Exploring the diffusion of fuel-cell cars in China

A scenario approach

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Abstract: Fuel cells are considered to be among the powertrain systems of the future. A fuel-cell car has a high efficiency, a low noise level, and the emissions levels of the car are low or even zero. Nevertheless, the diffusion of the fuel-cell cars has not taken place yet. Main obstacles are the high costs of the fuel-cell system and hydrogen fuel, hydrogen storage, and contamination of the fuel.
China is facing enormous environmental problems, especially in the (mega-) cities. Besides, China's automobile sector and car demand is booming. Considering these developments, the "environmentally friendly" fuel-cell car might play an important role in China's automobile sector of the future.
In this research the diffusion of fuel-cell cars in China has been explored till 2045, using the energy planning model MARKAL. For this purpose, four scenarios have been worked out, which are based on three (clusters of) driving forces: the role of the Chinese government with regard to emission control, technology development, and fossil fuel prices. All scenarios imply high technological development; the necessary condition for the diffusion of fuel-cell cars in China. In the scenario where there is strong environmental policy (strict regulation on emissions), in the scenario where energy resource scarcity leads to high fossil fuel prices, or in case of a combination of both, the diffusion of fuel-cell cars will set off. Without these conditions, the market will be dominated by (hybrid) gasoline, diesel and by (hybrid) natural-gas cars.

Keywords: fuel cell, China, scenario, powertrain, MARKAL, passenger car

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Summary

Air pollution is a major problem in China. Carbon monoxide (CO) levels and ozone concentrations exceed nationally specified limits, mainly due to coal combustion and vehicle exhaust emissions. In some megacities, like Chongqing and Lanzhou, SO_2, NO_x and PM emissions exceed World Health Organisation's air quality standards. The poor traffic management and environmental performance of Chinese vehicles have partially created this problem, and the air pollution will increase even more as the vehicle population is expanding.

The fuel-cell system represents a technology that can contribute to the reduction of carbon dioxide (CO_2) emissions -the major contributor to the greenhouse effect-, and can eliminate the local pollution problem to megacities of the industrial and the less-developed world. Other advantages of fuel cells are the high efficiency, low maintenance (due to only a few moving parts), and low noise level.

The Paul Scherrer Institute (PSI) in Switzerland considers fuel-cell technology as an important research activity and eventually a good opportunity for commercialisation of the technology and business. PSI is interested in how this technology will develop over the years in the specific market of China, by means of the energy-economic planning model MARKAL.

The environmental pollution in China, the advantages of fuel-cell cars, and the research activities and interests of PSI form the background of this research. The aim of the research is formulated as follows: *To explore the diffusion of fuel-cell cars on the Chinese market, using the MARKAL-model, and in forms of scenarios, and to analyse the implications of this diffusion for PSIs research activities.* The aim is transformed into the following research-question: *How and to which extend might the diffusion of fuel-cell cars in China take off towards the year 2045, and what does this mean for PSIs research activities?*

It can be appointed that this research is an *exploration*, and not a *prognosis*, *projection* or *speculation*, because the statements of the future are based on theories, but less on historical data and by use of a computer model. Scenarios can be applied in exploration studies. The time-horizon of the scenarios in this research will be from the present till 2045. This time period is long enough for three till four vehicle lifetimes, and this leaves enough room for developments.

The computer model that has been used in this research is the energy-economic planning model MARKAL. This model optimizes combinations of technologies that minimize total energy system cost but which at the same time meet the specified energy demand. The model is widely applied and suitable to explore alternatives with a long time horizon.

To carry out the research, a qualitative, multi-disciplinary scenario approach, adapted from Schwartz (1991) is combined with a more quantitative exploring approach, described in Schaeffer (1998). The resulting methodology contains twelve steps, divided over five phases. These phases are 1) topic and aim; 2) basic and future analysis; 3) designing scenarios, based on key factors and driving forces 4) analysis of model outcomes and working out scenarios and 5) implications.

The PEMFC and the DMFC fuel cells are considered to be appropriate for transportation applications, because of their low operating temperature. These fuel cells can be part of three types of fuel-cell vehicles: fuel-cell-powered vehicle, hybrid (parallel) fuel-cell vehicle, and the range-extender vehicles. The fuels for fuel-cell cars can be methanol (direct or reformed to hydrogen), gasoline (reformed to hydrogen) and pure hydrogen. Hydrogen faces some safety concerns of the public, due to its unfamiliarity and the Challanger and Hindenberg accidents.

To compete with the conventional cars, with an internal combustion engine, the costs of the fuel cell has to go down to at least 50 US$/kW. Currently, the costs are at least ten times higher. Besides, in case of hydrogen or methanol fuel-cell vehicles, there are the costs of the production and delivery of methanol or hydrogen. In addition, the conventional ICE powertrain and other alternative powertrains, such as hybrids and natural gas, are also improving. Competition between the powertrains is therefore increasing.

An actor analysis has given us insight in how and why the different actors (can) influence the diffusion of fuel-cell cars world-wide. From the actor analysis we draw the conclusion that the diffusion of fuel-cell cars (especially in the early stage) is influenced by: the willingness of the car manufacturers in the development of fuel-cell technology, the willingness of the fuel companies to invest in a hydrogen/methanol infrastructure, the energy resource scarcity, the incentives of the government, the (rising) customer preferences, and public pressure.

The analysis of China shows that a growing population and increasing population density (especially in the cities) leads to a growing energy demand and higher emission levels in the short run. China heavily depends on its coal resources. Natural gas supply is increasing as well as (foreign) oil supply. Coherent with the air pollution stands the water quality (and availability). It is assumed that shortage on clean (drinking) water will be first encountered in the Northern part of China and in the large cities.

Motorization is expected to grow rapidly, due to the growing Gross Domestic Product (GDP). The automobile market is maturing and booming. Produced cars, mostly gasoline cars, do not have state of the art technology, but fuel efficiency is increasing and emission levels are decreasing. Demonstration projects have increased the amount of LPG and natural-gas vehicles. Some universities, institutes and companies are working on the development of fuel-cell vehicles and a fuel-cell bus demonstration project is planned for 2003/2004.

The local and national government have a strong influence on the automobile industry, as there are state-owned car manufacturers, import tariffs, fees and other regulations. They have contrary incentives, stimulating car ownership on the one hand (a push for the automobile industry) and stricter environmental regulations on the other hand. But, environmental regulations for cars lag behind the state of market development.

Out of the basic and future analysis, twenty-one key factors and driving forces are derived that influence the diffusion of fuel-cell cars in China, and these are ranked on importance and uncertainty. Three crucial clusters of driving forces can be distinguished. The first cluster contains these driving forces that have to do with the role of the government, with regard to environmental policy (bounds or taxes on emissions). The second cluster of driving forces deals with technology development (higher efficiency, new techniques), which also includes the necessary infrastructural development. The third cluster contains the forces shortage on fossil fuels (after 2025) and the price of oil.

These three (clusters of) driving forces form the axes of the scenarios. Although there are eight possible scenarios with three axes, only four scenarios are worked-out. Namely, a first analysis with MARKAL shows that if the diffusion of fuel-cell cars in China wants to set off, high technological development is a necessary condition. Therefore, we reduce the amount of scenarios till four by keeping out the scenarios with low technological development.

For all scenarios hold approximately that before 2025, the gasoline car (with ICE or hybrid ICE) will dominate the market, although enormously improved with regards to current Chinese cars. First after 2025, the major differences in the diffusion of powertrains originate.

High technological development is not a sufficient condition for fuel-cell cars to diffuse on the Chinese market. This is the first conclusion. This is shown in the results of scenario one, “hybridisation of the car fleet”, where the long-term (till 2045) car fleet is dominated by gasoline (+ diesel) and natural-gas cars, after 2020 with a hybrid character.

This implicates for PSI that by remaining interest in the fuel-cell car technology, the focus will, in the coming years, continue to be on the fundamental research of fuel-cell technology, to solve the technological and economical obstacles (world-wide). The implication can be rendered into the following recommendation for PSI: continuation of the fundamental research on fuel-cell technology.

In the other three scenarios, *“a hydrogen economy”* (#2), *“environmental reformation” (#3)*, and “self-sufficiency” (#4) the diffusion of (hydrogen) fuel-cell cars sets off.

In scenario two, “a hydrogen world”, there are also no strong government interventions, but now the energy resource scarcity leads to an increase in fossil fuel prices after 2025. The price increase causes “alternative” fuels and technologies to become cost competitive (and innovations to take off). Hydrogen (out of coal) fuel cells gain interest, because of the lower fuel costs.

In scenario three, “environmental reformation”, the diffusion of fuel-cell cars sets off, because of the emission restrictions. The main force is the reduction of CO_2 emissions. Therefore, new technologies have to be implemented. In the passenger car sector, the hybrid natural gas, with low emissions, replaces the (hybrid) gasoline car, and from 2035 onwards, the fuel-cell car enters the market to meet the emission restrictions. The markets for fuel-cell busses and fuel-cell bicycles also initiate fuel-cell cars. In this scenario an important role is granted for natural gas, to obtain the emission target(s) and to produce hydrogen out of this fuel.

In scenario four, “self-sufficiency”, a combination of high fossil fuel prices and strong environmental policy, in an environment of high technological development, would have the highest impact on the diffusion of fuel-cell cars. In this scenario the natural-gas car starts to diffuse earlier, following similar diffusion pathways as in countries like Argentina, India, Pakistan and Egypt, initiated by the environmental policy (mainly CO_2 reduction, but also reduction of local emissions). After 2025, fuel-cell cars are the successors of the natural-gas cars. In this scenario the importance of reducing supply security fears is shown. China succeeded in building a self-supporting and clean energy-supply system.

As mentioned, the diffusion of fuel-cell cars depends on the willingness of the fuel companies to invest in a hydrogen infrastructure, the willingness of the car manufacturers to invest in fuel-cell technology and to make it their (core) business, and finally it is the customer who has to buy the fuel-cell car (deals with public acceptance). The actors’ perception can be forced (somewhat) by the three driving forces, on which the scenarios are based. So it is necessary to gain a high degree of consensus among the important actors and a breakthrough of the trend followed to set off the diffusion of the fuel-cell cars. The scenarios worked-out imply such consensus and breakthrough.

Based on the three scenarios where diffusion of fuel-cell cars take off, the second conclusion is formulated: The diffusion of fuel-cell cars in China will first and only take place after 2025, in case technological and economical obstacles can be removed, a niche market is found and the process of diffusion fetch up in a vicious circle, i.e. consensus among the important actors, driven by the technological development, and high prices of fossil fuels (energy resource scarcity) or (very) strict environmental regulations by the Chinese government, i.e. a breakthrough of the trend followed.

The implication for PSI is that in case there are signals for the diffusion of fuel-cells in China, as mentioned in scenarios two, three and four, there might be an enormous market for fuel-cell cars there, but also – maybe before the diffusion of fuel-cell cars - for small fuel-cells in bicycles and scooters. PSIs incentives to focus on small, cheap fuel cells for light vehicles might yield a profit if fuel-cell diffusion takes of in China.

With regard to the research activities of PSI, it can be recommended towards PSI to follow the signals, especially with regard to environmental policy in China, and profit from the possible development in China, to contribute in collaboration with (car) industry partners to the development of the product, which is (also) suitable for the Chinese market. Additionally, operating in a network of institutes and universities, PSI could cater to scientific collaboration with Chinese research institutes and universities, which carry out a large part of current fuel-cell research in China.

Furthermore, the results of MARKAL do show when and under which conditions fuel-cell cars might diffuse and that there is no restriction in the amount of hydrogen that can be produced to satisfy the demand. So, no hard statements can (will) be made about the extent of the diffusion of fuel-cell cars in China, but that in case those cars diffuse the market share will be significant and that the diffusion of fuel-cell cars in China is not restricted to the amount of hydrogen that can be produced in China to satisfy the demand.

Preface

This report is the result of my research, carried out (largely) at the Paul Sherrer Institute in Villigen, Switzerland, from January till July 2003. This research and its resulting thesis were the last task of my study at the Eindhoven University of Technology to obtain the diploma Master of Science in Technology and Society.

After six years of studying I have now come to the end of my students-life. It was a period in which I not only had the opportunity to academic education, but in which I also had many possibilities to develop myself, to do sports, to earn some money, and to enjoy life. Besides I had the privilege to go abroad twice for my studies.

Many persons have contributed to my study(-period) and to this report. Therefore I would like to express my gratitude to these persons.

I would like to thank Mr. S. Kypreos, my supervisor at PSI, for his feedback and for the freedom he gave me in carrying out my assignment. I also would like to thank my supervisors in the Netherlands, Dr. M.W. Smits, Dr. Q.C. van Est and Dr. G.J. Schaeffer for their feedback on my research. In addition, I would like to express my thanks to Dr. Alexander Röder (Cemex), for his provided information, to Prof. dr. A. Wokaun, for giving me the possibility to do my Master Thesis at PSI and the provided information, and to Jeroen Besuijen, for correcting (a large part of) the final report on English.

Many thanks go to my colleagues at PSI, Peter, Lukas, Daniel, Olivier, Arthur (with whom I also shared the office), Jeremy and Bob, for their assistance and their company. “Vielen Dank” also goes to Fritz von Roth, the other person with whom I shared the office, for the pleasant conversations that we have had.

Outside PSI, it were my Swiss friends (Michael Enz, Florian, Urs, Michael Bösch, André and Andrea), who I’ve met while studying in Sweden, that made my life in Switzerland very pleasant. But I also should not forget to mention my friends in the Netherlands; the ones with whom I studied, played soccer and went out.

It was my girl-friend Simone who brought me from Sweden (with a pit stop in Holland) to Switzerland. I would like to thank her for that and also for her love and support during the research. Thanks go also to her family and the friends of her that I’ve met. Last not but least, I would like to thank my farther and sister (plus their partners), who were always there for me and supported me (not only financially) as much as possible.

Villigen PSI, July 2003

Vincent Rits

List of abbreviations and acronyms

°C	degrees Celsius
adv	advanced
AFC	Alkaline Fuel Cell
avg.	average
cap	capita
CHP	Combined Heat Power
CI	Compression Ignition
CNG	Compressed Natural Gas
DI	Direct Injection
DMFC	Direct Methanol Fuel Cell
ECN	Energy Research Centre of the Netherlands
e.g.	for example
EU	European Union
ETSAP	Energy Technology Systems Analysis Programme
FC	Fuel Cell
FCV	Fuel-Cell Vehicle
gas	gasoline
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
i.e.	id est (that means)
IEA	International Energy Agency
J	Joule
K	Kelvin
kg	kilogram
km	kilometre
kW	kilowatt
l	litre
LPG	Liquid Petroleum Gas
m^3	cubic metre
MARKAL	MARket ALlocation
MCFC	Molten Carbonate Fuel Cell
MeOH	Methanol
mpg	miles per gallon
Mtoe	Million tons oil equivalent
MW	Mega Watt
O&M	Operating and Maintenance costs
OECD	Organisation for Economic Co-operation and Development
PEMFC	Proton Exchange Membrane Fuel Cell
p	person
ppp	purchasing power parity
p-km	passenger-kilometre
POFC	Phosphoric Acid Fuel Cell
POX	onboard partial oxidation
ppm	parts per million
PSI	Paul Scherrer Institute
R&D	Research and Development
RME	Rape Seed Methyl Ester
S	second
SI	Sparked Ignition
SOFC	Solid Oxide Fuel Cell
ST	Sociotechnical
t-km	ton-kilometre
vol	volume
yr	year

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1. Introduction

1.1 Background of the research

The transportation sector is a large consumer of energy. More than 25% of the total amount of energy consumed is used for this purpose.[1] As car sales and the total number of passenger cars continue to increase, the absolute amount of energy consumption by the transportation sector will further increase. In a time where pressure exists on the natural energy resources and the environmental consequences of energy consumption are apparent, new technological development / innovations are seen as a contribution to solve part of the problems we, mankind, are facing.

One of these problems is the air pollution in the Chinese megacities. Carbon monoxide (CO) levels and ozone concentrations exceed nationally specified limits, mainly due to coal combustion and vehicle exhaust emissions. The poor traffic management and environmental performance of Chinese vehicles has created this problem, and the air pollution will increase even more as the vehicle population is expanding. The consequences are already high: respiratory illness, caused by vehicular air pollution, accounts for 14% of all deaths in Chinese urban areas in 1998 (United Nations Development Programme / Global Environment Facility, 2002). In Europe, by comparison, related fatalities are around 3% and world-wide it is estimated to be around 5% (between 2,5% and 11%).[2]

Fuel-cell technology may contribute to the reduction of carbon dioxide (CO_2) emissions, the major contributor of the greenhouse effect, and can eliminate the local pollution problem to megacities of the industrial and the less-developed world. For a long time fuel cells have been used for spacecrafts and for military services only, but the fuel cell can also replace the conventional engine in passenger cars. On the level of transport, most experience has been gained regarding buses, and there are several numbers of passenger-car prototypes. As this technology develops, the potential for the passenger-car market increases. Therefore, its potential is analysed by interested parties, such as car companies, public services, fuel-cell manufacturers and research institutes.

The Paul Scherrer Institute (PSI) in Switzerland (see box 1.1), considers fuel-cell technology as an important research activity and eventually a good opportunity for commercialisation of the technology and business. In collaboration with universities, car manufacturer Volkswagen and some other companies, a new hydrogen fuel-cell car (prototype) has been developed, built and tested. PSI tasks are research and development of supercapacitors, Polymer-Electrolyte-Membranes (PEM) and stacks, as well as the coordination of the total project (Energie-Spiegel, 2002; Paul Scherrer Institute, 2002a).

The Energy Economics group of the Paul Scherrer Institute is exited about the possibilities for fuel-cell cars. They are interested in how this technology will develop over the years in a specific market. The market PSI would like to see analysed is the Chinese market. This interesting research area offers the enormous opportunities and challenges facing the Chinese market for mobility and the problems of pollution in the Chinese megacities. These problems are partly described in paragraph two. Besides, PSI have participated in the "China Energy Technology Program"[3] (CETP) and gained knowledge about the Chinese energy structure. Similar research on the subject of fuel cells has already been conducted for e.g. Europe and Switzerland.[4]

For this purpose, the technological features of a fuel-cell car for the Chinese market have to be analysed as well as certain market conditions. Besides this, PSI is interested in the factors and actors that influence the diffusion of fuel-cell cars. But, PSI is particularly interested in which cases the diffusion of fuel-cell cars will take place in the (Chinese) MARKAL-model. The MARKAL-model (an acronym for MARKet ALlocation) will thus be used as a tool to explore the diffusion of fuel-cell cars in China. This energy-economic planning model is suitable to explore alternative strategies - which is almost always done in form of scenarios (Schaeffer, 1998)-, on international, national or sector level, for long-time overviews and takes the whole energy system into account. The model finds the optimal

[1] Concluded from Statistics of the International Energy Agency (2002). *Key World Energy Statistics from the IEA*. IEA Paris; France.
[2] Europe: calculated by making use of statistics of the World Bank (population, urban population in %) and an article of the Earth Policy group (annually deaths by air pollution) (17th Sept. 2002, 13)
[3] May 1999 – April 2001
[4] See e.g. Röder, A. (2001b). *Integration of Life-Cycle Assessment and Energy Planning Models for the Evaluation of Car Powertrains and Fuels*. Diss. ETH No. 1429; Zürich.

development (i.e. least-costs while meeting energy demands) of an energy system in time under given technology characteristics (e.g. efficiencies, cost parameters) and boundary conditions (e.g. demand to be covered, prices for primary energy carriers) (Röder, 2001a). In addition, endogenous technological learning can be modelled and environmental externalities (such as emission-taxes and emissions caps) can be considered (Röder, 2001b).

To enlarge PSIs scientific insight in the diffusion of fuel-cell cars for this specific case of China, this research will 1) put new technological and economical data, related to fuel-cell car technology, into the MARKAL-model (Chinese database[5]); 2) map the forces influencing the diffusion of fuel-cell cars in a systematic and scientific way; 3) set-up different scenarios to explore the diffusion of fuel-cell cars in China, to look finally at the implications for PSIs research activities in this area.

Box 1.1 Paul Scherrer Institute, Department of General Energy, Group of Energy Economics

The Paul Scherrer Institute is one of the largest research institutes of Switzerland. Most of the research is multi-disciplinary and focuses on technology and natural sciences. Specifically, PSI focuses on basic and applied research, in the fields of solid state physics, materials sciences, elementary particle physics, life sciences, nuclear and non-nuclear energy research, and energy-related ecology (Eichler, 2002).

One of the departments is General Energy (Allgemeine Energie), where issues such as sustainability, renewable energies, energy storage, efficient and low-emission energy use are highlighted (Paul Scherrer Institut, 2002b). Part of the General Energy department, is the Energy Economics group. This group focuses on Life Cycle Analysis, Multi-Criteria Analysis, Energy-Economic Modelling and Scenario Generation. Together with other ETSAP-participants (e.g. ECN (NL)), some members of this group work with and on the development of the MARKAL-model.

1.2 Research goal

The aim of this research is formulated as follows:

To explore the diffusion of fuel-cell cars on the Chinese market, using the MARKAL-model, and in forms of scenarios, and to analyse the implications of this diffusion for PSIs research activities.

The aim can be divided into the following four parts:

- Description of technological characteristics of various fuel-cells systems for transportation and associated powertrain systems.
- Analysis of the market potential of fuel-cell cars and other new powertrain systems for China
- Mapping and analysing of the interplay between technological and social (f)actors that influence the diffusion of fuel-cell cars.
- Assessment of the diffusion of fuel-cell cars in China.

In this research, we define *diffusion* as the realisation of a breakthrough of a new technology in the society, after it has proven itself in a niche (Kruijsen, 1999). The diffusion is directly related to the *adoption* of the new technology by individual customers and companies (Vercoulen, 1998).[6] Furthermore, the adaptation of a technology will have consequences for organisations, consumers and other users. The way in which this takes plays, is called *implementation* (Vercoulen, 1998). All three aspects will be addressed in this research, but the diffusion aspect will be emphasized.

Furthermore, the powertrain[7] of a car can be defined as the part of the car that consists of all devices necessary to convert the energy stored in the fuel to vehicular motion plus the fuel storage system (Röder, 2001b).

1.3 Research question

The main research question is:

How and to which extend might the diffusion of fuel-cell cars in China take off towards the year 2045, and what does this mean for PSIs research activities?

[5] The MARKAL database used in this research is the one set up by Zongxin et al. (2001). For more information about this database see box 7.1 in chapter seven, http://www.princeton.edu/~cmi/research/papers/future.pdf for the full report and http://www.princeton.edu/~energy/publications/pdf/2001/Wu_01_ESD_Markal_modeling_China.pdf for the article published.
[6] See also appendix B.
[7] In some reports also expressed as drivetrain.

In order to answer this question the following *sub-questions* have to be answered[8]:

1. *Which models and methods can be used, in addition to the MARKAL-model, to answer the research question?*

2. *Which obstacles and challenges faces the fuel-cell car on its way to market introduction?*

3. *Which actors do influence the diffusion of the fuel-cell car and in which direction?*

4. *Which social, economical, technological, environmental, and political features and developments, have their influence on the Chinese automobile market?*

5. *What are the key factors and driving forces behind the diffusion of fuel-cell cars in China, and which scenario-axis can be fextracted on basis of these key factors and driving forces?*

6. *Which four scenarios give a plausible representation of probable pathways that the diffusion of fuel-cell cars in China might follow?*

7. *Which recommendations can be formulated:*
   a. for PSI, with regard to their fuel-cell research activities, on the basis of the four scenarios?
   b. for further research, with emphasis on the use of MARKAL?

1.4 Demarcation of the research
This study explores the diffusion of fuel-cell cars in China. However, the study is not carried out in the analysed country. This has both disadvantages and advantages. For an "insider" it is probably easier to receive the trends in the country (in particular, because it is a centrally planned country), and assess the importance of an issue. Besides, the stakeholders can be analysed by means of a survey. On the other hand, an "outsider" can see the issue from another perspective, maybe not as narrow as the prespective of an "insider" might be. By carrying out an extensive literature study, a good picture of the current and future situation in China is gained to counter disadvantages of the "outsider" approach as much as possible.

This research will focus on the transportation sector and the passenger car sector in particular. The automobile industry is a global industry, operating on the world market. In first instance, this research considers word-wide matters and developments, to focus on the Chinese-market afterwards. Although China is a developing country, some parts of the country and some issues are highly industrialized. Therefore, this research has to deal with issues in industrialized economies (global automobile industry and part of China) as well as certain aspects of developing economies. This distinction is particularly relevant for analysing the market, the MARKAL-results and when it comes to conclusions and recommendations.

With respect to the exploration, (max.) four scenarios will be analysed to give an overview of different possibilities of the diffusion of fuel-cell car in China. This choice is based on scientific literature and is discussed in chapter two.

The time-horizon in this study will be from the present till 2045. However, the results of MARKAL will have a time-horizon from 1995 to 2045, where the data of the passenger transportation sector for the period 1995-2000 are fixed. So the time period will be around 45 years, enough for three till four vehicle lifetimes.[9]

1.5 Type of research
The research is both descriptive and exploratory. Different kinds of the fuel-cell car technology and other powertrains will be inventoried and described, and some important aspects (Chinese) transportation market will be analysed as well as environmental conditions. These activities represent the descriptive part.

[8] The questions convey the report's structure and the structure itself coheres the methodology set up in chapter two.
[9] The lifetime of a car is between 10 and 15 years.

The exploratory part shows the relations between the different actors that influence the diffusion of fuel-cell cars. Four scenarios are next generated in the MARKAL-model, using these relations as input.

In addition, this research can be seen as an ex-ante (prospective) research.

1.6 Methods of data acquiring
Most data will be acquired by using existing reports, papers and other written documentation. Specific data and information has also been gathered via personal communication. The personal communication with experts at PSI gave the necessary information about the (Chinese) transport market, the MARKAL model, policy issues and hydrogen generation.

1.7 Structure of the report
Firstly, in chapter two, a study of literature will give insight into certain aspects of scenario generation and into the methodology that will be applied in this research. In chapter three the fuel-cell car technology and different powertrains will be described. The production and distribution of fuels for fuel-cell cars, and the related costs, will also be discussed briefly. In chapter four, the different actors, which influence the diffusion of fuel-cell cars will be highlighted and the linkages with the other actors will be discussed.

The first chapters are not limited to China. From chapter five onwards, the study will focus on the Chinese market. In chapter five some economical and energy-related issues with regard to China are discussed, and the Chinese transport sector and in particular the automobile industry is analysed. In chapter six, the key factors and driving forces which influence the diffusion of fuel-cell cars, which are derived from the previous chapters, are listed and ranked by importance and uncertainty. Out of this ranking, the different scenarios in which the diffusion of fuel-cell cars in China is highlighted will be designed. This is done in chapter seven. In chapter eight conclusions have been drawn and discussed, and recommendations towards PSI are given.

This report is written for a broad target group, varying from governmental bodies to students. Certain academic knowledge and knowledge about the energy and transportation sector is preferable, but not explicitly necessary.

2. Methodology: Future exploration and scenarios

This chapter answers the question which model/method can be applied to carry out this research, i.e. to answer the main research question. Firstly, the literature of future exploration and scenarios is reviewed and after this a methodology for this research is presented, based on this literature study.

2.1 Introduction

Looking into the future is a tough process and its results are uncertain, because the future can not be predicted fully. Schaeffer (1998) even writes: *"forecasting is always a risky enterprise"*. Nevertheless, human mankind is occupied with forecasting almost everyday, as we attempt to prepare ourselves for what is coming in the next few hours, weeks and years (Dammers, 2000).

For companies and governments, forecasting, and especially technology forecasting, has become an important strategic activity. Forecasts provide one way of reducing the decision maker's uncertainty and risk (Brannas & Zackrisson, 1992). But where reducing uncertainty was one of the goals of scenario generation, the emphasis has now become more about learning to deal with uncertainties (Becker & Dewulf in Dewulf, 1998). It is therefore becoming more important to *explore* the future (what might happen) than trying to forecast it, but this also depends on the purpose of the research.

2.2 Future research

There are different types of "future research"[10], or as Dammers (2000) prefers to call it: "future exploration".[11] To categorise the different types, Dammers uses two dimensions: *risk versus uncertainty* and *high systematic versus low systematic*. The choice for his categorisation is made because the explicit roles of exploration studies plus simulation model are emphasized (see section 2.3 and box 2.1). A simulation model will also be used in this research.

When data from the past are collected for a long time and these data display regularity, then statements can be made under (reduced) risks. If data of the past are not available or if they do not display regularity, then utterances of the future are made under uncertainty (Dammers, 2000).

Theories will be used to estimate developments, their relations and their impacts. Theories can be integrated into a quantitative or qualitative simulation model. A computer model is such a quantitative simulation model. The research method has a high systematic when a simulation model is used. So low systematic, on the other hand, occurs when no simulation model is used (Dammers, 2000).

By having these divisions, a 2 by 2 matrix, as shown in figure 2.1, can then be formed in which four future research methods can be distinguished:

- *Prognoses*: statements of the future, based on data and theories and (sometimes) by use of a simulation model.
- *Explorations*: statements of the future, based on theories, but less on historical data and (sometimes) by use of a simulation model.
- *Speculations*: statements of the future, by e.g. researchers and policy makers, based on logical insights.
- *Projections*: statements of the future, based only on data of the past.

Prognoses and projections are suitable for *forecasting* the developments within a stable and relative simple system, whereas within explorations a few statements of possible developments are given under uncertainty. *Scenarios* can only be applied in the case of exploration. The simulation model is often used as an instrument for the scenario methodology (Dammers, 2000).

By having cleared up the difference between forecasting and exploration and the question on when scenarios can be applied, we now state that this research will have an exploring character. For this

[10] See e.g. also Schaeffer (1998)
[11] Dammers (2000) prefers to use the term *"future exploration"*, which he defines as "*Strategic exploring and designing activities, where more or less on a systematic and creative way statements of the future will be made."* above *"future research"*, defined as e.g. *"strategic research, where on a scientific way statements of future events are made"* as this suggests a high certainty and high systematic, which is not always the case. (terms and definitions translated from Dutch)

research will discuss possible pathways of the diffusion of fuel-cell cars in China, which is hardly based on historical data (diffusion still has to take place). A computer model will explore this diffusion, in the shape of scenarios.

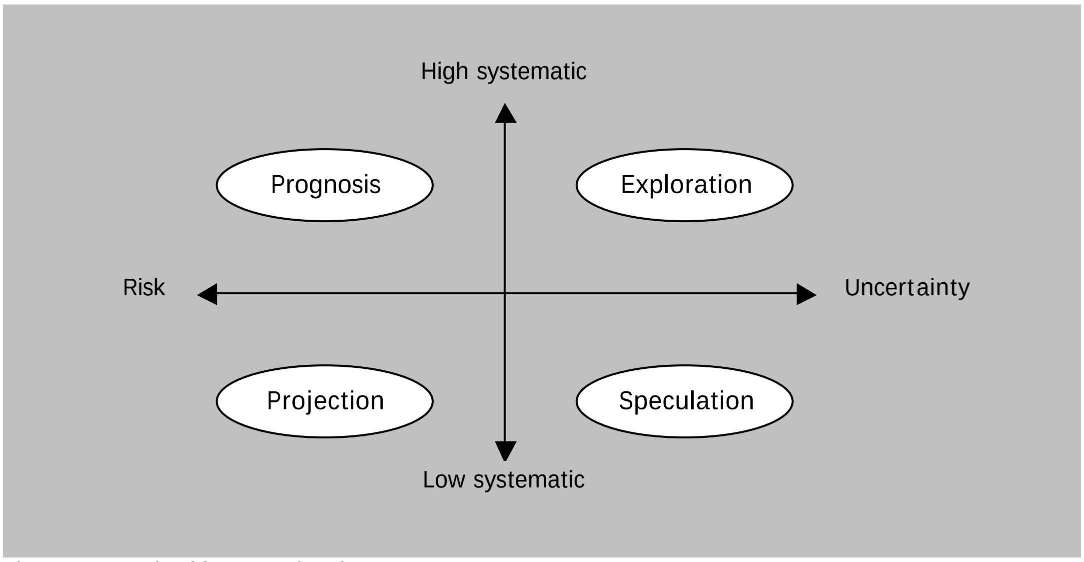

Figure 2.1. Matrix of future exploration.
Source: Dammers, 2000

2.2.1 Scenarios

As mentioned, scenarios are a tool used for exploration studies. A scenario can be defined as (EU, 1994 in Rienstra, 1998):

> *"a tool that describes pictures of the future world within a specified framework and under specified assumptions."*

The scenarios serve different functions, which can be described as (Rienstra, 1998):

- the *signalling* function
- the *communication* and *learning* function
- the *legitimation* function
- the *exploring* and *explaining* function
- the *demonstration* function

The *signalling* function of scenarios means that scenarios give greater insight in the possible developments and their impacts (Rienstra, 1998; Dewulf, 1998; Tijink, 1999; Ogilvy & Schwartz, 1995; Loveridge, 1995). Furthermore, scenarios can stimulate vision and outlook, provide decision-makers with (policy) options, including the impacts of the policy measures (Rienstra, 1998; Dewulf, 1998; Tijink, 1999; Loveridge, 1995). This is the *communication* and *learning* function. Thirdly, the outcomes of scenarios will give *legitimation* to people to change or respond to developments (Rienstra, 1998). The meaning of the *exploring* and *explaining* function is that scenarios show how solutions for specific problems may become reality, given certain policy priorities as well as they present possible solution strategies (Rienstra, 1998). Lastly, the demonstration function of scenarios is showing the consequences of specific situations (Rienstra, 1998). A remark on this classification is that the distinction between the functions is not always clear and there might be overlap.

There are also different kinds of scenarios. These can be distinguished by length, direction of forecasting (forecasting vs. backcasting), qualitative vs. quantitative, descriptive vs. normative, level of aggregation (international, national, sector) and level of exploration (exploratory vs. explicatory).[12] If need be, some sorts will be highlighted throughout this research.

To set up and work out scenarios different steps have to be followed. The general structure of the scenario methodology is (Dewulf, 1998):

[12] List not exhaustible; see e.g. Rienstra (1998), Dammers (2000) and Tijink (1999)

a) basic analysis
b) future analysis
c) designing scenarios
d) confrontation of strategies and scenarios

These components can be divided into more detailed steps (see Schwarz, 1991; Dammers, 2000), but all methodologies have more or less this general structure.

2.3 Methodology for this research

The structure of the methodology applied in this research is a combination of the ones described by Ogilvy & Schwartz (1995)[13] and Schaeffer (1998)[14], on the basis of the general structure. The methodology described by Ogilvy & Schwartz gives a detailed description of the phases of the scenario process, in which attention is paid to multi-disciplinary developments, but in which no specific attention is paid to computer models. Because the computer model MARKAL will be used in this research, I have added some specific issues/steps with regard to computer models into the model. *"The practice of technology forecasting"* by Schaeffer is a reflection of how he perceived the different stages the technological forecasters at the Energy Research Centre of the Netherlands (ECN) went through in carrying out their work with (energy planning) models.[15] His description of the process is focused specificcally on the use of computer models in future research (straightforward), but less attention is paid to multi-disciplinary developments (social, economical, technological, political and environmental trends), or at least it is not mentioned in specific steps. So, although both methodologies can be applied for this research independently, I have combined the methodologies to highlight the use of a computer model and of the multi-disciplinary approach.

In this research, the energy economic planning MARKAL (MARKet Allocation) model is applied to explore the diffusion of fuel-cell cars in China. MARKAL is a bottom-up, dynamic linear programming (LP) model (see box 2.1), which selects that combination of technologies that minimizes total energy system cost but which meets the specified energy demand (Ybema et al., 1997). It has several advantages for transport related exploration studies. It is a widely applied, accepted, complex (data-intensive) model, specialised on *total* energy systems, which can be applied on different aggregation levels. It is suitable for exploring alternatives with long time horizon. The time horizon is at least some 20 years and this corresponds to around two vehicle generations, and in a shorter time it is difficult to obtain meaningful results with this approach (Röder, 2001b). Besides, MARKAL finds lead-cost optimizations and costs play an important role in car industry (strong price competition). Moreover costs are yet a major barrier to the diffusion of fuel-cell cars. The model is also helpful to evaluate the effects of regulations, taxes, and subsidies (e.g. restriction on emission).

An important aspect of exploration by MARKAL is determining the input parameters, since the model itself only optimizes (least costs). Data can be hard to access, especially when we deal with new or emerging technologies. When data is found, the data's quality has to be checked, the data itself are based on a host of assumptions and earlier publications. The researcher has to select the data on his or her opinion. To tackle this issue an extensive literature study is carried out. In addition, to analyse the uncertainty of data a sensitivity analysis can be carried out, which is also done in this research.

To explore the diffusion of fuel-cell cars in China by means of MARKAL is one way to approach this topic. The adequacy of the use of MARKAL for this study will also be evaluated in section 7.8 and 8.1.

Box 2.1 The MARKAL model

MARKAL (MARKet Allocation) is a bottom-up, dynamic linear programming (LP) model (Fishbone et al., 1983), initially developed in by Brookhaven National Laboratory in the USA and Kernforschungsanlage Jülich in Germany in the late 70s (Röder, 2001). Since then it has been developed further and its activities are coordinated by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) (Seebregts et al., 1999; International Resources Group, 2000).

This optimization model interconnects the conversion and consumption of energy (International Resources Group, 2000) and its concept is as a predefined network of demands, sources and technologies of energy,

[13] Based on Schwartz, 1991.
[14] See also Appendix C.
[15] Schaeffer argues, and the author agrees, that although his analysis is derived from the practices observed at one specific location, ECN Policy Studies, it can be assumed that is not restricted to this location, because of ECN's linkages to many other energy forecasting practices in the world, where such practices (methods) as well as outcomes are shared and discussed.

which are interconnected by flows of energy carriers (Ybema et al., 1997). MARKAL considers both the synergy and competition between technologies at the energy supply and demand side of the energy system (Seebregts et al., 2001; Ybema et al., 1997). This demand for energy services can be disaggregated by sector and by specific functions within a sector (International Resources Group, 2000). In appendix D the predefined network is represented by building blocks.

Some characteristics of the technologies are specified, mostly economical and technological characteristics, for example: their investment cost, operating and maintenance costs, service life, fuel use, efficiency, availability, output, and maximum expected market penetration (ETSAP, 1993).

The model selects that combination of technologies that minimizes total energy system cost (Energy Technology Systems Analysis Programme, 2001), but which meets the specified energy demand (Ybema et al., 1997). See appendix C for an example. The result is an evolution over a period of usually 40 to 50 years of a specific energy system at the national, regional, state or province, or even the community level (Energy Technology Systems Analysis Programme, 2001).

In other words, MARKAL is a computer model, which plans an energy system under given technology characteristics and boundary conditions to find the optimal evolution (least-costs by meeting energy demands) of this energy system (Röder, 2001).

To make the model more dynamic and less linear, endogenous technological learning has been modelled into MARKAL. By incorporating the learning-by-doing concept, the former exogenous cost projections are "replaced" by learning, or experience curves (endogenous). These curves describe the specific (investment) cost as a function of the cumulative capacity for a given technology. It reflects the fact that technologies may experience declining costs as a result of its increasing adoption into the society due to the accumulation of knowledge through, among others, processes of learning-by-doing and learning-by-using (Seebregts et al., 1999).

Normally, different scenarios are designed and run by the model to look at alternative futures (Energy Technology Systems Analysis Programme, 2001). One is a reference case, whereas others are run by putting different constraints in the model. These constraints can vary from utilization of capacity to balancing energy inputs and outputs (Seebregts et al.,2001). Environmental issues can also be considered. This can be done by, for example:

- adding an emission-tax; the imposition of a tax or other fee structure could be modelled. This tax is then included in the objective function that has to be optimised.
- introducing environmental caps; sectoral or system-wide emissions limits on an annual basis or cumulatively over time additional constraints, which the model has to respect.

The following sum-up gives an overview of the different uses of MARKAL (Energy Technology Systems Analysis Programme, 2001):

- to identify least-cost energy systems
- to identify cost-effective responses to restrictions on emissions
- to perform prospective analysis of long-term energy balances under different scenarios
- to evaluate new technologies and priorities for R&D
- to evaluate the effects of regulations, taxes, and subsidies
- to project inventories of greenhouse gas emissions
- to estimate the value of regional cooperation

The combination of the two approaches of Olgivly & Schartz and Schaeffer has led to a set of specific steps, i.e. a specific methodology set up for this particular research. It contains the following five parts:

1. Topic and aim

The first issue is to select the topic and formulate the aim. What does the company want to be investigated and for what purposes are the scenarios used? Schwartz (1991) suggests to develop scenarios (for strategic purposes) "from inside out", i.e. to begin with the issue of decision relevant to the companies and then build outwards towards the environment. Important aspect is that there should be need for such a research and moreover there should be commitment of the assigner to the research and its results (Dewulf, 1998). Relevant for technology scenarios is to decide which technologies are investigated and which features are relevant, especially if it will be used as input in a computer model. At this step, the period of analysis has to be considered. The time horizon should be long enough to create new ideas, but at the same time not too long to avoid that scenarios become unrealistic (Tijink, 1999).

2. Basic and future analysis

The second issue is the basic and future analysis. Although sometimes considered separated issues / steps in scenario literature, I have put them together because when describing technology characteristics, key factors and driving forces, the actual situation and the relevant trends can be considered simultaneously. For technology scenarios the main features of the technology and trends of the technology development should be discussed. Special attention has to be paid to those characteristics that will serve as input parameters in the model (Schaeffer, 1998).

Key factors in the micro-environment will be discussed. Key factors are the factors that influence the success and failure of the decision taken in part one (Ogilvy & Schwartz, 1995). In this research, it will be the factors (and actors) that influence the diffusion of fuel-cell cars in China. These factors could also show up in a standard industry analysis (Ogilvy & Schwartz, 1995).

After identifying the key factors, the driving forces in a macro-environment will be determined. These are trends that influence the key factors in the micro-environment (Ogilvy & Schwartz, 1995). These trends can have social, economical, political, environmental and technological characters.
Taking into account the amount of time for this research and the use of the computer model, it is important to concentrate on the most essential key factors and driving forces and to work towards the parameters of the computer model.

3. Designing scenarios

Next, scenarios can be designed. The first step in this issue is to rank the key factors, determined in the previous steps, by importance and uncertainty (see methodology of Schwartz, 1991). Based on this ranking the two or three driving forces that are most important and most uncertain are picked to generate a few scenarios. The ranking of these factors and forces will actually determine the axes along which the scenarios will vary (Tijink, 1999). The factors or driving forces sometimes have to be reformulated or combined to form one of the axes of a scenario. By having determined the axes, a spectrum (along one axis), or a matrix (with two axes), or a volume (with three axes) can be constructed in which different scenarios can be identified and their details filled in (Ogilvy & Schwartz, 1995).

