set chainstation(lsfuelchainmember) /h2fspl,h2fstt,h2fslq,mefsne,mefsmo/;

Parameter mapfuelchain(lsfuelchainmember,carfuel) mapping of fuel chains to cars
/
        H2FSPL.h2         1
        H2FSTT.h2         1
        H2FSLQ.h2         1
        MEFSNE.meoh       1
        MEFSMO.meoh       1
        THFC.h2           1
        TMFC.meoh         1
/;

Parameters
pv(tp)          present value factor
crf(tech)       capital recovery factor
```

```
;
Scalar
discpp          discount to 1st year of period
RDrate           R&D costs reduction rate;
Set discppset /1*10/;

pv(tp) = (1/(1+disc))**(period*(ord(tp)-1));
crf(tech) = (disc*(1+disc)**((techdata(tech,'life')*period))) / ((disc+1)**(
(techdata(tech,'life')*period ))-1);
discpp = Sum(discppset, (1+disc)**(-Ord(discppset)));
RDrate = log(0.9)/log(2);

VARIABLES
COST_NLP                        present value of costs - thousand of $
;

POSITIVE VARIABLES
*cars
XE(tech,tp)                     activity of technology - 10**9 car-km per year or GJ
YE(tech,tp)                     accumulated activity of technology - 10**9 car-km per year or GJ

RD(tech,tp)                     activity of R&D for techs
RDE(tech,tp)                     cumulative activity of R&D for techs

;

Equations
EQ_demvkm(tp)                   vkm-demand balance

*fuel chains
EQ_gentra(tp,chainpath)          Generation-transmission balance
EQ_tradis(tp,chainpath)          Transmission-distribution balance
EQ_discars(tp,carfuel)          Distribution-car consumption balance
EQ_cumulativeT0(tech,tp)          calculation of cumulative capacity for the 1st year
EQ_cumulative(tech,tp)           calculation of cumulative capacity
EQ_expand(tech,tp)               Expansion of technologies
EQ_decline(tech,tp)             Decline of technologies
EQ_MeOH_out(tech,tp)              MeOH is out of the analysis

EQ_cumulativeRD(tech,tp)          Cumulative capacity of R&D
EQ_RD_growth(tech,tp)            Expansion constrain of R&D
EQ_RD_decline(tech,tp)           Decline constrain of R&D

EQ_OBJNLP                       Objective function
;


EQ_gentra(tp,chainpath)..
        Sum(gen$genmap(gen,chainpath),  xe(gen,tp)*techdata(gen,'ieff')*techdata(gen,'af') )
=e= Sum(tran$tranmap(tran,chainpath),  xe(tran,tp) );

EQ_tradis(tp,chainpath)..
        Sum(tran$tranmap(tran,chainpath),  xe(tran,tp)*techdata(tran,'ieff')*techdata(tran,'af') )
=e= Sum(dis$dismap(dis,chainpath),  xe(dis,tp) );

EQ_discars(tp,carfuel)..
```

```
        Sum(chainstation$mapfuelchain(chainstation,carfuel), xe(chainstation,tp)*techdata(chainstation,'ieff')*techdata(chainstation,'af') ) =g=
        Sum(chaincar$mapfuelchain(chaincar,carfuel), xe(chaincar,tp)/techdata(chaincar,'feff') );



EQ_demvkm(tp)..  Sum(cars, xe(cars,tp)) =g= demand(tp);

************************entrance and penetration of techs************************

*general - let's not go grazy with market penetration
xe.up(cars,tp) = 1.02*demand(tp);
*those not available penetrate at 0
XE.fx(tech,tp)$(ord(tp) LT techdata(tech,'ava')) = 0.0;

*first year callibration
XE.up(tech,tp)$((ord(tp) EQ 1) AND (ord(tp) EQ techdata(tech,'ava'))) = 1.01*YE0(tech);
XE.lo(tech,tp)$((ord(tp) EQ 1) AND (ord(tp) EQ techdata(tech,'ava'))) = 0.99*YE0(tech);

*initial launch
XE.UP(tech,tp)$((Ord(tp) GT 1) $ (Ord(tp) EQ techdata(tech,'ava'))) = ye0(tech);

