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Integration of Life-Cycle Assessment and Energy Planning Models for the Evaluation of Car Powertrains and Fuels

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A Note for the Reader

The software used to create this electronic document reproduces the original patterns used in most graphs at a very fine scale. As a consequence, the graphs might be hardly readable on screen. You can either zoom in (on the screen) or print out the document in order to cope with this problem.

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Abstract

The transportation sector in general and low-duty vehicle traffic in particular are known to contribute to a lot of environmental problems, including global warming, acid rain, or emissions of ozone-forming substances, to a significant extent. New technological developments are proposed to mitigate emissions from this sector. The present dissertation deals with the problem of evaluating different powertrain configurations (conventional internal combustion engine (ICE) and fuel cell (FC) powertrain) and fuels (from crude oil, natural gas, nuclear power, biomass, and solar irradiation) for passenger cars under various aspects.

The approach developed in this thesis is the integration of Life-Cycle Assessment (LCA) and Energy-Planning Models.

In a first step, a classical LCA of the different combinations of powertrain and fuel is performed. In this kind of analysis the potential environmental impact of a system throughout its life cycle is assessed. Already at this stage some important conclusions can be drawn. The results show the reduction potentials of alternative technologies concerning emissions of pollutants and greenhouse gases (GHG), but they also underline that the simultaneous mitigation of various emissions will probably call for a compromise. Moreover, the LCA allows detecting crucial issues in both the technologies assessed and the data available for this study.

In a second step the costs for driving cars with different powertrains and fuels are assessed for various scenarios. The scenarios differ in several parameters such as the prices for fossil primary energy carriers, the potential of emerging technologies to reduce costs, and the taxes that are applied to various emissions. The results show the potential of alternative technologies to enter the market under specific boundary conditions, but they also underline that enormous cost reduction is crucial for the FC to become competitive. However, this cost analysis has several drawbacks that mainly evolve from its static character.

This is why in a final step the detailed cost and LCA data of all technologies are included into MARKAL, a successful energy-planning model. This model allows including additional aspects into the analysis, such as restricted resource availability, the introduction of emission caps or time-dependent technological parameters. Of particular importance is the implementation of learning curves: with this feature the investment costs of some emerging technologies become an endogenous variable to the model, and these technologies are only installed when the higher investments that are necessary to mature them are outweighed by lower costs in later periods.

The results of the analyses with MARKAL, too, have a strong dependence on the boundary conditions chosen. They show, however, that under increased pressure to mitigate emissions of classical pollutants or GHG mainly the ICE car fuelled with compressed natural gas and the different FC vehicles are very attractive options.

The approach of integrating Life-Cycle Assessment (LCA) and Energy-Planning Models has proven to be a valuable tool for the comparison of different technologies. Nonetheless it has its limitations, and there is still much potential for improving the model.

Kurzfassung

Der Transportsektor im allgemeinen und der Personenwagenverkehr im besonderen gelten als Mitverursacher vieler Umweltprobleme wie des globalen Klimawandels, des Sauren Regens oder der Bildung bodennahen Ozons. Zur Verringerung der Emissionen dieses Sektors sollen neue technische Entwicklungen beitragen. Die vorliegende Dissertation beschäftigt sich mit der Evaluierung verschiedener Antriebssysteme (konventioneller Verbrennungsmotor (VM) und Brennstoffzellen (BZ)-Antrieb) und Treibstoffe (aus Rohöl, Erdgas, Kernkraft, Biomasse und Sonnenstrahlung) für Personenwagen unter verschiedenen Gesichtspunkten.

Der in dieser Arbeit entwickelte Ansatz ist die Integration von Life-Cycle Assessment (LCA, häufig als Ökobilanz übersetzt) und energiewirtschaftlichen Planungsmodellen.

In einem ersten Schritt wird eine klassische LCA der verschiedenen Kombinationen von Antriebssystem und Treibstoff durchgeführt. Bei dieser Art von Untersuchung wird der potentielle Umweltschaden eines Systems über den gesamten Lebenszyklus abgeschätzt. Bereits auf dieser Stufe können einige wichtige Schlussfolgerungen gezogen werden. Die Resultate zeigen das Reduktionspotential alternativer Technologien bezüglich der Emissionen von Schadstoffen und Treibhausgasen (THG) auf; sie unterstreichen aber auch, dass die gleichzeitige Verminderung verschiedener Emissionen wahrscheinlich einen Kompromiss erfordert. Darüber hinaus erlaubt es die LCA, Schwachstellen sowohl der untersuchten Technologien als auch der verwendeten Daten zu identifizieren.