According to the literature, the minimum amount of scenarios should be two and four should be the maximum. Although three scenarios seem appropriate, four is more preferred. With three scenarios there will likely be one reference, one best case and one worst case. With four one the other hand, there is room to set up an alternative scenario. But more than four scenarios will lead to confusion (see e.g. Tijink, 1999; Schwarz, 1991; Dammers, 2000). Besides, it is useful to use metaphors, to clear up the different scenarios (Dewulf, 1998). In order to design scenarios, the following principles are relevant (Tijink, 1999):

- Each scenario has to be plausible.
- The scenarios should be consistent, i.e. no contradictions in the scenarios.
- The scenarios should be relevant for the user(s).
- The scenarios should be original.

With regard to computer models, these scenarios(-axis) should be designed in such a way that it can serve as input for the model. By having determined the different scenarios(-axis), and eventually transformed into input parameters, these parameters can be put into the computer model and the model can run the different scenarios. Attention has to be paid on irregularities of the computer model (Schaeffer, 1998).

4. Analysis of model outcomes and working out scenarios

The outcomes of the computer model are often given in crude numbers. These have to be transformed into relevant graphs (and tables). By having the relevant graphs for the different scenarios, the scenario should be worked out in more detail, where according to Schwartz (1991) each key factor and trend should be highlighted somehow in each scenario.

The qualitative part (written) underpins the quantitative part (outcomes model) and the other way around, so that finally a relevant, plausible and original story arises.

5. Implications
The last issue is to analyse the different scenarios and look at the implications of each scenario. Ogilvy and Schwartz (1995) argue to go back to the focal point or decision and see in which way the scenarios are relevant for the key issue. This focal point or decision, made in phase one, is that issue that you want e.g. to change, to analyse or to invest in. More specific, the scenarios can be used for framing strategy, for which there are two approaches: 1) to move from scenario to strategic options and 2) to start with an existing strategy and tests it against a range of scenarios (Ogilvy & Schwartz, 2000).

Throughout the research it is sometimes necessary to go one phase or step backwards (Tijink, 1999; Schaeffer, 1998); The scenario process namely is a cyclical process. Besides, in practice, different steps can be executed simultaneously.

The different parts and steps are summed up in table 2.1. In the fourth column is shown in which chapter (Ch.) the different steps are reflected upon (more or less).

Table 2.1. Scenario methodology

Phases:	***Steps:***	**Note:**	**Ch.:**
1. Topic and Aim	1. Determine relevant issue or decision for the company 2. Selection of technologies and their dimensions to be forecasted		H1
2. Basic and future analysis	3. Characterisation of the technology 4. Key factors in the Micro-environment 5. Driving forces in the Macro-environment	Special attention has to be paid to those characteristics that will serve as input parameters in the model runs	H3-5
3. Designing scenarios	6. Rank key factors and driving forces by importance and uncertainty 7. Generate a few scenarios, based on the ranking 8. Put (scenario-)parameters into computer model 9. Run model	Design scenarios(-axis) in such a way that they can serve as input for the model.	H6
4. Analysis of model outcomes and working out scenarios	10. Get from crude numbers to relevant graphs 11. Work out scenario	Each key factor and trend should be given some attention in each scenario	H7
5. Implications	12. Look at the implications of the scenarios on the focal point or decision identified in issue 1, step 2		H8

2.4 Pitfalls
Lastly to mention are the pitfalls that "forecasters" and exploration research run into.
Forecasters have to be aware:[16]

1. not to overestimate the potential of new technology (e.g. performance / costs)
2. not to overestimate the speed of societal embedding of new technology
3. to anticipate on social and cultural changes
4. not to be subjective, but to be objective (enough distance from the object)
5. not to neglect or ignore theories
6. not to neglect existing or future role of the (new) technologies in society (generation, substitution)

It is important for this reason, to create loops (backwards) in the methodology to be able to modify the research / data where necessary and to let the work be reviewed by others. Actually, under ideal circumstances, the future exploration should be carried out in a team.

2.5 Conclusion
In this chapter a general overview of future exploration and scenarios has been given, directed towards this research, based on scientific literature. Following the classification of future research of Dammers (2000), we appoint that this research is an *exploration*, and not a *prognosis*, *projection* or *speculation*, because the statements of the future are based on theories, but less on historical data and by use of a computer model. Scenarios can be applied in exploration studies. These scenarios describe pictures of the future world within a specified framework and under specified assumptions.

[16] List not exhaustible; Literature of Schaeffer (1998) and Geels & Smit (2000)

The computer model that will be used in this research is the energy-economic planning model MARKAL. This model optimizes combinations of technologies that minimize total energy system cost but which meet the specified energy demand. Moreover, it is suitable to explore alternatives with a long time horizon.

Furthermore, a methodology has been designed to answer the research-questions of this exploration study, by combining the methodology of Ogilvy & Schwartz (1995) and the “practice of technology forecasting” of Schaeffer (1998). This methodology gives detailed steps of the scenario process, analysing relevant social, technological, economical, political and environmental issues, plus the relevant issues with regard to the use of computer models. The first part is explicitly described by Ogilvy & Schwartz and less by Schaeffer, and for the second part this is more or less the other way around. Therefore both methodologies will be combined. The methodology contains twelve steps, divided over five phases. These phases are 1) topic and aim; 2) basic and future analysis; 3) designing scenarios; 4) analysis of model outcomes and working out scenarios and 5) implications.

3. The fuel-cell car and its related technological artefacts

In this chapter different characterisations and developments of the fuel-cell system, with emphasis on transportation utilizations, are described as well as the fuel-cell car's related artefacts. This chapter answers research sub-question 2: which are the (technological, infrastructural, and economical) obstacles and challenges, that fuel-cell cars face on their way to market introduction? It reflects the step "characterisations of the technology" (#3) of the methodology.
First, after a brief introduction, the working of the fuel-cell system is explained. Then the different types of fuel-cells systems and which of them can be applied for transportation purposes are highlighted. Subsequently, the production and delivery of fuels for fuel-cell vehicles and the costs of fuel-cell powertrains are discussed. After having focused on some relevant aspects of the fuel-cell system and the fuel-cell vehicles, its competitors are highlighted. Finally, an overview of the fuel-cell and its related artefacts is given and conclusions are drawn.

3.1 Introduction
Although Humphrey Davy is identified in some publications (see Schaeffer, 1998) as the first to examine the possibility of a fuel cell (in 1801-1802), the Welsh lawyer and physicist Sir William Robert Grove (1811-1896) has the status of being the inventor the fuel cell (1839). Nonetheless, after many contemporaries had misjudged Grove's detection, the idea of the fuel cell fell into oblivion (BEWAG Innovationspark Brennstoffzelle, 2002). First after the Second World War, the fuel cell regained interest. This power source has been used now for more than forty years in aerospace and military applications. An advantage of the fuel cell for these utilizations is that they are lighter than batteries. Other advantages addressed by fuel cells are the high efficiency, low maintenance (due to only a few moving parts), low noise level and "zero emissions".

The general utilization of the fuel cells, however, remained limited, because they were more expensive than other competitive sources. Though the costs of fuel cells have declined strongly in the past forty years (see appendix G), through development of new concepts and technologies, the utilization for power supply and civil purposes has only been gaining particular interested since roughly ten years. This interest has led to the use of stationary fuel-cell power plants, the introduction of fuel-cell busses and several prototypes of fuel-cell cars. Still a lot of research and development has to be done, as the investment costs are still high compared to those of other power sources. Besides, there is a lack of infrastructure for fuel-cell technology to be used for transportation purposes.

The latter briefly shows the history of the fuel-cell, its applications and advantages over other power sources, and the recent interests in fuel-cells for transportation utilization.

3.2 What is a fuel cell?
The fuel cell inverts the process of electrolysis. By electrolysis the water is divided into the gasses hydrogen and oxygen by using electric power. The fuel cell uses these materials and transforms them into water. The electrical energy will then be released. In hydrogen the electrical energy is stored and by means of the fuel cell electrical power can be produced. This electrical circuit can than drive an electrical motor. In practice, different physical and chemical processes will cause losses.

The fuel cell itself contains three parts: two electrodes, the anode and the cathode, and one electrolyte. The anode and cathode serve as catalyst, while the electrolyte separates the electrodes and will adapt the electrolytes. As said, the process is the opposite of that of the electrolysis.

The voltage on one cell is approximately 0.7 Volt. To generate a higher and more utilisable voltage, several cells are stacked in a row. Such a package is called a "stack".
In figure 3.1 the process of the fuel cell is illustrated and in figure 3.2 a simple illustration of a stack is given.

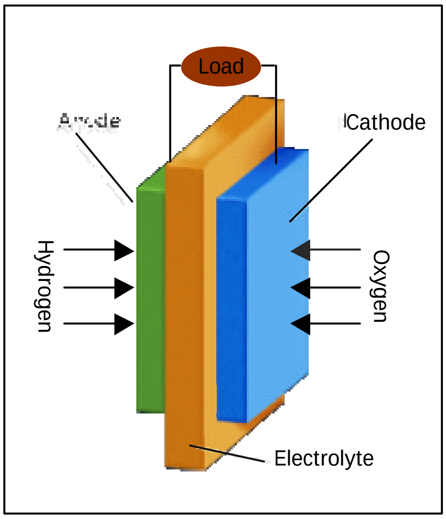

Figure 3.1. One fuel cell
Source: Bewag (figure modified)

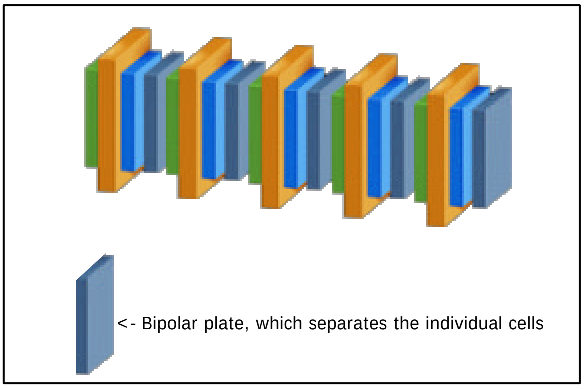

Figure 3.2. Schematic of a stack
Source: Bewag (figure modified)

3.3 Types of fuel cells

Currently, there are several types of fuel cells under development, each with its own advantages, limitations, and potential applications. In this section five types of fuel cells, categorized by their electrolyte[17], are discussed.

Alkaline AFC

AFC are mostly applied in aerospace, among others on the Apollo and Shuttle Orbiter. It operates at a temperature of between 50 and 100 degrees Celsius. The AFC has excellent electrode kinetics, when operating on pure hydrogen and oxygen. But the fuel supply for AFC is limited to pure hydrogen only; CO is a poison; and CO_2 reacts with KOH to form K_2CO_3, thus changing the electrolyte.
So for terrestrial applications, the additional economic restraints, which include the need to replace hydrogen by cheaper hydrocarbon or alcohol fuels, have provided severe problems for the materials selection and the associated fuel-processing technology (Larminie & Dicks, 2000; Northeast Advanced Vehicle Consortium, 2000).
Though the use of AFC systems with ammonia as the source of hydrogen fuel is recently considered, to overcome the problem of only pure hydrogen as fuel, the application for vehicle purposes remains limited (Steele & Heinzel, 2001).

Proton Exchange Membrane (PEMFC)

This relatively simple system has an operating temperature of around 70-80 °C, but it can vary from 50 to 100 °C. The electrolyte is an ion-exchange membrane, and the only liquid in this fuel cell is water, which minimizes corrosion problems (Hirschenhofer et al., 1999). It has a high power density, quick start-up, rapid response to varying loads and low operating criteria. These positive attributes outweigh its disadvantages of lower efficiency, and its low tolerance for carbon monoxide contamination (Northeast Advanced Vehicle Consortium, 2000) and sulphur (McNicol et al., 2001).

A special type of PEM is the Direct Methanol-Air Fuel Cell (DMFC). The DMFC utilizes methanol directly as a fuel and ambient air for oxygen. An advantage of this kind of fuel cell is that it eliminates the fuel reforming process, leading to a less-expensive fuel-cell technology. Preformance results are modest so far, although PEM research has shifted into DMFCs (Northeast Advanced Vehicle Consortium, 2000).

Phosphoric Acid PAFC

This commercialised fuel cell is used for stationary applications and has proven to be a very reliable and maintenance free power system. Although commercialised, the manufacturers have not been able to reduce the capital costs under US$3000/kW, where US$1000/kW or even US$500/kW is desired (Steele & Heinzel, 2001). Operating temperature is around 200 °C, an external reformer is needed,

[17] Over the years the classification of fuel-cells by their electrolyte is the most customary (Schaeffer, 1998). Other possible types of classifications are by range of operating temperature and by the categorisation as direct, indirect and regenerative fuel cells.

like the PEMFC. An advantage is that it has a higher tolerance level to carbon monoxide than other fuel cell types. Utilization for transport is in general difficult, because of the required warm-up period. In addition, these fuel cells are large and heavy, which would limit it to heavy-duty applications only. (Northeast Advanced Vehicle Consortium, 2000; Larminie & Dicks, 2000)

Molten Carbonate MCFC

Molten Carbonate Fuel Cells operates on a temperature of 650 °C. High-temperature fuel cells (MCFC and SOFC) are more efficient than low-temperature ones in generating electrical energy. In addition, they provide high-temperature waste heat which is a benefit in stationary cogeneration applications, but present a problem for transportation applications. The high temperature causes corrosion problems, and it requires the use of costly platinum metals for fuel-cell construction. It needs carbon dioxide in the air to function, but there is external reformer needed.
(Northeast Advanced Vehicle Consortium, 2000; Larminie & Dicks, 2000)

Solid Oxide SOFC

The advantages of the high operating temperature of SOFC (500-1000 °C), are the high efficiency and the high-temperature waste heat, but at the same time it puts constraints on the materials. Moreover, this fuel-cell system has a good tolerance for fuel impurities; gases can be used directly or can be internally reformed. The ceramic electrolyte reduces some problems associated with liquid electrolytes such as corrosion, but ceramic materials are expensive. In addition, the total system is large since extra equipment is needed to operate the system. Because of its size and warm-up time, transportation applications will also be limited to the heavy-duty sector. (Northeast Advanced Vehicle Consortium, 2000; Larminie & Dicks, 2000)

The main characteristics of the five types of fuel cells are shown in table 3.1. Please note that the row *applications* implies the applications of fuel cells at present.[18]

Table 3.1. Characteristics of the different fuel-cell types

Characteristics:	**Fuel-cell Type**				
	Alkaline AFC	**Proton exchange Membrane**	**Phosphoric Acid PAFC**	**Molten Carbonate MCFC**	**Solid Oxide SOFC**
Operating Temperature °C[a]	50-100	50-100	~ 200 (160-210)	~ 650	500 – 1000
Mobile Ion[b]	OH^-	H^+	H^+	CO_3^{2-}	O^{2-}
Fuel[c]	H_2	H_2 and reformed H_2	H_2 reformed from natural gas	H_2 and CO from internal reforming of natural gas or goal gas	H2 and CO from internal reforming of natural gas or goal gas
Oxidation media	Oxygen	Oxygen from air	Oxygen from air	Oxygen from air	Oxygen from air
Reforming	External (?)	External or direct MeOH	External	External or internal	External or internal, or direct CH_4
Feed for fuel processor[d]		MeOH, natural gas, LPG, gasoline, diesel, jet fuel	Natural gas, MeOH, LPG, gasoline, diesel, jet fuel	Gas from coal or biomass, natural gas, gasoline, diesel, jet fuel	Gas from coal or biomass, natural gas, gasoline, diesel, jet fuel
Current applications and notes[e]	Used in space vehicles, e.g. Apollo Shuttle, vehicle use investigated	Especially suitable for vehicles and mobile applications, but also for lower power CHP systems	Large numbers of 200 kW CHP systems in use	Suitable for medium to large systems, up to MW capacity	Suitable for all sizes of CHP systems, 2 kW to multi MW
Cell efficiency (% LHV)[d]		40-50	40-50	50-60	50-60

a) Larminie & Dicks, 2000
b) Hirschenhofer et al., 1999 & Larminie & Dicks, 2000
c) Wurster, 1999
d) Song, 2002
e) Larminie & Dicks, 2000

[18] Schaeffer (1998) shows in his Ph-D-dissertation the historical changes of in the question which types of fuel cells are suitable for which application (so called type-application-combinations).

3.4 *Fuel-Cell Vehicles*

3.4.1 Fuel cells for transportation

Two fuel-cell types can be considered for transportation application: the PEMFC and the DMFC. AFC may also have potential to be applicable in vehicle systems, but this type will not be considered here, since the development is very premature and relatively uncertain.

PEMFCs with high power density and low degradation are state of the art. Major barrier for commercialization are the high capital costs. PEMFCs can be operated on board of the vehicle, with: a) pure hydrogen (compressed gas hydrogen); b) methanol (on board steam reforming of methanol); and c) gasoline (on board partial oxidation (POX) of gasoline). In a report by L-B-Systemtechnik GmbH (2002), ethanol[19] is also discussed as a fuel for fuel-cell systems, but in most studies only hydrogen, methanol and gasoline are seen as future fuels for full and hybrid fuel-cell vehicles.

When hydrogen is produced on board of the vehicle, this is done by means of a fuel processor (reformer). The resulting fuel will not be pure hydrogen but will contain some CO_2, which results in a lower performance and some CO_2 emission (Weeda et al., 2002). The complexity of the drivetrain will be higher, but the infrastructure for production, transportation and distribution will not have to be changed radically. The fuels for the FCV play an important role in the total life-cycle costs of fuel-cell vehicles and in the diffusion of fuel-cell vehicles.

The DMFC operates on methanol. The cell is similar to the PEMFC, but the anode catalyst can itself draw the hydrogen from the liquid methanol, thereby eliminating the need for a fuel reformer, which reduces the weight and volume of the total system. Fuel crossing is a problem that remains to be solved (i.e. that the fuel crosses over from the anode to the cathode without producing electricity), and (like all fuel-cell systems) also the high initial costs remain problematic (Srinivasan et al., 1999).

3.4.2 Types of fuel-cell vehicles

Now that the different types of fuel cells have been distinguished, we will now discuss the different types of fuel-cell vehicles. Srinivasan et al. (1999) distinguish three types:

- Fuel-cell powered vehicles
  This vehicle type starts on its own and a battery provides initial power for auxiliaries. The fuel cell will start supplying the auxiliaries, once the fuel cell is operating.

- Hybrid (parallel) fuel-cell vehicles
  This system is like the previous type, but these vehicles now have an energy storage device to provide peak power. The power required for cold start, acceleration, and so forth, is derived from this energy storage sub-system (battery or flywheel). This system has the additional attractive capability of enhancing the efficiency of the system during generative braking and acceleration. The main disadvantage is the need for two power sources and the necessary controls.
  This energy-storage device can also be used in vehicles with the normal internal combustion engine (ICE).

- Range-extender vehicles
  A battery provides electricity to drive the vehicle. The fuel cell can recharge the battery while the vehicle is being driven. The fuel cell usually operates at the constant load to charge the battery. Possibly, the battery could be recharged by an external charger. In case the battery is recharged only by the external charger, it would actually be an electrical vehicle.

In figure 3.3 the structures of the different fuel-cell types are represented.

[19] Experience with ethanol infrastructure is gained in Brazil (McNicol et al., 2001). McNicol et al. (2001) also mention the use of ammonia as a fuel for fuel cell, but that this fuel has received little attention.

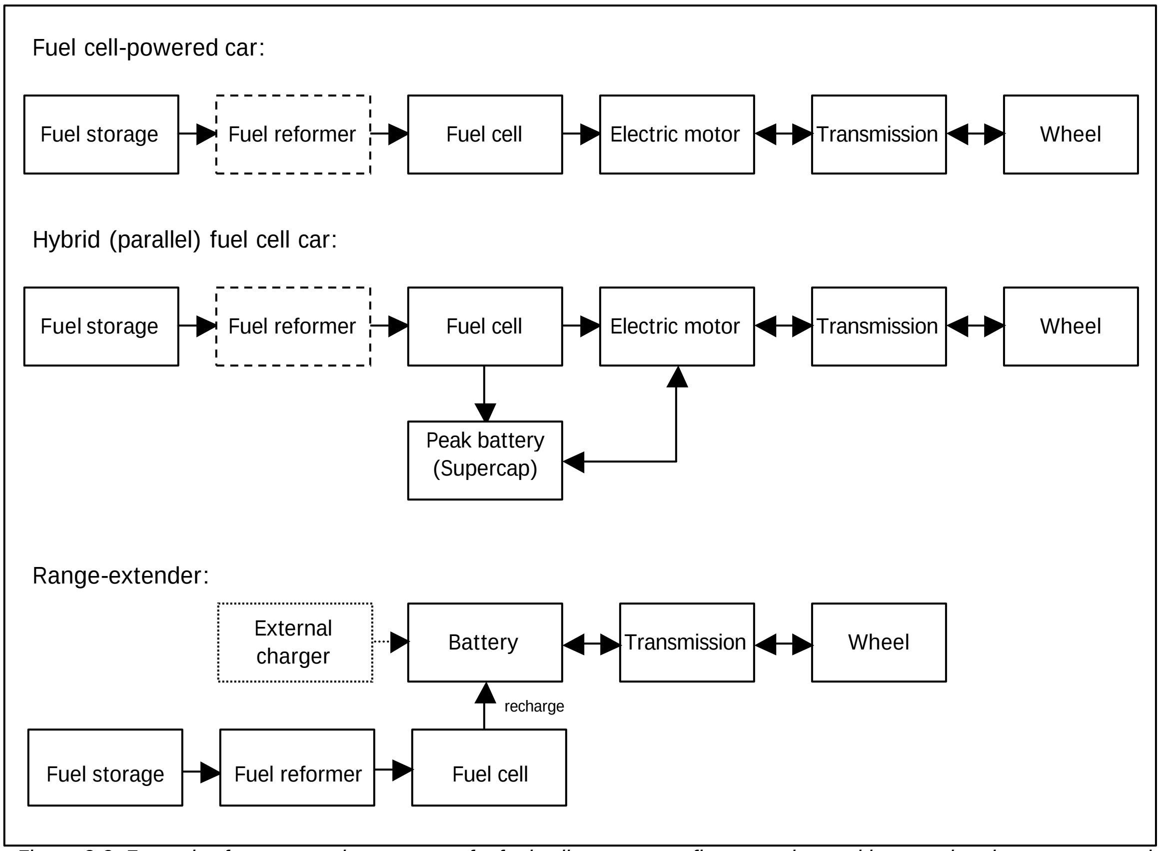

Figure 3.3. Examples for powertrain structure of a fuel-cell car; energy flows are denoted by arrowheads, components that are not necessary for all possible combinations are represented in dashed boxes; not represented are electronic devices.
Source: adapted and modified from Röder, 2001b

3.4.3 Distribution and delivery of fuels for fuel-cell vehicles

As most manufacturers are using PEMFC's[20], the difference between the systems lies in the fuel used to operate the FC vehicle. As mentioned in section 3.4.1, options for fuel storage onboard are hydrogen, methanol and gasoline (Ogden et al., 1999). There are various ways to produce and deliver (to the refuelling stations) these fuels.[21]

3.4.3.1 Gasoline production and delivery

Gasoline is normally produced out of crude oil. In a refinery the oil is distilled and one of the extractions is gasoline. Gasoline can also be produced, via some reforming processes, out of coal and biomass, but this is less common.

Crude oil is transported from the oil fields to the refineries or petrochemical factories by pipelines, trains, tankers and trucks (Van Thuijl, 2002). This depends mainly of the location of the oil field (inland, onshore or offshore).

From the refineries the gasoline is transported by pipelines and trucks to depots (sometimes trains). Delivery of gasoline to the refuelling stations normally takes place by trucks.

3.4.3.2 Methanol production and delivery

Methanol can be produced from natural gas and via gasification of coal, heavy liquids, biomass or wastes. In 1995, the world production of methanol amounted 23 million metric tonnes (capacity of 28 million tonne), of which about 90% from natural gas (Ogden et al., 1999). Twelve million was conveyed to remote users by sea (70%), rail, tank, wagon or barge (Ogden et al., 1999).

In theory, the unutilized methanol capacity (1995) could fuel a few million fuel-cell cars. For the introduction phase of fuel-cell cars, the existing methanol distribution systems could therefore be

[20] See http://www.fuelcells.org/fct/carchart.pdf
[21] See appendix F for an overview of different pathways for alternative vehicle power systems

sufficient, so no (or only a few) new terminals or tank trucks have to be built. Added costs will then mainly be the conversion of gasoline refuelling stations (Ogden et al., 1999). This situation holds true only for certain countries. In the case of China, this could be different.

Two options for production and delivery of methanol are discussed by Ogden et al. (1999): 1) Tanker ships transport methanol from production plants sited near inexpensive sources of natural gas to marine terminals, where the methanol is loaded into tank trucks and delivered to users; or 2) truck delivery of methanol, produced via gasification of coal, heavy liquids, biomass or wastes, to users.

3.4.3.3 Hydrogen production and delivery

Hydrogen can be produced centrally (large scale) and decentralised at the refuelling station (small scale). The vehicle refuels hydrogen at the station. Advantages are that the vehicle complexity will be reduced because a reformer is not necessary, and higher performance can be achieved (Weeda et al., 2002), although hydrogen fuel storage is still a source of some problems.

Around 98% of present-day produced hydrogen for industry is generated from fossil fuels, where steam reforming of natural gas is the most widely used (Garrity, 2002). For transportation purposes, the near-term options for the production and delivery of hydrogen transportation fuel (gaseous) are (Ogden et al., 1999):

- Hydrogen from natural gas in a large, centralized steam reforming plant, and truck delivered as a liquid to refuelling stations;
- Hydrogen produced in a large, centralised steam reforming plant, and delivered via small scale hydrogen gas pipeline to refuelling stations;
- Hydrogen from chemical industry sources, with pipeline delivery to a refuelling station;
- Hydrogen produced at the refuelling station via small scale steam reforming of natural gas;
- Hydrogen produced via small scale water electrolysis at the refuelling station.

And long term options are:

- electrolysis powered by wind and solar or nuclear power;
- gasification of biomass, coal or municipal solid waste;
- hydrogen delivered from hydrocarbons (NG, biomass or coal) with sequestration of CO_2.

For these options, the infrastructure has to be adjusted radically, which will result in high investment costs. Next to the high capital costs of the fuel cell, this is the main other problem of the delivery of hydrogen. And with respect to this issue the so called “chicken and egg” problem occurs, which other fuels such as natural gas are facing as well. Oil companies will only invest in new infrastructure and fuelling stations, at a certain number of a particular (alternative) vehicle. On the contrary, market sales remain low when there are only a few refuelling possibilities, which consequently blocks large market penetration.

The method of hydrogen production and delivery mainly determine the environmental benefits associated with the use of fuel cells. The fuel-cell car may itself not emit (or minimal amounts of) gasses; the production and delivery of hydrogen, however, do lead to emissions. A comparison of different powertrains can be made by carrying out a life-cycle assessment (well to wheels).[22]

3.4.4 Safety of hydrogen

Car customers and the public in general are reserved about the use of hydrogen. Although hydrogen was not responsible for the Hindenburg and Challenger accidents, they have caused concerns over hydrogen storage and use (Garrity, 2002; Ogden et al., 2001). The associated fears and risks are furthermore perpetuated by its unfamiliarity (Garrity, 2002).

Hydrogen is considered not to be safer or less safe than other fuels. The flammable limit and the ignition energy of hydrogen are known to be lower than those of other vehicle fuels (Lee et al., 2002). On the other hand the lower limits for flame emissivity make it a safer fuel in confined spaces, which is particularly important for vehicle fuel use. Hydrogen will disperse quickly in unconfined spaces, because of its very low density, whereas petrol has a tendency to puddle (see figure 3.4). Additionally, petrol is poisonous while hydrogen is non-toxic (Garrity, 2002). Because hydrogen has some different

[22] See e.g. Ogden, 2003; Röder, 2001b/c; LB-Systemtechnik GmbH, 2002

properties, other demands to the storage and usage are made compared to other fuels. How to store the low dense hydrogen in the car is one of the solutions still to be found (DeCicco, 2001).

The lack on codes and standards for transport purposes have to be overcome before large-scale use of hydrogen systems can be implemented. Furthermore, information has to be spread and training programs started.

Table 3.2. Comparison of safety properties between Gasoline, Methane and Hydrogen.

Property	Gasoline	Methane	Hydrogen
Density (kg/m^3)	4.4	0.65	0.084
Diffusion Coefficient In Air (cm^2/s)	0.05	0.16	0.61
Specific Heat at Constant Pressure (J/gK)	1.2	2.22	14.89
Ignition Limits In Air (vol%)	1.0-7.6	5.3-15.0	4.0-75.0
Ignition Energy In Air (MJ)	0.24	0.29	0.02
Ignition Temperature (°C)	228-471	540	585
Flame Temperature In Air (°C) Explosion	2197	1875	2045
Energy (g TNT/kJ)	0.25	0.19	0.17
Flame Emissivity (%)	34-43	25-33	17-25

Source: Veziroglu, 2002 in Garrity, 2002

Figure 3.4. Simulation comparing severity of a hydrogen and gasoline fuel leak and ignition.
Source: Swain, M. in Garrity, 2002

3.4.5 Costs of fuel cells

Although the costs of fuel cells have declined strongly in the past forty years (see appendix G), present-day manufacturing costs of fuel-cell systems for vehicles are not competitive to those of the conventional internal combustion engines. Arthur D. Little (ADL) has estimated the costs of a fuel-cell system for 2001 at 324 US$/kW (see table 3.3.), based on a production of half a million vehicles per year. This unit cost includes the fuel cell, 221 US$/kW, the fuel processor, 76 US$/kW, balance of plant, 17 US$/kW and the system assembly (10 US$/kW). For a fuel-cell system of 50 kW the total costs will then be more than US$ 16,000. By comparison, the total costs of standard US cars with ICEs are approximately US$ 18,000 - 19,000 (Ogden et al., 2001, Weiss et al., 2000).

Table 3.3. Existing FC systems costs based on present-day technology

Source:	Cost ($/kW)	Note:
AMI in Röder, 2001c	500	Incl. reformer & controls
OTA 1995 in Röder, 2001c	1700	LANL estimate 1995 ass. mass production
West 1998 in Röder, 2001c	1700	Ballard (?) 1998
Chalk et al., 1998 in Röder, 2001c	+/- 2500	Electronic Partners 10/97, stack only
ADL, 2001	324	Incl. Fuel cell (221 US$/kW), fuel processor, BOP, System Assembly; based on a production of 500,000 vehicles per year
Bar-On et al., 2002	200	General statement

The production costs of new technological products that are amenable to the economies of mass production tend to decline with cumulative production, via so called “learning by doing”. Cost reduction between 10 and 30 percent for each doubling of cumulative production is typical (Ogden et al., 2001). This trend has been documented for several power sys tems, such as photovoltaics, windmills and gas turbines.

These trends can be illustrated in a *learning,* or *experience curve*, which describes the specific (investment) cost as a function of the cumulative capacity for a given technology (Seebregts et al., 1999). An example of a learning curve for a 40-kW fuel-cell powertrain is illustrated in figure 3.5, which compares also with other powertrains of comparable size.

Based on such learning curves or based on set targets, several costs estimates for fuel-cell systems (or components of the system) are reported in scientific literature. Estimates from different authors diverge significantly, but most authors believe fuel-cell technologies can become cost competitive with time and increased production capacity. Some projections of future fuel-cell systems costs are given in table 3.4, and costs for components are given in table 3.5 (see for a more extensive overview Röder, 2001b).

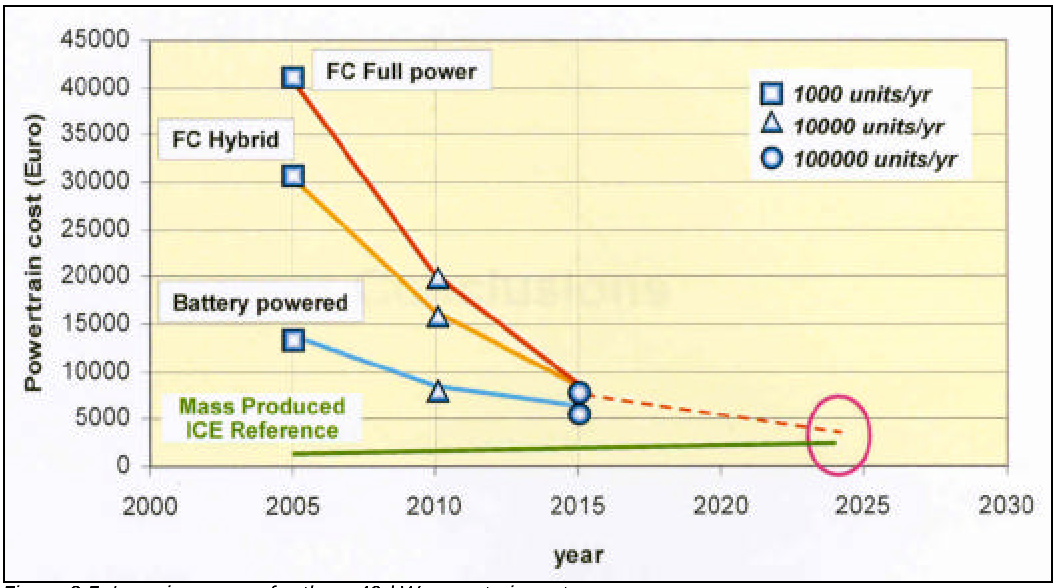

Figure 3.5. Learning curves for three 40-kW powertrain systems
Source: Centro Ricerche Fiat, 2002
Note:
- *Full power FC and ICE power: 40 kW*
- *Hybrid configuration power: 20 kW from FC + 20 kW peak from battery pack*
- *Battery vehicle power: 40 kW peak (18 kWh storage)*

Table 3.4. Unit costs of future fuel-cell systems; excl fuel and storage

Source	**100% Hydrogen ($/kW)**	**Gasoline reformate ($/kW)**
Weiss et al., 2000	60	80
DOE	28	45
FreedomCAR	30	30
ADL	105	130

Source: Weiss et al., 2003

Table 3.5. Cost estimates for mass produced fuel-cell vehicle components

Component	High estimate (US$)	Low estimate (US$)
Fuel-cell system	100/kW	50/kW
Fuel-processor system	25/kW	15/kW
Hydrogen storage cylinder (rated at 5000 psia)	1000	500
motor and controller	26/kW	13/kW
peak power battery	20/kW	10/kW
extra structural support	1/kg	1/kg
cost of 12 kg gasoline or methanol tank	100	100

Source: Ogden et al, 1999

3.5 Powertrain types

A powertrain is characterised by its propulsion system and its fuel. Combinations of these lead to a fleet of powertrains. Moreover, powertrains develop over time along an evolutionary path or by more radical innovations. According to Weiss et al. (2000), a vehicle can have an evolutionary or advanced character. The evolutionary vehicle has slight improvements with respect to the traditional technologies used now, i.e. higher fuel economy (l/100 km) and lower emissions. Advanced vehicles are fitted with light weight (aluminium-intensive) body chassis and have minimized losses in tires and drag.

In table 3.6, the various fuels, propulsion systems and the vehicle development are given.

Table 3.6. Various fuels, propulsion systems and vehicles characterising the different powertrains

Fuels	Propulsion System	Other Vehicle
Petroleum Gasoline	CI (DI) ICE*	Evolutionary
Petroleum Diesel	SI (DI) ICE*	Advanced**
Compressed Natural Gas	Various Transmissions	
Fischer-Tropsch Diesel	Hybrids	
Methanol	Fuel Cells	
Hydrogen	Batteries	
Electric Power		
Alternative fuels: - Ethanol - LPG - Alcohol - RME		

Source: Weiss et al., 2000
*CI (Compression Ignition), DI (Direct Injection), SI (Spark Ignition), ICE (Internal Combustion Engine).
**Light weight (aluminium-intensive) body and chassis, minimized losses in tires and drag.

Gasoline and diesel cars dominate the car markets in most countries. In the EU the share of gasoline and diesel cars is 80.6% and 17.8%[23] respectively in 1999 (European Commission, 2002). In some countries, like Argentina, Italy and Russia, natural gas vehicles also have a significant market share (up to 12 % in Argentina). Another available fuel for cars is LPG, but the market penetration of this fuel is very small.

Because of stricter environmental regulations, car manufacturers are forced to produce more efficient cars and examine the potential of other propulsion systems (that use traditional or alternative fuels). The traditional gasoline car has a sparked ignition internal combustion engine. The development of this car is that it will be advanced by direct injection systems, reduced body weight and some incremental developments (better tire and drag performance). The traditional diesel ICEV, with a compression engine, will also be advanced by direct injection and further incremental developments. Besides, both car types can be fitted with a battery for providing peak power, which gives them a hybrid (parallel[24]) character and will enable them to accomplish a higher efficiency.

[23] For new registrated passenger cars, the share of diesel cars has been increased; it rose from 29.0% in 1999 to 40.9% in 2002 (ACAE, 2002).
[24] There are two types of hybrids: the *series* hybrid electric vehicle and the *parallel* HEV (see McNicol et al., 2001; Thomas et al., 1998).The parallel hybrid version has been used extensively in this study, since this system has a greater potential to reductions in fuel consumption and has lower costs.

Other relatively new powertrain concepts, in terms of market commercialization, will be the advanced compressed natural-gas ICEV, the electric vehicle, the fuel-cell hybrid vehicles and the full FCV. Taking into account the three fuels for fuel cells (methanol, gasoline and hydrogen) six fuel-cell vehicle types can be distinguished (see table 3.7).

The large amount of fuels, the different propulsion systems (and its combinations) plus the vehicle developments, lead in total to a large number of possible powertrains. According to different authors[25], the fleet of powertrains which will represent the automobile market of the next two or three decades are the ones listed in table 3.7.

Table 3.7. Different existing powertrains and prospected ones

Technology	Fuel	Engine	Short name
Reference car	Gasoline	SI Sparked ignition	Gas SI ICE
	Diesel	CI Compression ignition	Diesel SI ICE
Advanced vehicle ICE	Gasoline	DI SI direct injection sparked ignition	Gas DI SI ICE adv
	Diesel	DI CI direct injection compression ignition	Diesel DI CI ICE adv
	CNG	DI SI	CNG DI SI ICE adv
Advanced vehicle ICE HEV	Gasoline	DI SI + battery	Gas DI SI HEV
	Diesel	DI CI + battery	Diesel DI CI HEV
	CNG	DI SI + battery	CNG DI SI HEV
Advanced vehicle fuel cell HEV	Gasoline	Reformer FC + battery	Gas FC HEV
	Methanol	Reformer FC + battery	MeOH FC HEV
	Hydrogen	FC + battery	H_2 FC HEV
Advanced vehicle fuel cell (pure)	Gasoline	Reformer FC	Gas FC
	Methanol	Reformer FC	MeOH FC
	Hydrogen	FC	H_2 FC
Advanced vehicle electric	Electricity	Battery	EV adv

Source: Weiss et al., 2000 (modified)

3.6 Technological map

In this section, the technological artefacts and their relationships, which are described in this chapter, will be summed up and schematically represented in a so called *Technological Map*. By doing this, an overview is given of how different technological artefacts are related with each other, and thus how changes of one artefact might influence another artefact (see Smit & van Oost, 1999). In this overview, the fuel-cell powertrain (full and hybrid) is set as the central point, from which the map is constructed. The map is represented in figure 3.6.

A range of fuel-cell-system types is shown, which consequently leads to quite a large number of fuel-cell vehicles, particularly when the different fuels (gasoline, methanol, hydrogen) are taken into account. On the "powertrain level", the fuel-cell car will compete with the traditional ICE cars, the improved ICE cars (advanced and hybrids) as well as the ICE cars with alternative fuels. All powertrains have several components, all with their own characteristics. The (set of) components make the distinction between the different powertrain systems.

In addition, which is not mentioned in the previous sections, the car is competing (on the "passenger traffic" level) with the plane, train, bus, motor cycle and bicycle. The car can be a substitution product as well a complementary product. The plane and train, for example, can be a substitution product for the car on long distances. On relatively short distances, the car is competing with the bike and public buses.

The latter paragraph deals with the demand for and use of cars, but when it comes to the diffusion of *fuel-cell* cars, the application of fuel-cells in bikes and buses could be the initiator of the fuel-cell car. These relations are not reflected in figure 3.6, otherwise the figure would have become indistinctly.

We have also seen that the different means of conveyance and the infrastructure are related and mutually dependent on each other. In this research the *refuelling stations, manufacturers, maintenance garages, roads and parking places* form the infrastructure.

[25] See e.g. Ogden et al., 2001; Röder, 2001a; Weiss et al., 2000 & L-B-Systemtechnik GmbH, 2002. In the reports of Röder (2001a,b) and L-B-Systemtechnik GmbH (2002) the ethanol vehicle is also discussed.

Key issue for the fuel-cell car is how hydrogen fuel will be produced. Internally reformed hydrogen, i.e. fuel reforming process to hydrogen inside the car, or hydrogen produced “outside” the car. Hydrogen produced outside the car can be near the refuelling station (onsite) or centralised, where the hydrogen is produced on a specific place and the hydrogen is transported to the refuelling station by means of truck delivery of pipeline delivery. These issues do not only determine the total costs of fuel-cell vehicles (well to wheel), but also the “cleanness” of the fuel-cell vehicles.

3.7 Conclusion

From the analysis of the fuel-cell systems we concluded that the PEMFC and DMFC are presently the best options for transportation utilization, mainly because of the low operating temperature and their simplicity. Three types of fuel-cell vehicles can be distinguished: *fuel-cell powered car*, *hybrid (parallel) fuel-cell car* and *range extender*. Still, the fuel cells, and its applications in vehicles, are in the developing stage. Main barriers to be overcome are the way of hydrogen storage, safety concerns and the high initial costs.

Another important issue is how the hydrogen (or methanol) is produced and distributed. This will not only have impact on the costs but also on the environmental friendliness of the total life cycle. Here the “chicken and egg” problem is encountered; the question rises whether (oil) companies want to invest in new infrastructure.

Besides, the conventional ICE powertrain and other alternative powertrains are also improving. Competition between the powertrains is therefore increasing. Competition also takes place on a higher level. The car itself competes with the plane, train, bus, motor cycle and bicycle. The development of these systems will influence the use of cars.