*expansion/declination
EQ_expand(tech,tp+1)$(Ord(tp) GE techdata(tech,'ava')).. XE(tech,tp+1) =l= XE(tech,tp) * ((expand(tech,tp)/100+1)**period);
EQ_decline(tech,tp+1)$(Ord(tp) GE techdata(tech,'ava')).. XE(tech,tp+1) =g= XE(tech,tp) * ((1-decline(tech,tp)/100)**period);
*

*EQ_cumulativeT0(tech,tp)$((Ord(tp) EQ 1))..        YE(tech,tp)    =e= XE(tech,tp);

EQ_cumulative(tech,tp)$(ord(tp) GE techdata(tech,'ava')).. YE(tech,tp) =e= (YE(tech,tp-1) +XE(tech,tp));
YE.FX(tech,tp)$(Ord(tp) LT techdata(tech,'ava')) = 0;

****other bounds which were used earlier for something
*XE.lo(tech,tp)$((ord(tp) gt 1) AND (ord(tp) EQ techdata(tech,'ava'))) = 0.99*YE0(tech);
*YE.fx(tech,tp)$(ord(tp) LT techdata(tech,'ava')) = 0.01*YE0(tech);
*YE.lo(tech,tp)  = 0.01*YE0(tech);
*$(ord(tp) LT techdata(tech,'ava'))

EQ_MeOH_out(tech,tp)..          YE('tmfc',tp) =e= 0;

************************R&D part*************************************************
Parameter
RDSC0    Initial cost of R&D
RDCC0    Initial CC0 of R&D;

RDCC0 = 1;
Scalar
RDindex  R&D learning index of 10% /10/
*keep in mind the units!!! in the OBJfunction, demand is in 1e9 vkm, costs are in 1e3$/1e3 vkm, so we get 1e9 vkm * 1$/1$, hence the result is in
*1000e9 $, so for R&D if we want to invest 10mln $, then express it as 1e-03$
RDUC     unit cost of R&D /0.01/;

EQ_RD_growth(tech,tp+1)$(techdata(tech,'lr') NE 0)..    RD(tech,tp+1) =l= RD(tech,tp)*2;
```

```
EQ_RD_decline(tech,tp+1)$(techdata(tech,'lr') NE 0)..   RD(tech,tp+1) =g= RD(tech,tp)*0.1;

*R&D is present
EQ_cumulativeRD(tech,tp)$(   (techdata(tech,'lr') NE 0)
                        ).. RDE(tech,tp) =e= RDE(tech,tp-1) + RD(tech,tp);
*obj-function equation fix

*first launch to the market
RD.up(tech,tp)$( (techdata(tech,'lr') NE 0)
                 $ (Ord(tp) EQ 1 )
               )
               = RDCC0;

RD.lo(tech,tp)$( (techdata(tech,'lr') NE 0)
                 $ (Ord(tp) EQ techdata(tech,'ava') )
                 $ (Ord(tp) EQ 1 )
               )
               = 0;
Parameter
blbd(tech,tp)    learning coef for LBD
blbs             learning coef for LBS;

*learning techs - not present on the market
blbd(tech,tp)$((techdata(tech,'lr') NE 0) AND (Ord(tp) GE techdata(tech,'ava'))) = (log((100-techdata(tech,'lr'))/100))   /log (2);
*learning techs - present on the market
blbd(tech,tp)$((techdata(tech,'lr') NE 0) AND (Ord(tp) LT techdata(tech,'ava'))) = 1;
*non-learning techs
blbd(tech,tp)$(techdata(tech,'lr') EQ 0)= 1;

blbs = (log((100-RDindex)/100)) /log (2);

************************OBJECTIVE FUNCTION FOR NLP

EQ_OBJNLP..  COST_NLP =e= faki*Sum(tp,pv(tp)*
                                  Sum(tech$(ORD(tp) GE techdata(tech,'ava')),discpp*(
*                                     costs of R&D
*                                         RD(tech,tp)*RDUC*crf(tech)
                                         +XE(tech,tp)*(
*                                     investments
                                                  crf(tech)*techdata(tech,'inv')
*                                     fixoms
                                                  +techdata(tech,'fixom')
*                                     varoms
                                                  +techdata(tech,'varom')
*                                     input comodity
*old version                                              +sum(fuels, fuelorgprice(fuels)*fuelpricegr(fuels,tp)*mapinput(tech,fuels))/techdata(tech,'ieff')
                                                  +sum(fuels, fuelorgprice(fuels,tp)*mapinput(tech,fuels))/techdata(tech,'ieff')
*                                     fuel for operation
*old version                                              +sum(fuels, fuelorgprice(fuels)*fuelpricegr(fuels,tp)*mapfuel(tech,fuels))/techdata(tech,'feff')* (effimp(tech,tp)/100+1)
                                                  +sum(fuels, fuelorgprice(fuels,tp)*mapfuel(tech,fuels))/techdata(tech,'feff')* (effimp(tech,tp)/100+1)
                                                 )
```