In einem zweiten Schritt werden die Kosten für Personenwagen mit unterschiedlichen Antrieben und Treibstoffen in verschiedenen Szenarien bestimmt. Die Szenarien unterscheiden sich in mehreren Parametern, z.B. den Preisen für fossile Primärenergieträger, dem Kostenreduktionspotential neuartiger Technologien und den Abgaben auf verschiedene Emissionen. Als Ergebnis sieht man die Potentiale alternativer Technologien, unter bestimmten Randbedingungen den Markt einzudringen, aber es wird auch deutlich, dass enorme Kostenreduktionen entscheidend sind, damit die BZ wirtschaftlich wird. Diese Kostenanalyse hat noch einige entscheidende Nachteile die hauptsächlich durch ihren statischen Charakter verursacht werden.

Darum werden in einem letzten Schritt die detaillierten Kosten- und LCA-Daten aller Technologien in MARKAL, ein erfolgreiches energiewirtschaftliches Planungsmodell, integriert. Dieses Modell erlaubt es, weitere Aspekte zu berücksichtigen, so z.B. die beschränkte Verfügbarkeit von Ressourcen, die Einführung von sektorweiten Emissions-Obergrenzen oder zeitabhängige technologische Parameter. Von besonderer Bedeutung ist die Implementierung von Erfahrungskurven: mit Hilfe dieses Werkzeugs werden die Investitionskosten einiger neuartiger Technologien modellendogene Variablen, und diese Technologien werden nur eingesetzt, wenn die höheren Investitionskosten, die in der Entwicklungsphase der Technologie benötigt werden, durch Einsparungen in späteren Perioden ausgeglichen werden.

Auch die Ergebnisse der Analysen mit MARKAL sind sehr stark von den gewählten Randbedingungen abhängig. Sie zeigen jedoch, dass unter verschärften Emissionszielen für klassische Schadstoffe und THG insbesondere das Erdgasfahrzeug mit VM als auch die verschiedenen BZ-Fahrzeuge sehr attraktive Optionen darstellen.

Es lässt sich feststellen, dass die Integration von LCA und energiewirtschaftlichen Planungsmodellen ein wertvolles Werkzeug zur vergleichenden Bewertung verschiedener Technologien darstellt. Nichtsdestotrotz hat auch dieses Werkzeug seine Grenzen, und es gibt noch ein grosses Potential zur Verbesserung des Modells.

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1 Introduction

1.1 Motivation

The transportation sector is nowadays one of the most important emitters of pollutants and greenhouse gases, and passenger cars make up a very large share of these emissions (see e.g. [Kolke 1998]). Suggestions to reduce these emissions do not only comprise the optimisation of the existing technology (better engine efficiency, lower driving resistance, more efficient pollutant control), but also the introduction of alternative fuels or new powertrain[1] concepts.[2] The alternative fuels proposed are mainly based on natural gas (NG) or renewable energy sources such as biomass or solar energy. The new powertrain concepts include hybrid vehicles and electric drivetrains with either batteries or on-board electricity generation in a fuel cell (FC).

The basic idea of this work is to compare different fuels and powertrains in a consistent way by integrating two different tools: Life-Cycle Assessment and the energy-planning model MARKAL.

1.1.1 The Tool of Life-Cycle Assessment (LCA)

With increasing interest in and knowledge of environmental[3] problems the ecologic evaluation of goods and processes became more and more complex. In the beginning, this evaluation focused on single aspects such as the emission of a specific substance (e.g., carbon monoxide (CO) from cars in the early seventies) or the energetic efficiency of a device (fuel consumption of a car, for instance). Later on, the scope broadened significantly in two dimensions:

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[1] 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.

[2] Measures to reduce demand such as incentives to use public transport are not subject of this analysis.

[3] In this work the notion of environmental problems or environmental damages is used in a rather broad sense; it includes also human health issues and damage to buildings, for instance.

1. a "horizontal" dimension that describes the number of interactions between a specific process and the environment that are included in the study
2. a "vertical" dimension, i.e. the expansion of the analysis from the direct interaction between a product and its environment to the whole life cycle of this product. This means that the analysis now comprises as well so-called up-stream processes like the production of a product or the provision of fuel, and down-stream processes, that is mainly recycling and disposal.

The tool of Life-Cycle Assessment (LCA) has been developed in order to give an environmental score of a good under consideration of these two dimensions. Simply said, the aim of an LCA is to express the total environmental burden caused by the use of a good, including manufacturing, production and distribution of the fuel (if applicable), the use phase, and disposal, in as few numbers as possible. A total aggregation (introduction of a single indicator for the total environmental harmfulness) is desirable, alas there is no methodology so far that has proven superior or is even widely accepted. Some attempts have been made to calculate total environmental costs, e.g. for the electric utility sector (see e.g. [Friedrich & Krewitt 1997]). This approach is particularly elegant because it makes the environmental harmfulness (that makes up at least a part of their external costs) directly comparable to the (private) costs of a product, but the method cannot be considered mature: There are still large uncertainties, and many emissions and effects are not considered.