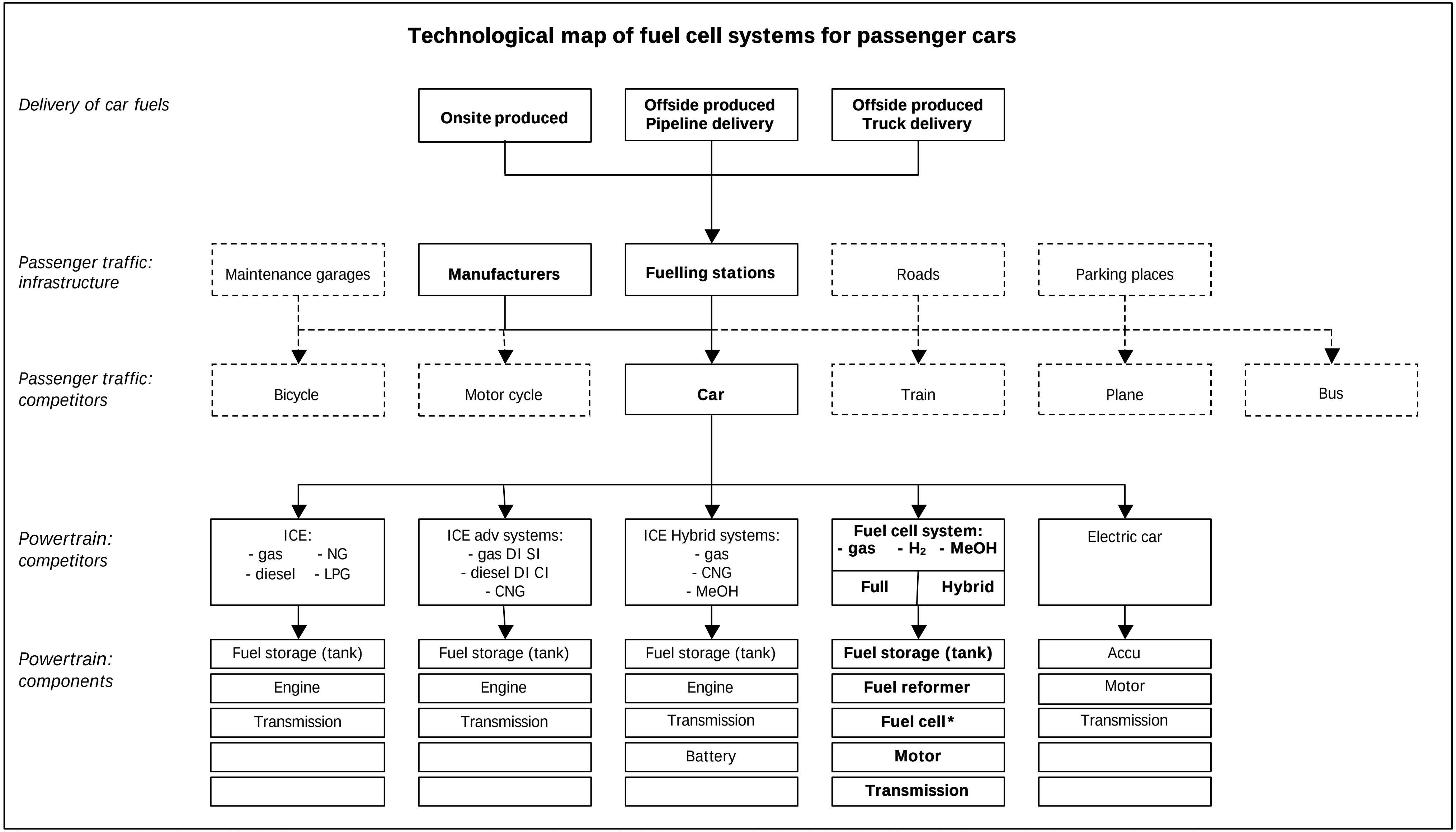

Figure 3.6. Technological map of fuel-cell systems for passenger cars, showing the technological artefacts and their relationships (the fuel-cell system is taken as starting point)
*Note: No connection from fuelling stations to bicycles; "roads" for trains are railway; * The different types of fuel cells are also competing among each other*

4. Actor analysis

In the previous chapter the focus has been on deriving technological, infrastructural, and economical obstacles and challenges that fuel-cell cars could face on their way to market introduction. In this chapter the relevant actors with regard to the (fuel-cell) car industry are given as well as the relationships between the actors. Thus, this chapter answers the research sub-question (#3): which actors influence the difussion of fuel-cell cars and in which direction? It reflects key factors and driving forces worldwide, the steps 4 and 5 of the methodology.
Firstly, the meaning of a multi-actor network of a socio-technological regime is highlighted and subsequently such a network is specified for this research. Next, the actors in the network are described, their relation to other actors and to fuel-cell (cars). In the conclusion the above mentioned question is answered.

4.1 Introduction

Technological changes in society are the result of processes by multiple actors. The actions of these actors direct technological development and influence the market share (and penetration) of a certain technology (see also appendix B). Actors can be classified in groups, and the groups will form a network.

To analyse which actors influence the diffusion of fuel-cell cars and in which way, the general characterisation of the multi-actor network of a socio-technological regime designed by Geels (2002b) is used as starting point to inventory the actors (see figure 4.1). It gives a good representation (example) of the various groups of actors in a socio-technological regime, and the representation contains those groups that, according to the author, also represent the automobile industry very well.[26]

4.2 Multi-actor network of a socio-technological regime

Sociotechnical (ST) configurations (technical artefacts plus social relations) are the result of activities of groups and actors, which create and maintain the elements and their linkages (Geels, 2002b). On the one hand the groups have their own distinctive features and relative autonomy. On the other hand they are dependent and interacting with each other, which leads to a certain stability of ST-configurations. But tensions between groups and de-alignment make the ST-configurations instable, so both processes occur by actions of and interactions between multiple social groups (Geels, 2002b).

It can therefore be said that the rules of the socio-technological regime are carried by a network of social groups. Geels (2002b) has designed a general characterisation of the multi-actor network of such socio-technological regimes. It contains these groups:

- financial network
- suppliers
- maintenance
- users
- research
- public authorities
- societal groups
- producer network

The actor-groups and their mutual relations are represented in figure 4.1.

[26] Probably because Geels his work was grounded with cases on transportation.

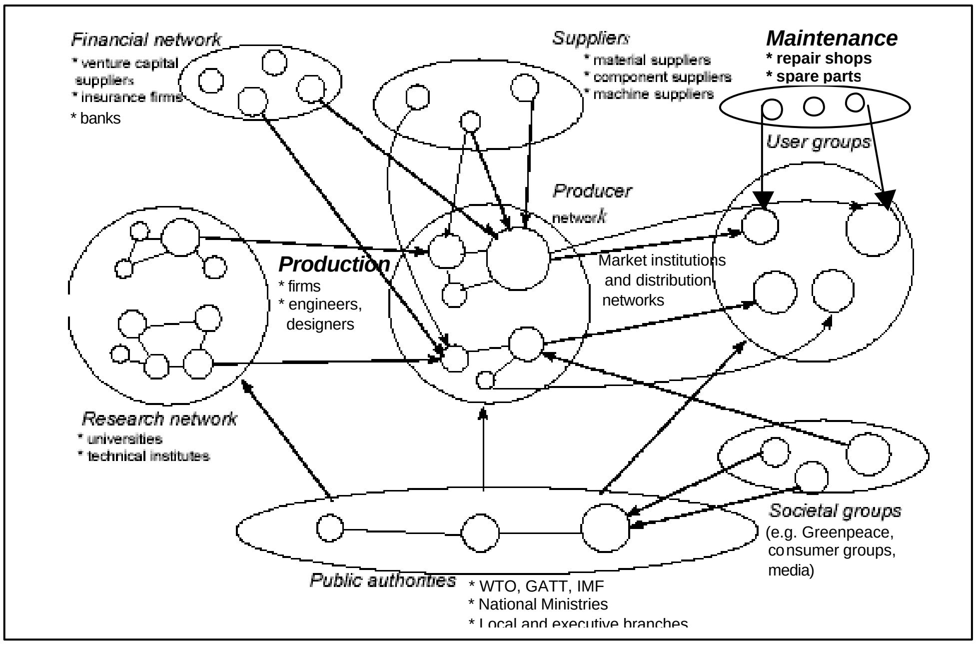

Figure 4.1. The multi-actor network of a socio-technological regime (Geels, 2002b, p.23)
Note: the large circles represent the actors; the small circles inside the larger ones represent the players.

Central element is the *producer network*, formed by several companies operating in the same cluster/sector. The producers are *supplied* with materials, components and machines by various companies. The producers *distribute* their products and the products are sold to the *users*, who all have certain demands and wishes regarding the product. Once the products are spread, there should be sufficient *maintenance* support.
The *public authorities* play a central role in the communication (direct or indirect) with the industry, other levels of government, academia and the community. Their policy creates a set of conditions in which the different actors can operate. The *public authorities* aggregate on local, sector, national and macro level. *Societal groups*, such as Greenpeace, bring pressure to bear upon both the governments and the producers to force these actors to redirect their policy.
Universities and research institutes provide scientific data for various purposes. *Research* is also carried out in the companies itself.
The *financial network* consists of venture capital suppliers, insurance firms and banks. This network is related to the *producer network*.

This general network will be specified for this research in the next section. This specification will refer to global fuel-cell (car) industry and will not be China specific, because the automobile industry is one of the most global of all the manufacturing industries[27] (Dicken, 1999) and the diffusion of fuel-cell cars will probably first take place on a global level before reaching in China (Shell International, 2001).[28]

4.2 Social Map for the fuel-cell car industry

In figure 4.2 the social network for the fuel-cell vehicle industry is given. The general characterisation of the multi-actor network of a socio-technological regime by Geels (2002b) is taken as the basis for this network. It is a simplified version, showing only the main actors and relations. The car manufacturers are the central element in the network. The *user group* and *societal group* are taken together, forming the *community*. Besides, the *financial network* and *maintenance* have been left out of the model, because, after a first brief analysis of the actors, it was concluded that these groups have less influence on the car manufacturers and the other actors in this specific case.

[27] "The world automobile industry is predominantly an industry of transnational corporations. The ten leading automobile producers account for no less than 71 per cent of world production. Almost 90 per cent of the world total is produced by a mere twenty companies." (Dicken, 1999). Note: Although this statement is based on data from 1994 and since then some mergers have taken place, this statement still holds more or less true.
[28] This is assumed in one of the two scenarios about energy systems to 2050, set up by Shell International (2001)

The four groups, community, industry, research, and public authorities, in figure 4.3, correspond again with the poles of the social-technical network as reflected in De Laat (1996, p.9).

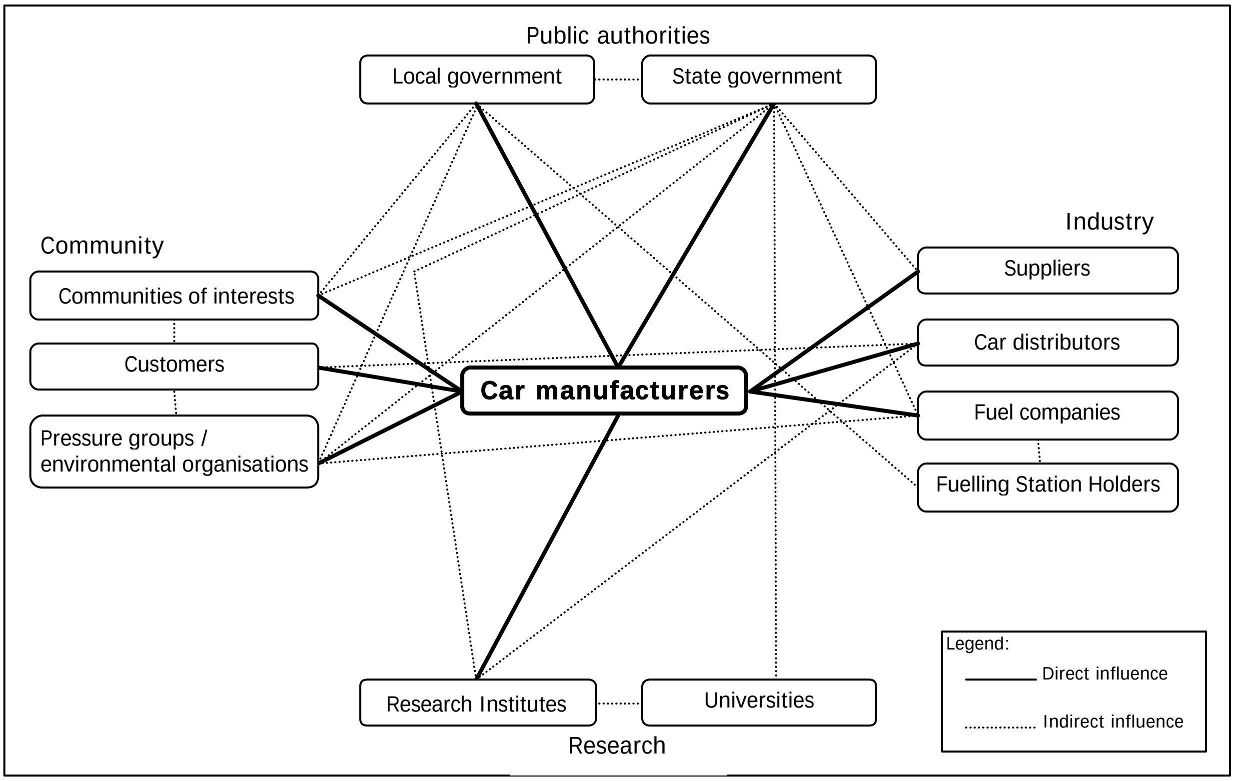

Figure 4.2. Social map: actors influencing (fuel-cell) car manufacturers
Note: only most crucial relations are highlighted

In the next sections the different actors, indicated in figure 4.2 will be discussed. In the discussion the actor its interests, its preferences and its relations[29] with other actors will be highlighted.

4.2.1 Industry

<u>*Car Manufacturers*</u>
Car manufacturers are producing in large volumes and operating world-wide, under fierce competition (Dicken, 1998). They have a dominant position in the traffic markets and their interest is to remain their position (van Thuijl, 2002). The internal combustion engine plays a key role in today's position, which will also ensure them of large revenues in the coming decades.

Stricter regulations, discussions about GHG emissions and energy-related problems, are forcing the car manufacturers to produce more efficient vehicles (i.e. lower emissions per km). The internal research centres, in conjunction with suppliers and academia, are focusing on fuel efficiency, reduced emission levels, reduced tyre and drag resistance, mass (weight) reduction and alternative powertrains. Investments in alternative powertrains, mainly fuel cell and hybrid systems, are only interesting when these investments can be paid back by large sales volumes. (see Dicken, 1998, p. 326; van Thuijl, 2002, p.47)

Approximately all major car manufacturers[30] are engaged in fuel-cell development and have presented a prototype car. Since 1994 more than 40 fuel-cell car prototypes have been presented.[31] Most prototypes look exactly the same as the models we see on the highway, but a few of these cars have a more unconventional design. Fuel-cell powertrain systems enable the use of flat chassis, which gives the designers of cars freedom to create unique body styles. The mechanical systems for steering, braking, trottling and other functions with electronically controlled units can be replaced by the

[29] most relations are also reflected in Tijink (1999)
[30] BMW, DaimlerChrysler, Fiat, Ford, General Motors, Honda, Hyundai, Mitsubishi, PSA (Citroen, Peugeot), Renault, Suzuki, Toyota, Volkswagen. The developing of fuel cell cars by Daewoo is unknown.
[31] See http://www.fuelcells.org/fct/carchart.pdf

integration of the fuel cell with drive-by-wire technology (electronic systems are less bulky than mechanical ones) (Burns et al., 2002). This design freedom might be a challenge for fuel-cell car manufacturers to satisfy the (increasing/changing) customer needs, described in section 4.2.4.

For the applications of alternative fuels a sufficient infrastructure is needed, where deliberation and collaboration with the public authorities and fuel companies is necessary. The “chicken and egg” problem, discussed in section 3.4.3.3, between car manufacturers and fuel companies occurs here.

Although the car manufacturers are the ones that have to design and built the fuel-cell car, they can not be seen as the actual force behind the diffusion of FCV. The development of fuel-cell technology and other alternative powertrains is mainly initiated by government’s policy.

Fuel (Oil) Companies
The world-wide operating oil companies attach great importance to continuing oil production and supply and to maintain stable oil prices, assuring them of high turnovers and profits (van Thuijl, 2002). These large capital companies dominate the refinery sector as well as the petroleum market, where entrance of new companies is hardly possible (van Thuijl, 2002). They are prudent with large capital investments in new technologies as the returns are uncertain (Shell International, 2001). Yet, they are improving their existing range of products and processes to maintain the high profits.

Only if the middle and long term market perspective of a certain technology are good, the oil companies will invest. Other reasons to invest are improving their environmental image (which is generally poor), to keep their innovative image and to extend the range of products. Shell, for example, have set up two new divisions, *Shell Renewables* and *Shell Hydrogen* in the past years and British Petroleum (BP) are providing their (new!) refuelling stations with solar cell panels. Though their incentives are twofold: trying to maintain their oil market position and, on the other hand, changing towards renewable energy resources.

Energy resource scarcity is also often mentioned as a motive to shift to alternative fuels and alternative resources (see e.g. Tijink, 1999). However, according to Shell International (2001) energy resource scarcity occurs rarely at a global level, when demand growth cannot be met because resources are limited or the costs of new production capacity are too high. They state that oil and gas scarcity will not occur before 2025. However, after 2025, energy resource scarcity (mainly oil and gas) will be one of the driving forces for shifting to alternatives fuels/resources (Shell international, 2001).

Fuel-station Holders
In Europe, a refuelling station holder serves around 1500 vehicles on average[32] (VNPI, 1998). Fuel station holders depend on their customers to gain sufficient revenues.

In general, the refuelling station is either owned by the oil company or the holder has a franchise contract with the oil company (Janssen, 2003). The influence of the biggest oil companies is large, new entries in the markets are difficult and price competition is very low (the price is set by the big oil companies) (Van Thuijl, 2002).

Refuelling station holders face high investment costs. These high investment costs are a barrier for fuel-cell car diffusion, because the holders don’t want to invest if revenues are uncertain. According to Ogden et al (1999) one hydrogen refuelling station costs between US$ 0.7 and 5.7 million, depending on production form of hydrogen and location (centralized or onsite). Besides, a conversion from gasoline into methanol was estimated to be US$ 45,000 (Ogden et al., 1999). Till now, around 20 hydrogen refuelling stations are built worldwide.[33]

Fuel station holders are related to the local government (planning, procedures and certain regulations) and to the fuel company.

[32] Average of 15 Western-Europe countries plus Czech Republic measured in amount of vehicles per service station; original source: EPTC.
[33] See Http://www.fuelcells.org/H2FuelingStations.pdf

Suppliers of automobile components
The automobile industry is essentially an assembly industry. A large amount of (specialised) companies supply the car manufacturers, from components to semi-manufactured goods. The production of these components comprises a specialized set of industries. Leading firms themselves have become transnational as the automobile industry was globalising (Dicken, 1998). Most car-manufacturers have a specific set of suppliers, sometimes formed in joint-ventures. It is in the suppliers' interest that the demand for cars remains at the same level or, even better, increases as they are dependent on the demand of the car manufacturers. It is argued that suppliers might adapt relatively easy to changes in demand by car manufacturers for new components (van Thuijl, 2002).

There are a numbered amount of fuel-cell manufacturers and they collaborate with particular car manufacturers. Ballard, UTC fuel cells, Fuel Cell Technologies Ltd., De Nora and H-power are the major fuel-cell manufacturers. Ballard is world-leading fuel-cell manufacturer and is partly owned by DaimlerChrysler and Ford. For the continuance of these suppliers, the diffusion of fuel-cell cars is important.

Car Distributors:
Car distribution takes place in various ways. In a presentation by Podlipny (2002) of Skoda Auto six pathways of car distribution are mentioned, of which number one is most common:

1. from producer to importer/dealer to customer
2. from producer to dealer group to customer
3. from producer to dealer groups to car brokers to customer
4. from producer to car brokers to customer
5. from producer to hypermarket to customer
6. from producer to customer

The dealer is the intermediate between the customers and the producers. In general, the dealer has most contact with the consumer and does know what their preferences are. The dealer will cater to the customer's preferences, but is bound to a fixed range of products supplied by the producer. The producer is the one who wants to have its fixed range of products sold in the largest amounts possible.

The power of the producer on the distributor is large, but the distributor (dealer) can provide the producer with information about the car preferences of the customers. The dealer is interested in maintaining his local market share and opposes the other distribution pathways.

4.2.2 Research
Universities and research institutes provide and distribute scientific know-how for general and specific purposes. Researchers are the link between the fundamental research of the universities and the application of knowledge in the market (ECN, 2003b). The research is mainly funded by government bodies, but an increasing money flow comes from the industry.

The universities and institutes have (close) relationships with the industry and public authorities. Research institutes and universities carry out independent consulting work to government bodies, companies and others. The research institutes also gain knowledge and develop technologies by order of government bodies and the industry (ECN, 2003a).

The role of the universities and institutes in this network is primarily supplying, but we can distinguish a trend in the research of research institutes and some universities, from basic / fundamental research to more market-oriented research (where possible).

In addition to the points above the universities and institutes have an educational role. They educate and train various groups, from scholars, to students, to employees.

As mentioned, research is also carried out in the car manufacturer companies itself.

Box 4.1 Research institute: Paul Scherrer Institute profile

Paul Scherrer Institute's priorities lie in areas of basic and applied research in natural science and technology, and particularly in fields which are relevant for sustainable development (PSI, 2000). Fuel-cell technology is such an field.

The focus on basic and applied research result in new knowledge, which actively pursues its application in industry. Therefore, PSI promotes, in collaboration with the industry, the transfer and application of research results into new products, techniques and processes. Technology transfer at PSI aims at generating economical benefits, generating funds for research projects at PSI, and supporting industry in particular (PSI, 2002). In addition, PSI carries out independent consulting to government bodies, companies and others.
Besides, PSI provides education and training, which lie beyond the possibilities of a single university department. This is done in close collaboration with (technical) universities.

In the field of fuel-cell technology, PSI focuses on the cost-reduction of efficient fuel-cells, and on its application in small, low-weighted vehicles. Together with industrial actors, PSI develops such vehicles. Where possible, they would like to commercialise their products and gain benefits from technology-transfer in this research-area (Wokaun, 2003).

4.2.3 Public authorities

The Government has a mandate to look after the common good of the nation's people. It is the government's role to track social, economical and environmental problems and to create conditions for a certain development, by means of a set of regulations, procedures, funding etc, for the benefit of its population. The awareness of energy and environmental consequences has resulted in stricter regulations on emissions and efficiency by the national governments and in international agreements. Still the political awareness and support are low (Garrity, 2002). Politicians are focused more on short-term issues, whereas the sustainability issue requires long-term policy (Tijink, 1999).

There is a certain tension among the objectives of the Government. On the one hand, they have set up environmental regulations, because of the negative environmental consequences of current car use. On the other hand, there are the economical motives: car industry and employment, infrastructure etc. An other question also rises: do you stimulate (clean) car use or do you stimulate public transport?

The State Government plays a central role in the communication (direct or indirect) with the industry, other levels of government, academia and the community. Depending on the country, the Local Government has a role in planning, procedures and regulations. Moreover, it has a closer link to the user group than the state government

4.2.4 Community

The community consists of the *user* and *societal groups* of the model of Geels (2002b). It represents individuals or groups of people and parties, sometimes in the form of an organisation.

<u>*Customers*</u>

Studies in industrialized countries show that the far most important consideration of customers when intending to buy a car is the price of it, whereas fuel economy and emissions only play a small role (van Thuijl, 2002). But with increasing income levels, considerations such as comfort and performance become more important and the price of a car will play a less dominant role.
The following list sums up the main customer's considerations (van Thuijl, 2002[34]; Gan, 2003):

- price of the car
- safety
- comfort
- performance (range, acceleration)
- reliability
- post-sales services
- fuel economy and emissions

In general, customers are not willing to make concessions regarding the above mentioned aspects at the introduction of new powertrain concepts or fuels. In addition, they would like to have freedom in

[34] Based on interviews with experts (in the Netherlands)

choosing their car (dealers, brand and models). The customer's destitution has to be filled, without changing their behaviour. Alternative cars have to have a similar or better performance, comfort and safety rate as the existing car fleet (van Thuijl, 2002). The expected higher performance, a longer lifetime and less maintenance of alternative are positive selling arguments.

Customers require acceptable fuel prices. Price increase, e.g. by taxes, will lead to higher variable costs, but this will not lead to large decline of the demand, i.e. the price elasticity is small. Of customers interest is also the fuel availability. The number of refuelling stations and their reachability should be sufficient to fulfil the customer's needs.

As mentioned in 3.4, car customers are reserved about the use of hydrogen. How and which *information* they will receive, determines their opinion and attitude (van Thuijl, 2002; Tijink, 1999). Environmental organisations, the media and the government play an important role in reducing the unfamiliarity of hydrogen use and the lack of confidence in the safety of hydrogen.

Communities of interests
Under communities of interests come those groups and organisations, who have particular interest in a certain development. Examples of such communities are consumer organisations, the media and the local people. Environmental organisations are also communities of interests. However, they are distinguished in this research as a separate actor, because of their specific interests in this matter.

The communities of interest have a signalling and communicating function. For example, consumer organisations and the media might express themselves positively about the efficiency and emission levels of fuel-cell, but it can also be that they focus on hydrogen safety issues and performance (acceleration, range etc.). Their views will influence the consumers' preferences. Besides, the consumers can express themselves via the communities of interests, who in turn will communicate these signals (directly or indirectly) to the car manufacturers.

Pressure groups / environmental organisations
Environmental groups, such as Greenpeace and the World Nature Foundation, exert influence on the *industry, public authorities* and the public opinion (here: *customers*) (van Thuijl, 2002; Tijink, 1999). These groups have an eye for general developments and are critical, especially to non-sustainable developments (van Thuijl, 2002). On the one hand, these groups form a favourable opinion of alternative (cleaner) vehicles, as they reject the large use of oil with its negative environmental consequences. On the other hand, they do not stimulate the use of cars in general.

4.3 Conclusion
A variety of groups, formed by actors, form a network. In such a network, the actions of these actors direct technological development and influence the market share of a certain technology.

For the fuel-cell car industry we can distinguish four main groups, derived from the multi-actor network of a socio-technological regime by Geels (2002b): industry, community, public authorities and research. These groups are divided into twelve sub-groups. Appertain to industry are the car manufacturers, the suppliers, the car distributors, the fuel companies and the fuelling station holders. The research institutes, universities are part of the group research, whereas local government and state government come under public authorities. Lastly, appertain to community are the communities of interests, the customers, the pressure groups/environmental organisations.

From the actor analysis we can draw the conclusion that the diffusion of fuel-cell cars (especially at the early stage) is influenced by:

- the willingness of the car manufacturers
  Will car manufacturers focus on the improvement of the ICE powertrain or will they focus on the fuel-cell car? In other words, will fuel-cell cars be their core business or will it be a minor business? Crucial for fuel-cell introduction are the technological development and cost reduction achieved by the manufacturers and fuel-cell suppliers. Besides, the diffusion of fuel-cell cars is dependent on the hydrogen/methanol infrastructure development.

- the willingness of the fuel companies
  Aspects such as cost, revenues, and potential health risks play an important role in the decision of these companies to invest in hydrogen/methanol infrastructure.

- the energy resource scarcity after 2025
  The question rises whether this will be a major issue in the coming decades? Will fuel prices go up? If indeed, this will change our energy structure, where one possibility will be to shift to a hydrogen society (Shell International, 2001).

- the incentives of the government
  The government, national and local, set the policy of the country or region. With their policy, depending on the environmental awareness, they shape the conditions within the companies can operate. Without proper regulation the incentives for the companies to innovate are lower.

- the customer preferences
  The price of the car is still an important consideration for customers, but especially in high income countries comfort and performance considerations become more important. New powertrain concepts should have similar or even better performance aspects (acceleration, range) than the conventional powertrains to become attractive. One advantage that fuel-cell cars have in order to meet increasing customer needs, is its design-freedom.

- Public pressure (environmental)
  Public pressure will have its impact on governments policy and tension between the industry and the public. The public can accept a new technology or they can reject the technology. Information provision is a strong medium.

5. Case China

In the previous part of the report, the focus has been on global issues and developments, as the development and diffusion of fuel-cell cars take place on a world-wide level. From this chapter on, the focus will be on China, to finally come to four scenarios for China, in which the diffusion of fuel-cell cars are highlighted. This chapter anwers research sub-question 4: Which social, economical, technological, environmental, and political features and developments, have their influence on the Chinese automobile market? It derives the key factors and driving forces in China itself, with regard to diffusion of fuel-cell cars in China (step 4 and 5 of the methodology).

5.1 Society

5.1.1 Population and density

In 2000, China's population amounted 1261 million people, which is a fifth of the world's population. They are living on a surface area of more than 9 and a half million square km. This corresponds to 135.2 persons per square kilometre (p/km^2), but in the centre of mega-cities this amount can come up to 30,000 p/km^2 (in Beijing centre; average Beijing 723 p/km^2) (Gan, 2003). The urbanization rate is around 37% and has increased the last years (The World Bank, 2002). Population growth has declined over the years, due to government regulations, and was 0.9% in 2000.

China has more than 90 cities with more than 1,000,000 inhabitants. Three of them, Shanghai, Beijing and Chongqing (artificial mega-city[35]) are mega-cities, by having more than 10,000,000 inhabitants (Bezlova, 1999). Tianjin is reaching the status of a megacity by having 9.2 million inhabitants in 2000.

With a growing population, as indicated in table 5.1, and an increasing urbanization rate, the number of large- and mega-cities will grow, and consequently the population density in the cities will be higher.

Table 5.1. Projections of China's population by different studies (in billion).

Source:	Year													Note:
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	
Zongxin et al., 2001	-	1.211	1.294	1.34	1.386	1.441	1.495	1.528	1.56	1.575	1.59	1.583	1.575	
IEA, 1998	-	1.206	-	-	1.372	-	1.469	-	-	-	-	-	-	
UN Population Div, 2002	1.155	1219	1.275	1.321	1.366	1.410	1.446	1.471	1.485	-	-	-	-	
Buen, 1998	1.143	-	-	-	-	-	1.450 1.455 1.447	-	-	-	-	-	-	Source: SPC Tsinghua Univ. World Bank

5.2 Economy

5.2.1 Open door policy

Before 1978, China's economy was centrally planned (Zhou & Sperling, 2001). Its system was to distribute proceeds for business and agriculture to local governments and the people, but this was not always done equally. Zhou & Sperling (2001) mention that some parts of the country received substantially more than other parts, and that the people didn't migrate to follow resources, because of the constraints imposed by the system. The system of local registration allocated housing, jobs, education and other social benefits to individuals according to where they were registered.

China opened its "doors" in 1978, admitting market forces to emerge and allowing foreign investments. This change has led to enormous change for both the economy and the society. The still existing registration system has now less impact on people's economy and social life, because the market system is providing a part of the basic goods and services (Zhou & Sperling, 2001). With the expanding markets, the choices on what is consumed, what kind of jobs are taken and where people live have become far greater (Zhou & Sperling, 2001). According to Zhou & Sperling (2001) many more functions of the planned economy gradually are coming under the control of market forces.

[35] Created through merging Chongqing proper with the Three Gorges basin (Bezlova, 1999)

5.2.2 Gross Domestic Product

Since 1978, China's economy has been growing rapidly. This growth is in contrast to other countries experiencing reforming processes. The national economy, in terms of Gross Domestic Product (GDP), grew by 10% between 1980 and 1999, whereas the industrial growth rate was even higher during that period, with 12.7% per year. Between 1985 and 1995, the per-capita GDP growth rate was 8.3% annually (Gan, 2003). [36] The real income per capita is also increasing rapidly, as inflation is around 5% (1997) (Energy Information Administration, 1997).

Projections of Chinese GDP show that it will continue to increase with 4 to 8% annually. In table 5.2 some of these projections are reflected. Inhabitants of China are now reaching an income level (GDP per capita) att which can afford to buy a car. Rapid growth of motorization starts at an income level of 3000-4000 US$ per capita. See also appendix H.

Table 5.2. Projections of GDP by different studies

		Year													
Item:	**Source:**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Note:**
GDP (billion)	Zongxin et al., 2001	-	709	1104	1549	2172	2839	3710	4849	6338	7711	9382	11414	13887	US$ 1995
GDP per capita	Zongxin et al., 2001	-	585	853	1156	1567	1971	2482	3175	4063	4896	5901	7213	8817	US$ 1995
GDP ppp / cap	Zongxin et al., 2001	-	2930	3780	4542	5422	6069	6775	7555	8347	8958	9586	10203	10845	US$ 1995
GDP ppp (billion)	IEA, 1998	-	3404	-	-	8426	-	13123	-	-	-	-	-	-	US$1990
GDP per capita	IEA, 1998														US$1990
GDP ppp / cap	IEA, 1998	-	2820	-	-	6140	-	8930	-	-	-	-	-	-	US$1990
GDP (billion)	Buen, 1998	376	-	-	-	-	-	3290 3140 3800	-	-	-	-	-	-	Source: SPC Tsinghua Univ. World Bank
GDP / capita	Buen, 1998	330	-	-	-	-	-	2269 2158 2625	-	-	-	-	-	-	Source: SPC Tsinghua Univ. World Bank
GDP (billion)	Energy Information Administration, 2002	427	-	1037	1588	2287	3146	4315	-	-	-	-	-	-	US$1997 reference case
GDP (billion)	Energy Information Administration, 2002	427	-	1037	1730	2654	3911	5693	-	-	-	-	-	-	US$1997 High Econ. Growth
GDP (billion)	Energy Information Administration, 2002	427	-	1037	1343	1669	1988	2338	-	-	-	-	-	-	US$1997 Low econ. Growth

5.2.3 Transportation sector

5.2.3.1 Growth of the transportation sector

Both freight transport and passenger transport have been growing the last few decades. The passenger traffic in China from 1950 till 2001 is represented in figure 5.1. The amount of passenger-km has been increasing exponentially from 24 passenger-km in 1950 till 1219 billion passenger-km in 2001. In this time period the share of road traffic has increased to 54% in 2001, mainly at the expense of rail transport (37%). The same trend holds true for the increase of air transport (8%), which is graving of water transport (1%). This development of the transportation mode split is reflected in figure 5.2 (see appendix I for data).

[36] Experts widely agree that the figures published by China's statistical authorities underestimate the GDP level and inflation, and overestimate the real growth rate. Six often-cited PPP estimates of the size of the GDP (at 1990 U.S. dollar values) range from $1,286 billion to $4,834 billion; they average $2.65 billion, well above the $1.83 billion derived from official statistics.5 (IEA, 2000)

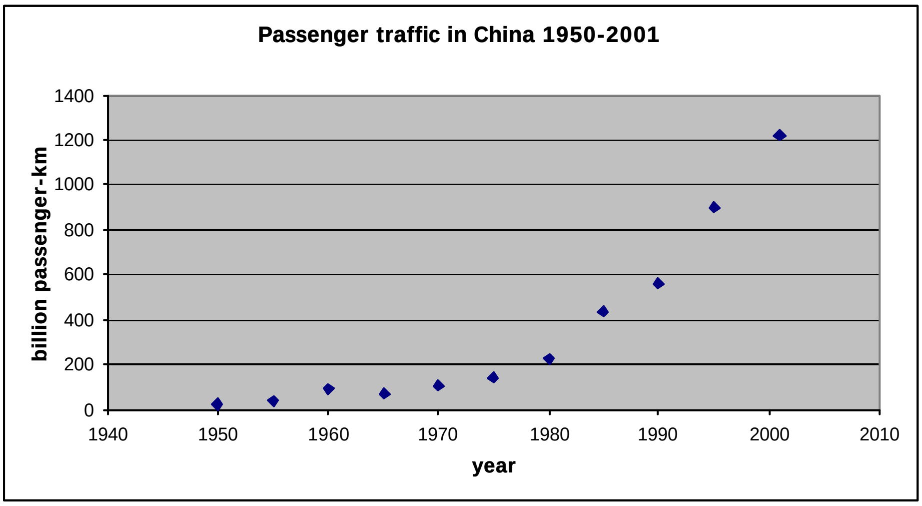

Figure 5.1. Passenger Traffic in China 1950-2001
Sources: The World Bank, 1985 (data 1950-1980); Zhang, 1995 (1985); Lin & Jianhua, 1999 (1990); Zongxin et al., 2001 (1995); National Bureau of Statistics of China, 2002 (2001)

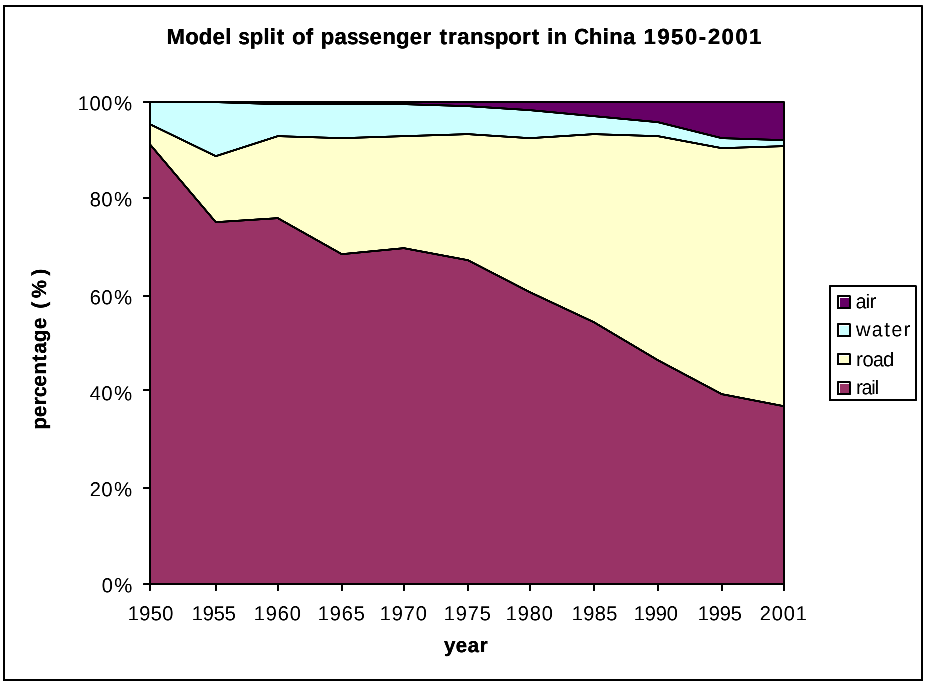

Figure 5.2. Model Split of passenger transport in China 1950-2001
Sources: The World Bank, 1985 (1950-1980); Zhang, 1995 (1985); Lin & Jianhua, 1999 (1990); Zongxin et al., 2001 (1995); National Bureau of Statistics of China, 2002 (2001)

Of the 660 billion passenger-km per year (2000) of the mode *road transport*, roughly 5/6 is bus activity and 1/6 is passenger car activity. The rapid increase of the mode *road transport* is mainly driven by the increased living standards. This increase leads to demand for quality transportation services and convenient and flexible transportation systems. Especially wealthy and middle-class people prefer the use of private cars. This holds true for both industrialized and developing countries (Gan, 2003). In addition, the Chinese government is encouraging private ownership of passenger cars by policies introduced in 1998. These policies include low interest loans and reduced tariffs and fees (Gan, 2003).

In numbers, China's motor vehicles for civil use have been increasing at an annual rate of 12.7 per cent since 1978. Table 5.3 reflects this increase in motor vehicle use for the period 1990-1999. In 1995, China reached the level of 10 million civil used motor vehicles (10.40), of which 4.18 million were used for passenger services, 366,700 for special purposes and 5.85 million for freight transport. Twenty-four percent (~2.5 million) of total motorized vehicles were privately owned motor vehicles. Besides, 20.87 million motorcycles, tractors and other types of motor-driven vehicles were in use

(Chen, Piao & Xiao, 1998). In 1999, there were already 15 million motor vehicles, of which 6 million were passenger cars (Gan, 2003). This is still in contrast to the amount of bicycles in China (around 500 million).

Table 5.3. Average annual increases in registered civilian motor vehicles, 1990-1999

Vehicle category	Avg. growth rate (%)
Passenger vehicles:	19
Privately owned	33
Other ownership	14
Trucks:	7
Privately owned	17
Other ownership	4
Specialty vehicles	7
Passenger Vehicles and Trucks	12
Motorcycles	26

Source: ZTN, 2000 in The World Bank, 2001

Development of road infrastructure lags behind the development of motorized vehicles. Increasing infrastructure (land use for road transportation) may lead to food production uncertainties, as only 7% of the world's arable land is used to feed 22% of the world's population (Gan, 2003). Furthermore it will have high impact on global warming and energy consumption (Hook & Replogle, 1996). In high population density areas, the increasing motorization will lead to even more congestion. Building more roads will not solve the problem of congestion, since new roads make travel less costly than before, which will increase motor vehicle use (Gan, 2003).

5.2.3.2 Automobile industry

The automobile sector is in the middle of rapid transition. Since the "open door" policy from 1978, the demand and related supply of automobiles have been boosted (Gan, 2003). This boost led to a shortage in production capacity, which was ironed out by the Government due to industry-investment such as acquiring foreign technology and stimulating technology development. This has decreased the technological gap between the Chinese automotive industry and the world's leading carmakers (Mu, 2000), but according to Gan (2003) the Chinese car makers have still a remarkably weak R&D-capacity compared to the world leaders.

The Chinese state government has a strong influence in the car industry. Thirteen major companies, controlling 90% of the automotive market, are state-owned (Gan, 2003). The competition among the, in total, 148 automakers is strong. There are three industry groups: First Auto Works, Shanghai Automotive Industry Corp., and Dong Feng Motors (Gan, 2003). Foreign car makers, such as Volkswagen, General Motors (GM), Toyota, Ford, Peugeot Citroen, Nissan, Daimler-Chrysler and Suzuki enter the market by joint ventures. The more luxury automakers, Volvo, BMW and Mercedes-Benz enter the market by first exporting their products to China (Gan, 2003). But there are quotas on the number of cars that could cross its borders, with import licenses needed to legally purchase a foreing-made vehicle. It was the Government's incentive that by the year 2000, domestic production should meet 90% of the demand (Feenstra et al., 2001).

The annual production of motorized vehicles was 1.85 million in 1999 (Mu, 2000), about 10 times as many as in 1981. Of this 1.85 million, around 600 thousand were passenger cars (2001), which is about 175 times as many as in 1981. Average growth rate of passenger cars is around 40% per year (Gan, 2003). China is already one of the leading car-manufacturing countries of the world. Its passenger-car capacity has passed the one million cars per year. The annual production of vehicles and passenger cars from 1981-2000 are presented in figure 5.3 (data: Appendix J).

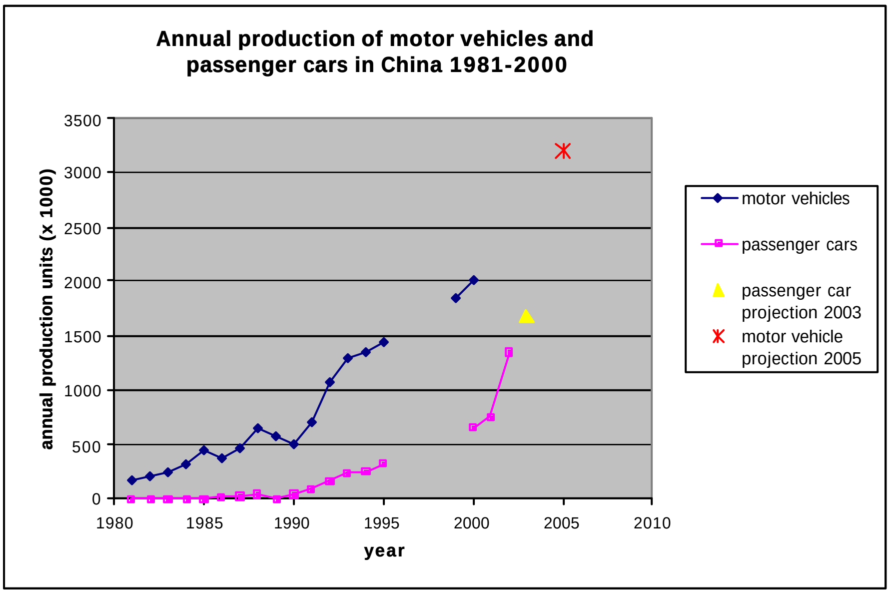

Figure 5.3. Annual production of motor vehicles and passenger cars in China (1981-1995)
Sources: Chinese Automobile Industry Yearbook 1999, p.5 in Mu, 2000 and Gan, 2003

5.3 Technology

5.3.1 Existing car fleet

The number of passenger cars in China amounted approximately six million in 1999 (Gan, 2003), of which almost all of them were gasoline cars. Only a very small fraction were diesel cars and natural gas cars. Taking into account the production numbers of 2000 till 2002 (figure 5.3), the passenger-car fleet should be around nine million at the end of 2002. The Chinese car fleet can be categorised as middle-sized, as the majority of sold cars are Volkswagen Santana's and furthermore the engine class that is produced most in 2000 is 1.6 to 2.5 litre (see table 5.4). An upcoming market is the small car market. VW, Ford, Toyota and GM (Opel) are producing or are going to produce small cars.