```
*                                  learning component of investments
                                        +XE(tech,tp)*crf(tech)*techdata(tech,'linv')
*                                  LBD
                                                        *((    (YE(tech,tp)+1e-6)  /YE0(tech))** blbd(tech,tp) )
*                                  LBS
*                                                        *((   (RDE(tech,tp)+1e-6)       /RDCC0)** blbs)

                                                                  )

                               )
                             );

***Model segment****************

MODEL LBD_NLP   /
********************************
*cars
EQ_demvkm
EQ_gentra
EQ_tradis
EQ_discars
EQ_MeOH_out
*EQ_cumulativeT0
EQ_cumulative
EQ_expand
EQ_decline
*R&D
*EQ_cumulativeRD
*EQ_RD_growth
*EQ_RD_decline

*total
EQ_OBJNLP
          /;

option NLP=CONOPT3;
*option NLP=MINOS5;
Solve LBD_NLP minimizing COST_NLP using NLP;

Display
xe.l
*,ye0
*,ye.l
*,ye0
*,rd.l
*,rde.l
*,costkm
*,rdcc0
*,pv
*,crf
*,discpp
,blbd
,blbs


```

```

;

Put F1;
Put 'h2kw=',techdata('thfc','linv'),'lr=',techdata('thfc','lr'), 'mekw=',techdata('tmfc','linv'),'lr=',techdata('tmfc','lr'), ' BBL=',basefuelprice /;
Put 'technologies'  /;
Put ';' ; Loop (TP, Put TP.TL, ';'); Put /;
Loop (tech,
        put tech.tl , ';';
        Loop (tp, put xe.l(tech,tp), ';');
        put /;
      );

PutClose;

*$include h2bump.gms
```

File techdata.dat

```
Table techdata(tech,param)        'specification of technologies [$/GJ] or [$/k vkm]'
                         INV       LINV     LR      FIXOM     VAROM    IEFF       FEFF       AF    LIFE    AVA
*cars
               TGSL     1062       0        0       70        8.1      1          0.3054     1       1       1
               TDSL     1171       0        0       70        8.1      1          0.4081     1       1       1
               THYB     1257       0        0       70        8.1      1          0.7648     1       1       1
               THFC     941        1714     20.00   70        8.1      1          1.2000     1       1       4
               TMFC     1012       1714     15      70        8.1      1          1.2000     1       1       4
               TELC     1285       200      10      70        8.1      1          1.7800     1       1       6
*generation
               H2NGLQ   38.73      0        0       1.94      4.56     0.762      0.3369     0.9     2       2
               H2NGPL   13.30      0        0       0.67      0.40     0.762      0.0216     0.9     2       2
               H2NGTT   22.40      0        0       1.11      0.88     0.762      0.0528     0.9     2       2
               H2RCPL   31.16      0        0       1.55      1.28     0.76       0.0771     0.9     2       2
               H2CRLQ   75.46      0        0       3.77      6.37     0.694      0.4505     0.9     2       2
               H2CRPL   43.62      0        0       2.17      1.79     0.694      0.1082     0.9     2       2
               H2CRTT   57.10      0        0       2.86      2.54     0.694      0.1583     0.9     2       2
               H2BMLQ   76.13      0        0       3.81      6.48     0.76       0.4600     0.9     2       2
               H2BMPL   49.69      0        0       2.48      2.29     0.76       0.1448     0.9     2       2
```