One of the main conceptual disadvantages of LCA is that it is static; it is only a snapshot of a given situation.

1.1.2 Energy-Planning Models like MARKAL

Energy planning models like MARKAL are dynamic, but they usually are much less detailed than an LCA in the technology description and especially in the interaction of the technosphere with the environment. In simple words, MARKAL (an acronym for MARket ALlocation) computes the optimal development of a technology park in time under given constraints (see e.g. [Fishbone et al. 1983]). The user-defined database contains detailed descriptions (including costs, efficiencies, emissions (if desired), availability and so on) of all available technologies. Starting from a given technology park, the model calculates its development in a way that the utility function is maximised without violating the constraints. A necessary constraint is the demand to be satisfied in every time period. Other constraints include maximum or minimum installed capacity or activity of processes or peak power demand. Environmental issues can be modelled in two ways: either by introducing a tax on emissions (or the use of a resource), or by restricting emissions of the total energy system to a maximum allowable level. So far, however, the consideration of emissions was restricted, mainly to greenhouse gases (GHG) and to direct emissions from conversion technologies and end-use devices. Emissions from the fuel chain or the production of the infrastructure were emitted or treated in a very simplified way[4].

An important disadvantage of the original MARKAL version is that all technological changes are exogenous, i.e. they depend only on time, but not on the actual use of the technology or other parameters endogenous to the model. Recent developments allow introducing endogenous technological learning [Barreto 2001]; this concept describes how key parameters (mainly the investment cost) of a technology evolve as a function of the cumulative installed capacity of this technology.

1.1.3 Integration of the Tools

The two tools depicted above are complementary methods for an ecological comparison of future technologies such as different car powertrains and fuels:

LCA is a very detailed and comprehensive, but static approach where the future scenario has to be defined exogenously in much detail.

A model of the energy system, like MARKAL, on the other hand, generates many features of the scenario endogenously from the starting situation and some general assumptions. However, because of its historical background as a least-cost planning tool it has so far been used mainly to answer economic questions; when environmental issues are included, this is usually done in a very simple and straightforward way.

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[4] Emissions of CO_2 are usually calculated by multiplying total consumption of a specific energy carrier with the corresponding emission factor. This reflects only emissions related to consumption (burning) of the fuel in earlier steps of the fuel chain, e.g. pipeline transport of gas or energy consumption in the refinery.

An integration of these tools looks very promising. It offers the potential to incorporate the strengths of both methods. Some studies that include aspects of LCA in MARKAL models have already been performed; in the MATTER project (MATerials Technologies for CO_2 Emission Reduction) material flows are introduced in order to optimise integrated energy and materials systems (see e.g. [Gielen & Kram 1998]) with respect to emissions of CO_2. In another project, estimated external costs for a few pollutants have been introduced, but they are not calculated on a life-cycle basis [Proost & van Regemorter 1999]. An approach that integrates real life-cycle emission data for various substances has – to my knowledge – not been performed yet.

The passenger car sector in OECD Europe promises to be a suitable object for a first case study:

- Many of the upstream processes (car manufacturing, raw materials extraction and processing) take place in the same geographical region.
- Despite regional inhomogeneities a sufficiently adequate model can easily be developed.
- Data quality should be sufficient.
- New fuels and powertrain concepts have been discussed in recent years. The main drivers for these developments are mainly environmental concerns.
- So-called indirect emissions from the fuel chain or car manufacturing make up a significant part of the total environmental burdens, especially with decreasing fuel consumption as assumed for the future (see, e.g. [Volkswagen 1998]). Moreover, the ratio of total to indirect effects depends on the technology actually used, mainly the fuel.

1.2 Structure of the Thesis

After this introductory chapter, two different powertrains (ICE and FC) and fuels (based on crude oil, NG, uranium, biomass, and solar irradiation) are compared in three subsequent steps (Figure 1):

The second chapter outlines the general theory of Life-Cycle Assessment (LCA), followed by an application of LCA for car powertrains and corresponding fuels. It is complemented by sensitivity analyses on various technological and methodological parameters.

In the third chapter, the costs of all these technologies are calculated for four different scenarios: the base case is characterised by constant prices for fossil fuels and moderate assumptions on emerging technologies. In the other cases, prices for fossil fuels are much higher and/or more optimistic assumptions are used for the potential of emerging technologies. The results of the LCA are integrated by application of various taxes.

The fourth chapter goes another step further: both economic and environmental parameters of the vehicles and fuels analysed are entered into an energy-planning model called MARKAL. Compared to the static analysis in the third chapter this approach allows a more refined analysis of the competitiveness of the various technologies under different boundary conditions. The scenarios and tax strategies applied here are based on those developed in the third chapter. Moreover, various greenhouse gas caps are introduced.