Table 5.4. Motor vehicle production in 2000 and total fleet in 1999, China

	Production volume	**Total fleet (units)**
Vehicle total	2,069,069	+/- 15,000,000
Car	604,677	+/- 6,000,000
2.5-4.0 l	46,459	
1.6-2.5 l	367,554	
1.0-1.6 l	62,988	
less than 1 liter	127,676	

Source: CAC China Auto Consulting and CCPIT, 2002 in NAE, 2003

Automobiles, and also other forms of motor vehicles, are mostly old and out-dated. The fuel economy performance (l/100 km) is poor, compared to standards in Western-Europe (10–30% more energy consumption) (Gan, 2003). This holds also true for the emissions: Chinese cars emit 2.5-7.5 times more hydrocarbons, 2-7 times more nitrous oxides, and 6-12 times more carbon monoxide than foreign cars (Gan, 2003). Chinese fuels use unleaded, but high sulphur fuels. A comparison of the fuel consumption of cars in China, the USA and West-Europe is given in table 5.5.

Table 5.5. Fuel consumption reference gasoline car (in l/100km)

	Present	**Note:**
China		
Zhou et al., 2001	9.35	-
USA		
Weiss et al., 2003	7.66	yr 2001, 1300 kg, 100 kW
Weiss et al., 2000	8.46	yr 1996, 1444 kg, 110 kW
Ogden et al., 2003	8.71	100 kW
Dietrich et al., 2000	10.4	end 90's, 1390 kg, 110 kW, 2.8 l
Western-Europe		
Dietrich et al., 2000	7.8	End 90's, 1090 kg, 75 kW, 1.6 l
European Environment Agency, 2002	6.8	2000, new car

Stricter environmental regulations and the strong market competition among carmakers are forcing carmakers to build cleaner and more efficient cars. However, as price is a major determinant for automobile demand, the cost reduction issue can push carmakers to use cheaper products or lower efficiency and emission standards, especially while the emission standard (EURO 1)[37] lags behind the state of the market development (Gan, 2003).

The price of a passenger car differs from region to region. Special fees by the local government can raise the price of a car enormously and this in addition to the taxes and fees of the State Government. Local governments try to have its citizens purchase specific cars. And with success, Shanghai's streets are now full of VW Santanas (Feenstra et al., 2003). Feenstra et al., 2001 mention another example in which the locally produced Citroën Fukang was promoted by the city of Wuhan: non-Fukang car buyers had to pay a special fee up to US$ 8400.
The price of the mostly produced vehicle in China, the VW Santana, is said to be US$22000 (Feenstra et al., 2001). The price of a small car is approximately US$ 10000.

Table 5.6. Price of car in China

	Price	Source:
Medium sized (VW Santana)	22,000 US$*	Feenstra et al., 2001
Small	10,000 US$	Zhou et al., 2001
Luxury car class**	48,190 - 72,280 US$	Gan, 2003

* expected to drop by 25-30% over next 5-6 years
** imported cars?

5.3.2 Alternative Fuels and Technologies in China

Air pollution by motorized vehicles leads to smog in many Chinese cities (Cropper, 2002). To clean up the environment and also to reduce China's dependency on oil, there will be an impulse by the Government to develop clean vehicle technologies. The possibilities for market penetration of these technologies will be increasing as there will be stricter environmental regulations, rising gasoline prices and increasing supply of natural gas (Gan, 2003).

As mentioned in section 3.5, there are different power train options as well as alternative fuels. Main obstacles in China for implementation of alternative fuel technologies and alternative cars are (Gan, 2003):

- the weak R&D capacity within industrial enterprises
- underdeveloped marketing networks
- the infrastructure, i.e. refuelling stations
- reducing costs for technology adaptation
- low rate of technology dissemination

<u>5.3.2.1 LPG and natural gas</u>

Though facing these implementation obstacles some market niches have been found for alternative fuel technologies. Demonstration projects have increased the amount of LPG and CNG vehicles from 5000 in 1998 to 80,000 in 2000 (Gan, 2003). Natural gas filling stations were increased from 40 to around 300 in the cities where these projects were implemented (Gan, 2003; Xiucheng & Logan, 2002), but are mainly subsidized by the Chinese government. Although the market acceptance is wide, adaptation by particular actors is difficult.[38]

<u>5.3.2.2 Fuel Cells</u>

In China, the transportation market is seen as the most important market of fuel cells (UNDP/GEF, 2002). According to Cropper (2002) the initial market for fuel cells will be in replacement of batteries in electric bicycles, while later on buses and car markets will emerge. Electric bicycle sales have been rising strongly since 1997, from 15.000 to 240.000 in 2000, and will be around 1.000.000 units per year in 2002. This is due to the banning of gasoline fuelled scooters and bicycles in several Chinese cities (among them Beijing and China) from 1996 onwards (Cropper, 2002).

[37] EURO standards (I-IV) give the maximum amount of exhaust, in gram per kilometre, per emission-type (NO_x, CO, PM, Hydrocarbons HCs) that a passenger car is allowed to emit. A distinction is made between diesel and gasoline cars. These are set up by the EU for the EU-countries, but are applied in many other countries.
[38] Some taxi drivers complaining about the slow acceleration of the car with the alternative fuel (Gan, 2003)

Different institutes and companies in China are in fuel-cells programs and their application to vehicles. This provides a strong technical foundation and compared to most other developing countries, its research on fuel cell is quite developed and advanced (UNDP/GEF, 2002). Some programs are partly subsidized by the Chinese government. It is investing e.g. 12 million US$ in a three year proton exchange membrane fuel cell (PEMFC) development programme, from January 2002 onwards (Cropper, 2002). A push for fuel-cell vehicle development is also caused by the Olympic Games in Beijing in 2008, while Beijing wants to reduce pollution in the city before the games (Cropper, 2002).

The institutes and universities dealing with fuel-cell related research are (UNDP/GEF, 2002): Changchun Institute of Applied Chemistry, Tsinghua University, Tianjin University, Fudan University, Shanghai University (in cooperation with Beijing Petroleum University), the Beijing University of Science and Technology, Tianjin Institute of Power Sources, the South China University of Technology, the Dalian Institute of Chemical Physics, South-North Institute for Sustainable Development, Newco Developing Center and Nankai University. In addition, the following companies are dealing with fuel-cells research or manufacturing: Bejing Fuyuan Century Fuel Cell Power, Beijing Fuyuan Pioneer New Energy Material, BYD Battery Co Ltd, Dalian Sunrise Power Co. Ltd, Shandong Blue-Sky New Energy Co Ltd and Shanghai Shen-Li High Tech Co Ltd (Cropper, 2002).

Several fuel-cell stacks have been built recently, with an output range of 1 till 15 kW and a PEMFC system. The application of fuel cells in vehicles is under development. From 2000 to 2002, four fuel-cell vehicles have been demonstrated successfully in Beijing and a fuel-cell bus is being demonstrated by the Institute of Electric Engineering of the Chinese Academy of Science (UNDP/GEF, 2002).

<u>5.3.2.3 Barriers for fuel-cell systems in China</u>
As we have seen in chapter 3 and 4, there are still several barriers for the diffusion of fuel cells. For China, these barriers include (UNDP/GEF, 2002[39]):

Technical:
- the need for further development of fuel-cell design and manufacturing technology
- inadequate hydrogen (and methanol) infrastructure
- the need for better storage technology

Economical:
- high initial costs
- continued availability of cheap fossil energy
- limited global demand for clean technologies
- inability to achieve manufacturing economies at current levels of production
- modest institutional capacity*

Social:
- the under-valuation of environmental and other societal benefits
- poor public perception
- low levels of awareness*

Political:
- an inadequate regulatory framework
- contradicting interests of government

5.4 Environment

5.4.1 Energy
With the largest population of the world and rapid economic growth, China has become a new major player in the global energy system and already a large consumer of energy, ranking second behind the United States (Energy Information Administration, 1997).

Coal is China's most important energy carrier. It dominates the primary commercial energy consumption in China with a percentage of 72% (1998), followed by oil (20%) and natural gas with

[39] The points marked with * are added to the list of UNDP/GEF.

2%. Total primary commercial energy consumption amounted 1,360 million tonnes of standard coal equivalent in that year. Coal consumption and supply has been important for Chinese economic growth over the past decades (Kypreos & Krakowski, 2002) and will be a major energy carrier for China in the coming decades. But by converting coal to secondary energy at low efficiency level with little or no emission control, it has led to environmental problems both within and outside China (Kypreos & Krakowski, 2002). Some environmental problems are discussed in the next two sections.

Oil use has been growing the last years with 6.4% annually (1990-1998), compared to 3.3% for coal and 4.1% for natural gas (UNDP/GEF, 2002). With regard to natural gas it can be stated that this will continue to grow till 2015, as China will take greater advantage of its large domestic reserves (Energy Information Administration, 1997). Oil consumption and supply will also continue to increase. In 1998, China was the 7th largest oil producing country, accounting for nearly 10% of non-OPEC oil, but has though been a net importer of oil products since 1992 and of crude oil since 1993 (IEA, 2000). In 1997, imported oil amounted 40 million tons (Gan, 1998; National Statistics Bureau, 2000), where it increased to 65 million tons in 2000. Chinese estimates of future petroleum imports show a significant increase, which is reflected in table 5.7.

This increased demand for oil is mainly caused by the growing transportation sector. This sector accounted for nearly 20% of China's oil consumption in 1998 and relies heavily on oil (UNDP/GEF, 2002). Energy consumption by the transportation sector amounted around 100 billion tons of standard coal in 1995. Of this, about 7% of the country's total was consumed by urban transportation (Chen, Piao & Xiao, 1998).

In general, China's energy consumption can be characterised by 1) a high (but falling) output per unit, 2) an energy use per dollar of gross domestic product (GDP) average that is three times higher as the world, and twice as high compared to all developing countries, but declining and 3) a low per capita consumption, but rising (Energy Information Administration, 1997).
Other issue of China's energy structure is that energy efficiency is low and needs to be improved in all sectors. Besides, industrial processes still require large amounts of fuel in relation to output, which is also valid for motor vehicles.[40] The International Energy Agency (1997) recommends raising the industrial energy efficiency of China to international standards, to achieve a reduction of energy consumption by 30 to 50 percent, indicated by China' Energy Research Institute.

Table 5.7. Chinese Estimates of Future Petroleum Imports (million of tonnes)

	Year			
	2000	**2010**	**2020**	**2050**
Demand	200	260	320	520
Domestic Supply	155	165	180	80
Deficit	45	95	140	440
Deficit met by:				
Substitution fuels	--	10	51	280
Oil imports				
*projections 1996**	45	85	89	160
*projections 1999***	35	60-75	130	--

* RPC (1996) *China Energy Strategy Study (2000-2050),* Beijing
** *China Oil, Gas and Petrochemicals Newsletter,* Vol.7, No. 24, 15 December 1999, p.1
Source: IEA, 2000

[40] Motor vehicles burn excessively large amounts of gasoline or diesel fuel relative to their size, power and capacity (IEA, 2000)

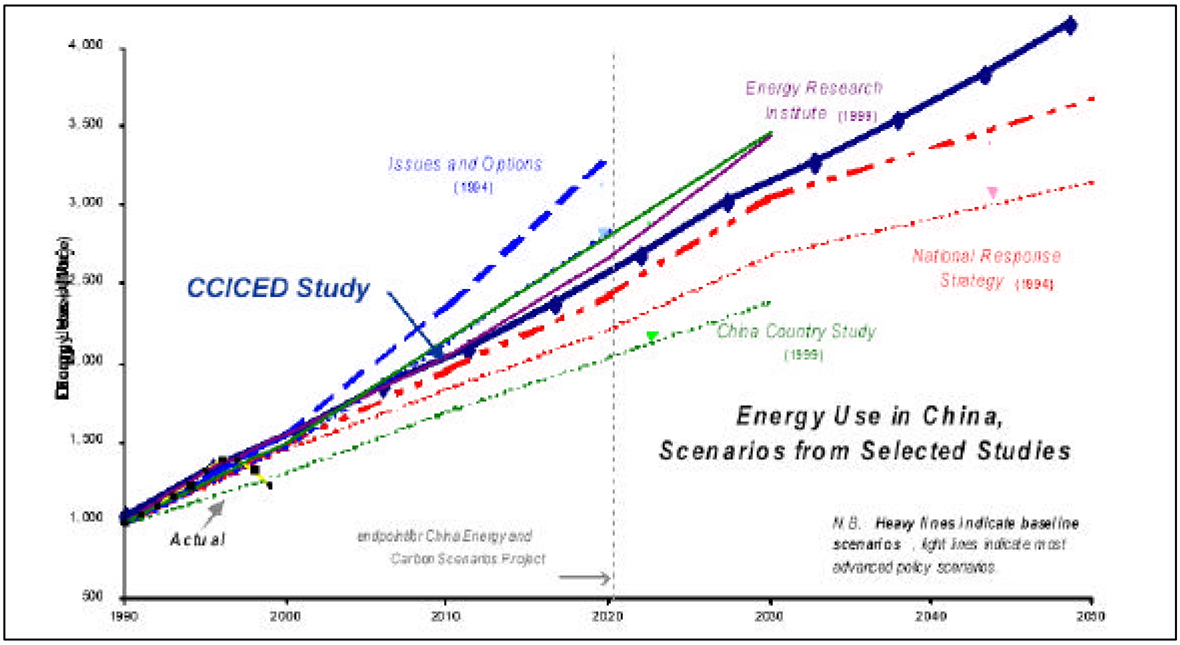

Figure 5.5. Comparison of Various Energy Demand Projections for China (see also appendix K)
Source: Zongxin et al., 2001

5.4.2 Emissions

"Some Chinese cities are so swathed in smog that they become virtually invisible on satellite photographs for long periods." (Ogilvy and Schwartz, 2000)

Air pollution is a major environmental problem in China. In table 5.9 the sulphur oxides (SO_x), nitrous oxides (NO_x), particulate matter (PM), ammonia (NH_3) and carbon dioxide (CO_2) emissions of 1998 are presented. These emissions are mainly caused by inefficient burning of fossil fuels. Coal, for example, has a high sulphur content and besides it is not only used in the power sector but also for cooking. With increasing population, rapid economic growth and without strict environmental regulation these numbers will increase dramatically. Already, the years of life lost per year caused by outdoor pollution in China is 9.1 million (Hirschberg et al., 2001). Hirschberg et al. (2001) also state that the total damage costs (health effects and damage to crops) are 6-7% of Gross National Product (GNP) for China.

Particular in cities with high population density the pollution is very high, as we see in table 5.8 and then compare these numbers to the World Health Organization's (WHO) annual mean guidelines for air quality standards: 90 µg/m^3 for total suspended particulates, and 50 µg/m^3 for sulphur dioxide and nitrogen dioxide (Gan, 2003). Exhaust pollution from automobile use is one of the major sources (Gan, 2003).

Table 5.8. Air pollution indicators for major cities in China (microgram per cubic meter)

City	Population in millions (2000)	Total suspended particulates (1995)	Sulphur dioxide (1998)	Nitrogen dioxide (1998)
Tianjin	9.1	306	82	50
Chongqing	5.3	320	340	70
Wuhan	5.2	211	40	43
Shenyang	4.8	374	99	73
Guangzhou	3.9	295	57	136
Harbin	2.9	359	23	30
Zibo	2.7	453	198	43
Jinan	2.6	472	132	45
Guiyang	2.5	330	424	53
Taiyuan	2.4	568	211	55
Zhengzhou	2.1	474	63	95
Lanzhou	1.7	732	102	104
Urumqi	1.6	515	60	70
WHO standard	-	*90*	*50*	*50*

Source: The World Bank, 2001 in Gan, 2003

Table 5.9. Emissions in China in 1998

	SO_x (kt/yr)	NO_x (kt/yr)	PM (kt/yr)	NH_3 (kt/yr)	CO_2 (Mt/yr)
China (all sectors)[a]	22,500	11,184	27,740	11,499	~ 3,000
World [b]					23,444

[a] Source: Hirschberg et al., 2001
[b] Source: IEA, 2002

5.4.3 Shortage on (clean) water

The water availability of, and quality in rivers, lakes, and groundwater dropped in the last decades. This holds especially true for the northern part of China (The World Bank, 2001; Shell International, 2001). More than 80 percent of surface waters are polluted, forty percent of urban drinking water supplies are below-standard, and three quarters of the largest cities are expected to be short of water by 2000 (Ogilvy and Schwartz, 2000). In the next decades, the problems of municipal wastewater discharges, but also of agricultural and industrial wastewater will require decisive action (the World Bank, 2001).[41]

5.5 Politics

The huge population, the rapid economic growth, combined with high energy demands and low energy efficiency have led to serious environmental problems. Local emissions e.g. have caused smog in (mega-)cities. The Chinese government has therefore prioritized climate impacts in its policy agenda (Gan, 2003). In this section the government's goals and policy issues are discussed briefly.

The Government's *Overall Goals* are to (UNDP/GEF, 2002):

- reduce urban air pollution;
- climate change policies, which include poverty eradication, enhancement of food security, and economic development;
- reduce greenhouse gas emissions in the energy sector.

These overall goals are transformed into national laws and regulations. In the *Constitution of the People's Republic of China (1982)*, article 26 proscribes that "The state protects and improves the environment in which people live and the ecological environment. It prevents and controls pollution and other public hazards," and Article 9 proscribes that "the state ensures the rational use of natural resources and protects rare animals and plants. Appropriation or damaging natural resources by any organization or individual by whatever means is prohibited." (UNDP/GEF, 2002). Furthermore, there is the *Environmental Protection Law (1989)*, which is a basic law of environmental protection in China and is central to the whole system of environmental law since it makes comprehensive prescriptions in principle on the important environmental protection issues. (UNDP/GEF, 2002). Lastly to mention, the *Law on Prevention and Control of Atmospheric Pollution* (revised in 2000) deals with road pollution. Article 34 in chapter *Preventing and Controlling Vehicle Pollution* claims that "the government encourages the production and consumption of clean fuel vehicles." This has led to six or more specific national standards to air pollution for different types of road vehicles (UNDP/GEF, 2002).

In addition, the provinces or municipalities can formulate laws and regulation themselves. Beijing, one of the mega-cities, has released six standards on the control of air pollution and these are set stricter than the national standards (UNDP/GEF, 2002). Shanghai, another mega-city, has enforced several laws, regulation and emission standards since 1980. Among them also the special regulations for urban road construction, applications of clean fuel automobiles and public transportation (UNDP/GEF, 2002).

Initially, eighteen cities and provinces banned leaded gasoline in 1998, which was later on expanded by the State Counsel to 46 cities (1999). Since 1 July 2000, the use of leaded gasoline has been banned by the government for the whole country. Gasoline producers are not longer allowed to produce leaded gasoline and the car manufacturers are required to install catalytic converters and electric-ignition systems in all newly produced cars (Gan, 2003). On the other hand, the sulphur content (in parts per million: ppm) in both gasoline and diesel is still high. Although the sulphur content standard for gasoline has been upgraded from 1200 ppm to 800 ppm by January 2003 (Green

[41] These water issues do not only play a role in China, but in many developing countries and is actually a global issue. See for example Young, Dooge & Rodda (1994). *Global Water Resources Issues*. Cambridge University Press.

Diesel Initiative, 2000), this is still much higher than in Europe (<150 ppm). The sulphur content in Chinese diesel is even worse (average 3000 ppm) (Green Diesel Initiative, 2000), compared to 350 ppm in Europe. For diesel there are not even sulphur content standards. So it can be concluded that the fuel quality (high sulphur content) and implemented emissions regulations (EURO-standards), as described in section 5.3.1, are not drafted together.

But the incentives to control air pollution and climate change are in contradiction with the encouragement of private car ownership by low interests loans and reduced tariffs and fees to stimulate economic development (Gan, 2003). Furthermore, there will be inefficient allocation of resources and inequities between motorists and other users, if road transport systems are being developed through general taxes rather than being paid by motorists through fuel taxes or vehicle registration fees (Gan, 2003).
It is therefore necessary to come to a balanced policy (framework) for emission control, but not without satisfying transport demand for both the poor as the more affluent social groups.

Long term policy of the Chinese government with regard to the automobile industry is unclear. In the short run, Euro 2 and 3 emission standards will be introduced, first in some municipalities and later on in the whole country (Gan, 2003). In addition, import tariffs for passenger cars (now 80-100%) will be reduced (Feenstra et al., 2001).

5.6 Conclusion
We can conclude the following from this chapter:

- A growing population in absolute terms and increasing population density (especially in the cities). This consecutively leads to a growing energy demand, an increase in transportation demand and higher emission levels in the short run.

- Projections of GDP show a growth of 4-8% annually over the next 20 years; the country is developing and a certain amount of people are reaching an income level at which they can afford to buy a car. Motorization is expected to grow rapidly.

- China heavily depends on its coal resources. Natural gas supply is increasing as well as oil supply. Since 1993, China has been a net importer of oil and the dependency on oil imports is expected to grow in the coming decades, especially if gasoline and diesel will be the fuels in the expanding passenger-transportation sector.

- Air pollution, especially in the large cities, is a major environmental problem. This has already resulted in lots of casualties. Without proper measures, the air pollution in China will be a disaster, not only for the country itself but also for the rest of the world. In relation to the air pollution stands the water quality (and availability). It is assumed that shortage on clean (drinking) water will be first encountered in the Northern part of China and in the large cities.

- The automobile market is maturing and booming. Produced cars don't have state of the art technology, but fuel efficiency is increasing and cars emission levels are decreasing. Car manufacturers are introducing small cars on the market, where present vehicle class is middle-sized. Certain developments are going on with regard to alternative fuels and powertrains. Demonstration projects have increased the amount of LPG and CNG vehicles from 5000 in 1998 to 80,000 in 2000. Some universities, institutes and companies are working on the development of fuel-cell vehicles and a fuel-cell bus demonstration project is planned for 2003/2004.

- The local and national government have a strong influence on the automobile industry, as there are state-owned car manufacturers, import tariffs etc. They have contrary incentives, stimulating car ownership on the one hand (a push for the automobile industry) and stricter environmental regulations on the other hand. Besides, environmental regulations for cars lag behind the state of market development.

All points are all related to the diffusion of fuel-cell cars in China, as shown in the next chapter.

6. Listing and ranking of key factors and driving forces

In the previous chapters the key factors and driving forces that influence the diffusion of fuel-cell cars in China were mentioned randomly. In the first part of this chapter all the key factors and driving forces are listed systematically, by summing them up by issue (technology, society, economics, politics and environment). Subsequently, each trend or development is ranked by importance and uncertainty. This is step 6 of the methodology. Out of this ranking, several scenarios can be generated, which is step 7 of the methodology. This generation is based on the three driving forces that are most important and most uncertain. Thus, this chapter answers the (5th research-sub) question what the key factors and driving forces behind the diffusion of fuel-cell cars in China are, and which scenario-axis can be formulated on basis of these key factors and driving forces?

6.1 Key factors and driving forces

In this section all the key factors and driving forces will be listed systematically and briefly discussed. Each key factor and driving force is clustered in one of the following categories: *technology, society, economics, politics* and *environment*. Per item it will also be mentioned, whether this key factor or driving force influences the diffusion of fuel-cell cars worldwide or only in China.

6.1.1 Society

Growing population

A growing population in absolute terms and increasing population density (especially in the cities) (see section 5.1.1), leads to a growing energy demand and to higher emission factors in the short run. A growing population leads to more transportation demand, partly fulfilled by passenger car transport.

In an expanding market, there might be room for alternatives. Besides, in a young, not saturated market, the balance of power (gasoline and diesel cars versus alternatives) might not be so strong as it is in Western-European countries and in North-America.

Trend or development: China

(International) Crises

The oil crisis in the seventies led to political awareness of the consequences of fossil energy use. Such crises and also other crises (caused e.g. by wars, political instability) can have a serious impact on Government's policy and public awareness.[42] Environmental issues, for example, can have higher or lower importance than other issues, which result in other demands for products. In case of an environmental crisis, alternatives (e.g. such as hydrogen fuel-cell cars) are put on the agenda. In cases of, for example, war or political instability, environmental issues are not put on the agenda.

Trend or development: Global

Willingness of car manufacturers and oil companies to invest in a hydrogen infrastructure

The diffusion of fuel-cell cars, and also of other alternative powertrains, is closely related to the development of the accompanying infrastructure. (New) Refuelling stations or pumps have to be built and pumps have to be transformed (converted). Besides, fuels have to be produced and have to be delivered to the pump. New plants (centralised or decentralised), new pipelines, new delivery trucks may have to be produced.

As mentioned in section 3.4.3.3 and 3.6 and 4.2.1, oil companies will only invest in new fuelling stations, if there are sufficient numbers of fuel-vehicles on the roadways. On the contrary, market sales remain low when there are only a few refuelling possibilities, which consequently blocks large market penetration. Car manufacturers will only produce if there is a certain demand for the fuel-cell cars. Customers will not buy these cars if the reachability of the refuelling stations is poor. Thus, the willingness of the car manufacturers and the oil companies play an important role in the diffusion of fuel-cell cars.

[42] See Ogilvy & Schwartz (2000)

In China, however, the situation is different. The large oil companies are state-owned, although liberalisation of the market is takeing place. The state still has some control over the policy of the companies, which could influence the policy towards new refuelling stations. Besides refuelling station infrastructure is in a young stage yet, which leaves opportunities for alternative fuels.

Trend or development: Global

Growing environmental awareness
Public concern is growing and this has succeeded in increasing pressure on the government to tighten environmental regulation policies. But still, as mentioned in section 5.3.2.3 a barrier for fuel-cell cars in China is the poor public perception and lack of awareness.

Growing public concerns and awareness will lead to stricter environmental regulations and to changes in customer's (car) demand or preferences. This might favour fuel-cell car diffusion.

Trend or development: China (also global)

Reducing hydrogen storage concerns
As mentioned in section 3.4.4, the car customers and the public in general are reserved about the use of hydrogen. The fears and risks are caused by the unfamiliarity of hydrogen and the Hindenburg and Challanger accidents.

Necessary condition for the diffusion of hydrogen fuel-cell cars is that hydrogen safety concerns are overcome. This can be done by spreading information and starting training programs.

Trend or development: global

Increasing customer preferences: design freedom
In highly industrialized countries the income has reached such levels that other issues than only the price play a role in the choice of the customer on which car he/she is buying. Issues such as passenger space, comfort and convenience, and exterior styling become more important (DeCicco, 2001). Potential buyers are willing to pay a bit more for extra accessories.

The fuel-cell car has in this respect a major advantage. Fuel-cell powertrain systems enable the use of flat chassis, which gives the designers of cars freedom to create unique body styles. The mechanical systems for steering, braking, throttling and other functions with electronically controlled units can be replaced by the integration of the fuel cell with drive-by-whire technology (electronic systems are less bulky than mechanical ones) (Burns et al., 2002).

The design freedom is thus a great challenge to satisfy (increasing/changing) customer needs.

Trend or development: Global

6.1.2 Economics

Increasing price of oil
The price of oil has increased over the last 30 years. Consequently, the variable costs of passenger car use have become higher. However, this increase has not led to a large decline in the passenger car traffic volume (price elasticity is small), although customers require acceptable fuel prices.

Nevertheless, a very high price increase of gasoline and diesel might benefit the use of alternative fuels and alternative powertrains. The higher price of the alternative powertrain will than be paid back by the lower variable costs.

Trend or development: Global

Growing GDP
Projections of GDP show a growth of 4-8% annually over the next 20 years (see section 5.2.2); the country is developing and GDP per capita has come to a stage where (a certain amount of) people

can afford buying a car. It is assumable that vehicle ownership (cars/1000 inhabitants) will increase rapidly in the coming decades, with increasing GPD, as has occurred in other countries.[43]

Thus, a rapid diffusion of cars will take place in the coming decade and as the car market is not saturated yet, there will be room for "alternative" technologies.

Trend or development: China

Decreasing investment costs of FCs
At the present, costs of fuel-cell systems are still too high, so that fuel-cell cars are not able to compete with the traditional cars (see section 3.4.5). The diffusion of fuel-cell cars is blocked partly by these high investment costs. Diffusion of fuel-cell cars will take place when the costs are lower; on the other hand costs will become lower as diffusion takes place (learning effect, economies of scale).

Shell International (2001) assumes that the diffusion of fuel cells in China will take place, once fuel cells will take off in OECD countries. Therefore, China can profit from the development that will take place on a global level.

Trend or development: Global

Blocking of foreign cars
China is blocking the import of foreign cars. Import tariffs, which are up to 80-100% for passenger cars, block technology from foreign countries and protect the national companies. Besides, there are import licensing requirements: the quotas vary by year on number and value of imported vehicles. Moreover, foreign enterprises can not import motorized vehicles directly. In addition, distribution, retail, and after sales service is going by Chinese companies (Feenstra et al., 2001).

In the current situation, the above mentioned issues will form a barrier for the introduction of fuel-cell cars in China, because it is likely that the technology has to come from abroad, as Chinese research and manufacturing capabilities are too low to produce low costs fuel-cell cars.

Trend or development: China

6.1.3 Technology

Improving efficiency (engine, fuel cell)
As mentioned in section 3.5, a major challenge for car manufacturers is to produce propulsion systems with a higher efficiency. This is sometimes stimulated by the national governments, but producing cars with a higher efficiency is also a way of competition between car manufacturers (e.g. commercial of the Volkswagen Lupo: 3 l per 100 km).

As fuel-cell cars have a higher efficiency than the traditional cars, a shift towards higher efficiency cars can have a positive effect on the diffusion of fuel-cell cars. But with increasing efficiency of the conventional cars and the hybrid cars this advantage is declining.

Trend or development: global

Lower car emissions
As mentioned in section 3.5 and 5.3.1, automobile manufacturers are developing new less polluting cars, either by improving the currently produced cars or by developing new cars, with alternative fuels and alternative propulsion systems.

[43] See e.g. 1) Ingram, G.K. & Liu, Z. (1999). *Determinants of Motorization and Road Provision*. Research Advisory Staff and the Transport Division, Transport, Water, and Urban Development Department. The World Bank; Washington D.C. (USA). Http://www.worldbank.org/html/dec/Publications/Workpapers/wps2000series/wps2042/wps2042.pdf. Accessed on 12-02-2003; 2) Dargaya, J. & Gately, D. (1999). *Income's effect on car and vehicle ownership, worldwide: 1960-2015*. Transportation Research Part A (33). Pp. 101-138; and 3) Schafer, A. & Victor, D.G. (2000). *The future mobility of the world population*. Transportation Research Part A (34). Pp. 171-205

Fuel-cell car emissions are very low or even zero, so the development of fuel-cells cars is a way to meet low car emission demand, but with declining car emission levels of the competitors of fuel-cell powertrains the relative advantage of fuel-cell powertrains declines.

Trend or development: global (and China in particular)

Solving contamination and storage problem
We have seen that the fuel-cell car is neither technological nor economical competitive yet in relation to the conventional cars. Two technological problems have to be overcome. The first is the hydrogen storage, as mentioned in section 3.4.1 and 3.4.4. Secondly, only pure hydrogen can be used for PEM fuel cells, so any form of contamination has to be solved.[44] Before the diffusion of these cars can start, these problems have to be solved.

6.1.4 Environment

Increasing energy demand and supply
How will China meet its energy demand in the coming decades? With the largest population of the world and rapid economic growth, China has become already a new major player in the global energy system and a large consumer of energy and this will continue to increase.

New energy infrastructure for energy supply, e.g. natural gas and hydrogen pipelines, will have a positive impact to reduce some of the barriers that “alternative” cars face.

Trend or development: China

Shortage on fossil fuels
The proven and exploitable oil reserves can meet our energy demand of circa 50 years (+gas reserves of 60 years). According to Shell International (2001) there will be no energy resource scarcity before 2025 (see also section 4.2.1). However, after 2025, the limited resources of fossil energy carriers (oil & gas) are a driving force behind the changes in the energy systems (Shell International 2001.

The demand for alternative fuels will increase in the coming decades if we want to meet the increasing energy and transportation demand. This need will indirectly influence the diffusion of fuel-cell cars.

Trend or development: Global

Shortage on water
As mentioned in section 5.4.3, Chinese urban drinking water supplies are often below standard. Especially in the northern part of China and in large cities, access to clean drinking water is starting to become problem. Also globally, these issues play an important role in developing countries.
The residue of the fuel-cell process is water. The water can be intercepted and used for different purposes.

Trend or development: Global

6.1.5 Politics

Stimulating car ownership (car industry)
Development of the vehicle industry is one of the most important priorities for industrial growth in China. As mentioned in section 5.5, China has a strong influence on the car industry. Most car manufacturers are state-owned. China's government is stimulating car ownership, to give positive impulses to the car industry.

The way the Chinese government stimulates car ownership influences the diffusion of (fuel-cell) cars. If a policy measure is applied to all types of cars (e.g. a subsidy), the fuel cell probably does not profit from this measure, because the cost of the fuel cell remains higher. But when the government

[44] This has also a positive impact on the efficiency of the fuel cell.

applies, for example, subsidies to cleaner cars and fees to others, the cost competitiveness of fuel-cell cars (and other alternative types) improves, which might have a positive impact on the diffusion of fuel-cell cars.

Trend or development: China

Increasing dependency on foreign energy suppliers
As mentioned in section 5.4, China has become a net importer of oil since 1993. The increased demand for oil is mainly caused by the growing transportation sector. This sector accounted for nearly 20% of China's oil consumption in 1998 and relies heavily on oil (UNDP/GEF, 2002).

In the case that China does not want to depend heavily on foreign energy suppliers (see Zongxin et al., 2001) and thus wants to be highly self-sufficient, the demand for alternative fuels can increase and this might favour the diffusion of fuel-cell cars.

Trend or development: China

Increasing emissions control
One of the big problems is the air pollution in China, especially in the mega-cities (see section 1.1 and 5.4.2). CO levels and ozone concentrations exceed nationally specified limits, mainly due to coal combustion and vehicle exhaust emissions. The consequences are already high: respiratory illness, caused by vehicle air pollution, accounts for 14% of all deaths in urban areas in 1998 (United Nations Development Programme / Global Environment Facility, 2002).

Emission can be controlled by various policy measures. Three of such measures are:

- Stricter environmental regulations with regard to emissions of cars
As mentioned in section 5.5, China's Government has put stricter environmental regulations on cars (EURO I standards in 1999) and banned leaded gasoline (but still high sulphur content). EURO-standards II and III will be implemented in the coming years, and other regulations could be implemented in the future.

These regulations push for better and cleaner technology and thus might favour the low or zero emission fuel-cell vehicles.

- Putting taxes on emissions (externalities)
In a recent OECD report, it is estimated that the external environmental costs of road transportation and aviation could amount to 8% of GDP in OECD European countries (Gan, 2003). These external costs are only the impacts from road transportation operations. If the costs of vehicle production and maintenance, construction of infrastructure, fuel production and distribution, and disposal of used vehicles also are taken into account, i.e. the costs of the whole life-cycle, then would this add 15-30% additional costs to the operational costs (Gan, 2003). So, if the "true costs" are taken into account for the use of cars, it is likely that powertrains other than the conventional ones will become more cost competitive. By putting taxes on emissions, external costs can be internalised.

As mentioned in section 5.5, the long term policy of the Chinese government with regard to the automobile industry is unclear. Putting taxes on emissions could be an option for the Chinese Government to favour cleaner technologies (e.g. fuel-cell cars).

- Bounds on emissions
Most countries have set targets / committed themselves to reduce their emission levels (e.g. Kyoto protocol). Such emission bounds can also be set by the Chinese government, not only on national level but also on local level or on the transport sector level.

Such bounds should stimulate product development or even product substitution. Fuel-cell cars can make a contribution to meet the (transportation sector) targets.

Trend or development: China (and global)

Increasing regional influence
The strong influence of the local government is mentioned in section 5.3.1 and 5.5. At the moment, their regulations and targets with regard to automobile emissions are stricter than those of the state government. Besides, they have the power to stimulate certain types of car (e.g. the streets of Shanghai, filled with Volkswagen Santanas). The policy of the local governments, with regard to passenger cars (automobile industry), will have the first influence on the automobile market.

Positive results with alternative fuels and powertrains in some cities can have a positive impact on new projects in other cities and region. A niche market can be created, which is the first step in getting to larger scale sales of fuel-cell cars.

Trend or development: China

Development of public transport means (e.g. high speed trains)
As mentioned in section 3.6, the car (regardless of its powertrain) competes to a certain extent with the plane, the train, the bus and the bicycle. Development of the public transport sector in particular, influences the diffusion of cars negatively and thus the diffusion of fuel-cell cars. This development can make the use of public transport more attractive than the use of a car. This holds especially true in areas with (very) high population densities, where congestion problems by automobile increase may favour faster public transport modes.

Trend or development: China

6.2 Ranking of key factors and driving forces
By having listed the factors and driving forces, the next step is to rank these factors and forces on importa nce and uncertainty, with regard to the diffusion of fuel-cell cars in China. For all trends and developments a score between 0 and 10 is given on the aspects of *importance* and *uncertainty*. A score of zero stands for not important/very certain and a score of ten for very important/very uncertain. In table L.1 of appendix L the scores for each item are presented and in figure 6.1 the ranking is presented schematically. This ranking is step six of the methodology.

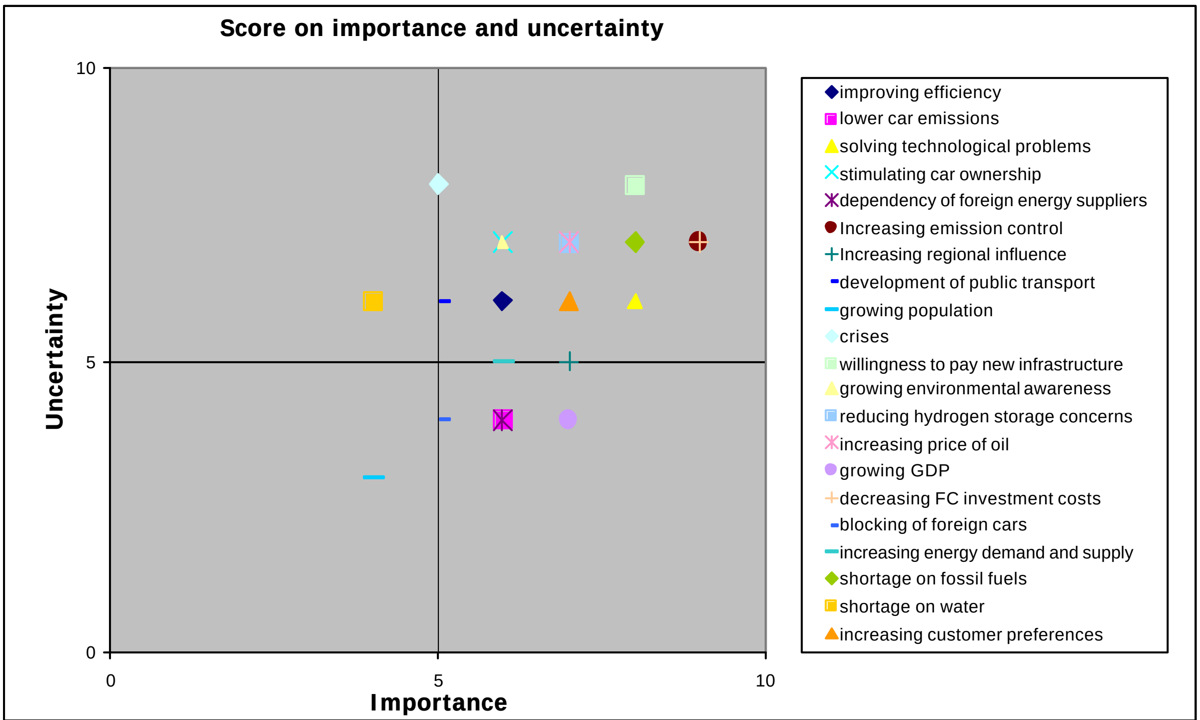

Figure 6.1. Ranking by importance and uncertainty

The ranking process is a highly subjective business. A possibility, to get a relatively plausible ranking, is to carry out a survey. The ranking of the driving forces on importance and uncertainty can then be based on statistical data (see Poot, 2002). However, due to time restrictions it was not possible to do such a survey in this research. In this research, the scores on importance and uncertainty are based on an extensive literature study (which is said to be relevant in literature). This literature study contained an analysis of, primarily, articles in scientific journals, university and institutes reports, consultancy reports, and companies' publications (e.g. Shell).

Decreasing fuel cell costs form a necessary condition for the diffusion of fuel-cell costs, because otherwise it would not be cost-competitive in relation to the internal combustion engine. Besides, the interest in fuel cells is powered by the environmental policy of the government. Without environmental policy, the incentives for companies to invest in clean technology are lower. Therefore these forces are ranked the highest on importance. Also on uncertainty, they have high scores. The environmental policy in China is not of major importance yet, and despite some incentives, there is no real sign yet that this will change radically in the coming years. With regard to the price of fuel cells, the questions remain whether it will go down to the level at which large-scale utilization of technology becomes attractive, but also when? Especially for China, the diffusion of fuel cells is related to the diffusion of this technology in industrialized countries. Besides, this price reduction is closely linked with hydrogen/methanol infrastructure. Therefore the willingness of the fuel companies to pay new infrastructure is ranked high on importance and uncertainty.

As concluded in chapter three, hydrogen storage problems and contamination of the fuel remain technological bottlenecks, though the fuel-cell car prototypes show improvement. That is why 'solving technological problems' is ranked slightly lower than the previous points. The same holds true for 'lower car emissions', but here the uncertainty is lower, because of the results achieved by car manufacturers in Western Europe, North America, and Japan. The forces 'growing GDP' and 'dependency on foreign energy suppliers' (especially in the coming decade) also have low uncertainty, which is supported by the fact that they have been listed and projected in many reports.