```
        H2BMTT   60.97    0    0    3.05    2.96    0.76    0.1894    0.9    2    2
        H2ELLQ   115.88   0    0    5.79    0.49    0.635   1.9348    0.9    2    2
        H2ELPL   95.33    0    0    4.77    0.21    0.635   1.6341    0.9    2    2
        H2ELTT   101.40   0    0    5.07    0.35    0.635   1.6343    0.9    2    2
        MeGSLQ   21.58    0    0    0.86    0       0.52    1         0.9    2    2
        MeARLQ   24.95    0    0    1.00    0       0.59    1         0.9    2    2
        MeSCLQ   22.24    0    0    0.89    0       0.58    1         0.9    2    2
        MeSCMR   19.78    0    0    0.79    0       0.57    1         0.9    2    2
        MeHGAR   24.91    0    0    1.00    0       0.56    1         0.9    2    2
        MESCSR   20.95    0    0    0.84    0       0.54    1         0.9    2    2
*transmission
        H2PL     101.57   0    0    6.14    0       0.997   1         0.9    2    2
        H2TT     23.75    0    0    13.08   0       0.997   10.10     0.9    1    2
        H2LQ     2.19     0    0    1.12    0       0.997   166.66    0.9    1    2
        METR     0.7842   0    0    0.008   0.0408  0.998   285.71    0.9    1    2
*distribution
        H2FSPL   35.71    0    0    2.49    0       0.997   57.0181   0.9    2    2
        H2FSTT   35.71    0    0    1.82    0       0.997   114.0363  0.9    2    2
        H2FSLQ   46.99    0    0    2.17    0       0.997   142.5242  0.9    2    2
        MEFSNE   0.5932   0    0    0.38    0       0.997   1         0.9    2    2
        MEFSMO   0.2542   0    0    0.38    0       0.997   1         0.9    2    2
;

table expand(tech,tp)    expand coefs
                2000   2010   2020   2030   2040   2050   2060   2070   2080   2090   2100
*cars
        TGSL    10     10     10     10     10     10     10     10     10     10     10
        TDSL    10     10     10     10     10     10     10     10     10     10     10
        THYB    10     10     10     10     10     10     10     10     10     10     10
        THFC    10     10     10     10     10     10     10     10     10     10     10
        TMFC    10     10     10     10     10     10     10     10     10     10     10
```

```
		TELC	10	10	10	10	10	10	10	10	10	10	10
*generation
		H2NGLQ	10	10	10	10	10	10	10	10	10	10	10
		H2NGPL	10	10	10	10	10	10	10	10	10	10	10
		H2NGTT	10	10	10	10	10	10	10	10	10	10	10
		H2RCPL	10	10	10	10	10	10	10	10	10	10	10
		H2CRLQ	10	10	10	10	10	10	10	10	10	10	10
		H2CRPL	10	10	10	10	10	10	10	10	10	10	10
		H2CRTT	10	10	10	10	10	10	10	10	10	10	10
		H2BMLQ	10	10	10	10	10	10	10	10	10	10	10
		H2BMPL	10	10	10	10	10	10	10	10	10	10	10
		H2BMTT	10	10	10	10	10	10	10	10	10	10	10
		H2ELLQ	10	10	10	10	10	10	10	10	10	10	10
		H2ELPL	10	10	10	10	10	10	10	10	10	10	10
		H2ELTT	10	10	10	10	10	10	10	10	10	10	10
		MeGSLQ	10	10	10	10	10	10	10	10	10	10	10
		MeARLQ	10	10	10	10	10	10	10	10	10	10	10
		MeSCLQ	10	10	10	10	10	10	10	10	10	10	10
		MeSCMR	10	10	10	10	10	10	10	10	10	10	10
		MeHGAR	10	10	10	10	10	10	10	10	10	10	10
		MESCSR	10	10	10	10	10	10	10	10	10	10	10
*transmission
		H2PL	10	10	10	10	10	10	10	10	10	10	10
		H2TT	10	10	10	10	10	10	10	10	10	10	10
		H2LQ	10	10	10	10	10	10	10	10	10	10	10
		METR	10	10	10	10	10	10	10	10	10	10	10
*distribution
		H2FSPL	10	10	10	10	10	10	10	10	10	10	10
		H2FSTT	10	10	10	10	10	10	10	10	10	10	10
		H2FSLQ	10	10	10	10	10	10	10	10	10	10	10
```

```
                MEFSNE   10       10       10       10       10       10       10       10       10       10       10
                MEFSMO   10       10       10       10       10       10       10       10       10       10       10
;