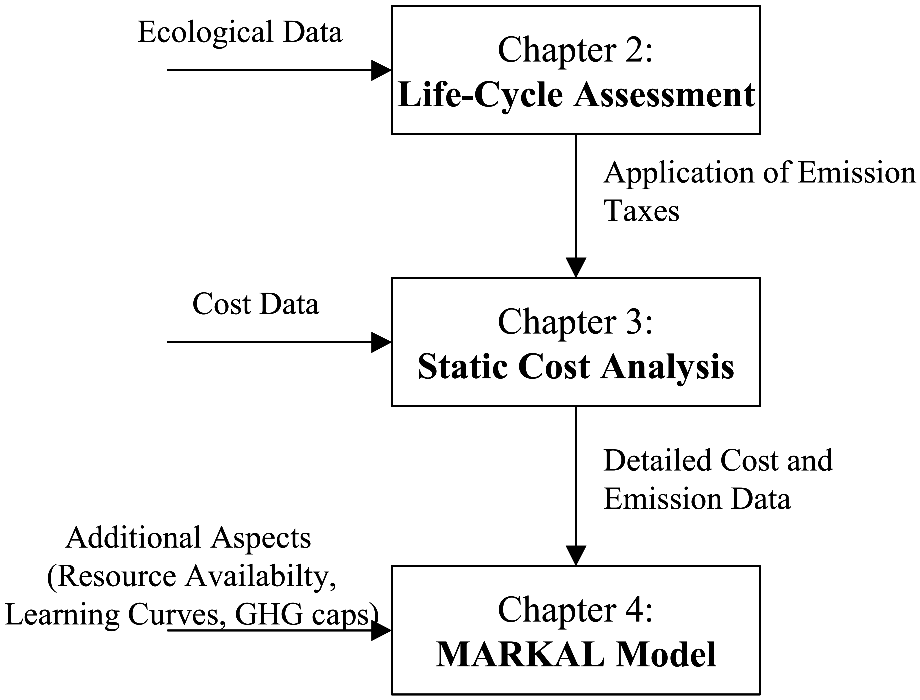

Figure 1: Schematic outline of the thesis.

The appendix contains supplementing data and a list of abbreviations used.

2 LCA of Different Powertrains

2.1 The LCA Tool

Life Cycle Assessment (LCA) is a tool for environmental management of product and service systems. It encompasses the assessment of impacts on the environment from the extraction of raw materials to the final disposal of waste.

[TC207 2001]

An LCA includes the complete life cycle of the product "from cradle to grave", and it also considers different impacts on the environment. Interest in LCA has grown that much that now international standards have been elaborated that the procedure has been standardised in recent years. For details on the theory of LCA the reader can therefore refer to these standards [ISO 14040ff].

An LCA is divided in four phases:

- Definition of Goal and Scope
- Inventory (LCI)
- Impact Assessment (Classification)
- Interpretation

Although a comprehensive standard has been elaborated, the individual analyst still has ample space for individual decisions that have a large influence on the final result of the study.

In the following sections the four phases are depicted in more detail.

2.1.1 Goal and Scope Definition

According to the ISO standards, goal and scope definition must be explicitly stated in an LCA. The goal contains some background information on the study, and the scope definition describes in detail the methodological framework.

2.1.2 Life-Cycle Inventory

In this step, all material and energy flows that are relevant to the system are described and integrated. It is usually the most labour-intensive part of an LCA. As a result of this step, all inputs and outputs of the system are represented, normalised to the functional unit, e.g. total CO_2-emissions per kWh of electricity produced or non-renewable energy consumed per vehicle-km.

Simply said, in the inventory all processes are characterised by their (useful) output and a vector containing the following parameters:

- Inputs (materials)
- Ancillaries (e.g. energy)
- Use of other services (disposal of by-products, transports, infrastructure)
- Direct elementary interaction with the environment in the form of
    - Emissions
    - Use of Resources

The resulting set of vectors represents a set of linear equations that can be solved in order to determine all elementary interactions with the environment that are induced by any of the processes, e.g. total CO_2 emissions per kWh of electricity from a specific plant or non-renewable energy consumed per km in a defined vehicle.