Regional influence is important, especially in the early stages of market introduction, for the forming of niches, but the uncertainty is less high, because we have seen the results of regional influence in some mega-cities (section 5.3.1). In the same line of importance (value seven) are 'shortage on fossil fuels' and its related 'price of fossil fuels'. Shell International (2001) has stated their (at least the energy resource scarcity) importance and uncertainty in the world-energy scenarios. Two other important and related forces ('increasing customer preferences' and 'reducing hydrogen storage') deal with the acceptance of the fuel-cell car by the customers. The importance of such acceptance can be indicated by, for example, the failure of electric cars in California.

The force 'improving efficiency' has not a high score on uncertainty because of the continuous improvements of fuel cells and conventional engines over time. But how the difference in efficiency is between the fuel cell and the conventional and hybrid powertrain is has a higher uncertainty. This difference determines the relative advantage of fuel cell powertrains compared to conventional engines and hybrid powertrains, and is therefore of certain importance but not ranked the highest, because fuel economy is not first customer's consideration (see section 4.2.4).

The occurrence of (international) crises is obviously uncertain (not predictable) as well as the impact of these crises on the diffusion of fuel cells. Crises such as war or political instability will put off environmental issues in some agenda's, but environmental crises will put such issues on the agenda.

That the Chinese government is stimulating car ownership has been indicated in chapter five. How the Chinese government will stimulate car ownership in the future is, however, uncertain. The importance is present if the Chinese government stimulates fuel-cell car technology financially (this may stimulate niche forming), but normally such stimulations are temporarily.

Energy demand and supply is going to increase (so low uncertainty) as shown in figure 5.5, due to increasing population and growing GDP. How the increasing energy demand will be filled in, i.e. by which technologies is more uncertain, although the use of coal technologies is naturally. Its importance lies in the side effect that the use of hydrogen power plants and the construction of hydrogen and natural gas pipelines can have on fuel cells in the transportation sector.

Increasing environmental awareness will lead to more public pressure, and changing customer preferences. The uncertainty lies in the question whether environmental awareness will increase till such a level (i.e. power of public pressure) that this will lead to radical environmental changes (see also Tijink, 1999). Its impact will be stronger in a liberalised country than in a communistic country.

The growing population is a demographic development, with low uncertainty. Schwartz (1991) calls this 'in the pipeline' force. The force 'blocking foreign car' has both a low importance and a low uncertainty, because of the intention of China to enter the World Trade Organization (Feenstra et al., 2001).

6.3 Scenario generation

Out of this ranking some scenarios can be generated. Poot (2002) mentions four criteria for choosing the driving forces for scenario generation:

1. high score on both importance (impact) and uncertainty
2. a trend should be able to develop in two opposite directions
3. not too narrow; driving forces should cover some space, enough to put in some ideas
4. driving forces should be independent, no overlap between the trends.

I add another criterion to this list, which is related to the use of MARKAL (see third column of table L.1 in appendix L):

5. Out of the driving force a scenario should be designed, which can be served as input for MARKAL.

Not all driving forces can be used to generate scenarios in (plain) MARKAL. Input data for MARKAL is restricted to energy data (e.g. demand, supply, capacity), environmental data (emissions) and economical data (fuel prices, investment costs, O&M costs, discount rate, taxes and subsidies). Influences such as customer preferences or shortage on water can not be transformed into input data for MARKAL. The applicability of a driving force as input for MARKAL is indicated in appendix L.

As the most crucial driving forces can not always be used directly as a scenario(-axis), it might be that the driving force has to be reformulated or that a few driving forces will have to be taken together to form a scenario(-axe).

After having analysed the scores on both importance and uncertainty, three crucial clusters of driving forces can be derived, which have high scores on impact/importance and uncertainty. The first cluster contains these driving forces that have to do with the role of the government (bounds and taxes on emissions). The second cluster of driving forces deals with technology development (higher efficiency, new technologies), which also includes the necessary infrastructural development. The third cluster contains the forces shortage on fossil fuels (after 2025) and the price of oil. The first two forces correspond (coincidentally) approximately to the key driving forces behind changes in world-wide energy systems as described in Shell international (2001)

Both clusters of crucial driving forces will be the scenario-axes:

- Technological development: low versus high
- The role of the government with regard to environmental policy: no emission restrictions versus high emission restrictions
- The price of fossil fuels: "normal" (increase) versus high (increase)

With "normal" prices, we mean the prices that were already added into the database of Zongxin et al. (2001).

The following matrix with the different scenarios can be designed:

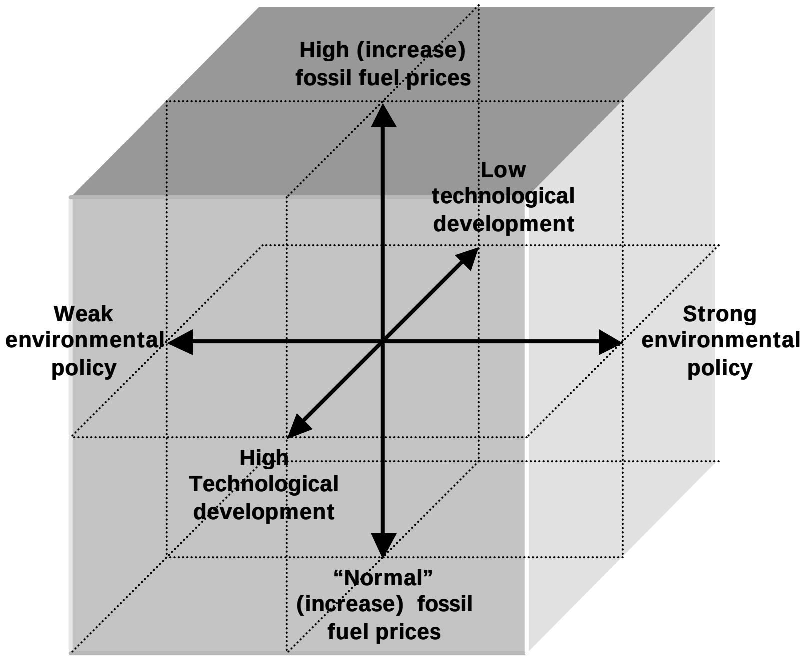

Figure 6.2 Three scenario-axes; eight scenarios

Poot (2002) states that the axes should be independent from each other. This independence is hard to realise, as forces are sometimes related to each other (they actually form clusters of forces). Environmental policy creates a boundary wherein technological development could take place or even accelerate, but such policy is not always necessary. Instead, in Western Europe and North America the idea holds that a liberalised market (less government intervention) stimulates innovations. Besides, environmental policy will adjust to technological development and increasing fossil-fuel prices.

Although technological innovations could reduce the pressure on fossil fuels to some extent, for example by the use of new exploitation techniques and high-efficiency technologies, and therefore influence the price of fossil fuels, the (cost) price itself is determined on the world market (influenced by many other factors). The same holds true for environmental policy, which can have their influence on the price of fossil fuels (e.g. taxes on fuels).

Despite the fact that the forces are to some extent interrelated, the forces can form individual axes, because they are not always related directly to each other and encompass enough possibilities to put in (new) ideas.

In chapter two, it is discussed that maximum four scenarios should be worked out, and with three axes, there are, in total, eight scenario possibilities. A first analysis with MARKAL shows us, however, that if the diffusion of fuel-cell cars in China is to set off, high technological development is a necessary condition. Therefore, we reduce the amount of scenarios till four by keeping out the scenarios with low technological development (see figure 6.3). It can be argued that by doing this we might not get an complete view of possible future car fleets in China, but as the aim of the research is explicitly to explore the diffusion of fuel-cell cars, this can be justified.

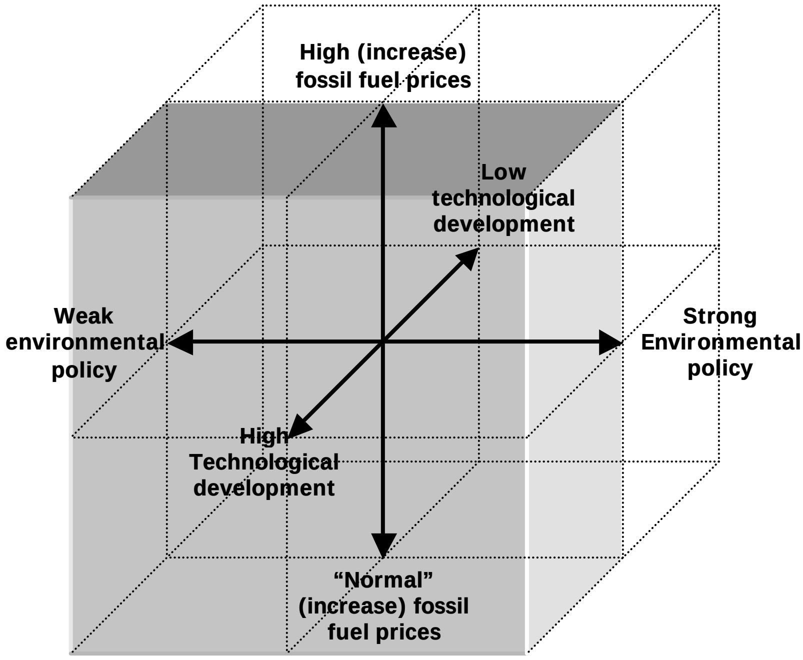

Figure 6.3. Three scenario-axes; reduction till four scenarios

In the next chapter the four scenarios will be worked out. Main points in these scenarios are obviously the three (clusters of) driving forces, but all other driving forces, which are mentioned in this chapter, will come up as well.

6.4 Conclusion

Out of the basic and future analysis, twenty-one key factors and driving forces are derived that influence the diffusion of fuel-cell cars. The set of factors and forces are subdivided into five categories: technology, politics, economy, environment, and society. After this, the key factors and driving forces are ranked by importance and uncertainty. From this ranking three conclusions are drawn. The first is that the role of the government, with regard to emission control, is important for the diffusion of fuel-cell cars, but that policy of the (Chinese) government is highly uncertain. Secondly, the technology development, including the infrastructural development, is important. But also here the uncertainty is high, because of the different interests of the actors. Thirdly, the forces 'price of fossil fuels' and 'energy resource scarcity after 2025' have a high score on both importance and uncertainty.

These three (clusters of) driving forces form the axes of the scenarios. Although the forces are related to each other, i.e. they are not independent from each other, they will form individual axes, because it encompasses enough possibilities to put in (new) ideas.

With three axes, eight scenarios are possible, which eventually has to be reduced till four, as we have stated in chapter two that the maximum amount of scenarios worked out should be four. A first analysis with MARKAL showed, that if the diffusion of fuel-cell cars in China wants to set off, high technological development is a necessary condition. Therefore, we reduce the amount of scenarios till four by keeping out the scenarios with low technological development.

In total, the following four scenarios will be worked out:

1. A scenario with high technological development, weak environmental policy measures and "normal" fossil fuel prices
2. A scenario with high technological development, weak environmental policy measures and high fossil fuel prices
3. A scenario with high technological development, strong environmental policy measures and "normal" fossil fuel prices
4. A scenario with high technological development, strong environmental policy measures and high fossil fuel prices

7. Scenarios

By having determined the scenario-axis in the previous chapter, this chapter focuses on filling-in the four scenarios that give a plausible representation of probable pathways that the diffusion of fuel-cell cars in China might follow (research sub-question 7). Besides, the content of this chapter corresponds to steps 10, getting form crude numbers of the model to relevant graphs, and 11, work out scenario, of the methodology (methodology-steps 8, putting parameters into the model, and 9, run model are preliminary work). The scenarios are described both qualitatively and quantitatively, but always in cohesion with each other. In the quantitative part, the results of MARKAL are discussed. At the end of the chapter, a sensitivity analysis is carried out to examine the robustness of the outcomes of MARKAL.

7.1 Scenario parameters

In this research we make use of the energy economic MARKAL model to design the different scenarios. The MARKAL-database used for China is set up by Zongxin et al. (2001) (see box 7.1). For this research, the data of the passenger car sector in the existing model has been updated. Instead of data of four passenger cars, with one type of fuel-cell car, now data for ten passenger cars are available, with three types of fuel-cell cars (see appendix M till R).

In table 7.1 the parameters for the four scenarios that serve as input for MARKAL are given. These parameters are mostly adapted from Zongxin et al. (2001). For detailed data see appendix R.

Table 7.1. Parameter choices MARKAL

Parameter	**Scenario 1: "hybridisation of the car fleet"**	**Scenario 2: "a hydrogen economy"**	**Scenario 3: "environmental reformation"**	**Scenario 4 "self-sufficiency"**
Advanced technologies[a] in China + low-costs FC	*available*	*available*	*available*	*available*
High fossil fuel prices, after 2025[b]	-	*2025: prices per GJ times 2 after 2025: prices per GJ times 4*	-	*2025: prices per GJ times 2 after 2025: prices per GJ times 4*
Emission control[c]	-	-	*66 GtC over period 1995-2050*[45]	*66 GtC over period 1995-2050*

[a, c] based on Zongxin et al. (2001), see also box 7.1
[b] based on Graus (2002)

In the analysis of the MARKAL results, attention is paid to the impact of the constraint on the diffusion of fuel-cell cars (main aim of the research), air pollution (motive to shift to fuel-cell cars), the allocation of energy carriers (the dependency on fossil fuels), and the dependency on foreign energy suppliers (tension on world's oil & gas market). This is the quantitative analysis of the scenarios. In the qualitative part the situation in 2045 is imagined and how such a situation comes into being.

Box 7.1. The study of Zongxin et al. (2001) and its relation to this study

The study of Zongxin et al. (2001) identifies and highlights key implications of different advanced-technology strategies that could allow China to continue its social and economic development while ensuring national energy-supply security and promoting environmental sustainability. For this research a simplified MARKAL-database was build to represents China's energy system. Different scenarios were explored with the MARKAL-model, and the overall conclusion was that there are plausible energy-technology strategies that would enable China to continue social and economic development through at least the next fifty years while ensuring security of energy supply and improved local and global environmental quality.

The MARKAL-database of Zongxin et al. (2001) is used in the quantitative part of this research to examine the diffusion of fuel-cell cars in China. The focus lay on the passenger-car sector, but the whole energy system was taken into account. For this research, the data of the passenger-car sector have been updated to give a representative overview of future Chinese car-fleet (appendix Q, U and V).

[45] The time horizon of the scenario runs is 2050, but results are presented up to 2045; this avoids end-of-simulation effects. (see also Röder, 2001b). Although MARKAL should correct such end-of-simulation effects, the author percieved such end-of-simulation effects sometimes.

7.2 Scenery of the scenarios

The four scenarios will all have the same scenery, on which the scenarios are formulated/based. This means that certain issues, forming the scenery, will be (more or less) the same in all the scenarios. These issues are trends or developments, of which it is quite clear that these are going to happen (e.g. driving forces with a low uncertainty).

In this research the general scenery will be one, in which there will be increasing car demand, caused by the rising GDP, but also partly by the growing population. These two factors are also fundamentals for the increasing energy demand and supply, where coal supply will play a dominant role in. Obviously, the rate in which GDP rises and population grows might be slightly different in all the scenarios. Besides, in all scenarios the urbanization rate will increase and road infrastructure development can hardly keep up with the increasing motorization.

Moreover, as mentioned in section 6.3, all scenarios explicitly imply high technological developments (a necessary condition). This reveals itself in the availability of advanced technologies in China (see table 7.1) and, more specific, in the low costs of fuel cells for passenger cars (till around 30 US95$ per kW).

7.3 Scenario 1: "Hybridisation of the car fleet"

7.3.1 The streets of China in 2045

Gasoline and diesel cars still are dominant in the market, although natural-gas vehicles have a significant share. New types of the gasoline and diesel car entered the market, but first after it became a success in OECD countries. You can scarcely see the exhaust out of the tailpipe anymore, as you could twenty till thirty years before, but the dirty clouds still hang above the cities. Namely, the increasing car fleet partly offsets the improvement in efficiency and the reduction of tailpipe emissions. In some, more wealthier, cities, public transport is well organised, the car fleet contains mostly NG vehicles and environmental problems are visible, but relatively under control. However, their policy has not led to big changes in the State's policy.

The economy matters for the Chinese government, environmental issues play a less dominant role. The car industry is a large sector in China, and offers a lot of employment. EURO-standards are set, but the process of introduction went slowly, leaving enough time for system optimization. Import restrictions on cars may have been removed, China still stimulates its own market as much as possible.

The energy sector grew very fast. New power systems, such as nuclear power plants and wind power systems, have entered the market, but coal still is the major energy source. Introduction of new technology went at a slow pace. For the energy companies, no real incentives were there, to innovate. Stationary hydrogen power plants only supply a small share of electricity. Hydrogen infrastructure exits in some regions, but is relatively small. This holds also true for methanol infrastructure.

The environmental problems are high. The transport sector is one of the major contributors. Respiratory illness and mortality due to air pollution has serious impact on the economy. The economic loss, due to environmental pollution, corresponds to more than 10% of GDP. Environmental awareness of the public is relatively high, but no entrance is found to the government.

The pressure from foreign countries on China's (environmental) policy has been increasing over the years, but China kept its autonomy. Besides, on a global level, environmental issues still are not the most important ones. Dependency on foreign energy suppliers is high, but this has not led to oil import restrictions or a substantial increase of the price of oil. Besides, the fuel in China is barely taxed.

Alternative powertrains (e.g. fuel-cell cars) have (had) problems to enter the market. For the (car) industry there were no real motives to invest in such cars, while there was no push from outside. Although several pilot projects for alternative powertrains have been started, and some niches have been found, the way to market introduction never has been found. Only natural-gas vehicles have succeeded, also because of available natural gas infrastructure, initiated by the power sector.

7.3.2 Analysis of MARKAL-results: scenario 1

7.3.2.1 Market share of the powertrains

By running the model without any constraints (with advanced technologies available), the results of the model can be classified as “business as usual” or “baseline scenario”. The model takes the least total energy costs, and the outcomes for the passenger car sector are reflected in figure 7.1 and 7.2.

The data for 1995 and 2000 were available and therefore set as fixed outcomes of the model (this holds true for all scenarios). The gasoline car (light blue in graph) has the highest share, a small share is for diesel cars (dark red) and since 1995 the better performing (and less dirty) gasoline ICE car has been entering the market. After 2000, the better performing gasoline ICE vehicle takes over the market. In the outcomes the diesel car looses its share, but this will probably not be the case in reality. The diesel car does not show up in the results, because it has higher investment costs, but the lower variable cost (fuel cost) does not offset the higher investment costs.

Especially for persons who drive many kilometres a year, the diesel car is attractive, but in the model no distinction is made between groups, who drive many kilometres a year and those who do not. I assume the share of diesel cars (ICE and ICE HEV) will rise and will maximally reach a 20% market share (this corresponds to Western-European shares).

After the “evolutionary” gasoline car has taken over the market, the hybrid gasoline DISI car, with high performance, but also higher investment costs, enters the market and takes over the market in a time period from 10 years (this corresponds exactly to 1 lifetime of a car). However, this is not likely to occur, but because MARKAL is a cost optimization model, it takes the least cost option, and when there is no restriction (e.g. capacity or maximum share) a technology can take over the whole market. It is assumable that the evolutionary gasoline and diesel ICE car will remain their share over a period longer than 10 years.

From 2035 onwards the hybrid natural gas car enters the market, probably because the fuel price of natural gas in relation to the fuel price of gasoline is low enough to offset the higher investment costs.

Figure 7.1 MARKAL results scenario 1: fleet share

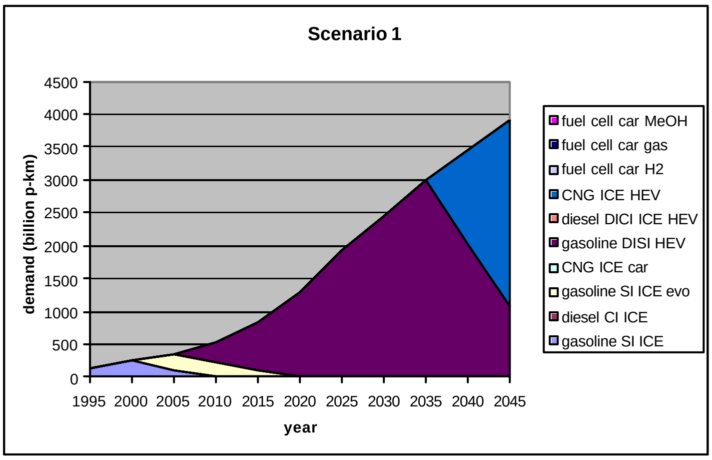

Figure 7.2. MARKAL results 1: demand for passenger cars

7.3.1.1 Emissions and energy supply

In this scenario, the outcomes of MARKAL show that the total amount of resource-based CO_2 emissions, over the analysed period, are 79,000 million tonnes of carbon, the CO_2 emissions from the transport sector is 8,500 million tonnes of carbon. Total CO_2 emissions per year double from 1995 till 2045, which is reflected in figure 7.3. Total NO_x amounts 1 billion tonnes, of which 155 million tonnes come from the transportation sector. The total NO_x emissions show an increase from 13 million tonnes per year in 1995 till 21 million tonnes per year in 2045. However, the NO_x emissions per year in the transportation sector reach the same level in 2045 as that in 1995, after reaching its maximum in 2030. PM emissions of the transportation sector[46] show a steady increase until 2030, mainly caused by

[46] PM emission are only given for the transportation sector. The total PM emission can not be calculated or represented because of lack of data in the other sectors.

the expanding demand. After 2030, PM emissions per year decline, due to the introduction of NG-vehicles. Finally, the total SO_2 emissions amounted some 1,880 million tonnes, of which 84 million tonnes come from the transportation sector. Figure 7.1 shows that introduction of natural-gas vehicles (from 2035 onwards), have a strong impact on the PM, NO_x and SO_2 emissions in the transportation sector.

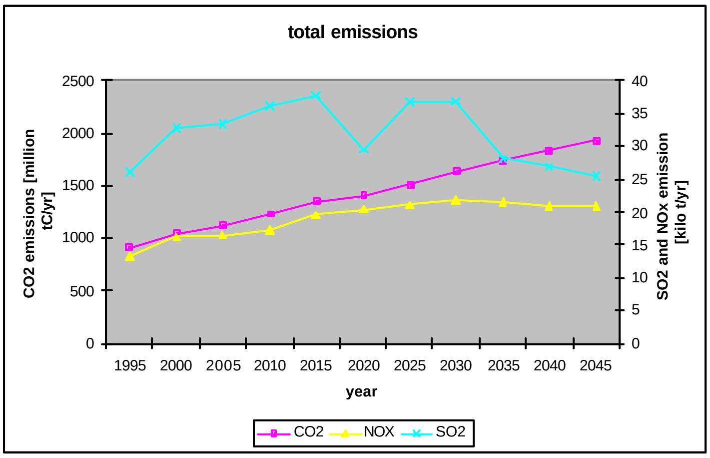

Figure 7.3. Total emissions; scenario 1

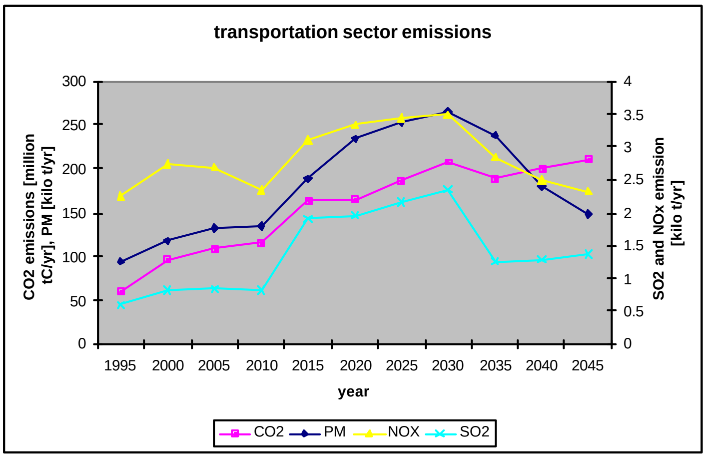

Figure 7.4. Total emissions transportation sector; scenario 1

In table 7.2 data of energy supply –domestic extraction, export and import - for this scenario are given. Total primary energy demand increases by a factor of 2.5 over a period of fifty years. Domestic extraction is the primary energy supply. Imports play a small role, but in absolute terms it triples between 2045 and 1995.

Table 7.2. Energy supply data (in EJ); scenario 1

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
Domestic Extraction	36.6	37.9	42.3	47.1	52.2	56.2	62.5	68.3	73.8	77.7	81.9
Exports	0.6	0	0	0	0	0	0	0	0	0	0
Imports	1.5	5.8	4.9	5.1	5.6	4.2	3.9	3.7	3.4	3.8	4.3
Total Primary Energy	39.2	46.8	50.9	56.6	63.8	71.9	78.6	85.4	91.9	98.0	104.3

In figure 7.5 the final primary energy supply is reflected. This figure gives us insight in the way energy carriers are allocated. Coal is and will be the primary energy carrier in the future. Renewables and nuclear will reach a share of around 17% in 2045.

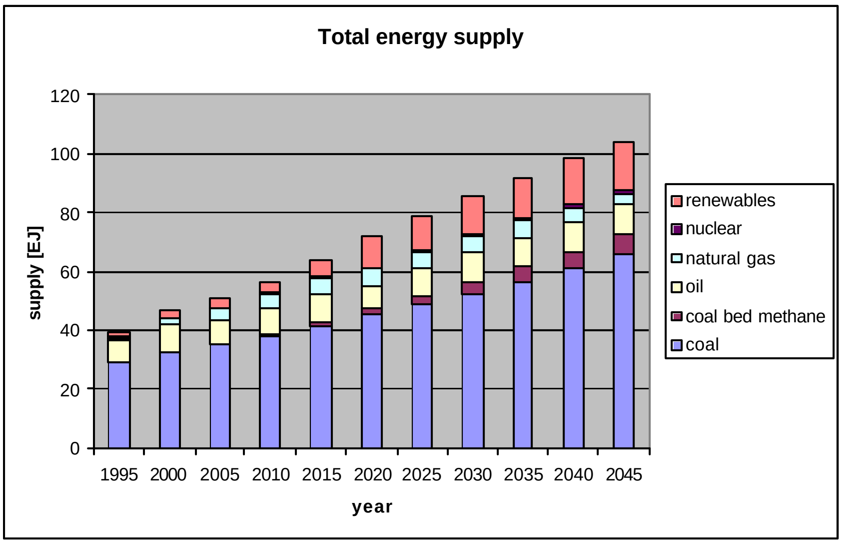

Figure 7.5. Total primary energy comparison; scenario 1

7.4 Scenario 2: "A hydrogen economy"

7.4.1 The streets of China in 2045

Hydrogen is the new energy carrier in the world. Since roughly twenty years the hydrogen market is expanding rapidly. First there were the stationary hydrogen power plants and the hydrogen buses, later on the fuel-cell cars entered. There had been several pilot projects in the United States of America and Europe, which resulted in a niche market.

The main driving forces were the oil & gas scarcity and the technology development.[47] *The governments only created some (boundary) conditions in which a hydrogen market could develop. The whole process was fetched up in a vicious circle. The oil & gas scarcity led to an increase of the fossil fuel prices, industry changed (innovations), technological development increased, the costs of fuel-cell stacks (US$/kW) dropped to a level similar of that of internal combustion engines, the environmental awareness rose (also because of the shortage on water), acceptance of renewables and fuel-cell cars increased etc. 'A hydrogen economy' could be created.*

A hydrogen infrastructure was also built in China, following the global trend. Plants and refuelling stations were built, pipelines constructed and distribution channels set up. Hydrogen for fuel-cell cars can not only be bought at the refuelling station, but also in some supermarkets, in fuel boxes of 12 litres (Shell International, 2001), which is especially popular in the USA.

Today, in 2045, the totally crowded streets in the cities of China show a variety of types of cars. Most types are fuel-cell cars, some natural-gas vehicles, but also gasoline or diesel cars. Buses are either fuel-cell or natural gas ones. The quality of public transport and road infrastructure is moderate: developed but fairly chaotic.

The car industry is an important industry, and has adapted to the changing economy. Competition among the car manufacturers is high. The government regulates, but the industry is mainly market driven. The efficiency of the car has improved substantially as well as the emission levels.

The impact of the developed and new technologies on the environment is visible, especially in the cities. Respiratory illness and mortality due to air pollution has not been increased dramatically since 2025, i.e. the situation has not deteriorated. The people see the benefits of the fuel-cell car, and therefore it is widely accepted.

7.4.2 Analysis of MARKAL results: scenario 2

7.4.2.1 Market share of the powertrains

In this scenario, the main driving force was the oil and gas scarcity, which resulted in higher fuel prices. The prices for oil and gas went up after 2025. In MARKAL, the prices of fossil fuels were multiplied with four from 2030 onwards (in 2025 multiplied with two).

The results of MARKAL for this scenario are reflected in figure 7.6 and 7.7. It shows us that with high prices for fossil fuels the fuel-cell technology becomes cost competitive. In the first period, until 2020, the technology with the least cost takes over the whole market, which is unlikely to happen in reality (as mentioned in section 7.3.2.1). Diesel cars and perhaps natural gas vehicles will have their share in the market. After 2025, were the fossil fuel prices go up (times four), three technologies form the market: gasoline hybrid cars, hydrogen fuel-cell cars and natural-gas vehicles.

In the left figure the hydrogen fuel-cell car seems to enter the market smoothly, but in the right figure can be seen that this corresponds to an increase of around 1500 billion p-km in 20 years. In total amount of cars this corresponds to 84 million FC-cars in 20 years. The question rises whether such a large hydrogen infrastructure can be formed in this period and whether the production capacity of fuel-cell cars can meet the demand?

[47] Scenario partly based on Shell International (2001)

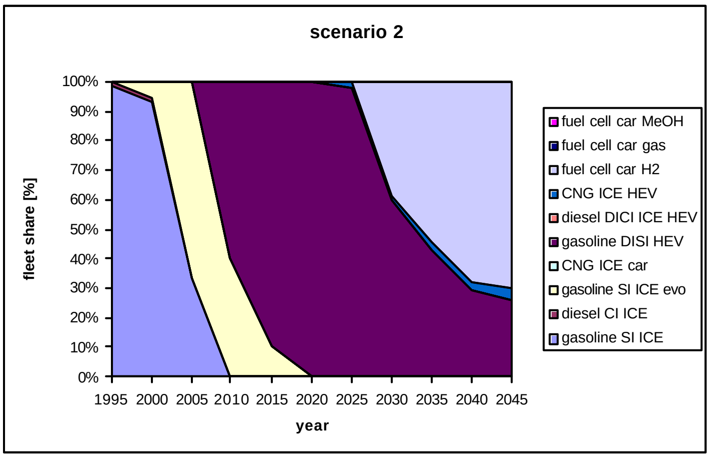

Figure 7.6. MARKAL results scenario 2: fleet share

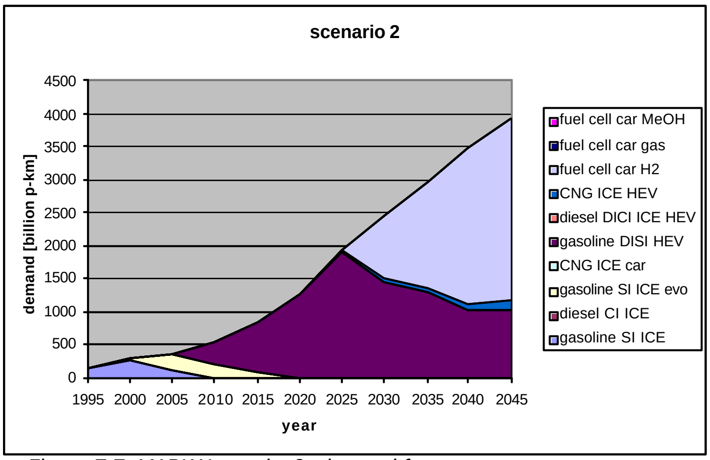

Figure 7.7. MARKAL results 2: demand for passenger cars

7.4.2.2 Emissions and energy supply

The levels of emissions are not regulated by government intervention. Therefore CO_2 emission accrues over the period, as shown in figure 7.8. CO_2 emissions decrease because of the use of better technologies. NO_x emissions grow from 16.2 million tonnes in 2000 to 18.5 million tonnes in 2045, with a total of around 1 billion tonnes over fifty years.

For the transportation sector, we see in figure 7.9 an increase of SO_2 and CO_2 emissions. Only in the period 2010-2020 a bump can be seen in the SO_2 emissions. This is probably partial due to the use of gasoline cars in a rapid expanding market. After 2020 fuel-cell vehicles, with no sulphur emissions, take over the market, and the curve continues like before 2010. PM and NO_x emissions also decline after the entering of fuel-cell vehicles in the market.

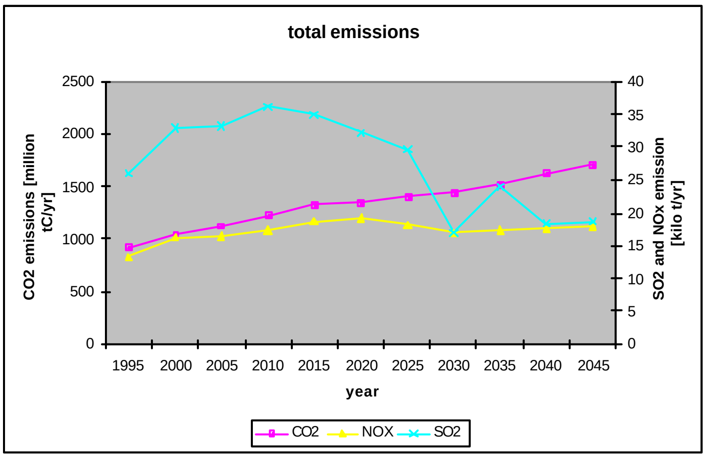

Figure 7.8. Total emissions; scenario 2

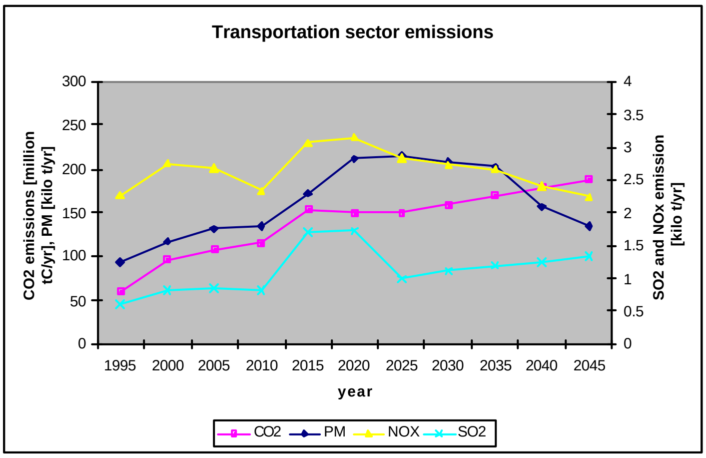

Figure 7.9. Total emissions transportation sector; scenario 2

In table 7.3 some data of energy supply in this scenario are given. Total primary energy demand shows a similar trend as in scenario one. Imports decrease by a factor five after the prices of fossil fuels increase. Domestic extraction increases steadily from 38 EJ in 2000 to 71 EJ in 2045.

Table 7.3. Energy supply data (in EJ); scenario 2

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
Domestic Extraction	36.6	37.9	42.3	47.1	51.9	53.7	57.1	60.1	64.0	67.7	70.8
Exports	0.6	0	0	0	0	0	0	0	0	0	0
Imports	1.5	5.8	4.9	4.9	4.9	4.5	2.6	0.9	1.0	1.0	1.0
Total Primary Energy	39.2	46.8	50.9	56.5	63.0	69.9	77.8	84.2	91.5	98.6	105.7

In figure 7.10 the final primary energy supply is reflected. Because of the increase in the prices of fossil fuels, the use of cheaper coal (in relation to the other fossil fuels) increases in the results of MARKAL. The electricity is supplied by nuclear power and renewables. Oil supply amounts 6 till 9 EJ. Natural gas is hardly used after 2025, which might be surprisingly, because the price of natural gas is, after the increase of prices for all fossil energy carriers, much lower than that of oil. Besides, the low use of natural gas means that the hydrogen is produced out of coal.

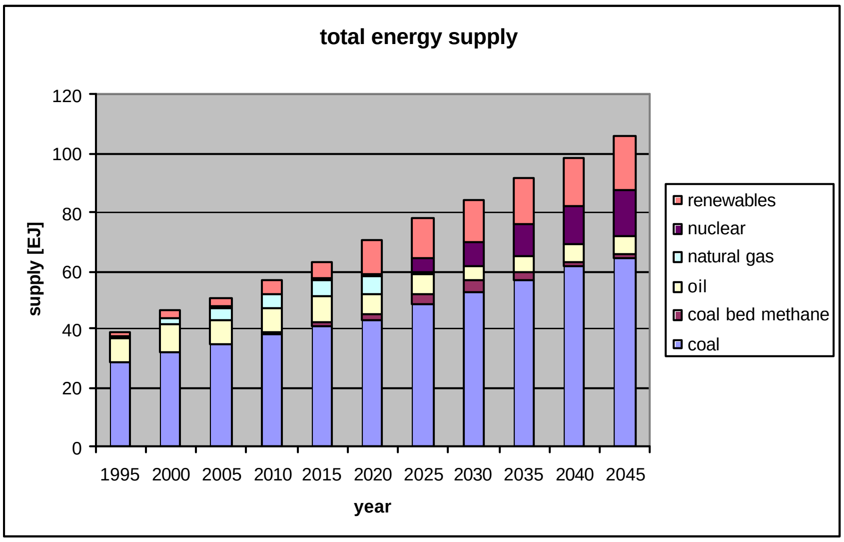

Figure 7.10. Total primary energy comparison; scenario 2

7.5 Scenario 3: "Environmental reformation"

7.5.1 The streets of China in 2045

It was 25 years ago that Mr. Wong bought his first fuel-cell car. By then, he was one of the first private owners of a fuel-cell car in his city Zibo. Now, looking out of the window of his office, he sees that half of the vehicle fleet are fuel-cell cars. He can recognize the fuel-cell cars quite easily; their design is different of that of the other passenger cars, which are mostly natural gas vehicles. The cars are passing by slowly, but at a constant speed.

The 60-year old professor saw it all happen, the development of China. It started in the nineties of the last century; economic growth was 8%, China was building in a rapid space, but the environment suffered from this growth. At the beginning of the century, the first signs towards a cleaner environment could be recognized, although the incentives of the government were still unclear by that time. Projects were started, but were of minor importance than economic development, or in case of the fuel-cell buses for the Olympic Games in Beijing 2008, the project was only important for the face of China in the world. By 2010 it started to change. The black clouds above the cities were thick and large, the main activity in the hospitals was to help people with respiratory illness and the economic losses because of environmental pollution became visible for the government. Pressure on the government's policy came from the public but also from foreign countries. Something had to change.

Stricter environmental regulations were applied. Emission targets were set and coal power plants had to be provided with scrubbers. Besides, China did not want to become too dependent on foreign fuel suppliers, and restricted oil imports.

In the car industry, first the EURO III and IV[48] standards were applied, and later on it went to SULEV-standards (Super Ultra Low-Emission Vehicles). Natural gas vehicles and hybrid cars became more important, and new technologies were imported (or "copied" from the industrialized countries). The existing infrastructure could be transformed at once, that is also why the gasoline and diesel remained the dominant fuels in the passenger-car market. Natural-gas vehicles profit from their existing niche, build up in the beginning of the century, and from the expanding use of natural gas in the power sector. For the NG power sector, large pipelines were constructed. Natural gas was also imported by pipelines from Siberia and central Asia. The oil and energy companies responded to the changes.

Since roughly fifteen years the fuel-cell car has entered the Chinese market. The costs of the fuel cells have decreased rapidly, initiated by developments in foreign countries, the market entering of fuel-cell bicycle, fuel-cell busses, and stationary hydrogen power plants in China several years before. The problems of range, acceleration, and hydrogen storage were solved as the car found its market in the industrialized countries. Fuel-cell cars have two advantages over the other powertrains: 1) no

[48] EURO 1 standard was applied in China in 1999.

emissions, and 2) the only residue is water, which can be used for other purposes. Besides, because of the existing hydrogen infrastructure for the other purposes, described above, infrastructural problems for the passenger car sector were minimized.

Road infrastructure could hardly keep up with the growing car fleet. Nonetheless, the Chinese government succeeded in building sufficient roads for the car fleet. Road infrastructure also became well structured, with separate lanes for busses, bicycles and pedestrians. Some congestion problems were tackled by the quality of public transport (among others high speed trains).

China profit from the (technological) experience the industrialized countries had gained in the second half of the twentieth century, and China learned from their failures. Successful projects and policy measures in some cities or regions were expanded to more regions and finally adapted to the whole of China.

7.5.2 Analysis of MARKAL-results: scenario 3

7.5.2.1 Market share of the powertrains

In this scenario maximum environmental benefits are gained, against the lowest possible energy costs. For CO_2 emissions a cumulative emission limit of 66 GtC is enforced (Zongxin et al., 2001). The results for the passenger-car sector are reflected in figure 7.11 and 7.12.

The figures show until 2025 a similar pattern as the ones in the other scenarios. Still gasoline (and diesel) are the fuels for the passenger cars, but after 2030 NG takes take over the market, followed by hydrogen fuel-cell cars from 2035 onwards.

The reason why there is a shift in the MARKAL results towards NG and later on towards hydrogen fuel-cell is not only that these car emit less SO_2, PM and NO_x, but most important is the reduction of CO_2 emissions. In relation to the other car types, most profit can be yield on this item. So, to meet the CO_2 constraint of 66 GtC over the analysed period in MARKAL, there is a shift towards hydrogen cars.

The hydrogen fuel-cell cars do not only take part of the expanding market, but also that takes over part of the existing market. This is unlikely, because the market (under our assumptions) is growing from 78 million cars in 2035 till 120 million in 2045. This corresponds already to 4.2 million cars per year. However, the actual growth, derived out of the results of MARKAL, is 87 million cars in ten years. Thus, the question rises if it is possible to set up a capacity for hydrogen fuel-cell car of 4.2 or 8.7 million a year in a period of 10 years. And can associated industries, such as suppliers and maintenance garages, keep up with this trend.