Parameter YE0(tech)      initial capacities
/
*cars [1e9 vkm]
*                TGSL     0.875
*                TDSL     0.875
*                THYB     1.275
                THFC     12.25
                TMFC     1.275
                TELC     1.275
*generation  [PJ] initial capacity calculated to cover the initial CC of h2fc's
*generation
                H2NGLQ   1.950146
                H2NGPL   1.950146
                H2NGTT   1.950146
                H2RCPL   0.950146
                H2CRLQ   0.950146
                H2CRPL   0.950146
                H2CRTT   0.950146
                H2BMLQ   0.950146
                H2BMPL   0.950146
                H2BMTT   0.950146
                H2ELLQ   0.950146
                H2ELPL   0.950146
                H2ELTT   0.950146
                MeGSLQ   0.950146
                MeARLQ   0.950146
                MeSCLQ   0.950146
                MeSCMR   0.950146
                MeHGAR   0.950146
                MESCSR   0.950146
*transmission
                H2PL     0.950146
                H2TT     0.950146
                H2LQ     0.950146
                METR     0.950146
*distribution
                H2FSPL   0.950146
                H2FSTT   0.950146
                H2FSLQ   0.950146
                MEFSNE   0.950146
                MEFSMO   0.950146
/;

parameter fuelgrowthindex (fuels)       growth rate for fuels after 2010
        /
        gasoline      5
        diesel        5
        hydrogen      1
        biomass       1
        naturalgas    1
        resid         1
```

```
        coke          5
        methanol      1
        electricity   1
        temp          1
        /;


Scalar                         BaseFuelPrice BBL price;
BaseFuelPrice = 55;
Parameters
OilPrice                  price of oil in $ a GJ
GasolinePrice             price of gasoline
DieselPrice               price of diesel;

*from the original runs
*GasolinePrice = (BaseFuelPrice/22.96)*1000/(3.7854118*30.618);
*DieselPrice = GasolinePrice * 0.865;
*including taxation and transmission

OilPrice = BaseFuelPrice / (159 * 30.618 / 1000);
GasolinePrice = BaseFuelPrice / (159 * 30.618 / 1000) + BaseFuelPrice / (159 * 30.618 / 1000) * 1.6;
DieselPrice = GasolinePrice * 0.75;

parameter fuelorgprice(fuels,tp);
*fuel pricing for 2000
fuelorgprice('gasoline'   ,'2000') = 18.07;
fuelorgprice('diesel'     ,'2000') = 16.25  ;
fuelorgprice('hydrogen'   ,'2000') = 0            ;
fuelorgprice('biomass'    ,'2000') = 3.6          ;
fuelorgprice('naturalgas' ,'2000') = 2.5          ;
fuelorgprice('resid'      ,'2000') = 0.5          ;
fuelorgprice('coke'       ,'2000') = 5.86     ;
fuelorgprice('methanol'   ,'2000') = 0            ;
fuelorgprice('electricity','2000') = 12.5         ;
fuelorgprice('temp'       ,'2000') = 0            ;

*fuel pricing for 2010
fuelorgprice('gasoline'   ,'2010') = GasolinePrice;
fuelorgprice('diesel'     ,'2010') = DieselPrice  ;
fuelorgprice('hydrogen'   ,'2010') = 0            ;
fuelorgprice('biomass'    ,'2010') = 3.6          ;
fuelorgprice('naturalgas' ,'2010') = 2.5          ;
fuelorgprice('resid'      ,'2010') = 0.5          ;
fuelorgprice('coke'       ,'2010') = OilPrice     ;
fuelorgprice('methanol'   ,'2010') = 0            ;
fuelorgprice('electricity','2010') = 12.5         ;
fuelorgprice('temp'       ,'2010') = 0            ;

Loop (TP$(ORD(TP) GT 2),
        fuelorgprice(fuels,tp) = (fuelgrowthindex(fuels)/100+1)*fuelorgprice(fuels, tp-1)
     );
display 'paliwa',
  oilprice,
  gasolineprice,
  dieselprice,
  fuelorgprice;
```