Of course, in a real economy the relations between sectors, companies and processes are very complex and for the model they have to be simplified in many respects. One of the most important simplifications in LCA is the introduction of system boundaries or cut-off criteria. Without these boundaries, the inventory of nearly any process would require an analysis of the whole national economy. The boundaries now systematically cut off processes that are perceived to have only a small influence on the result for the process in focus, i.e. for the process that produces the functional equivalent. If the aim of an LCA is the comparison of different technologies, good LCA praxis requires that the boundaries are uniform for all technologies assessed. To clarify what is meant, have a look at the following example: In the LCA of a car, the production of the car should be included in the inventory. The manufacturing of the *plant* where the vehicle is produced, however, will hardly have a significant influence on the results for the car and is therefore usually omitted. Similarly, many environmental burdens (especially emissions) that are associated with fossil power plants are dominated by fuel provision and direct emissions from the plant, so for a comparison of airborne emissions from different fossil power plants it would be defendable to omit the construction of the plant. For many renewable power plants like wind turbines or photovoltaic power plants, however, airborne emissions are nearly completely determined by the manufacturing of the plant. If fossil electricity is to be compared to these power plants, the inventory should include the manufacturing of all power plants. This does not necessarily imply that the manufacturing has to be analysed to the same degree of detail. Usually, processes that are likely to have only a minor effect on the final result are analysed in less detail.

Generally, inventory input data can be derived in two ways: the bottom-up approach is based on technology-specific data; it is also called process chain analysis. In the top-down approach, sector-wide indicators (such as total energy use) and input-output tables (that describe the interaction of sectors in a national economy) are used to generate more generic data like average emission factor or steel requirement per monetary unit of commodities/services produced in a sector. While the latter method surely gives only rough estimates for the actual process parameters, it can be nearly universally applied, once the necessary statistics are available. The bottom-up method, however, is more time-consuming, and in many cases the data are valid for one specific technology that is not necessarily representative for the process in general[5]. A detailed analysis that averages the input data of all technologies used for a given process is not only very time consuming, in many cases it will not be feasible due to limited data availability. At most it can be done for some key processes and the most important parameters (e.g. the database of European coal power plants in [Frischknecht et al. 1996]). A widely accepted practice is to rely on the bottom-up procedure wherever possible and to use top-down data only to cover data gaps or for verification purposes.

Another aspect of data suitability is the use of homogenous commodities where the physical origin cannot be traced back, such as the appropriate electricity mix (for a very good introduction and case study see [Ménard et al. 1998]). Recycling processes as well pose methodological problems (see [Kehrbaum 1997]). In many studies, however, these processes only have a small influence on the final result.

In multi-output processes environmental burdens have to be allocated to the different outputs in a "fair" way. The methods available can in general be classified in two groups: substitution or system enlargement, and allocation keys. In the substitution approach, all but one of the outputs is assumed to replace the same commodity/service from an optional process, and the original process is credited with the environmental burdens from this replaced process. System enlargement is equivalent; here the environmental burdens from the optional process are added to those processes that the multi-output process is compared to. When using an allocation key, however, the total environmental burdens of the multi-output process are allocated according to appropriate properties of the commodities/services produced, such as mass, heating value or economic value (market price).

An example might illustrate these two basic methods:

When, for example, comparing electricity from a combined heat and power plant (CHPP) with electricity from a gas-fired combined cycle power plant (GCC), the heat from the CHPP might be seen as a substitute for heat produced in conventional gas-fired boilers. The amount of any environmental indicator (emissions, use of resources) that is assigned to one unit of electricity from the CHPP is

$$Ind_{el,CHPP} = Ind_{tot,CHPP} - y \cdot Ind_{heat,boiler}$$

where $Ind_{tot,CHPP}$ = total indicator of CHPP, normalised to electricity production (i.e. without credits for heat production)

$Ind_{heat,boiler}$= indicator of gas-fired boiler, per unit of heat production

y = units of heat per units of electricity produced in the CHPP

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[5] This remark, however, does not apply to processes where specific technologies are analysed, e.g.

The substitution approach is equivalent to the system enlargement method where the functional unit is redefined to include both electricity and heat (in the ratio given by the CHPP). In this case, electricity and heat from the CHPP are compared to electricity from the GCC plus a corresponding amount of heat from a gas-fired boiler, i.e. the term $y \cdot Ind_{heat,boiler}$ is not subtracted from the emissions from the CHPP, but added to those of the GCC. If, however, an allocation key is used, total environmental burdens caused by the CHPP are divided by the total amount of the key quantity produced. For energy as an allocation key the figures for electricity from the CHPP are then

$$Ind_{el,CHPP} = \frac{Ind_{tot,CHPP}}{1 + y}.$$

In addition to these methodological problems the analyst usually faces insufficient data, especially for future scenarios with changing boundary conditions (e.g. electricity mix, production of basic materials), and the inclusion of technologies that nowadays are still at a very early stage of development. In such cases, detailed prediction of manufacturing processes and materials used to produce a commodity or service is often hardly possible. Since a classical error calculation is impossible in most cases, other tools have to be used such as semi-quantitative estimates or sensitivity analyses.

Although the inventory looks at first sight like a mere accounting procedure that contains no methodological problems, it is a very complex task. The analyst's choice of methodology or his approach to close data gaps can have a dominating influence on the final result of the study. Therefore, a detailed documentation of the LCI is a necessary part of any LCA.