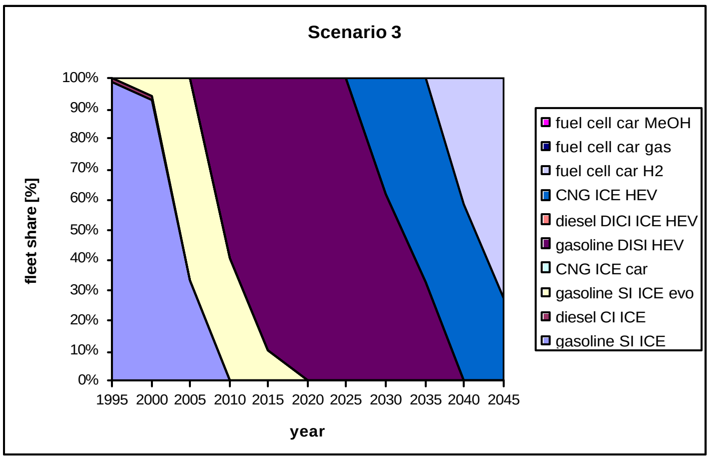

Figure 7.11. MARKAL results scenario 3: fleet share

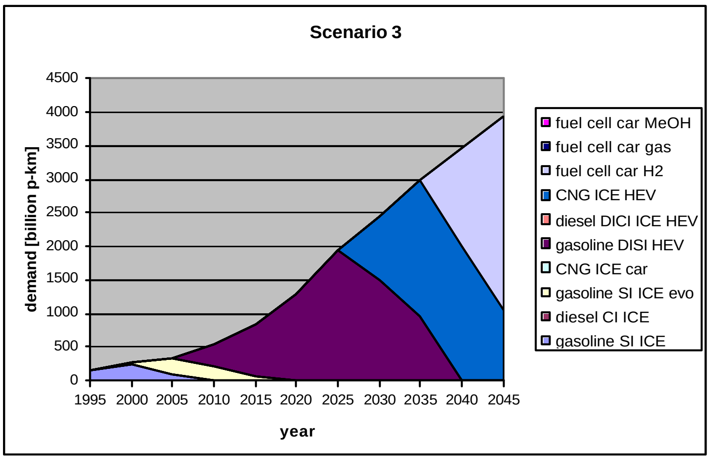

Figure 7.12. MARKAL results 3: demand for passenger cars

The results shown in figure 7.11 and 7.12 are the result of a MARKAL run, where a CO_2 bound of 66 GtC has been applied (see Zongxin et al., 2001). Similar results can be obtained by putting a tax on emissions (see appendix S). No mandated SO_2 and NO_x emission levels have been applied in this scenario; because of the strict CO_2 bound, the SO_2 and NO_x emissions go down automatically.

7.5.2.2 Emissions and energy supply

For this scenario, the outcomes of MARKAL show that the total amount of resource-based CO_2 emissions, over the analysed period, are around 60 GtC and the CO_2 emissions from the transport sector are around 8 billion tonnes of carbon. Compared to the scenario 1, we see a reduction of around 20,000 million tonnes of carbon. Total NO_x amount does not exceed the 1,000 million tonnes boundary. All emissions show a decline in tonnes per year after 2025, except for the SO_2 emissions, which starts to decline after 2010. The emissions per year in the transportation sector show a steady increase over time. Apparently, the lower emissions can not offset the increasing demand.

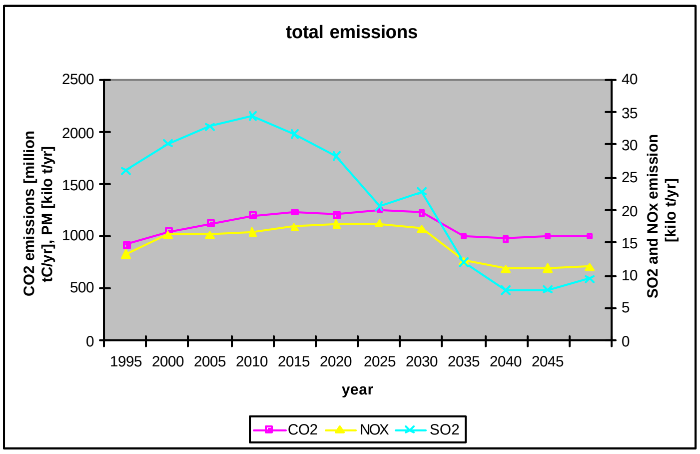

Figure 7.13. Total emissions; scenario 3

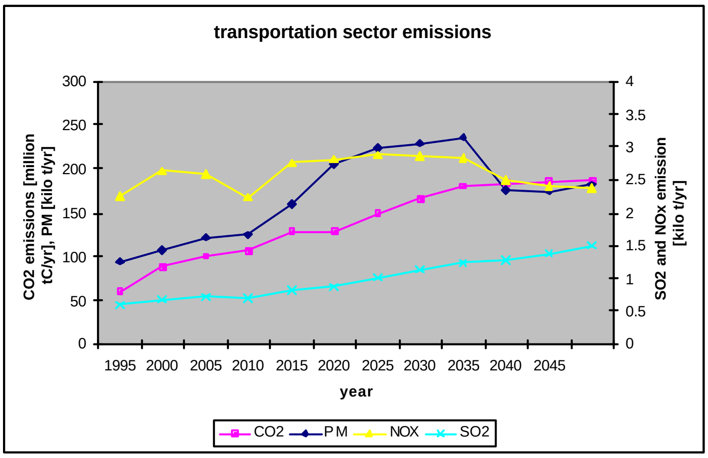

Figure 7.14. Total emissions transportation sector; scenario 3

In table 7.4 some data of energy supply for this scenario are given. In this scenario the total primary energy demand increases from 47 EJ in 2000 to nearly 100 EJ in 2045. Domestic extraction is the primary energy supply, but imports play a significant role.

Table 7.4. Energy supply data (in EJ); scenario 3

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
Domestic Extraction	36.6	37.9	42.3	46.1	48.0	47.7	52.3	54.4	42.8	41.0	43.4
Exports	0.6	0	0	0	0	0	0	0	0	0	0
Imports	1.5	5.5	4.6	4.9	6.1	7.4	8.0	10.2	23.9	28.1	27.8
Total Primary Energy	39.2	46.5	50.6	56.2	62.0	68.5	74.6	79.9	83.8	90.5	99.2

In figure 7.15 the final primary energy supply is reflected. This figure gives us insight in the way energy carriers are allocated. Coal is the major primary energy carrier until 2030. After 2030 natural gas gains a similar share as coal. Renewables and nuclear will reach a share of 19% and 14% respectively in 1995.

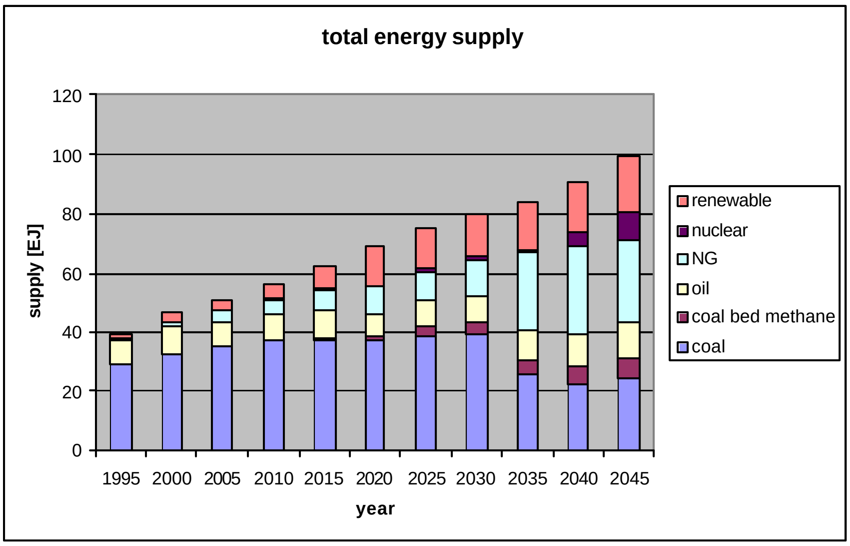

Figure 7.15. Total energy supply; scenario 3

7.6 Scenario 4: "Self-sufficiency"

7.6.1 The streets of China in 2045

Natural-gas vehicles dominated the streets of China between 2010 and 2040 to a large extent. China's car market has followed a similar pathway as the ones in Argentina, India, Pakistan and Egypt. In an expanding market, the government stimulates the use of natural gas as a fuel for passenger cars. Pilot projects are started, infrastructure is built, the market is formed, and because it is an expanding market, there is room for alternatives.

China has made a reflection between the environment and the economy. They have chosen to stimulate a known technology, which can be implemented relatively easy and cheap, but which has a positive impact on the environment. Cities, like Beijing[49] *and Chongqing, were the first ones who stimulated natural-gas vehicles. For more than 30 years, all the buses in these cities ran on natural gas.*

A natural-gas grid was constructed for the transportation sector and partial for the power-sector. Coal is the dominant energy supplier. The increase in energy demand is answered by the use of coal, nuclear power, and renewables.

So, the policy of the Chinese government towards the passenger-car market had focused on roughly one substitute: the natural-gas cars. No real legislative boundary was created for other alternative powertrains (e.g. fuel-cell cars), till the increase of fossil fuel prices (as result of the perceived energy resource scarcity). Hydrogen out of coal (with CO_2 sequestration) becomes cost competitive for the passenger-car sector, whereas the hybrid natural-gas and gasoline cars loose their attractiveness of high fuel-economy with low fuel prices. Hydrogen fuel cells are attracted by the application of fuel-cell buses from 2015-2020 onwards. Besides the market for fuel-cell bicycles stimulates fuel-cell car technology.[50] *The swift towards hydrogen transportation means went not without striking a blow. The increase in fossil fuel prices entailed economical problems in some sectors (especially freight sector), leading to strikes and protests, but also to more environmental awareness, not only by politicians but also by the public. This led to changes in the transportation sector, with a dominant role of fuel-cell cars in the passenger-car sector.*

The increase in fossil fuel prices after 2025, did not produce changes in the energy supply, but did so in the (conversion) processes and end-use technologies. It stimulated the use of cheap coal, but by utilization of environmentally friendly technologies, and of nuclear power, to obtain the CO_2 emission target. Also hydrogen fuel (out of coal) is one of the means to obtain the target.

For a long time, CO_2 emissions were a point of discussion in the world. China committed itself to achieve a strict CO_2 emission reduction target. By the strict CO_2 emission constraints, these emissions – despite the enormous energy growth – are well under control. Emissions per year of PM, NO_x and SO_2 has dropped significantly over the years, due to the emission targets.

Dependencies on the fossil energy carriers, oil and gas, are not high. Imports have been roughly constant over the last 40 years. China is the world's largest energy consumer of the world, which leads to certain political and economical tension in (parts of) the world, but not stringently because of China's self-supporting energy supply. Moreover, China's (environmental) policy was able to counterattack the increasing fossil-fuel prices because of its self-sufficiency.

7.6.2 Analysis of MARKAL results: scenario 4

<u>7.6.2.1 Market share of the powertrains</u>

In this scenario, the government has enforced a cumulative emission limit of 66 GtC for CO_2 emissions (see also appendix Q; similar to scenario three). Besides, the fossil fuel prices have increased two times in 2025 and four times in the period after 2030 (similar as in scenario two).

[49] See Yang, M.; Kraft-Oliver, T.; Yan, G.X. & Min, W.T. (1997). *Compressed Natural Gas Vehicles: Motoring Towards a Cleaner Beijing*. Applied Energy (56). Elsevier Science Ltd. Pp. 295-405

[50] A technology can profit from the succes of another related technology. For example, the diffusion of fuel-cell power plants will cause declining fuel cell costs, and will effect (positively on) the costs of fuel-cell cars. The technologies form clusters, and such a cluster can experience declining costs. This issue is also implemented in new MARKAL versions.

The results for the passenger car market are given in figure 7.11 (market share) and 7.12 (demand). The results in the first 15 years are similar to all other scenarios – first gasoline cars, followed by better performing gasoline cars -, but now the hybrid natural gas car enters the market already in 2010, whereas in the other scenarios the hybrid gasoline car enters first. In this scenario the hybrid gasoline car enters first in 2015, takes a share at the expense of hybrid natural-gas cars, but loses it again after 2025 (when fossil fuel prices go up). Till 2030, the hybrid natural-gas vehicle and hybrid gasoline car dominates the market. After 2030, hydrogen fuel cells become cost-competitive, due to the high fossil fuel prices, and this car type takes over the market.

The same remark about the dominance of gasoline cars and the absence of diesel cars in the results, made in section 7.2.2.1, holds also true in this scenario. Diesel cars gain a certain market share, which is also likely for the natural gas ICE car (the predecessor of the hybrid natural-gas car). With the stimulation of NG buses in some major cities in China (e.g. Beijing and Chongqing), and the stimulation of NG cars later on, the entering of hybrid natural gas market is then a more logical result. It might therefore be option to flatten out the figures, with the appearance of diesel ICE and NG ICE cars, to get a more realistic view.

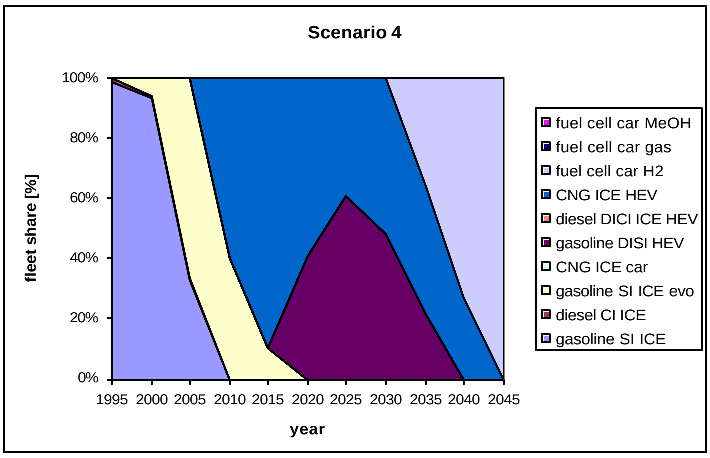

Figure 7.16. MARKAL results scenario 4; fleet share

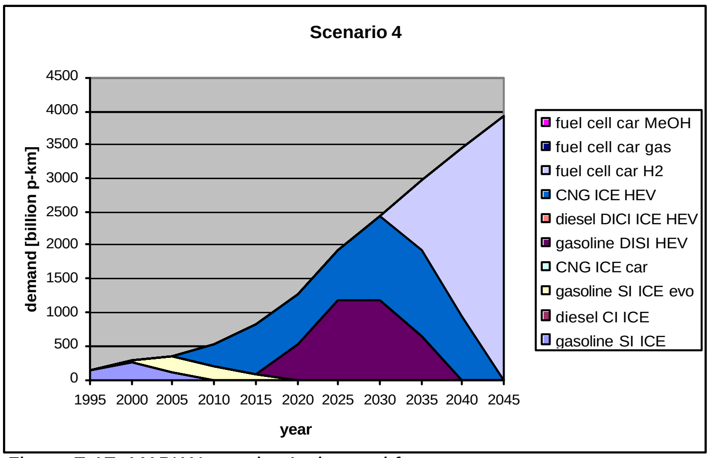

Figure 7.17. MARKAL results 4; demand for passenger cars

<u>7.6.2.2 Emissions and energy supply</u>

In this scenario, the outcome of the total CO2 emission level is given by the constraints. Till 2030, CO_2 emissions per year increase, due to the increasing energy demand and existing technologies, but after 2030 the CO_2 emissions per year decline by the imposed constraint. Although energy demand is increasing, SO_2 emissions per year decline, due to the utilization of advanced technologies, which is necessary to achieve the CO_2 emission constraint. NO_x emissions per year increase slightly, but go down below the value of 2000 after 2035.

For the transportation sector, we see in figure 7.19 a steady increase of SO_2 and CO_2 emissions. The booming demand leads to higher emissions. Only NO_x and PM emissions per year decline in the last period (2023-2045) due to large-scale use of hydrogen transportation means.

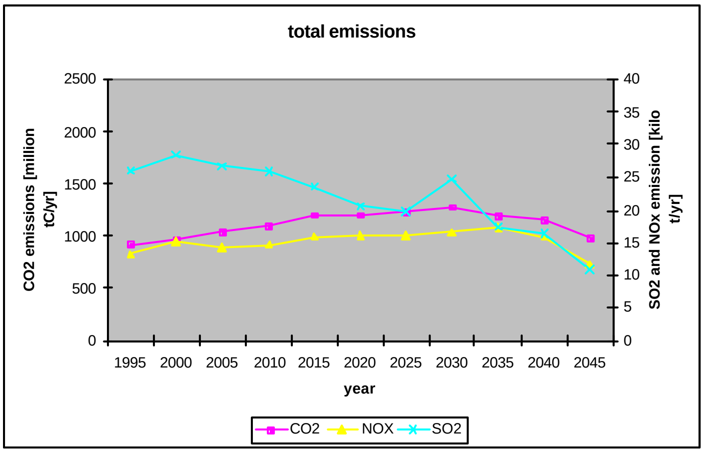

Figure 7.18. Total emissions; scenario 3

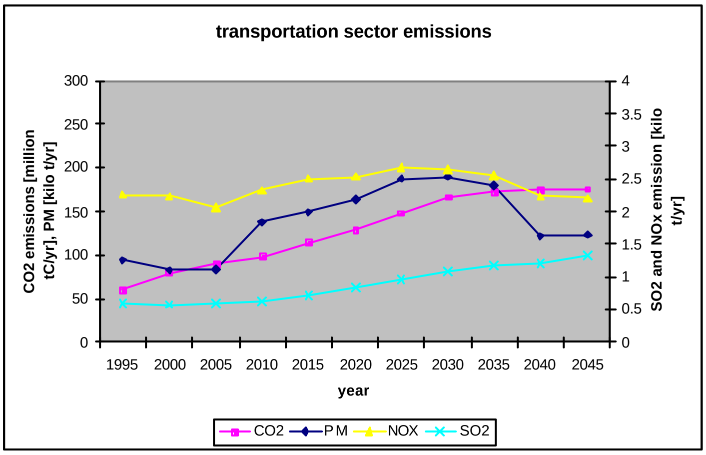

Figure 7.19. Transportation sector emissions; scenario 3

In table 7.5 energy supply data of this scenario are given. Total primary energy demand increases from 40 EJ to 120 EJ in 2045; the largest grow of primary energy supply in the four scenarios. Compared to scenario one, the total primary energy supply is 14% more in 2045. Primary energy is supplied by domestic extraction. Import share is very low and remains stable over the total period.

Table 7.5. Energy supply data (in EJ); scenario 4

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
Domestic Extraction	36.6	38.7	40.9	44.0	49.1	53.3	58.9	65.6	68.0	73.4	84.0
Exports	0.6	0	0	0	0	0	0	0	0	0	0
Imports	1.5	0.9	1.7	1.5	0.9	0.9	0.9	0.9	0.9	1.0	1.0
Total Primary Energy	39.2	49.4	55.0	60.2	65.2	70.0	76.3	83.5	94.1	104.7	119.3

In figure 7.20 the total energy supply over a period of 50 years is reflected. The allocation of coal increases steady over the period. Nuclear and renewable power fill a large part of the new demand. Oil and natural gas use varies between 5 and 7 EJ after 2025.

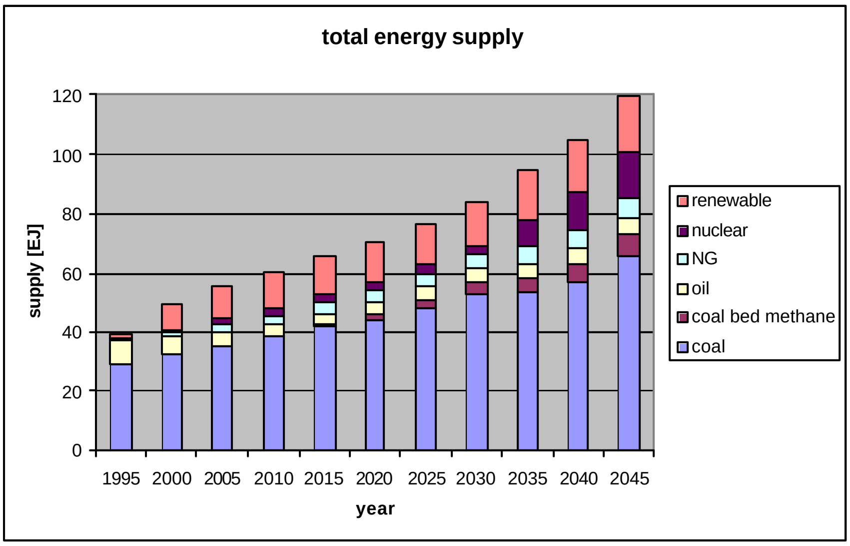

Figure 7.20. Total energy supply; scenario 4

7.7 Sensitivity analysis

The outcomes of the model depend on a large number of inputs – e.g. efficiency, investment cost, emissions - from various sources, each with a host of assumptions, and many of which have considerable uncertainties. To examine the robustness of the outcomes a sensitivity analysis was carried out.

To do this, several different methodologies exists (see Saltelli et al., 2000). Without discussion them all, a simple and basic approach will be used in this research. For this research, the estimated or assumed values of the variables (parameters) will be varied to examine the effect on the final result (distribution of demand for passenger cars and fuel-cell cars in particular). The following four of the most important or uncertain assumptions will be examined:

1. Investment cost

The investment costs of the natural-gas car (ICE and hybrid), the hybrid gasoline and diesel car are all in a range of US95$ 600 from each other, and three of them in a range of 300 US$95 (see appendix Q). As soon as the investment cost of one type is lower than the other the technology appears in the results of MARKAL (expect for the natural-gas car) and might even take over a large share of the market. This holds also true for the three fuel-cell cars, but here the range is more than US$95 700.

2. Variable operating and maintenance costs

The variable operating and maintenance (O&M) costs are the annual costs for maintenance & tires. In the model these costs have the same value for all passenger car types (43.9 US$95 million/ billion p-km). The sensitivity analysis carried out on this variable shows that, in the base case, a decrease of one US$95 per 1000 km for the hybrid natural gas and hybrid diesel car (all other values kept constant) is enough to replace or gain a share in the market. The switching value of the variable O&M cost for the Hydrogen fuel-cell car is 42 US$95 per 1000 p-km. Switching values of the same order can also be found for the other scenarios.

3. Emission control
We have varied the constraints of CO_2, but also examined the effect of SO2 emission and NO_x on the diffusion of fuel-cell cars. From the emissions constraints, the CO_2 emission constraint has the largest influence on the appearance of fuel-cell cars in the results of MARKAL. This can be derived from the fact that only with strict CO_2 constraints the diffusion of fuel-cells cars takes off (scenario three and four). The switching value (no fuel-cell cars in results) lies around 70.5 GtC.

NO_x emission constraints seem to have impact on the diffusion of hybrid natural-gas cars. Higher SO_2 emission constraints do not lead a higher diffusion of hybrid natural-gas cars or the entering of fuel-cell car technology in the results.

4. Fossil fuel price
In scenario two the prices of fossil fuels are increased by a factor of four, after 2025. Sensitivity analysis show that if the prices go up till a maximum of three times higher, the gasoline cars still dominate in the outcomes of MARKAL. Above five times higher fossil fuel prices after 2025, show an increase in demand for fuel-cell cars, eventually leading to a take over of almost the whole market.

7.8 Conclusion and discussion
In this chapter the four scenarios as derived out of the key factors and driving forces in chapter six are worked out. In chapter six we have stated that high technological development is a necessary condition for the diffusion of fuel-cell cars in China to set off, but scenario one shows that this is not a sufficient condition. Instead, hybrid cars with high efficiency and relatively low emission levels diffuse.

In case of high technological development with strict environmental policy the diffusion of fuel-cell cars in China could also set off. By the cumulative CO_2 constraint of 66 GtC over the period 1995-2050, the utilization of natural gas, hydrogen out of natural gas, and CO_2 sequestration techniques are stimulated. A transition from gas to hydrogen out of gas in the passenger car sector occurs.

The diffusion of fuel-cell cars in China could set off in case of increasing fossil fuels prices after 2025, which makes the use of hydrogen out of coal cost competitive. Though this increase should be enormous (times four per GJ in MARKAL). Before 2025 the car fleet is similar to the car fleet in scenario one: gasoline and diesel cars.

A combination of high fossil fuel prices and strong environmental policy, in an environment of high technological development, would have the highest impact on the diffusion of fuel-cell cars. According to Lako & de Vries (1999) high-energy prices occur in scenarios with high-energy demand, and therefore such scenarios are normally not easy to combine with a strict CO_2 reduction policy. However, MARKAL analysis shows the possibility, although against a high primary energy supply and high costs.

The difference in the scenarios where hydrogen fuel cells diffuse expresses in the use of coal or natural gas for hydrogen production. Normally, hydrogen out of gas is the cheapest option, but with increasing fuel prices, the low costs of coal get the upper hand in the cost consideration.

A discussion point is the assumption of the increase in fossil fuel prices. How and till which extend can fossil fuel prices increase? Graus (2001) states that a scenario with an increase of (end use) energy prices times five is not only an experimental-thought, but might also be a possible future. If the production of oil should decline steadily, this will cause an increase in energy prices, especially when demand increases. Resource scarcity is background variable. Lako & de Vries (1999) have made long-term (till 2100) projections of fossil-fuel prices and their results show various scenarios, one with a maximum and steady increase of energy prices (per GJ) of 2.5 times higher (in relation to 2000 prices). However, they do not assume depletion of gas and oil reserves before 2100. In this research the high increase of fossil-fuel prices is an extreme (thought), based on the latter. See for a reflection of the high fossil-fuel prices appendix T.

With regards to the results of MARKAL, there are three important discussion points. As noticed, in some of the scenarios the so called “flip-flop effect”[51] (Schaeffer, 1998) occurred. It means that if one technology is cheaper than the other, even if the difference is marginal, only this technology is picked, at least to its maximum potential. For the more expensive one, the lower bound is picked, which if often zero.[52] Besides, the optimization, calculated by the model, neglects stakeholders with different and conflicting interests, which are active on real life markets. Moreover, social influences, such as customer behaviour (preferences) are not taken into account. Especially in this research, where end-use demand is analysed, this is important.[53]

MARKAL is used here especially to examine the order of magnitude of the regulations or issues. The results underpin the story and the outcomes are kept consistent with the possibilities of the total energy system. The sensitivity analysis has showed that the switching value of the cumulative CO_2 emission constraint lies at 70.5 GtC over the 50-year period. For fossil fuels prices the switching value lies between 3.5 and 4 times higher prices. Due to time constraints it was not possible anymore to find the switching value for scenario four, i.e. by which combination(s) of higher fossil fuel prices and cumulative CO_2 constraint, hydrogen fuel-cell cars appear at the minimum in the MARKAL results.

[51] Also called “penny-switching”.
[52] In case bounds are used, by using market penetrations curves, the results can sometimes already be foreseen in (plain) MARKAL.
[53] Moreover, a change in prices will influence the demand for a technology. In plain MARKAL, used in this research, the demand is fixed, so no adjustments are made.

8. Conclusions and recommendations

In this chapter, an answer is formulated on the main research-question. The research-question is twofold:

- *How and to which extend might the diffusion of fuel-cell cars in China take off towards the year 2045?*
- *What does this mean for PSIs research activities?*

The latter point corresponds to step 12 of the methodology: look at the implications of the scenarios on the focal point or decision for the company. Out of the implications result the recommendations towards PSI with regard to their fuel-cell research activities (research sub-question 7a). Moreover, this chapter gives the recommendations for further research (research sub-question 7b).

8.1 Conclusions and recommendations

The aim of this research is to explore the diffusion of fuel-cell cars in China, using the MARKAL model, and in the form of scenarios. To carry out the research, a qualitative, multi-disciplinary scenario approach, adapted from Schwartz & Ogilvy (1995) is combined with a more quantitative exploring approach, reflected in Schaeffer (1998). This research shows that a combination of the two methodologies can be successfully applied to carry out future explorations, where, al least, the qualitative part can "underpin" the quantitative part and the other way around (see also the scenarios of Shell International, 2001). There is one important remark on it; a problem encounters, if a driving force, on which you want to build your scenario, can not be transformed in the model parameters. This happens, for example, if the major driving forces are social ones, which are sometimes hard to quantify.

The results in chapter seven shows that under certain conditions (scenario thought) the diffusion of fuel cells in China might set off. But even under these circumstances the diffusion process is difficult, although the scenarios show possible pathways.

Before diffusion of (hydrogen) fuel-cell cars can take place in OECD-countries, and later on in China, three problems have to be solved. The first is the problem of hydrogen storage. Although improvements have been made in storage of hydrogen, no solution has been found to store this low-density fuel. Secondly, the problem of fuel contamination has to be solved. This influences the lifetime and efficiency of the fuel cell. Third, the costs of the fuel cell have to be reduced with a factor of at least ten till twenty, before it can be cost competitive with the conventional powertrains. The system is cost competitive when the price of fuel cell is around 50 US$ per kW, but more preferable is a price of 30 US$ per kW. Without these achievements diffusion of fuel-cell cars will not set off. This is strengthened by the fact that, because of the increase in performance of conventional powertrains and the decline of emissions per kilometre, the diffusion of hybrid cars, and in some countries, the diffusion of natural-gas cars, the relative advantages of the fuel-cell car (high efficiency, low or zero emission) declines. Moreover, the high price of hydrogen production and delivery

Scenario one, "hybridisation of the car fleet", shows that high technological development alone is not a sufficient condition for the diffusion of fuel-cell cars to set off. Instead, the hybrid gasoline and natural-gas car sales set off.

Therefore, the first conclusion is that:
High technological development is a first necessary condition, but not a sufficient condition to set off the diffusion of fuel-cell cars in China.

This has the following implication for PSI:
By remaining interest in the fuel-cell car technology, the focus will, in the coming years, continue to be on the fundamental research of fuel-cell technology, to solve the technological and economical obstacles (world-wide).

Next, the implication is rendered into the following recommendation for PSI:
Continuation of the fundamental research on fuel-cell technology.

Before 2025, the conclusion can be drawn that the better performing gasoline car enters the market, which replaces the dirty existing cars, followed by the hybrid gasoline car (diesel cars might also gain a significant market share). Apparently, the investments already made in the energy infrastructure and the high price of alternatives do not allow changes in this infrastructure. First after 2025, the differences in the diffusion of powertrains (could) originate.

In the scenarios *"a hydrogen economy"* (#2), *"environmental reformation" (#3)*, and "self-sufficiency" (#4) the diffusion of (hydrogen) fuel-cell cars sets off after 2025.

In scenario two, "a hydrogen world", there are also no strong government interventions, but now the energy resource scarcity leads to an increase in fossil fuel prices after 2025. The price increase causes "alternative" fuels and technologies to become cost competitive (and innovations to take off). Hydrogen (out of coal) fuel cells gain interest, because of the lower fuel costs.

The incentives of the government play a significant role in the diffusion process, as they shape the policy, and a boundary (conditions) wherein the car or energy companies can operate. In scenario three, "environmental reformation", the diffusion of fuel-cell cars sets off, because of the emission restrictions. The main force is the reduction of CO_2 emissions. Therefore, new technologies have to be implemented. In the passenger car sector, the hybrid natural gas, with low emissions, replaces the (hybrid) gasoline car, and from 2035 onwards, the fuel-cell car enters the market to meet the emission restrictions. The markets for fuel-cell busses and fuel-cell bicycles also initiate fuel-cell cars. In this scenario an important role is granted for natural gas, to obtain the emission target(s) and to produce hydrogen out of this fuel.

In scenario four, "self-sufficiency", a combination of high fossil fuel prices and strong environmental policy, in an environment of high technological development, would have the highest impact on the diffusion of fuel-cell cars. In this scenario the natural-gas car starts to diffuse earlier, following similar diffusion pathways as in countries like Argentina, India, Pakistan and Egypt, initiated by the environmental policy (mainly CO_2 reduction, but also reduction of local emissions), and possible because of the expansion of the market. After 2025, fuel-cell cars are the successors of the natural-gas cars, initiated by the higher fossil fuel prices. In this scenario the importance of reducing supply security fears is shown. China succeeded in building a self-supporting and clean energy-supply system.

As mentioned, the diffusion of fuel-cell cars depends on the willingness of the fuel companies to invest in a hydrogen infrastructure, the willingness of the car manufacturers to invest in fuel-cell technology and to make it their (core) business, and finally it is the customer who has to buy the fuel-cell car (deals with public acceptance). The actors' perception can be forced (somewhat) by the three driving forces, on which the scenarios are based. So it is necessary to gain a high degree of consensus among the important actors and a breakthrough of the trend followed to set off the diffusion of the fuel-cell cars. The scenarios worked-out imply such consensus and breakthrough.

Based on the three scenarios where diffusion of fuel-cell cars takes off, the <u>second conclusion</u> is formulated:
The diffusion of fuel-cell cars in China will first and only take place after 2025, in case technological and economical obstacles can be removed, a niche market is found and the process of diffusion fetch up in a vicious circle, i.e. consensus among the important actors, driven by the technological development, and high prices of fossil fuels (energy resource scarcity) or (very) strict environmental regulations by the Chinese government, i.e. a breakthrough of the trend followed.

The three scenarios have the following <u>implication for PSI</u>:
In case there are signals for the diffusion of fuel-cells in China, as mentioned in scenarios two, three and four, there might be an enormous market for fuel-cell cars there[54]*, but also – maybe before the diffusion of fuel-cell cars - for small fuel-cells in bicycles and scooters (see 5.3.2.2). PSIs incentives to focus on small, cheap fuel cells for light vehicles might yield a profit if fuel-cell diffusion takes of in China.*

[54] But the diffusion of fuel-cell cars will largely depend on the development of fuel-cell cars in the OECD-countries.

With regard to the research activities of PSI, it can be recommended towards PSI:
To follow the signals, especially with regard to environmental policy in China, and profit from the possible development in China, to contribute[55] in collaboration with (car) industry partners to the development of the product, which is (also) suitable for the Chinese market. Additionally, operating in a network of institutes and universities, PSI could cater to scientific collaboration with Chinese research institutes and universities[56], which carry out a large part of current fuel-cell research in China.

It is hard to estimate till which extent (i.e. in manufacturing units) the diffusion of fuel-cell cars will diffuse in China, because of the 'flip-flop' effect in the results of MARKAL (suddenly an appearance in the model results of one technology, which takes over the whole market), because no determination is made of the maximum amount of fuel-cell cars that can produce annually, and because we only look at the least costs and not at customer behaviour in MARKAL. What can be said about manufacturing units, is that if the whole passenger-car fleet would be fuel-cell cars in 2045, this would correspond to around 120 million vehicles, and as diffusion will not set off before 2025, this comes down to six million fuel-cell cars a year on average. Just to fulfil the increasing car demand after 2025, the manufacturers have to produce four million cars a year on average.

Furthermore, the results of MARKAL do show when and under which conditions fuel-cell cars might diffuse and that there is no restriction in the amount of hydrogen that can be produced to satisfy the demand. So, no hard statements can (will) be made about the extent of the diffusion of fuel-cell cars in China, but that in case those cars diffuse[57] the market share will be significant and that the diffusion of fuel-cell cars in China is not restricted to the amount of hydrogen that can be produced in China to satisfy the demand.

8.2 Recommendations for further research

This research closes with the recommendations for further research. The recommendations bear on three topics:

1. Diffusion of fuel-cell cars in China:

- *To do a depth analysis. An interesting point would also be to analyse the market potential of fuel-cell-powered bicycles and scooters in China.*
  In this research many issues, varying from technical to social are discussed, which are based on an extensive literature study. This research can be used as a starting point for depth analysis.

- *To do a field research in China.*
  The views of stakeholder can be analysed, there is the possibility to access other (local or regional) data and the researcher can obtain a better perception of the current (environmental) situation in China.

- *To carry out (more) interviews.*
  By doing this, specified data can be acquired, for example about technologies, trends and developments that are going on in the market. By carrying out a survey (oral or written), the ranking of the driving forces on importance and uncertainty can be based on statistical data (see Poot, 2002).

2. China MARKAL database:

- *In general, to adjust the China MARKAL database.*
  Some inconsistencies were found in the used database of Zongxin et al. (2001). For example, calculated values of passenger car demand and SO_2 emissions for transport modes and listed in the report of Zongxin et al. (2001), were not the same as the values in the computer database. Where possible, these inconsistencies (also flowchart inconsistencies) are corrected. See also appendixes U and V. Not analysed sectors of the model were seen as black boxes.

[55] Such contribution implies knowledge, technology and money tranfer.
[56] See section 5.3.2.2.
[57] So after niche-forming.

- *Include endogenous learning.*
  In the MARKAL-database used for this study (by Zongxin et al., 2001), but also in other database, it is seen that some data are kept constant over time (and only some data vary over time), whereas it is expected that the data should vary over time with continuing technological development. One way to deal with this, is to incorporate the learning-by-doing concept. The former exogenous cost projections are “replaced” by learning, or experience curves (endogenous). It reflects the fact that (clusters of) technologies may experience declining costs as a result of its increasing adoption into the society due to the accumulation of knowledge through, among others, processes of learning-by-doing and learning-by-using (Seebregts et al., 1999).

- *Including LPG and Ethanol/Methanol ICE cars in the passenger car sector.*
  In the existing and future passenger car fleet, set up for the analyses by MARKAL, the demand for LPG vehicles and ethanol vehicles is not taken into account, although LPG vehicles have a small share in the transportation sector in China (see section 5.3.2.1). This was done because there was not enough sufficient data about this powertrain available.

- *Introducing other ways of hydrogen production. In the model hydrogen can only be produced out of coal and natural gas. Other forms of hydrogen production, mentioned in section 3.4.3.3, might be an option in China.*
  Although hydrogen out of coal and out of natural gas are representative (and it was in this research restricted by the model), other forms might play a role in thirty or forty years, which are mentioned in section 3.4.3.3. These are not analysed in this research, because the main focus lay on updating the passenger car sector, and not on the extension of the whole energy system.

- *To make a distinction between different car classes (e.g. small, medium, and large vehicles or private and commercial), instead of using one reference class.*
  In this research only a standard car, with a fixed amount of kilometres per year, is applied to represent the passenger car sector. This gives a representative view of the car sector. No distinction is made between private and commercial car use. The problem mentioned in section 7.3.2.1, about high and low mileage, which might favour vehicles with higher investment costs and lower annual costs, might be overcome. Besides, there are differences between the prices, efficiencies, emissions of small, medium, and large vehicles (see Röder, 2001b). By making a distinction between the different car classes, instead of using one reference class, a more detailed representation of car demand can be given. This is also be done by Röder (2001b).

<u>3. MARKAL:</u>

- *To use market penetration constraints (e.g. MARKAL-SAGE)*
  As described in section 7.8, it might happen that a “flip-flop” effect can be seen in the results of (plain) MARKAL. One way to deal with this effect is to use market penetration constraints, and MARKAL-SAGE calculates such market penetration constraints. Namely, the Kydes diffusion model is implemented, which calculates the market penetration constraints, based on logit functions without perfect foresight. Besides the system can optimize not only for the whole period at once, but also in periods of 5-10 years. This version is relatively new at PSI, and its application has to be assayed (e.g. comparing the outcomes of the runs with plain MARKAL in this research with the outcomes of the runs with MARKAL-SAGE).

References

Arentshorst, A. & Oude Luttikhuis, S. (2000). *OPEC: Geolied marktmechanisme blijft winnen.* Interface Magazine (17), Issue 2. December 2000. Faculteit Bedrijfskunde & Studievereniging SVIIB, Erasmus University, Rotterdam (NL).

Arthur D. Little (2001). *Cost Analysis of Fuel Cell System for Transportation*. Arthur D. Little, Inc. Cambridge, Massachusetts (USA).

BEWAG Innovationspark Brennstoffzelle (2002). *Die Geschichte der Brennstoffzelle*. Bewag. http://www.innovation-brennstoffzelle.de. Accessed in October 2002.

Bezlova, A. (1999). *China: China looks to new megacities to spur growth*. Atimes, 27 October 1999. http://www.atimes.com/china/AJ27Ad02.html. Accessed on 15-02-2003

Brannas, K. & Zackrisson, U. (1992). *On forecasting of innovations.* Quality & Quantity (25). Pp. 95-112.

Buen, J. (1998). *Review Article: China's Energy–Environmental Dilemma – Strategies and Framework Conditions*. Centre for Environment and Development, Norwegian University of Science and Technology. Dragvoll (Norway).

Burns, L.D.; Byron McCormick, J. & Borroni-Bird, C.E. (2002). *Vehicle of Change. Hydrogen fuel-cell cars could be the catalyst for a cleaner tomorrow*. Scientific American, Inc. Pp. 64-73

Centro Ricerche Fiat.(2002). *Current activities and perspectives on fuel cell vehicles at Fiat Research Centre*. Geering, H. P. Internationales SATG-Symposium Wil 2002; Brennstoffzellen im Automobil; Wil, Switzerland.

Chang, D.T. (2002). *A New Era for Public Transport Development in China.* China Environment Series – Issue 3. Pp 22-27.

Chen, Y.; Piao, A. & Xiao, Z. (1998). *China's Transport Prospects*. The Institute of Comprehensive Transportation State Planning Commision. Beijing, China. Presented at the 17th World Energy Congress held in Houston, Texas, USA in September 1998. http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/4_1_19.asp. Accessed on 10-01-2003.

China Motor Vehicle Documentation Centre (2003). *Chinese cars.* China Motor Vehicle Documentation Centre, Aldeboarn (NL). http://www.chinesecars.net/. Accessed on 28-03-2003.

Contadini, J.F. (2000). *Social Cost Comparison Among Fuel Cell Vehicle Alternatives*. Institute of Transportation Studies - University of California at Davis. For the Methanol Institute; Washington DC (USA). http://www.methanol.org/fuelcell/special/contadini_pg1.cfm. Accessed on 31-03-2003

Cropper, M. (2002). *Fuel Cells in China: A Fuel Cell Today Market Survey*. Fuel Cell Today. http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/IndustryInformationDisplayArticle/0,1168,481,00.html#. Accessed on 12-02-2003.

Dammers, E. (2000). *Leren van de toekomst; over de rol van scenario's bij strategische beleidsvorming*. University of Leiden (NL); Social Sciences. Ph.D. report. ISBN 90-5166-793-0

DeCicco, J.M. (2001). *Fuel Cell Vehicles; Technology, Market, and Policy Issues*. Society of Automotive Engineers, Inc. Warrendale, PA (USA). ISBN 0-7680-0873-5.

Dewulf, G. (1998). *De Kunst van het ontwerpen van strategische scenario's.* In: *"Differentiatie en Samenleving. Opstellen voor Henk Becker."* By Hermkens, P; van Rijsselt, R. & Sanders, K.. Thela Thesis; Amsterdam (NL). Pp. 200-215

Dicken, P. (1998). Global Shift; Transforming the World Economy. Paul Chapman Publishing Ltd; London. Third Edition. ISBN 1 85396 367 4.

ECN (2003a). *Mission, strategy and future*. Energy Research Centre of the Netherlands, Department of Policy Studies, Petten (NL). Http://www.ecn.nl/ps/missie.en.html. Accessed on 18-07-2003.

ECN (2003b). *Welcome to ECN*. Energy Research Centre of the Netherlands, Petten (NL). Http://www.ecn.nl/corp/welkom.nl.html. Accessed on 18-07-2003.

Eichler R. (2002). Welcome to the Paul Scherrer Institut. Paul Scherrer Institute. http://www.psi.ch/willkommen/welcome.shtml. Accessed on 04-11-2002.

Eliasson, B. & Lee, Y.Y. (2003). *Integrated Assessment of Sustainable Energy Systems in China; The China Energy Technology Program.* Kluwer Academic Publishors; Dortrecht (NL). ISBN 1-4020-1198-9

Energie-Spiegel (2002). *Auf dem Weg zur Emissionsfreien Mobilität*. Paul Scherrer Institute & Federal Institute of Technology Zürich. Nr. 6. (in German)

Energy Information Administration (1997). *China: An Energy Sector Overview*. United States Energy Information Administration. http://www.eia.doe.gov/emeu/cabs/china/china97.html Last modified 28-10-1997. Accessed on 12-02-2003

Energy Technology Systems Analysis Programme (2001). *MARKAL*. Http://www.ecn.nl/unit_bs/etsap/markal/main.html. Latest update 06-12-2001. Accessed on 07-01-2003

ETSAP (1993). *MARKAL Demystified*. ETSAP; Appendix A to Annex IV. http://www.ecn.nl/unit_bs/etsap/reports/markal-a4-a1.pdf. Accessed on 12-11-2002.