```

File F1 /out.DK/;
*
```

Curriculum Vitae

Name:	Daniel A. Krzyzanowski
Date of birth:	1st March 1974
Place of birth:	Gdansk, Poland
Nationality:	Polish

Education register

Dates		School/College/University	Subject/Course
From	To		
02.2003	07.2006	Swiss Federal Institute of Technology Zurich (ETHZ) (Zürich, Switzerland)	PhD study on Hydrogen Economy; Long Term Mitigation Options with Emphasis on the Transportation Sector
09.1999	08.2001	Delft University of Technology (Delft, Netherlands)	Master of Science degree (MSc) Department of System Engineering, Policy Analysis and Management
10.1994	10.1998	Technical University of Gdansk (Gdansk, Poland)	Bachelor of Science degree (BSc) Chemistry Department, Environment Protection and Management
10.1993	07.1994	University of Torun (Torun, Poland)	Law Faculty; Semester I and II
09.1989	06.1993	Secondary School no. 5 and 10 (Gdansk, Poland)	Grades 1~4; A-levels
09.1984	12.1986	International School of Lusaka (Lusaka, Zambia)	Grades 4,5 and Form 1
09.1981	06.1989	Primary School no. 71 (Gdansk, Poland)	Grades 1~3, 6~8

Professional experience

Dates		Organisation	Position held
From	To		
06.2002	07.2002	United Nations	External Consultant for the project "Capacity Building for the Rapid Commercialisation of Renewable Energy in China (CPR/97/G31)"
09.2001	12.2002	Ecofys Polska (Poznan, Poland)	Project Manager (field: biomass/project development) Co-ordinator Biomass Group and Municipal Services
07.2000	08.2001	Ecofys bv (Utrecht, Netherlands)	Project Manager (field: biomass)
12.1999	06.2000	Ecofys bv (Utrecht, Netherlands)	Apprenticeship
03.1999	08.1999	Municipality of Gdansk, Department of Environment Protection and Agriculture (Gdansk, Poland)	Waste Management Officer

The results of the work presented in this document have been disseminated to the broader community in form of the following contributions:

Krzyzanowski, D.A., Kypreos S., Barreto, L. (2006) – "Assessment of Market Penetration Potential of Hydrogen Fuel Cell Vehicles - A Study Using an Optimization Model"; presentation at CORS/Optimization Days 2006 8-10 May 2006, Montreal (Canada)

Krzyzanowski, D.A., Kypreos, S., Barreto, L., (2006): Supporting Hydrogen Transportation: case Studies of Governmental Policy Measures. Paper submitted to the Journal of Computational Management Science (Special Issue on Managing Energy and the Environment)

Krzyzanowski, D.A., Kypreos, S., Barreto, L., (2006): Assessment of Market Penetration Potential of Hydrogen Fuel Cell Vehicles. International Journal of Energy Technology and Policy (Special Issue on Technology Characterisation and the Modelling of Energy and Climate Policy), (in press)

Krzyzanowski D.A., Barreto L., Kypreos S. (2005) – "Modeling the Hydrogen-based Transport Sector in an optimisation framework"; EMPA International Conference "Low Carbon Fuels – Methane and Hydrogen Based Mobility" Poster Session, 7-8 November 2005, Dübendorf (Switzerland)

Barreto L., Wokaun A., Kypreos S., Rafaj P., Krzyzanowski D.A., Turton H. (2005) – "Technology Assessment and Climate Policy"; NCCR Climate Pit stop Conference, Presentation/lecture at Final Event of Phase I. 17 May 2005. Bern (Switzerland)

Krzyzanowski D.A., Kypreos S., Gutzwiller L., Barreto L. (2005) – "Implications of Technology Learning in Energy-Economy Models of the Transportation Sector"; Report to the Alliance for the Global Sustainability (AGS); Report no.: PSI-PR-05-06, Paul Scherrer Institut, Villigen (Switzerland)

Wokaun A., Kypreos S., Barreto L., Krzyzanowski D.A., Rafaj P., Schulz T.F. (2005) – "Strategien für eine kosteneffiziente Klimaschutzpolitik"; NCCR Climate Pit Stop Conference, Presentation/lecture, 17 May 2005 Bern (Switzerland)

Kypreos S., Krzyzanowski D.A., Barreto L. (2004) – Modelling the Global Transportation Sector"; 6th IAEE European Conference "Modelling in Energy Economics and Policy" Poster Session, 1-3 September 2004, Zürich (Switzerland)

Krzyzanowski D.A. (2004) – "Hydrogen Economy: Long Term Mitigation Options with Emphasis on the Transportation Sector"; Colloquim "Selected Aspects of Sustainable Development", 13 May/17 June 2004; ETH Zürich/NIDECO, Zürich (Switzerland)