2.1.3 Impact Assessment (Classification)

The results of an inventory can be very extensive and hard to overview. For example, for each process analysed [Frischknecht et al. 1996] list more than 600 different elementary interactions with the environment such as emissions to air, water, and soil,

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when comparing different suppliers or optimising a given process chain in a company.

or the use of resources. In order to reduce the complexity of this output, one tries to classify these interactions in a relatively small number of impact classes and to aggregate them within these classes. A list of impact categories that was suggested by [Udo de Haes et al. 1999] includes the following impacts:

- Extraction of abiotic resources
- Extraction of biotic resources
- Land use:
  - Increase of land competition
  - Degradation of life supporting functions
  - Bio-diversity degradation
- Climate change
- Stratospheric ozone depletion
- Human toxicity
- Eco-toxicity
- Photo-oxidant formation
- Acidification
- Eutrophication

This list is neither mandatory for a particular LCA nor exhaustive. The number and type of impacts included depends on the goal of the study, the anticipated relevance of each impact class for the system analysed, data availability, and other factors.

In the common aggregation model different interactions are added using fixed weighing or equivalence factors that relate the interaction to a lead interaction (e.g. CO_2 emissions in the case of greenhouse gases or SO_2 emissions in the case of acidification precursors). Fixing equivalence factors is a very strong simplification of the real processes causing an effect. Mathematically spoken, a fixed equivalence factor is only universally correct when the environmental burdens caused by all the different interactions that contribute to an impact category (for example the emissions of different substances) are

- linear in the measure of the interaction (an increase of 1 unit causes always the same additional effect) and
- independent from all case-specific parameters, especially it must be independent from releases or background concentrations of all other substances.[6]

These criteria are approximately met only for the two global impacts mentioned in the list above, global warming and stratospheric ozone depletion[7]. For all other categories, the generically defined equivalency factors are less representative; the acidification caused by an emission of acid substances, for instance, depends on the pH value of the water where it is dissolved. This value is in its turn is determined by the concentration of all acids and bases. Nonetheless for acidification and some other impact classes the equivalence factor is still a good proxy for the potential impact; for other impact classes such as human toxicity, however, the weighing factor can at most give an idea of the relative relevance of an emission (cf. e.g. [SETAC 1997]). Different approaches have been developed to overcome these hurdles (cf. e.g. [SETAC 1997, Friedrich & Krewitt 1997, Nigge 2000]); they require, however, additional data such as the location of emissions or detailed information about the location of the impact.

For further details on single impact classes cf. also section 2.2.3 "Impacts Selected for the Impact Assessment".

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[6] This implies also additivity of all interactions in one class.

[7] In the case of global warming, the relative effect of a species compared to CO_2 (global warming potential, GWP) is depending on the time horizon because of different lifetimes of species in the atmosphere. Therefore, three sets of weighing factors have been elaborated by the IPCC (for 20, 100, and 500 years, respectively) [IPCC 1996].

2.1.4 Interpretation

The final step of the LCA includes three issues:

- Interpretation of crucial processes
- Evaluation of the quality of the LCA (reliability of the results, consistency of inventory and impact assessment with goal and scope definition)
- Conclusions and recommendations

2.1.5 Interaction between Steps

In theory, the goal and scope definition are supposed to set the framework that largely determines the other steps: After the fixing of impact categories, an appropriate method for impact assessment is to be selected or developed. This impact assessment method, then, defines requirements for the inventory. The results from the inventory are processed in the impact assessment. Finally, the interpretation is performed.

In actual praxis, this scheme can hardly be followed. Rather, a constant interaction of the four steps is necessary: restricted data availability may force the analyst to set much narrower system boundaries, inventory data may induce altering of the impact assessment methodology, and an interpretation may reveal that the system boundaries should be extended, e.g. because a process that was analysed in little detail turned out to be dominant in at least one of the impact categories.

2.1.6 Advantages and Drawbacks of LCA

The strong and weak points of LCA can be summarised as follows:

- LCA is a powerful method to shift ecological analysis towards a more integrated approach that includes the whole life cycle and several impacts.
- The methodology of LCA has constantly matured in recent years; procedures have been developed that allow coping with various problems in both the inventory and the impact assessment step (e.g. recycling, allocation; classification, derivation of equivalence factors).

- With the ISO 14040 series an internationally accepted standard has been established

- Databases for energy provision basic materials as well as calculation tools are publicly available; the databases often provide input tables as well so that adaptations to a particular study (system boundaries, emission legislation…) is easily done

But LCA also has drawbacks that have to be mentioned:

- There is no widely accepted tool for aggregating figures from various impact classes to a single indicator that describes the total environmental burden connected to a process or even to express these environmental burdens as external costs; the latter means that by now there is no generally accepted way of integrating economic and ecologic analysis.