European Commission (2002). *European Union Energy & Transport in Figures; Statistical Pocketbook 2002*. European Commission, Directorate-General for Energy and Transport; in co-operation with Eurostat. Brussel (BE). ISNN 1225-1095. Http://europa.eu.int/comm/energy_transport/etif/etif_2002.pdf. Accessed on 19-03-2003.

Federal Reserve Bank of Minneapolis (2003). *Consumer Price Index, 1913-*. http://minneapolisfed.org/research/data/us/calc/hist1913.cfm. Accessed on 015-02-2003.

Feenstra, R.; Sperling, D.; Branstetter, L.; Harwit, E. & Hai, W. (2001). *From Import Substitution to WTO Accession: Government Intervention in the Chinese Automotive Market.* Institute of Transportation Studies; Program on Pacific Rim Business and Development; University of California. Davis (USA). Http://www.its.ucdavis.edu/Publications/2002/RR-02-03.pdf. Accessed on 04-03-2003.

Gan, L. (2003). *Globalization of the automobile industry in China: Dynamics asnd barriers in greening of the road transportation*. Energy Policy (31). Pp. 537-551

Garrity, L. (2002). *State Sustainability Strategy Background Paper `The Hydrogen Economy´*. Institute for Sustainability and Technology Policy, Murdoch University; Oil Vulnerability and Hydrogen Economy Reference Group.

Geels (2002a). *Understanding Technological Transitions: A critical literature review and a pragmatic conceptual synthesis.* Paper for Twente Workshop `Transitions and System Innovations`, 4-6 July, Enschede (NL).

Geels, F. (2002b). *Understanding the Dynamics of Technological Transitions; A co-evolutionary and socio-technical analysis*. University of Twente; Centre for Studies of Science, Technology and Society. Ph.D-thesis. Twente University Press, Enschede (NL). ISBN 90 365 1797 4.

Geels, F. & Smit, W.A. (2000). *Failed Technology Futures: Pitfalls and lessons from a historical survey*. Futures (32). Pergamon, Elsevier Science Ltd. Pp. 867-885

Gorman, T. (1998). *Has the gas car a future?* 17th World Energy Congress, September 1998, Houston. http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/2_3_24.asp. Accessed on 15-04-2003.

Graus, W. (2001). *Energiebesparing bij de Provincie Noord-Brabant: een blik op de toekomst.* Technische Universiteit Eindhoven; Eindhoven (NL).

Green Diesel Initiative (2000). *New Fuel Standards for China*. Green Diesel Initiative. http://www.green-diesel.com/english/press/P-6.asp. Accessed on 14-05-2003.

Hirschberg, S.; Ganter, U.; Burgherr, P. & Heck, T. (2001). *China Energy Technology Program: Towards a more sustainable electricity supply in China*. PSI Annual Report 2001, Annex IV, Villigen PSI (CH). Pp. 13-26

Hirschenhofer, J.H.; Stauffer, D.B.; Engleman, R.R. & Klett, M.G. (1999). *Fuel Cell Handbook; Fourth Edition*. Business/Technology Books; Orinda. For U.S. Department of Energy, Federal Energy Technology Center. ISBN 0-89934-359-7.

Hook, W. & Replogle, M. (1996). *Motorization and non-motorized transport in Asia*. Land use Policy (13). 1. Pp. 69-84

IEA International Energy Agency (1998). *World Energy Outlook; 1998 Edition.* International Energy Agency, Paris (France). ISBN 92-64-18513-5. Http://www.worldenergyoutlook.org/weo/pubs/weo1998/WEO98.pdf. Accessed on 03-03-2003.

IEA International Energy Agency (2000). *China's Worldwide Quest for Energy Security*. International Energy Agency. ISBN 92-64-17648-9. Http://www.iea.org/books/studies/2000/china2000.pdf. Accessed on 12-12-2002.

IEA International Energy Agency (2002). *Key World Energy Statistics from the IEA*. International Energy Agency; Paris (F) http://www.iea.org/statist/keyworld2002/keyworld2002.pdf. Accessed on 12-12-2002.

International Resources Group (2000). *Energy Planning and the Development of Carbon Mitigation Strategies; Using the MARKAL Family of Models*. International Resources Group and The Partners in the International Energy Agency – Energy Technology Systems Analysis Programme. Washington, DC.

Janssen, A. (2003). Personal communication with A. Janssen, Department of General Energy, Paul Sherrer Institut, 3-4-2003.

Katz, E.; Hamilton, H. & Levin, M.L. (1963). *Traditions of research on the diffusion of innovations*. American Sociological Review 28. Pp. 237-253.

Ki-Chun Lee, Seo-Ho Choi, Soo-Whan Kim, Tae-Won Lim dm Won-Suk Cho (2002). *Hyundai Santa fe FCV powered by hydrogen fuel cell power plant operating near ambient pressure*. Hyundai Motor Co. In: SAE International (2002). *Fuel Cell Power for Transportation 2002*. SP-1691. ISBN 0-7680-0959-6. Pp. 1-4

Kruijsen, J. (1999). *Photovoltaic Technology Diffusion – Contact & Interact*. Eburon: Delft (NL).

Kypreos, S. & Krakowski, R.A. (2002). *Electrical-Generation Scenarios for China*. General Energy Research Department, Paul Scherrer Institut, Villigen (CH).

Lako, P. & Vries, H.J.M. de (1999). *Voorraden en prijzen van fossiele brandstoffen; Schattingen en projecties voor de 21ste eeuw met het oog op klimaatbeleid*. Energy Research Centre of the Netherlands, by order of the Dutch Ministry of VROM. Report ECN-C--99-022.

Larminie, J. & Dicks, A. (2000). *Fuel Cell Systems Explained*. John Wiley & Sons Ltd.; Chichester. ISBN 0 471 49026 1.

L-B-Systemtechnik GmbH (2002). *GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicles Systems - A European Study*. General Motors, L-B-Systemtechnik GmbH, British Petroleum, ExxonMobil, Shell, Total Fina Elf. Ottobrun (GE). Http://www.lbst.de/gm-wtw/. Accessed on 18-03-2003.

Lin, G. & Jianhua, G. (1999). *Railway Trends in China*. Japan Railway & Transport Review (21). Pp. 34-37

Loveridge, D.(1995). *What are scenario's for?* In: Proceedings od Profutures Workshop "Scenario Building. Convergences and Differences." Sevilla (Spain). European Commission. Pp. 13-16

Mu, R. (2001). *Technology Transfer from Germany to China; Case Studies on Chinese Carmakers and Parts Suppliers*. Technische Universität Berlin (GE); Fachbereich Kommunikations- und Geschichtswissenschaft. Ph.D. report. ISBN, 3-7983-1814-X

McNicol, B.D.; Rand, D.A.J. & Williams, K.R. (2001). *Fuel cells for road transportation purposes - yes or no?* Journal of Power Sources (100). Elsevier Science B.V. Pp. 47-59

NAE National Academy of Engineering (2003). *Personal cars and China*. Committee on the Future of Personal Transport Vehicles in China, National Research Council, Chinese Academy of Engineering. ISBN 0-309-08492-X (Electronic version accessed). Http://www.nap.edu/books/030908492X/html/. Accessed on 03-03-2003.

National Bureau of Statistics (2002). *Stastical Communique of the People's Republic of China on the 2000 National Economic and Social Development*. National Bureau of Statistics People's Republic of China. http://www.stats.gov.cn/english/newrelease/statisticalreports/200203290018.htm. Last modified on 28-02-2001. Accessed on 10-02-2003

Nevada Department of Taxation (2002). *Questions and answers regarding short term lease of passenger cars*. Nevada Department of Taxation; Nevada (USA). Http://tax.state.nv.us/taxnew/documents/qa_stl.pdf. Accessed on 10-05-2003.

Northeast Advanced Vehicle Consortium (2000). *Future Wheels; Interviews with 44 Global Experts On the Future of Fuel Cells for Transportation And Fuel Cell Infrastructure AND A Fuel Cell Primer*. M.J. Bradley and Associates. Submitted to Defense Advanced Research Projects Agency. Boston (USA). http://www-rocq.inria.fr/imara/docs/FuelCells.pdf. Accessed on 12-12-2002.

Ogden, J.M.; Steinbugler, M.M. & Kreutz, T.G. (1999). *A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development*. Journal of Power Sources (79). Elsevier Science S.A. Pp. 143-168

Ogden, J.M.; Williams, R.H. & Larson, E.D. (2001). *Toward a Hydrogen-Based Transportation System*. Center for Energy and Environmental Studies, Princeton University. Princeton.

Ogden, J.M.; Williams, R.H. & Larson, E.D. (2003). *Societal lifecycle costs of cars with alternative fuels/engines*. Energy Policy, Article in press. Elsevier Science Ltd.

Ogilvy, J. & Schwartz, P.(1995). *Rehearsing the future through scenario planning*. In: Proceedings od Profutures Workshop "Scenario Building. Convergences and Differences." Sevilla (Spain). European Commision. Pp. 62-68

Ogilvy, J. & Schwartz, P. (2000). *China's Futures; Scenarios for the World's Fastest Growing Economy, Ecology, and Society*. Written with Joe Flower. Jossey-Bass Publishers: San Fransisco (USA). ISBN 0-7879-5200-1.

Paul Scherrer Institute (2002a). *Brennstoffzellenauto BORA HY. Power im ersten Härtetest erfolgreich.* Http://www.psi.ch. Accessed on 15-11-2002. (in German)

Paul Scherrer Institute (2002b). *Our goals*. Http://ene.web.psi.ch/goals.html. Accessed on 04-11-2002.

PSI (2000). *Profile.* Paul Scherrer Institute, Villigen PSI, Switzerland. Http://www.psi.ch/willkommen/welcome_profile.shtml. Accessed on 18-07-2003.

PSI (2002). *Policy of the Technology-Transfer at PSI.* Paul Scherrer Institute, Villigen PSI, Switzerland Http://techtransfer.web.psi.ch/. Accessed on 18-07-2003.

Podlipny, P. (2001). *Development of E-business in Car Sales - The Role of Leasing*. Skoda Auto. Eurofinas & Leaseurope Joint Annual Conference; Warsaw, October 14 - 16, 2001. Http://www.eurofinas.org/working_meetings/ppt-acrobat/Podlipny.pdf. Accessed on 03-06-2003.

Poot, E.H. (2002). *Toekomst van Telen. Verslag van de workshop "Toekomstverkenningen plantaardige teelten in Nederland"*. 19-06-2002, Born-Zuid Wageningen. Praktijkonderzoek Plant & Omgeving B.V.: Wageningen (NL).

Reumers, J.R.J. (2002). *Enhancement of the ODYSSEE Database*. Eindhoven University of Technology, Faculty of Technology Management: Eindhoven (NL). Master Thesis.

Rienstra, S.A. (1998). *Options and Barriers for Sustainable Transport Policies; a scenario approach*. Vrije Universiteit van Amsterdam; Faculteit der Economische Wetenschappen en Econometrie. Ph.D-Thesis. ISBN 90-9011775-x

Röder, A. (2001a). *Integrating LCA Data into Market Allocation Model Car Powertrains*. PSI Scientific Report / Volume 5 /General Energy. Pp. 146-147

Röder, A. (2001b). *Integration of Life-Cycle Assessment and Energy Planning Models for the Evaluation of Car Powertrains and Fuels*. Swiss Federal Institute of Technology (ETHZ) (CH); Paul Scherrer Institute, Villigen. Ph.D. Diss. ETH No. 14291

Röder, A. (2001c). *Life-Cycle Inventory and Costs of Different Car Powertrains*. Department of General Energy; Paul Scherrer Institute. Villigen PSI (CH). PSI Bericht Nr. 01-16. ISSN 1019-0643.

Rogers, E.M. (1983). *Diffusion of innovations.* Macmillan Publishers: London (UK).

Satelli A.; Chan, K. & Scott, E.M. (2000). *Sensitivity Analysis*. John Wiley & Sons Ltd; Chichester (UK); Wiley series in probability and statistics. ISBN: 0-471-99892-3.

Sawicki, M. (1997). *Bill M 209 -- 1997; Motor Vehicle Amendment (Motorized Cycles) Act*. Legislative Assembly of British Columbia. Queen's Printer, Victoria, British Columbia (CA). Http://www.legis.gov.bc.ca/1997/1st_read/mem209-1.htm. Accessed on 02-05-2003

Schaeffer, G.J. (1998). *Fuel Cells for the future; A contribution to technology forecasting from a technology dynamics perspective*. Univerity of Twente; Ph.D.-Thesis. ISBN 90 365 12 30 1

Schafer, A. & Victor, D.G. (2000). *The future mobility of the world population*. Transportation Research Part A (34). Pp. 171-205

Schwartz, P. (1993). *Stappen om scenario's te kunnen ontwikkelen.* Appendix in: "*De Kunst van het lange termijn denken"*. Book translated from English. Orginal title: *"The art of the long run. Planning for the future in an uncertain world"*. Currency & Doubleplay; New York (USA), 1991. Pp. 208-214

Seebregts, A.J.; Goldstein, G.A. & Smekens, K. (2001). *Energy/Environmental Modeling with the MARKAL Family of Models*. Energy Research Centre of the Netherlands (ECN). Petten.

Seebregts, A.J.; Kram, T.; Schaeffer, G.J. & Bos, A.J.M.(1999). *Modelling technological progress in a MARKAL model for Western Europe including clusters of technologies*. ECN. European IAEE/AEE Conference 'Technological Progress and the Energy Challenge', 30 Sep - 1 Oct 1999; Paris (FR). ECN-RX--99-028. 16

Seebregts, A.J.; Kram, T.; Schaeffer, G.J.; Stoffer, A.; Kypreos*, S.; Barreto*, L.; Messner**, S. & Schrattenholzer**, L. (1999). *Endogenous Technological Change in Energy System Models; Synthesis of Experience with ERIS, MARKAL, and MESSAGE*. Netherlands Energy Research Foundation, Paul Scherrer Institut* (CH) & International Institute for Applied Systems Analysis** (AU). Petten (NL).

Shell International (2001). *Energy Needs, Choices and Possibilities; Scenarios to 2050*. Exploring The Future. Global Business Environment Shell International Limited 2001. London (UK).

Smit, W.A. & Oost, EJ. van (1999). *De wederzijdse beïnvloeding van technologie en maatschappij; Een Technology Assessment-benadering.* Coutinho, Bussem (NL).ISBN 90 6283 169 9 CIP.

Song, C. (2002). *Fuel processing for low-temperature and high-temperature fuel cells; Challenges, and opportunities for sustainable development in the 21st century*. Catalysis Today (77). Elsevier Science Ltd. Pp. 17–49

Srinivasan, S.; Mosdale, R.; Stevens, P. & Yang, C. (1999). *Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-First Century*. Annual Review of Energy and Environment (24). Pp. 281-328

Srinivasan, S.; Mosdale, R.; Stevens, P. & Yang, C. (1999). *Fuel Cells: Reaching the Era of Clean and Efficient Power Generation in the Twenty-First Century*. Annual Review of Energy and Environment (24). Pp. 281-328

Steel, B.C.H. & Heinzel, A. (2001). *Materials for fuel cell technologies*. Insight review articles (414). Macmillan Magazines Ltd. Nature,15 November 2001. Pp. 345-352

The World Bank (1985). *China; The Transport Sector.* The World Bank. Washington, DC.

The World Bank (2001). *China: Air, Land and Water; Environmental priorities for a new millennium*. The International Bank for Reconstruction and Development / The World Bank. Washington D.C. (USA). ISBN 0-8213-4937-6.

The World Bank (2002). *World Development Indicators database*. The Word Bank Group. http://www.worldbank.org/data/dataquery.html. Accessed on 10-02-2003.

Thuijl, E.v. (2002). *Grootschalige toepassing van biobrandstoffen in wegvoertuigen; Een transitie naar emissiearm vervoer in Nederland*. Eindhoven University of Technology; Faculty of Technology Management. Master Thesis; Research carried out by Energy Research Centre of the Netherlands, Petten (NL).

Tijink, D. (1999). *Wetenschapsverkenningen als vorm van participartieve beleidsanalyse. Een empirisch onderzoek naar succesbepalende factoren*. Delft University; Delft.

United Nations Development Programme / Global Environment Facility (2002). *China: Demonstration of fuel cell bus commercialization In China*. United Nations Development Programme / Global Environment Facility. Washington & New York.

Vercoulen, F. (1998). *Inleiding meso-/micro-sociologische analyse van technologische ontwikkeling (SATO-1)(0A380/82)*. Eindhoven University of Technology: Eindhoven (NL). http://www.tm.tue.nl/owinfo/SATO1/sato.pdf. Accessed on 11-12-2002.

VNPI (1998). *Aantal inwoners en voertuigen per service station.* Vereniging Nederlandse Petroluem Industrie, Den Haag (NL). Http://www.vnpi.nl/cijfer/. Accessed on 28-07-2003.

Walsh, M.P. (2002). *Offroad Vehicles and Engines; The Unfinished Agenda*. STAPPA/ALAPCO Spring Meeting. http://www.4cleanair.org/Walsh2.pdf. Accessed on 08-05-2003.

Weber, K.M. (1998). *Innovation Diffusion and Polictical Control of Energy Technologies (A comparison of Combined Heat and Power generation in the UK and Germany).* Physica-Verlag.

Weeda, M.; Dijkstra, J.W.; Ouden, A.C.B.d.; Smidt, R.P.d. & Weijers, E.P. (2002). *Inventarisatie milieupotentiaal brandstofcelvoertuigen voor het Nederlandse wegverkeer*. Energy Research Centre of the Netherlands. Petten (NL). ECN-C-01-100. Http://www.ecn.nl/library/reports/2002/c01100.html. Accessed on 12-02-2002.

Weiss, M.A.; Heywood, J.B.; Drake, E.M.; Schafer, A. & AuYueng, F.F. (2000). *On the road in 2020; A life-cycle analysis of new automobile technologies*. Energy Laboratory, Massachussets Institute of Technology. Energy Laboratory Report # MIT EL 00-003. Cambridge, Massachusetts (USA). Http://web.mit.edu/energylab/www/. Accessed on 06-03-2003.

Weiss, M.A.; Heywood, J.B.; Schafer, A. & Natarajan, V.K. (2003). *Comparative Assessment of Fuel Cell Cars*. MIT Massachusetts Institute of Technology; Laboratory for Energy and the Environment. MIT LFEE 2003-001 RP. Cambridge (USA).

Wokaun, A. (2003). Personal communication (by e-mail) with Prof. dr. A. Wokaun, Head of the General Energy Department, Paul Scherrer Institute, 10-07-2003.

Wurster, R. (1999). *PEM Fuel Cells in Stationary and Mobile Applications; Pathways to Commercialization*. Sixth International Technical Congress - BIEL'99. 13th – 19th September 1999. L-B-Systemtechnik GmbH; Ottobrunn (GE). Http://www.gydrogen.org/wissen/pdf/biel99.pdf. Accessed on 27-01-2003.

Xiucheng, D. & Logan, J. (2002). *Expanding Natural Gas Use in China*. A Joint Sino-U.S. Research Report. Prepared by the University of Petroleum-Beijing and Pacific Northwest National Laboratory. Sponsored by the U.S. Environmental Protection Agency and China State Development Planning Commission. PNNL-13853.

Ybema, J.R.; Lako, P.; Kok, I.; Schol, E.; Gielen, D.J. & Kram, T. (1997). *Scenarios for Western Europe on Long Term Abatement of CO2 Emissions*. Netherlands Energy Research Foundation (ECN). Petten.

Zhang, A. (1997). *Industrial Reform and Air Transport Development in China*. Department of Economics University of Victoria, Victoria BC Canada and Visiting Professor, 1996-98 Department of Economics and Finance, City University of Hong Kong, Hong Kong. Http://www.capi.uvic.ca/pdf/ZHANG.pdf. Accessed on 21-02-2003.

Zhou, H.; Sperling, D.; Delucchi, M. & Salon, D. (2001). *Transportation in Developing Countries; Greenhouse Gas Scenarios for Shanghai, China*. Tongji University, Shanghai & Institute of Transportation Studies, University of California, Davis. Shanghai & Davis.

Zongxin, W.; DeLaquil, P.; Larson, E.D.; Wenying, C. & Pengfei, G. (2001). *Future Implications of China's Energy-Technology Choices*. Prepared for the Working Group on Energy Strategies and Technologies (WGEST) and China Council for International Cooperation on Environment and Development (CCICED).

Appendixes

Appendix A. Definitions

Adoption: Adopting new technologies by individual customers and companies. (Vercoulen, 1998)

Alternative fuels: Biodiesel, electric fuel, ethanol, hydrogen, methanol, natural gas (CNG/LNG), propane (LPG), P-series, and solar fuel. (US Department of Energy in Gan, 2003)

Diffusion: Realisation of a breakthrough of a new technology in the society, after it has proven itself in a niche. (Kruijsen, 1999)

Fuel cell: fuel cells are electrochemical devices that convert the chemical energy of reaction directly into electrical energy (Hirschenhofer, Stauffer & Engleman (1994) in Schaeffer, 1998).

Driving forces in the macro-environment: Trends that influence key factors. (Ogilvy and Schwartz, 1995)

Implementation: The way on which the adaptation of a new technology will have consequences for internal processes of organisations, consumers and other users. (Vercoulen, 1998)

Key factors in the micro-environment: Different factors from the direct environment, which have influence on the organisation. (Tijink, 1999)

Load factor: Average number of occupants in a vehicle, sometimes expressed as a fraction of capacity, sometimes as number of people. Also used for freight vehicles, expressed as fraction of capacity or number of tons (Zhou et al., 2001)

Minicar: Car designed for urban use. In Japan, defined as a vehicle with engine capacity of 660 cc or less. Also known as “city car.” (Zhou et al., 2001)

Modal split: The share of total passenger or freight travel on different kinds of transportation, usually measured as a percent or fraction. (Zhou et al., 2001)

Passenger-kilometre: One passenger moving one kilometre. This is the same as one person-kilometre. (Zhou et al., 2001)

Passenger cars: A passenger car is defined as a motor vehicle designed to carry 10 persons or less. Passenger car *does not* include motorcycle, power cycles, motor driven cycles, motor trucks, or motor homes. (NRS 482.087, 482.071, & 482.073) (Nevada Department of Taxation, 2002)

Powertrain: The powertrain of a car consists of all devices necessary to convert the energy stored in the fuel to vehicular motion plus the fuel storage system. (Röder, 2001b)

Sensitivity analysis: The study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the given model depends upon the information fed into it. (Saltelli et al., 2000)

Social technological regime: Semi-coherent set of rules carried by different social groups. (Geels, 2002a)

Social map: A schematic representation of a network of actors involved and their mutual relations. (formulated on the basis of Smit & van Oost, 1999)

Technological map: A schematic representation of a network of technological artefacts and their mutual relations. (formulated on the basis of Smit & van Oost, 1999)

Vehicle-kilometre: One vehicle moving one kilometre. (Zhou et al., 2001)

Vehicles: means a device in, on or by which a person or thing is or may be transported or drawn on a highway, except a device designed to be moved by human power or used exclusively on stationary rails or tracks, and excludes motorized cycles. (Sawicki, 1997)

Appendix B. Diffusion process

In this section relevant issues of the diffusion process are discussed and these issues form part of the train of thought behind this research. Thus, it gives a nearer foundation or background of the theory, definitions in section 1.2, the role of actors in the diffusion process, and the scenarios. A part of the text is adapted from Reumers (2002).

There are several definitions of diffusion. In this research, we have used the definition of Kruijsen (1999):

"The realisation of a breakthrough of a new technology in the society, after it has proven itself in a niche."

Rogers (1983), on the other hand, defined the process of innovation diffusion as:

"... The process by which an innovation is communicated through certain channels over time among the members of a social system."

And Katz et al. (1963) defined innovation diffusion as follows:

" (1) the acceptance (2) over time, (3) of some specific item, idea or practise (4) by individuals, groups or other adopting units, linked to (5) specific channels of communication, (6) to a social structure, and (7) to a given system of values."

These definitions have some similarities. Four resembling independent variables can be distinguished: time, communication channels (not in Kruijsen's definition), the innovation itself and the social system (Reumers, 2002). Another point, is that all imply the role of actors in this process, which is confirmed by Weber (1998): *"the diffusion of an innovation is the result of more or less co-ordinated decision processes along economic, political and informational channels based on the aims, interests and expectations of the actors involved."* He also concludes that the technology will diffuse, which can achieve the highest degree of consensus among the important actors (Reumers, 2002). Kruijsen, specifically mention the niche-market in his definition, whereas the other definitions do not talk about large-scale introduction.

As stated in section 1.2, there is distinct relation between diffusion and adoption. Each adoption unit subsequently undergoes its individual decision process in the adoption of a technology. According to Rogers (1983) this decision process consists of the following phases:

- *Knowledge*: when an individual or other decision-making unit learns about the innovation's existence and gains some understanding of how it functions
- *Persuasion*: when an individual forms an attitude toward the innovation
- *Decision*: when an individual engages in activities that lead to a choice to adopt or reject the innovation
- *Implementation*: when an individual puts an innovation into use
- *Confirmation*: when an individual seeks reinforcement of an innovation-decision that has already been made, but the individual may reserve this previous decision if exposed to conflicting messages about the innovation.

There are five groups of adopters, which shape the cumulated S-curve of frequency of adopters in time: the innovator (2.5%), then by the early adopters (13.5%), early majority (34%), late majority (34%) and at last by the laggards (16%).

The role of actors is important in the diffusion process. The actor's perception determines the decision regarding that technology. In Rogers (1983) five innovation features are discussed, as perceived by the innovation receiver and according mechanism, which are determinative to the diffusion of an innovation:

- *relative advantage* is the degree to which an innovation is perceived better by the adopters than the idea it supersedes. Relative advantage indicates the strength of the reward or punishment resulting form adoption of an innovation. Indicators are profitability, social benefits, time saving, hazard removed, productivity, labour, and requirements.

- *compatibility* is the degree to which an innovation is perceived as being consistent with existing socio-cultural values, beliefs, past practices, experiences and ideas (acceptability and exchangeability) and needs of potential adopters (desirability). The more compatible an innovation is, the less change it presents.
- *complexity* is the degree to which an innovation is perceived as difficult to understand and use.
- *triability* is the degree to which an innovation may be experimented with on a limited base.
- *observability* is the degree to which the results of an innovation are visible to others. In addition to this communicability is mentioned. Communicability is the degree to which aspects of an innovation may be conveyed to others.

These features and phases are not worked out explicitly in the main text of this report, but do recur in the text.

To close, a quote out of Reumers (2002) is given, showing again the relevance of finding the key factors in driving forces behind the diffusion process in this research:
"The diffusion of an innovation is the result of accumulated adoption decisions of individuals or other decision-making units and moreover a dynamic process, which interconnects social, technological, economic and political driving forces. Therefore the diffusion of an innovation is a complex process influenced by a multitude of heterogeneous factors operating at different levels."

Appendix C. "Step by step plans" in Ogilvy & Schwartz and Schaeffer

Two "step by step plans" presented in the form of a table: the one of Ogilvy & Schwartz (1995) and the one described in Schaeffer (1998). The one of Ogilvy and Schwartz is a more general approach, whereas the one from Schaeffer is focusing on technology forecasting by means of computer models. A computer model is also used in this research.

Table C.1. Steps in the scenario process by Ogilvy and Schwartz (1995)

Steps:	**Issues:**
1. Identify Focal Issue or Decision	Begin with a specific decision or issue relevant for the company, then build outwards towards the environment
2. Key Forces in the Micro-environment	Factors influencing the success or failure of that decision: - competitors, both direct and indirect - market trends
3. Driving forces in the Macro-environment	Listing driving trends in the macro-environment that influence the key factors: - *What are the forces behind the micro-environmental forces?* Checklist: - social trends - economic outlook - politics - technology - environment
4. Rank by importance and uncertainty	To identify the two or three factors that are most important and most uncertain, after ranking the factors by those two criteria
5. Selecting scenario logics	Generating a few scenarios whose dissimilarities make a difference to decision-makers. In a form of identifying axes of crucial uncertainties
6. Fleshing out the scenarios	Each key factor and trend should be given some attention in each scenario
7. Implications	Look at the implications of the scenarios on the focal point or decision identified in step 1
8. Selection of leading indicators	Identifying a few indicators to monitor the course of history as it actually unfolds.

Table C.2. The practice of technology forecasting by Schaeffer (1998)

Steps:	**Issues:**
1. Selection of technologies and their dimensions to be forecast	Which technology or technologies should be the object of the forecast and which features of these technologies should be explored?
2. Characterisation of the technologies	- characterisation of the technologies subject - develop an overall vision on the technology. - Special attention is paid to those characteristics that will serve as input parameters in the model runs.
3. Judgement on the values of the parameters that will function as model input	- the determination of the values of the parameters that will serve as input in the model. - Involves some discussions and considerations of a kind not directly related to the specific technology.
4. Construction (including adaptation) of a forecasting model	- From building and introducing new models to minimally changing existing models
5. Model run	- the running of a model functions as a test of the model construction and judgement process.
6. Analysis of the model outcomes	- get from the crude numbers to the relevant graphs
7. The construction and presentation of translated outcomes, based on the model outcomes	- the model outcomes are turned in 'translated outcomes'.

Appendix D. Example MARKAL

Example taken over from ETSAP (1993), but modified.

General:
A linear program is a set of linear equations (or, more precisely, inequations that specify "greater than" or "less than" relationships) with variables and coefficients and constraints defined by the user as input data.

The solution to the linear program describes a set of energy technologies and energy flows that constitute an energy system that is feasible and optimal. Feasibility means that all the numbers add up correctly and that all the constraints are satisfied. Optimality means that of the hundreds or thousands of feasible solutions, this is the one that has the least cost (if cost is the objective function).

Example:
The problem, illustrated in figure C.1, is to meet the projected need for electric generating capacity at least cost, choosing from three candidate energy technologies X, Y, and Z. In the top graph, the required total capacity during some years in the future is shown together with the residual amount of existing capacity which gradually declines over time. Initially, no additional capacity is needed because the residual value exceeds the required capacity. Soon, however, the two curves cross over, and additional capacity must be built. (The required margins of safety to assure system reliability are assumed to be included in the curves shown.)

The three lower graphs show the maximum market penetration that can be achieved by the three candidate technologies beginning at the point where additional capacity is required. The greatest rate of build-up is possible in Technology Z, which might be, for example, a conventional pulverized coal plant. Technology X, a new development, cannot actually be introduced until later.

Technology X will be the least expensive of the plants, measured in terms of cost per kilowatt-hour of electricity generated, and Technology Z the most expensive. That is, A is less than B is less than C.

The first decision is to choose which technologies to provide in time to fill the gap between the required and the residual electric generating capacity (figure C.1). The two technologies initially available are Y and Z. Inasmuch as Y is less expensive than Z, as much of Y as possible is therefore built. The additional capacity is provided by Z, the actual use of which is less than its maximum potential market penetration.

The first change in the choice of technologies occurs when Technology X, the cheapest, becomes available (figure C.1). At that point, Technology X begins to be built to the limit of its potential market penetration. Technology Y, the next cheapest, continues to be used to its limit. Finally, the difference between the required capacity and the sum of X and Y is supplied by Technology Z, the actual use of which continues to be less than the maximum that could be built.

Sum-up:
In sum, this simplified example illustrates the following points about the workings of MARKAL:

- *The energy system is constructed of the set of technologies that satisfies demands at least cost (if cost is the objective function).*
- *Technologies are selected in the order by their cost (if cost is the objective function) up to the point where the constraints are satisfied.*
- *Maximum market penetration and allowable levels of emissions are examples of constraints that limit the use of a technology.*
- *Emission reduction may be considered either by constraints (equivalent to emission standards) or in the objective function (equivalent to an emissions tax).*
- *The value of a technology depends not only upon its nominal cost and emission characteristics, but by what it replaces (or is replaced by) elsewhere in the energy system.*
- *MARKAL makes it possible to compare on the same scale the value of technologies anywhere in the energy system by measuring their effect on the objective function.*

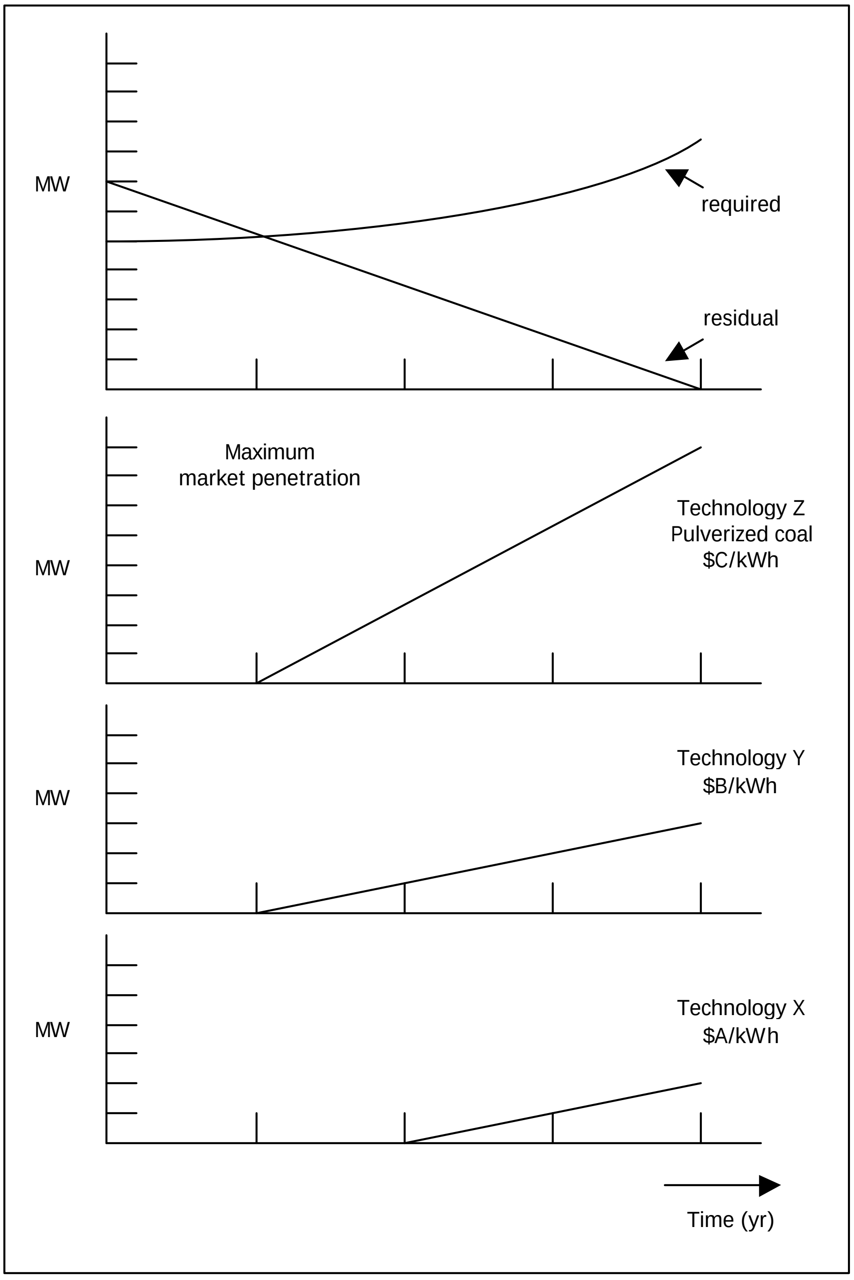

Figure D.1. Example MARKAL

Appendix E. MARKAL Building Blocks

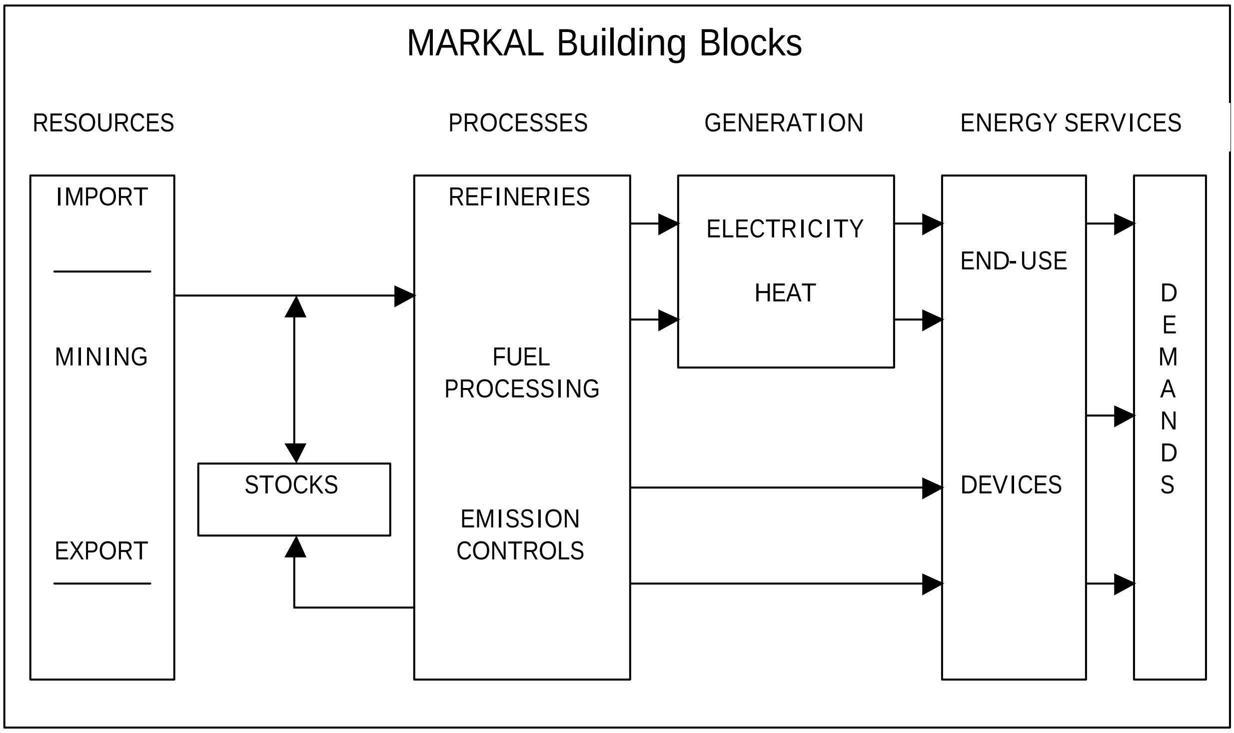

Figure E.1. Markal Building Blocks
Source: International Resources Group, 2000

Appendix F. Fuel pathways for alternative vehicle power systems

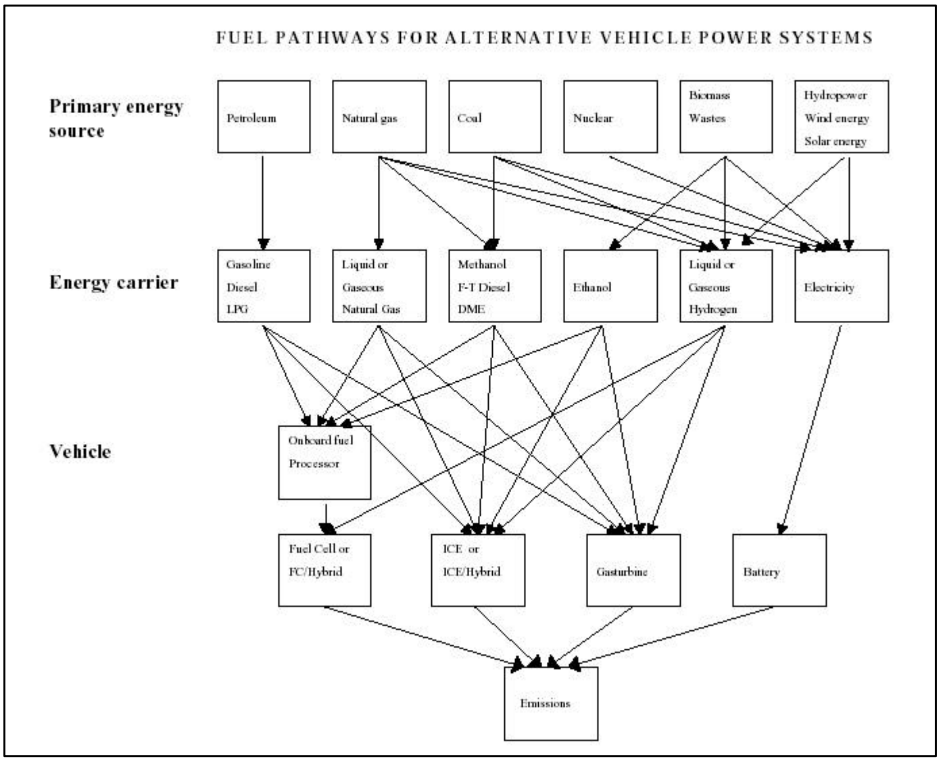

Figure F.1. Fuel pathways for alternative vehicle power systems
Source: Weeda et al. 2002

Appendix G. Historical development of specific costs of fuel cells

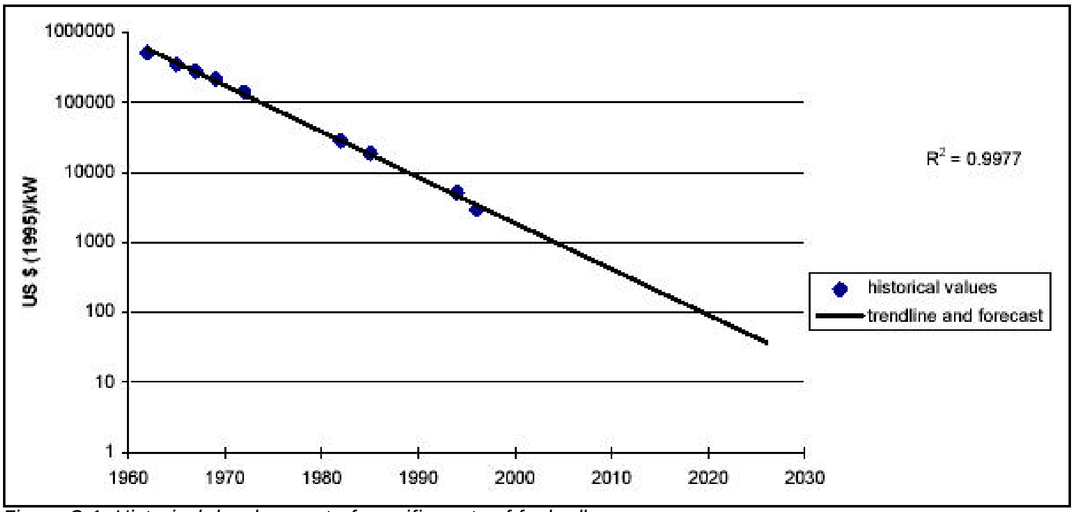

Figure G.1. Historical development of specific costs of fuel cells
Source: Schaeffer, 1998