- In some impact categories such as human toxicity the aggregation step is still subject to very large uncertainties.

- LCA is a relative approach that produces indicators for environmental burdens with respect to a functional unit; one of the consequences, the difficulty to assess the relevance of different processes, is overlapping with the lack of a method for total integration of environmental burdens. Another consequence is that constraints like limited availability of a resource cannot be modelled within the framework of LCA.

- A disadvantage that applies especially to the comparison of future technological options (like different power plants or car powertrains) is that LCA is a static approach; it is always a snapshot of a well-defined situation; the methodology as such cannot model endogenous developments like the change of the electricity mix due to tightening of environmental standards.

2.2 Goal and Scope Definition

In recent years, car manufacturers all over the world have started to develop fuel cell (FC) cars; one of the main drivers is the perceived superiority of this technology over the conventional system, the internal combustion engine (ICE). This perception, however, is mainly based on the high efficiency of electricity production in the fuel cell and the fact that a fuel cell fuelled with hydrogen produces no emissions but water and small amounts of unburned hydrogen. A comprehensive analysis of the environmental impacts of different powertrains is further complicated by the fact that both ICE and FC can be fuelled with different fuels. In this chapter I present an overview over an LCA of different fuel-/powertrain combinations. The detailed documentation has been published in [Röder 2001].

2.2.1 Systems Analysed and Functional Unit

In order to ensure a fair comparison I used a virtual car body (small four-seater, comparable in size to a Volkswagen Lupo or a Renault Twingo, for example, weight without powertrain 560 kg) that was equipped with the different powertrain configurations. Structural reinforcements required by heavier powertrains were systematically considered. This makes sure that all vehicles analysed are comparable in terms of maximum payload. Possible changes of useful space have not been reflected in the model.

Actual performance such as top speed or acceleration with such different powertrain concepts are hard to compare because of different characteristics of combustion engine and electric motor. Electric motors have nearly constant maximum torque at low speeds and nearly constant maximum power at high speeds whereas both torque and power show a pronounced maximum in an ICE. This tends to give electric cars a better acceleration at low and medium speeds, compared to conventional cars with the same specific power. On the other hand FC cars are in general a little heavier than conventional cars, and as a consequence of these two controversial effects I assumed that the maximum power of the ICE on the one hand and the electric motor on the other hand are equal. While the fuel type has only negligible influence on the weight of the FC vehicle because the reformer offsets the weight advantage of the MeOH and diesel tanks, ICE-driven cars still show significant differences of nearly 15% (809 kg with gasoline, 922 kg with CNG, each including 140 kg of payload). Nonetheless I treat these vehicles as being of comparable performance. All vehicles are able to run the US city cycle (FTP-75).

For all vehicles the model year 2010 has been analysed. The consumption of all vehicles has been calculated with a simulation tool that was developed at ETH Zürich [Guzzella & Amstutz 1997]. In these simulations I do not assume best available efficiency for all components but rather what I consider to be a realistic estimate for a typical efficiency. Nonetheless, compared to today's models the cars analysed turn out to be quite efficient. This is due to the reduction of driving resistance (weight, rolling resistance, air drag) assumed and the relatively small power of the engine or motor in the car. The latter has effects mainly in the case of ICE-driven cars.

The powertrain configurations analysed are:

- Advanced internal combustion engine (ICE): spark ignition (SI) engine for gasoline, compressed natural gas (CNG), methanol (MeOH), ethanol (EtOH) and compressed hydrogen (CH_2), compression ignition (CI) engine for diesel and rapeseed methyl ester (RME). This is the predominant type of powertrain that dominates the worldwide market. The overwhelming majority of vehicles runs either on gasoline or diesel. These are the reference technologies for the whole study.

- Fuel cell car with supercapacitors for short-time energy storage fuelled with MeOH and diesel fuel (with on-board reformer) and CH_2. This concept allows downsizing of the FC and recuperation of braking energy (see e.g. [Dietrich et al. 2001]).

The following fuel chains have been analysed:

- Low-sulphur (low-S) gasoline; gasoline from crude oil has been the dominating fuel in the history of the automobile up to now. The most important improvement in the foreseeable future is the switch to a much lower concentration of S. As S is a serious catalyst poison, this is a prerequisite for the introduction of vehicles that fulfil stricter emission regulations.

- Low-S diesel oil; the first mass-produced diesel passenger car was introduced in the mid-30s. Today, the share of diesel vehicles in the LDV sector shows large regional differences that are mainly called by national fuel tax policies. Due to its high efficiency and reliability the diesel car has been especially suited for applications with high yearly mileage. The reason for the reduction of S content is the same as for gasoline.