Appendix H. Motorization in Asia

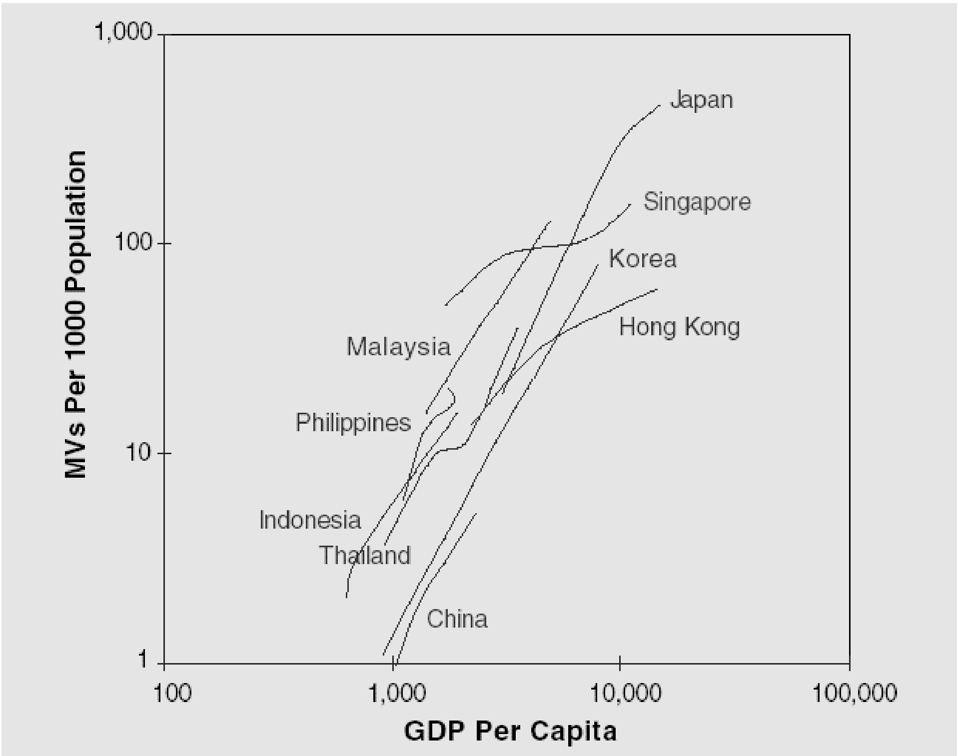

Figure H.1. Motorization in Asia (1960-1990)
Source: Chang, 2002

Appendix I. Passenger traffic in China by mode

Table I.1. Passenger traffic in China by mode, 1950-2001 (in billion passenger-km)

	Year										
Mode:	**1950**	**1955**	**1960**	**1965**	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2001**
railway	21	27	67	48	72	96	138	242	261	355	448.8
highways	1	5	15	17	24	37	73	172	262	460	660
water	1	4	6	5	7	8	13	18	17	17	10.4
airways	0.0	0.1	0.2	0.3	0.2	1.5	4	12.0	23.0	68.0	99.6
total	24	35	88	70	103	144	228	434	563	900	1219

Sources:

Data 1950-1980: The World Bank , 1985

Data 1985: Yearbook 1995 in Zhang, 1995

Data 1990: Lin & Jianhua, 1999

Data 1995: Zongxin et al., 2001

Data 2001: National Bureau of Statistics China, 2002

Appendix J. Production volumes of the Chinese automotive industry

Table J.1. Major Economic Data of the Chinese Automotive Industry (1981-1995)

Year	**Total (unit)**	**Passenger car (unit)**
1981	175,645	3,428
1982	196,304	4,030
1983	239,886	6,046
1984	316,367	6,010
1985	443,377	5,207
1986	372,753	12,297
1987	472,538	29,865
1988	646,951	36,798
1989	586,936	28,820
1990	509,242	42,409
1991	708,820	81,055
1992	1,061,721	162,725
1993	1,296,778	229,697
1994	1,353,368	250,333
1995	1,452,697	325,461
1996	-	-
1997	-	-
1998	-	-
1999 (a)	1.85 million	-
2000 (a,b)	~2 million	600,000-650,000
2001 (b)	-	757,905
2002 (b)	-	1,350,106
2003 (b,c)	-	1,687,900
2005 (a,c)	3.2 million	-

Source till 1995: Chinese Automobile Industry Yearbook 1999, p.5 in Mu, 2000
(a) Source: Gan, 2003
(b) Source: China Motor Vehicle Documentation Centre, 2003
(c) Projection

Appendix K. Projections of China's total primary energy demand

Table K.1. Total Primary Energy Demand in Mtoe 1971-2020 (in Mtoe)

	Year				
	1971	**1995**	**2010**	**2020**	**1995-2020 (%)**
Solid fuels	190	664	1087	1416	3.1
Oils	43	164	355	506	4.6
Gas	3	17	57	81	6.5
Nuclear	0	3	19	33	9.6
Hydro	3	16	39	62	5.5
Other Renewables	0	0	2	3	--
Total	239	864	1539	2101	3.6

Source: IEA, 2000

Appendix L. Key factors and driving forces: scores on importance and uncertainty

Table L.1. Ranking of key factors and driving forces by importance and uncertainty

	Importance	Uncertainty	Ranking	MARKAL
Society				
growing population	4	3	21	+/-
crises	5	8	8	-
willingness to pay new infrastructure	8	8	1	+/-
growing environmental awareness	6	7	8	+/-
reducing hydrogen storage concerns	7	7	5	+/-
increasing customer preferences	7	6	8	-
Economics				
increasing price of oil	7	7	5	+
growing GDP	7	4	14	+/-
decreasing FC investment costs	9	7	1	+
blocking of foreign cars	5	4	20	+/-
Technology				
improving efficiency	6	6	12	+
lower car emissions	6	4	18	+
solving technological problems	8	6	5	+/-
Environment				
increasing energy demand and supply	6	5	14	+/-
shortage on fossil fuels	8	7	4	+
shortage on water	4	6	18	-
Politics				
stimulating car ownership	6	7	8	-
dependency of foreign energy suppliers	6	4	19	+
Increasing emission control	9	7	1	+
Increasing regional influence	7	5	12	-
development of public transport	5	6	14	+/-

Legend:

- For importance and uncertainty: 0 = not important / certain – 10 = very important / very uncertain
- For ranking: 1 = highest average score on importance and uncertainty – 25 = lowest average score on importance and uncertainty
- Able to create a scenario in MARKAL: + = possible; +/- = possible but complex; - = not possible

Appendix M. Formulas MARKAL transportation sector, passenger cars

$$INV = \frac{price\ of\ the\ car}{occupancy * mileage} \tag{1}$$

where:

INV = investment costs in US$1995/p-km/yr
price of the car = price of new car in US$1995
occupancy = number of people per car (also called load factor)
mileage = average miles/kilometres per year per car in km/yr (also called kilometrage)

$$EFF = \frac{occupancy}{fuel\ economy * energy\ density * 100} \tag{2}$$

where:

EFF = efficiency in p-km/MJ
fuel economy = litres per 100 kilometre (l/100 km)
energy density = energy per litre (MJ/l)

$$EMM_{NO_x, PM_{10}} = \frac{emission_{NO_x, PM_{10}}}{fuel\ economy * energy\ density} \tag{3}$$

where:

$EMM_{NOx, PM10}$ = emission of NO_x, PM_{10} in g/MJ fuel
$emission_{NOx,PM10}$ = emission of NO_x, PM_{10} in g/km

$$EMM_{SO_2} = \frac{ppm}{energy\ density_{fuel}} \tag{4}$$

where:

EMM_{SO2} = emission of SO_2 in g/MJ fuel
ppm = parts per million (~mg/kg)
$energy\ density_{fuel}$ = energy density of fuel in MJ/kg

$$DEMAND = population * motorization * mileage * occupancy \tag{5}$$

where:

DEMAND = demand for passenger cars in p-km
population = population
motorization = amount of passenger cars per 1000 inhabitants
mileage = average amount of kilometres driven per car per year
occupancy = amount of persons per car

$$\#cars = population * motorization = \frac{demand}{mileage * occupancy} \tag{6}$$

where:

#cars = the amount of passenger cars

Appendix N. Conversion factors

Table N.1. Conversion factors

Multiple by	mpg (Imp)	mpg (US)	l/100 km	MJ/km
mpg (Imp)		0.833	0.354	11.399
mpg (US)	1.201		0.425	13.685
l/100 km	2.825	2.352		32.2 (gas) 35.8 (diesel)
MJ/km	0.877	0.073	0.031 (gas) 0.028 (diesel)	

Energy density of gas = 32.2 MJ/l ~ 42.5 MJ/kg
Energy density of diesel = 35.8 MJ/l ~ 42.8 MJ/kg

1 statute mile = 1.609 km

kilo (k) = 10^3
mega (M) = 10^6
giga (G) = 10^9
tera (T) = 10^{12}
peta (P) = 10^{15}
exa (E) = 10^{18}

Appendix O. Conversion of cost data to US$1995

All costs are given in US$1995. Published costs expressed in dollars of other years were adjusted to 1997 dollars using the US Consumer Price Index. See table O.1.

Whenever a reference does not explicitly give the year to which its prices refer, it is assumed that it is for the year when the reference was published.

Table O.1. Conversion into US1995

Year	GDP–Deflator
1990	86
1991	89
1992	92
1993	95
1994	97
1995	100
1996	103
1997	105
1998	107
1999	109
2000	113
2001	116
2002	118

Source: Federal Reserve Bank of Minneapolis, 2003

Appendix P. Occupancy

Table P.1. Load factor / Occupancy (occupants/car)

Source:	2000	2020	2050	Note:
Zhou et al., 2001	2.5	2.5 or 3	-	Shanghai
Huapu, 2002	2.5	-	-	China
Schafer & Victor, 2000	2.5	2.3	2.0	Central Planned Asia: China, Vietnam and Mongolia
Schafer & Victor, 2000	2.0	1.8	1.6	Reforming regions
Schafer & Victor, 2000	2.2	2.1	1.9	Developing countries
Schafer & Victor, 2000 & European Environment Agency, 2002	1.7	-	-	Western Europe
Schafer & Victor, 2000	1.6	1.4	1.3	North America

Appendix Q. China's passenger cars: Assumptions

In appendix M the formulas are given to calculate the input data the passenger car sector of China MARKAL. In this section all the assumptions that are made, which are necessary to (re)calculate these input data for MARKAL, are reflected. Most assumptions are based on an extensive literature study.

Future car fleet in China
From the analysis of the fuel-cell car and its competitors, and the Chinese auto market, a most likely and representative future car fleet is set up. In 2000, the Chinese car fleet had around 6.5 million passenger car, of which around 99% were gasoline cars, around 1% diesel and a very small fraction were LPG and natural-gas cars. The existing gasoline car will be replaced by the gasoline car with higher performance and lower emissions per km, available from 2000 onwards. The diesel car is entering the market (e.g. VW producing diesel cars in China; Gan, 2003) as well as the compressed natural gas (CNG) car. Three fuel-cell systems will be added into the model. These are the hydrogen fuel-cell car (+HEV), the gasoline FC car and the methanol FC car. Other powertrains that are assumed to enter the market are the gasoline DISI ICE HEV, the diesel DICI ICE HEV and the CNG ICE HEV. These cars might be the successors of the traditional gasoline, diesel and NG cars.

Fuel economy:
The fuel economies of the ten cars are given in table Q.1. Most data are derived from Ogden et al. (2003), except for the gasoline SI ICE, the diesel CI ICE and the CNG SI ICE.

Table Q.1. Assumptions for China's passenger car sector; fuel economy

Car type		Fuel economy		Source:
		mpgge	l/100 km	
Car-	Gas SI ICE	25	**9.35**	Zhou et al., 2001
Car-	Diesel CI ICE	37	**6.33**	Zhou et al., 2001
Car-	evol Gas SI ICE	**27**	8.71	Ogden et al., 2003
Car-	CNG ICE	**31**	7.66	U.S. Departm. of Energy, 2003
Car-	gas DI SI ICE HEV	**58**	4.06	Ogden et al., 2003
Car-	diesel DI CI ICE HEV	**67**	3.51	Ogden et al., 2003
Car-	GNG ICE HEV	**62**	3.79	Ogden et al., 2003
Car-	H_2 FCV (+HEV)	**82**	2.87	Ogden et al., 2003
Car-	gas FCV	**38**	6.19	Ogden et al., 2003
Car-	MeOH FCV	**56**	4.20	Ogden et al., 2003

Energy efficiency:
The energy efficiency of the passenger cars, based on the fuel economy, was kept constant over the analysis period, because the load factor is declining, which offsets the improvements in efficiency.

Occupancy (Load factor)[58]:
For the load factor (persons/car) the results of Schafer (2000) are taken (see table Q.2). Although these values are valid for Central Planned Asia, it represents the values for China.

Table Q.2. Occupancy of car in Central Planned Asia from 2000 to 2050

Year	2000	2010	2030	2050
Load factor (persons/car)	2.5	2.4	2.2	2.0

Source: Schafer & Victor, 2000

Mileage (kilometrage):
Also for the mileage of a car (km/yr/car) the results of Schafer (2000) are taken (see table Q.3). These values are again valid for Central Planned Asia, but represent the values for China.

[58] See also appendix P.

Table Q.3. Kilometrage in Central planned Asia

Year	2000	2010	2030	2050
Mileage (km/yr)	19,000	19,000	18,000	14,000

Source: Schafer & Victor, 2000

Price of Car:

The average price of a gasoline car in China is assumed to be US$2001 22,000 (~ US$95 19,000). The extra powertrain costs for the other cars are derived from Ogden et al. (2003), expect for the compressed natural gas (CNG) and diesel ICE car, where the extra powertrain costs are derived from Röder (2001b). All cars are assumed to be commercially available and mass-produced (world-wide).

Table Q.4. Assumptions for China's passenger car sector; extra powertrain costs

Car type		Extra powertrain costs		Source:
		US$1999	US$1995	
Car-	Gas SI ICE	-	-	
Car-	Diesel CI ICE	1700 CHF98	1221	Röder, 2001a
Car-	evol Gas SI ICE	-	-	
Car-	CNG ICE	1700 CHF98	1121	Röder, 2001a
Car-	gas DI SI ICE HEV	1342	1231	Ogden et al., 2003
Car-	diesel DI CI ICE HEV	1863	1709	Ogden et al., 2003
Car-	GNG ICE HEV	1556	1428	Ogden et al., 2003
Car-	H_2 FCV (+HEV)	2459	2256	Ogden et al., 2003
Car-	gas FCV	5097	4676	Ogden et al., 2003
Car-	MeOH FCV	3220	2954	Ogden et al., 2003

Lifetime of a car:

The lifetime of a car is expected to increase in the coming decade, due to better construction and materials. Today's lifetime is around 10 years. Therefore, the cars that are available from 1995 and 2000 have a lifetime of 10 years (gasoline ICE, diesel ICE). The cars that are available from 1995 and 2000 (evolutionary gasoline ICE and NG car) have a lifetime of 12 years, and the cars available from 2015 (hybrids and FC cars) 15 years.

Emissions:

For the NO_x emissions most values are taken from Contadini (2000). According to Gan (2003). The existing Chinese car emits two till seven times more NO_x emissions as US/EU cars. In this research, I take 5 times higher values for NO_x (g/km). For CNG cars it is assumed that they emit 83% lower nitrogen oxides emissions compared to gasoline cars (Gorman, 1998).

CO_2 emissions (carbon content) are derived from Zongxin et al. (2001) and L-B-Systemtechnik GmbH (2002). The SO_2 emissions are calculated using ppm values (see table Q.5 for the assumed ppm values). For the PM10 emissions various sources are taken, which can be seen in table Q.5.

All assumed emission values are given in table Q.5.

Table Q.5. Assumptions for China's passenger car sector; emissions

Car type		Emissions SO_2		Remark
		kg/GJ fuel		
Car-	Gas SI ICE	0.019		800 ppm (policy China)
Car-	Diesel CI ICE	0.070		3000 ppm (average diesel in China)
Car-	evol Gas SI ICE	0.019		800 ppm (policy china)
Car-	CNG ICE	0.0002		5.5 mg/m^3
Car-	gas DI SI ICE HEV	0.004		150 ppm (European standards)
Car-	diesel DI CI ICE HEV	0.010		350 ppm (european standards)

Car-	GNG ICE HEV	0.0002		5.5 mg/m^3
Car-	H_2 FCV (+HEV)	0.000		no sulphur
Car-	gas FCV	0.004		150 ppm (european standards)
Car-	MeOH FCV	0.000		no sulphur
Car type		**Emissions NO_x**		**Source:**
		g/mile	**g/km**	
Car-	Gas SI ICE	5 x 0.35	5 x 0.22	Contadini, 2000 + Gan, 2003
Car-	Diesel CI ICE	0.8	0.497	Walsh, 2002
Car-	evol Gas SI ICE	0.35	0.218	Contadini, 2000
Car-	CNG ICE	0.018	0.011	Gorman, 1998
Car-	gas DI SI ICE HEV	0.05	0.031	Contadini, 2000
Car-	diesel DI CI ICE HEV	0.12	0.075	Walsh, 2002
Car-	GNG ICE HEV	0.01	0.006	Gorman, 1998
Car-	H_2 FCV (+HEV)	0.000	0.000	Contadini, 2000
Car-	gas FCV	0.004	0.002	Contadini, 2000
Car-	MeOH FCV	0.002	0.001	Contadini, 2000
Car type		**Emissions CO_2**		**Source:**
		tC/GJ	**tg CO2/GJ**	
Car-	Gas SI ICE	0.020	73.4	Zongxin et al. , 2001; L-B-Systemtechnik GmbH, 2002
Car-	Diesel CI ICE	0.020	72.8	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	evol Gas SI ICE	0.020	73.4	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	CNG ICE	0.015	56.4	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	gas DI SI ICE HEV	0.020	73.4	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	diesel DI CI ICE HEV	0.020	72.8	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	GNG ICE HEV	0.015	56.4	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	H_2 FCV (+HEV)	0.000	0.0	no direct CO_2 emission
Car-	gas FCV	0.020	73.4	Zongxin et al., 2001; L-B-Systemtechnik GmbH, 2002
Car-	MeOH FCV	0.019	68.6	Craven, 2001; L-B-Systemtechnik GmbH, 2002
Car type		**Emissions PM10**		**Source:**
		g/mile	**g/km**	
Car-	Gas SI ICE			Value of the old model taken
Car-	Diesel CI ICE	0.080	0.050	Walsh, 2002
Car-	evol Gas SI ICE	0.030	0.019	Contadini, 2000
Car-	CNG ICE	0.000	0.000	assumed
Car-	gas DI SI ICE HEV	0.025	0.016	Contadini, 2000
Car-	diesel DI CI ICE HEV	0.040	0.025	Euro IV standard
Car-	GNG ICE HEV	0.000	0.000	assumed
Car-	H_2 FCV (+HEV)	0.000	0.000	assumed
Car-	gas FCV	0.020	0.012	Contadini, 2000
Car-	MeOH FCV	0.020	0.012	Contadini, 2000

<u>Hydrogen production and delivery:</u>
Hydrogen is produced out of natural gas and coal. This is restricted by the model.

The costs for H_2 delivery are assumed to be 9 US95$ per GJ (based on Ogden et al., 2003; see table Q.6).

Table Q.6. Cost of hydrogen delivered to consumers at refuelling stations

	H_2 from natural gas via steam reforming (a)		H_2 from coal via O_2-blown gasification (b)	
	CO_2 vented	CO_2 captured	CO_2 vented	CO_2 captured
Production cost ($/GJ, HHV)	6.33	8.04	5.69	7.36
Total delivered costs ($/GJ, HHV)	15.33	17.04	15.57	17.24
Delivery costs without production costs ($/GJ, HHV)	9	9	9.88	9.88

Source: Ogden et al., 2003
(a) based on 1996 data
(b) based on 2002 data (?)

<u>Methanol and Compressed natural gas (CNG) production and delivery:</u>
Methanol and CNG are produced out of natural gas (import and gas mining). Methanol can also be produced out of coal.

The costs for methanol delivery are assumed to be US$95 5 per GJ. This value is based on figure Q.1 (fuel production is not taken into account).

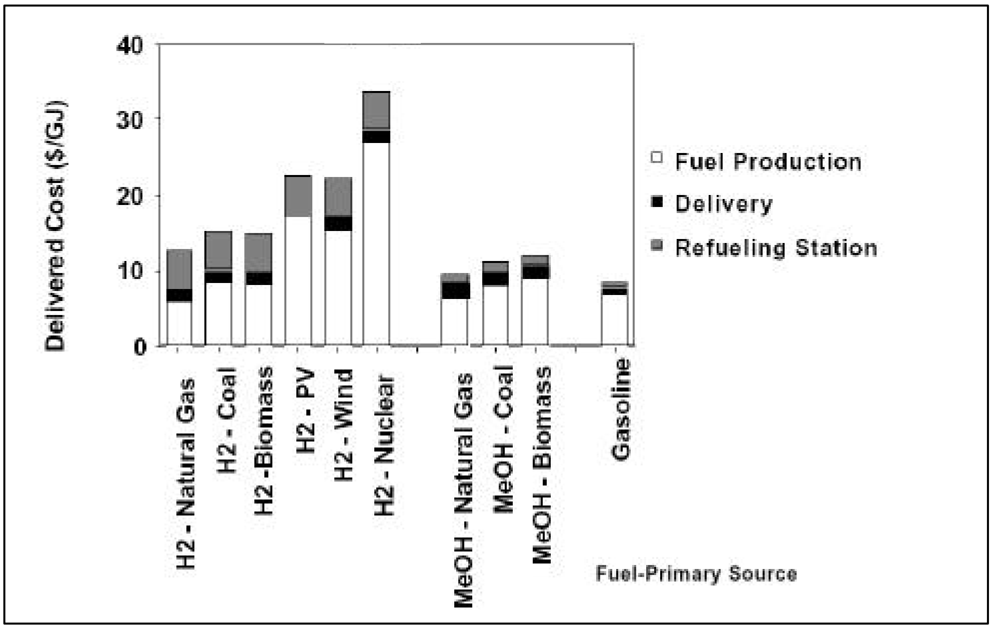

Figure Q.1 Delivered cost of hydrogen, methanol, and gasoline transportation fuels (US$93/GJ)
Source: Ogden et al., 1999
Note: All Hydrogen cases assume centralized, large (city) scale H_2 production with extensive, local H_2 pipeline distribution system (except PV H_2 which is produced onsite)

<u>Operating and maintenance (O&M) costs:</u>
No specific data was found for O&M costs. The original data (43 US95$ per 1000 p-km) in the model are used and kept constant for all types of car, which is also done in the original model.

<u>Year first available:</u>
The year first available is the year where the car is assumed to be commercially available. This means for the model that from that year onwards the car is an option to take. The taken years are based on the author's opinion.

<u>Demand projections:</u>
The demand for passenger cars is given in passenger-kilometre (p-km). The demand can be calculated by using formula 4, but can also be calculated if you know the amount of cars (see formula 5).

Demand projections for the passenger car sector have been made by Zongxin et al. (2001). In table Q.7 the results are given. In their projection both the occupancy and the mileage are kept constant over time, whereas the study of Schafer & Victor (2000) show a declining occupancy and mileage for the region of Central Planned Asia, which is related to the increasing GDP (see also section 5.2.2). The study of Schafer & Victor (2000) is based on extensive research, whereas the projections of Zongxin et al. (2001) are based on simple assumptions.[59] That is why the data of Schafer & Victor is applied to make new demand projections.[60]

Table Q.7. Old projections of passenger car demand in Zongxin et al., 2001

	year												
	1995	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Source:**
population (billion)	1.211	1.294	1.34	1.386	1.441	1.495	1.528	1.56	1.575	1.59	1.583	1.575	Zongxin et al, 2001
mileage (km/yr/car)	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	Zongxin et al, 2001
occupancy (persons/car)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	Zongxin et al, 2001
motorization (cars/1000)	2.0	3.6	5.6	8.5	13.2	19.5	28.1	39.5	49.2	61.0	76.1	94.7	calculated
demand (billion p-km)	54.9	103.8	169.3	266.3	428.6	655.3	965.3	1'388.(	1'744.(	2'181.6	2'710.8	3'356.8	Zongxin et al, 2001
cars (million)	2	5	8	12	19	29	43	62	78	97	120	149	calculated

Table Q.8. New projections of passenger car demand (with data of Schafer & Victor, 2000)

	Year												
	1995	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Source:**
Population (billion)	1.211	1.294	1.34	1.386	1.441	1.495	1.528	1.56	1.575	1.59	1.583	1.575	Zongxin et al, 2001
Motorization (cars/1000)	2.9	5.0	7.5	10.0	13.2	19.5	28.1	39.5	49.2	61.0	76.1	94.7	data old projection*
Mileage (km/yr/car)	19,000	19,000	19,000	19,000	19,000	19,000	19,500	18,000	17,500	17,000	15,500	14,000	Schafer & Victor, 2000
occupancy (persons/car	2.5	2.4	2.4	2.4	2.3	2.3	2.3	2.2	2.2	2.1	2.1	2.0	Schafer & Victor, 2000
demand (billion p-km)	166.3	296.4	458.3	632.0	832.4	1272.7	1924.2	2442.9	2984.2	3461.5	3921.6	4177.4	calculated
cars (million)	3.5	6.5	10	14	19	29	43	62	78	97	120	149	calculated

* data of 1995-2005 are modified

[59] But still give a good indication of future demand.

[60] Please note that the motorization rate (passenger cars per 1000 inhabitants) derived form the projection of Zongxin et al. (2001) corresponds to the figure in appendix H, with the GDP projections mentioned in section 5.2.2.

Appendix R. Input data MARKAL

Passenger car sector input
With the assumptions mentioned in appendix Q and the formulas in appendix M the input parameters for MARKAL have been calculated, and reflected in table R.1. All other data in the Chinese database for MARKAL set up by Zongxin et al. (2001) are kept constant.

Although the energy efficiency in p-km per MJ is kept constant over the period analysed, the energy efficiency in km per litre increases, due to the declining load factor (as shown in table P.2). Every twenty years the efficiency increases around 10%, which corresponds to the data in Röder (2002b) and Weiss et al. (2000).

Table R.1. MARKAL input for Chinese passenger car sector

Transport demand Technology	**Year First**	**Energy Efficiency 1000 p-km/GJ**			**Capital Cost**	**O&M Cost**	**SOx Emissions**	**NOx Emissions**	**CO2 Emissions**	**PM Emissions**
Passenger car		**2000**	**2010**	**2015-2050**	**$/1000 p-km**		**kg/GJ fuel**	**kg/GJ fuel**	**kgC/GJ fuel**	**kg/GJ fuel**
Gas SI ICE	1995	0.82	0.82	0.82	400	43	0.019	0.361	20	0.006
Diesel CI ICE (evol?)	1995	1.09	1.09	1.09	424	43	0.070	0.244	20	0.052
evol Gas SI ICE	**2000**	0.86	0.86	0.86	400	43	0.019	0.072	20	0.006
CNG ICE	**2005**	-	0.97	0.97	441	43	0.0002	0.005	15	0.000
gas DI SI ICE HEV	**2010**	-	1.84	1.84	444	43	0.004	0.024	20	0.006
diesel DI CI ICE HEV	**2010**	-	2.12	2.12	454	43	0.010	0.066	20	0.022
GNG ICE HEV	**2010**	-	1.96	1.96	448	43	0.0002	0.005	15	0.000
H_2 FCV (+HEV)	2015	-	-	2.60	466	43	0.000	0.000	0	0.000
gas FCV	2015	-	-	1.20	519	43	0.004	0.001	20	0.006
MeOH FCV	2015	-	-	1.77	481	43	0.000	0.001	19	0.006

Note: Costs are given in US95$

Scenario input
All scenarios:
Availability of advanced technologies (see Zongxin et al, 2001) and low fuel-cell stack prices (+/- 30 US$/kW)

Scenario 2: “a hydrogen economy”:
The fuel prices of fossil fuels are multiplied with 2 in 2025 and 4 from 2030 onwards (based on Graus, 2002).

Scenario 3: “environmental reformation”:
CO_2 emission constraint: 66 Giga tonnes of Carbon over the period 1995-2050 (Zongxin et al., 2001).

Scenario 4: “self-sufficiency”:
The fuel prices of fossil fuels are multiplied with 2 in 2025 and 4 from 2030 onwards, and CO_2 emission constraint of 66 Giga tonnes of Carbon over the period 1995-2050 (Zongxin et al., 2001).

Appendix S. Additional scenario: environmental taxes

We would like to show you the results of the scenario with environmental taxes (figure S.1 and S.2), that is not presented in the main results, but which is worthwhile to mention. They reflect the "true costs" of the energy system. With "true costs" we mean energy system costs plus environmental costs. They show similar results as scenario four. The levels of the taxes on SO_2, NO_x, PM and CO_2 are:

CO_2 tax: 120 US/tonnes C (source: Ogden et al., 2003)
SO_2 tax: 4249 US/tonnes (source: based on Eliasson & Lee, 2003)
NO_x tax: 3093 US/tonnes (source: based on Eliasson & Lee, 2003)
PM tax: 2379 US/tonnes (source: based on Eliasson & Lee, 2003)

In comparison with scenario four, we see also the entering of fuel-cell cars in the market, but now five years later, and we see an earlier entering of hybrid natural gas cars, without any share for the hybrid gasoline share.

The emission levels in the transportation sector show approximately the same values as in scenario four. Total emissions per year, however, go down earlier in this scenario but reach the same end values (in 2045) as in scenario 4. Total energy supply shows a radical shift in 2010 from coal to natural gas. In 2045, coal, natural gas and renewables all have a share of around 25%.

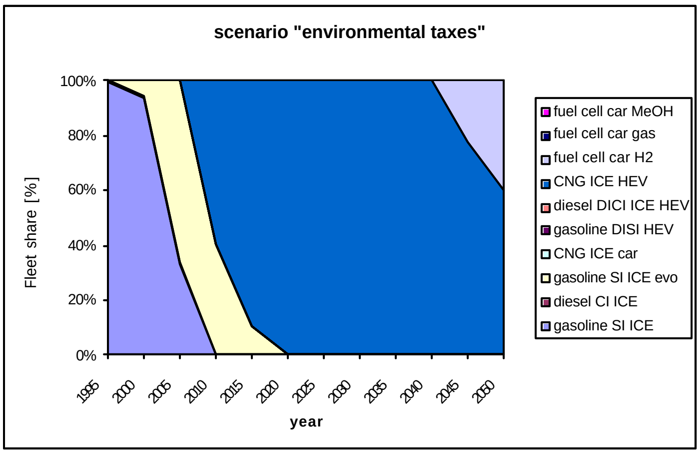

Figure S.1 MARKAL results: fleet share

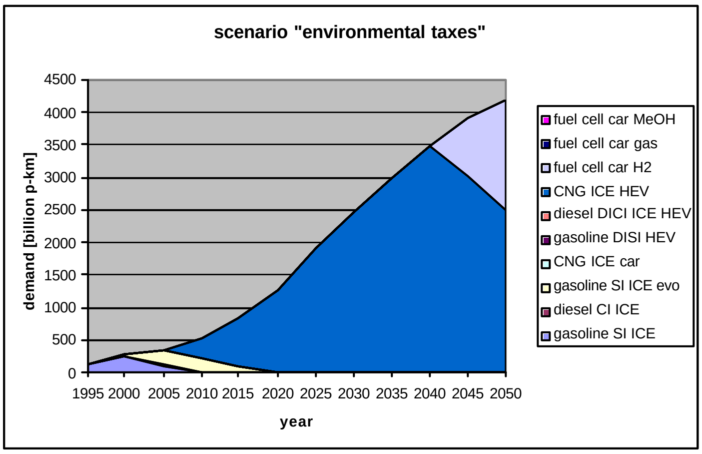

Figure S.2 MARKAL results: demand for passenger cars

Appendix T. Reflection of high fossil-fuels prices

We have seen the importance of increasing fossil-fuels prices in the results of MARKAL. Is a high price increase realistic? What determines the price of oil, gas and coal? This is a complex issue, influenced by many factors. In this section the realization of the energy prices is discussed, reflecting the decision made in section 6.3.

During the oil crisis from 1973 till 1985, the prices of energy have increased by 750% for oil, 700% for gas and 350% for coal (Scheepers en Batjes, 2000 in Graus, 2001). After 1985 the prices have decreased till the level of before the crisis. Also during the Golf Wars we saw an (temporary) increase of fossil-fuel prices.

The energy reserves of oil, gas and coal, and the extraction costs are important determinants for the volume and price of the energy supply (Lako & de Vries, 1999). Normally, the natural-gas price is coupled to the oil price. The price of coal is not directly related and more stable than the price of oil and gas, among others because of the larger reserves (Lako & de Vries, 1999).

According to Campbell and Laherrere (1998) (in Graus, 2001) around 2002 the maximum of world-wide energy production should have been reached. After 2002 the production of oil should decline steadily and will cause an increase in energy prices, unless the demand will decrease proportionally (Graus, 2001). However, the Energy Information Administration expects a 60% increase of oil demand in 2020 (Graus, 2001). So high-energy prices occur in scenarios with high-energy demand (Lako & de Vries, 1999). The high oil price in 2000 is a good example of the previous relation. But not only the reduced production of oil by OPEC-countries was the reason, but also the policy of the United States (keeping low interest rate), and low investment in exploration in industrialized countries, due to environmental pressure, contributed to the price increase in 2000 (Arentshorst & Oude Luttikhuis, 2000).

Lako & de Vries (1999) have made long-term (till 2100) projections of fossil-fuel prices and their results show various scenarios, all with steady increasing fossil-fuel prices. The study goes into expected fossil fuel prices in situations of CO_2 reduction policy or other reasons of moderate use of fossil fuels in this century. One scenario, with high-energy demand and low government intervention, shows a maximum (but steady) increase of energy prices (per GJ) of 2.5 times higher (in relation to 2000 prices). But Lako & de Vries (1999) assume no depletion of gas and oil reserves before 2100. Besides, the general thought in their scenarios is that the oil market will adjust gradually to the changes in the demand, and the production costs of non-conventional oil becomes more important.

A situation of high fossil fuel prices will lead to protest among the public, tensions in the economy and environmental awareness (Arentshorst & Oude Luttikhuis, 2000). Besides, if the OPEC tries to keep the price of oil high by production restrictions, the following points will undermine the cartel (Lako & de Vries, 1999; Arentshorst & Oude Luttikhuis, 2000):

- Exploitation of non-conventional oil reserves; necessary condition is the development of new exploitation techniques.
- Substitution to alternative sources of energy, such as nuclear power and renewables.

So the OPEC will not draw much benefit from this.

In conclusion can be said that the future fossil-fuel price will depend on the development of the demand, the energy resource scarcity, the extraction costs and environmental policy. Besides, Graus (2001) states that the liberalisation of the energy markets, the energy resource scarcity and political developments could cause a new energy crisis in the future, with high fossil-fuel price increase. She also states in her report that a scenario with an increase of (end use) energy prices times five is not only an experimental-thought, but might also be a possible future.

Also in this research the high fossil-fuel price is an experimental-thought, with the latter as a reflection of the likelihood and of the mechanisms behind the realization of fossil-fuel prices.

Appendix U. Flowchart; old passenger car sector

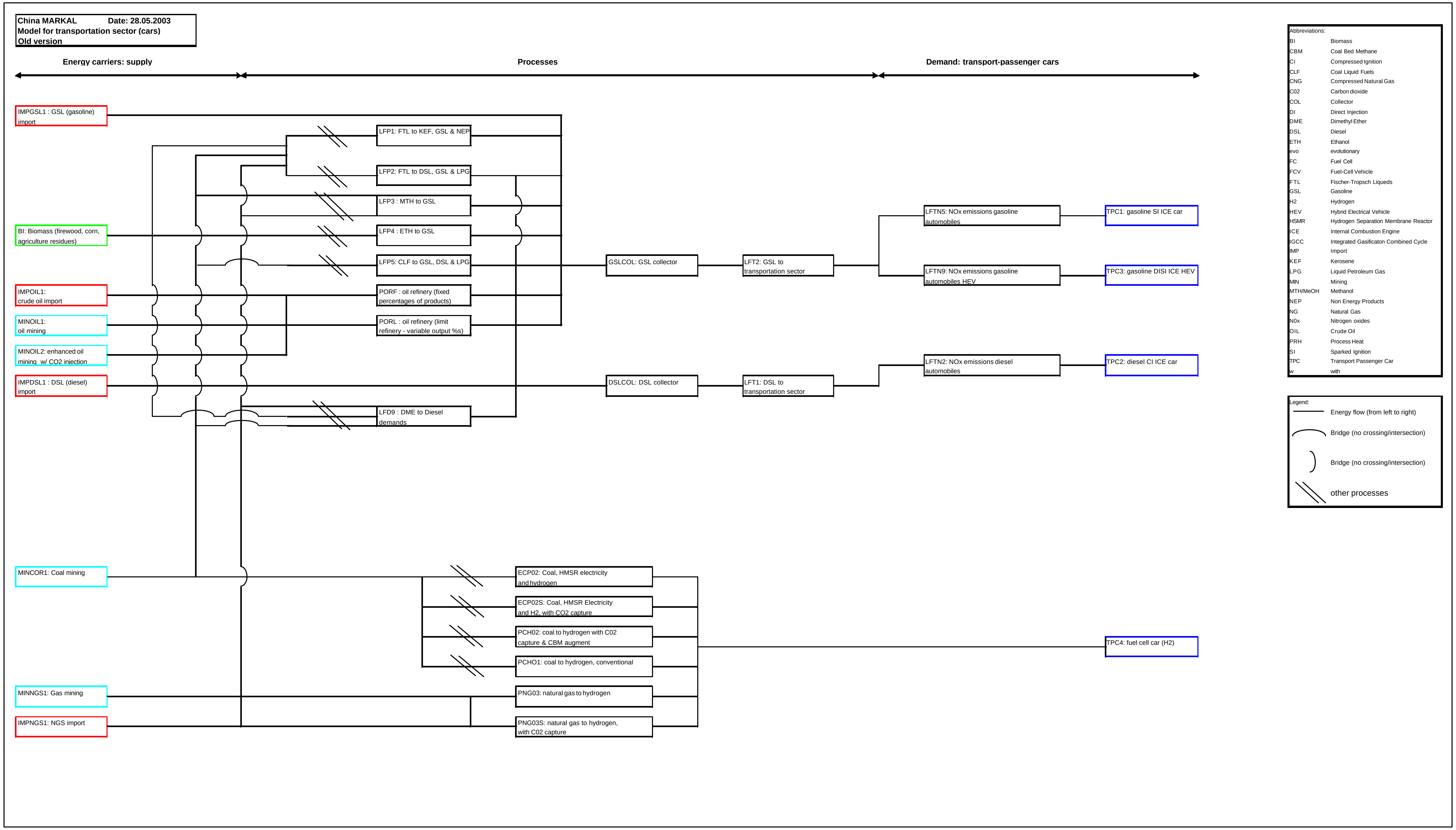

Figure U.1. Flowchart; old passenger car sector

Appendix V. Flowchart; updated passenger car sector

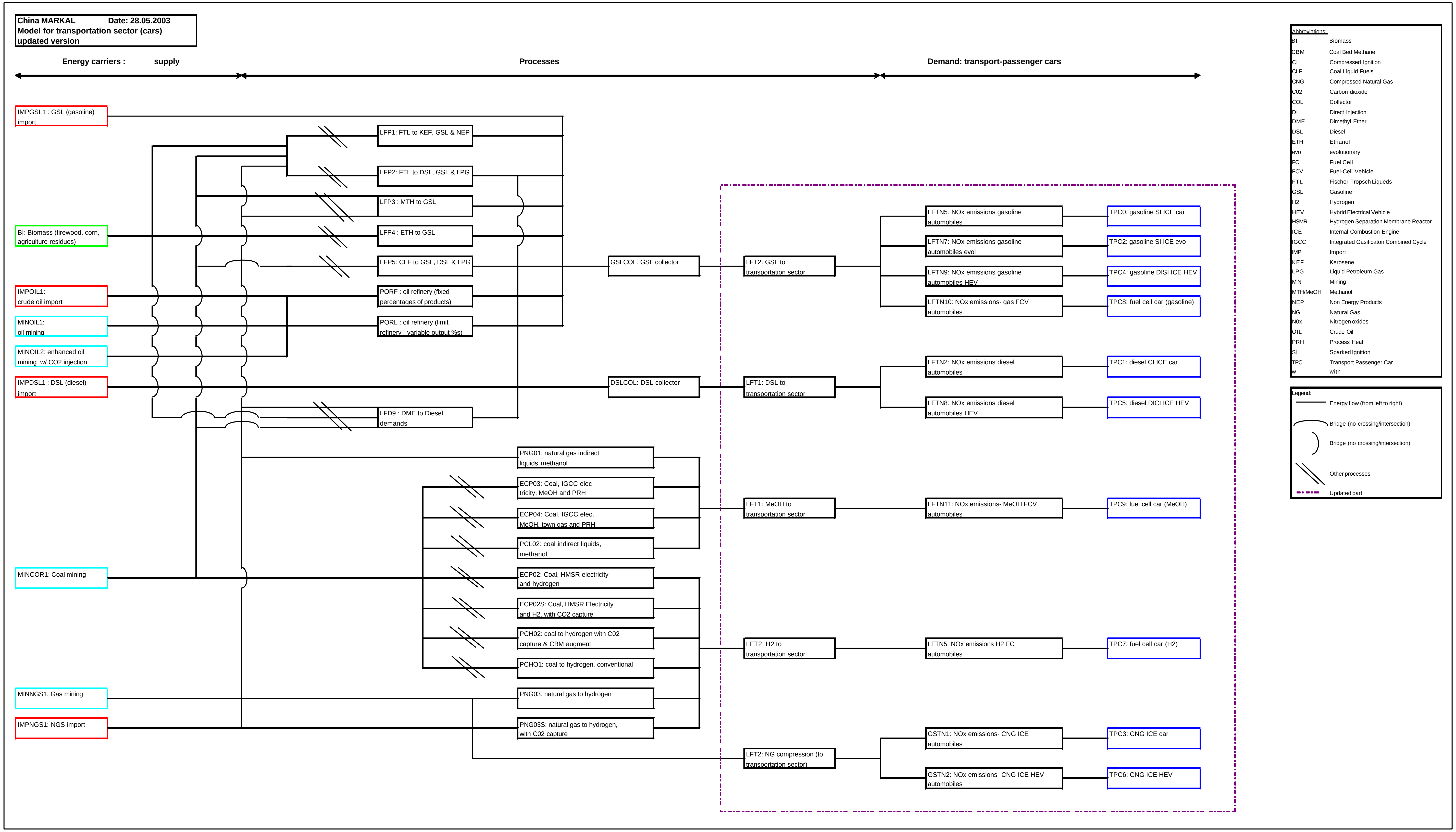

Figure V.1. Flowchart; updated passenger car sector