- Compressed natural gas (CNG) is already used in some countries as an automotive fuel. It promises lower emissions of regulated substances from ICEs. The potential to increase efficiency in an engine optimised for CNG (the higher octane number allows higher compression ratios) has not been exploited yet because most CNG cars are bi-fuel vehicles that can also run on conventional gasoline.

- MeOH from natural gas and wood (both short rotation poplar plantations and waste wood); the use of this alcohol as an automotive fuel has been mainly promoted in the US in order to both decrease emissions of regulated substances (especially in serious non-attainment areas such as the Los Angeles area) and dependency on oil imports. To date most alcohol vehicles have been FFVs (flexible fuel vehicles) that are not optimised to exploit MeOH's potential to increase the engines efficiency.

- EtOH from sugar beets and winter wheat; the reasons for its introduction are similar. Moreover, this fuel offers a possibility to support the local agriculture. Brazil has very actively promoted EtOH from sugar cane; this fuel has a considerable market share today.

- RME, or biodiesel, is mainly an issue in Europe. It can be used in many modern diesel engines without modification.

- CH_2 from natural gas (both centralized and decentralized reformer plants), Swiss photovoltaic (PV) and nuclear (NPP) power plants. Many people see hydrogen as one of the major secondary energy carriers for the future. At the moment, however, it is mainly used as a chemical feedstock, its use as energy carrier is limited to some niches like liquid hydrogen (LH_2) for spacecraft. In the LDV sector so far only prototypes have been built. Obstacles for a broad introduction of hydrogen are its high production costs (compared to fossil fuels), the need to establish a complete new distribution and refuelling infrastructure. Moreover, the handling of hydrogen requires special safety measures. Nonetheless hydrogen is believed to be a potential option when prices for fossil fuels are going up due to either depletion of resources or consideration of external costs.

For the production of hydrogen a large number of processes and a variety of possible feedstock commodities are in use or under development. Today, hydrogen is mainly produced from natural gas and crude oil [Wagner et al. 1996], the oil-based hydrogen, however, is mainly a by-product of refinery processes that is consumed on-site for other process steps.

In order to increase the volumetric energy density of hydrogen the gas can either be compressed or liquefied. I consider only compression in my analysis; liquid H_2 offers a much higher energy density, but the liquefaction process is very energy-intensive.

The functional unit was chosen to be an average km in the US city cycle (FTP-75), assuming a lifetime of 150'000 km for all vehicles. No further distinction (by season, location (country, city/highway), for example) is made. As explained in the section on fuel consumption (see 2.3.2.1 "Consumption"), choosing the new European driving cycle (NEDC) would have only a minor influence on the final results.

2.2.2 System Boundaries and General Guidelines for the Inventory

The inventory was performed within the framework of the ECOINVENT system [Frischknecht et al. 1996], so the methodology and system boundaries are oriented at this work.

The analysis includes direct emissions from the vehicles, the production and distribution of the fuels (fuel chain), maintenance, and the production of the cars. Infrastructure (roads, bridges etc.) is not considered because it is assumed to be the same for all vehicles[8].

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[8] Differing wear of roads due to variations in axle load are neglected.

Direct emissions are considered in a very detailed way; they refer to the assumed model year 2010. All vehicles fulfil the emissions levels proposed to be in force in the European Union from 2005 on (Euro IV)[9]. I do not assume tighter levels.

The fuel chain is tracked back to primary resources ("cradle-to-tank" approach). For all major conversion units such as oilrigs, refineries or power plants the infrastructure requirements are included as well. As many of these processes can be considered mature, I use the most recent data available also for the situation in around 2010. Only for processes with large improvement potential (mainly agriculture (production of biomass), plants for biomass conversion, and electrolysis of water) extrapolations are made to have a fair basis of comparison. A special case is the production of electricity in PV plants. In [Dones et al. 1996], both existing and future PV systems have been assessed. As the time horizon for their future systems lies beyond 2010 (the milestone year assumed in their study is 2030), I took the analysis for systems produced in 1995 as the base case; a sensitivity analysis was performed with the future results.

The production of the vehicles includes all major material chains, beginning with the extraction of raw materials. Here, however, no infrastructure requirements (furnaces, automobile plant etc.) are included. The analysis of most car components (including the body) is rather coarse for various reasons:

- Previous analyses of cars have shown that the fuel chain and direct emissions dominate the life-cycle inventory of cars (see, e.g., [Volkswagen 1998]). I expect that in future vehicles both fuel consumption and direct emissions will be significantly reduced while the environmental burdens from vehicle manufacturing might rise due to the use of more lightweight Al or Mg alloys, for instance. Moreover, alternative fuels that are much more ecologically benign than today's gasoline or diesel might be introduced. All this would increase the relative contribution of car production for the overall inventory. This effect, however, is in part compensated by the expected higher lifetime of future vehicles.

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[9] Actually, this is a hybrid construction, because the Euro IV legislations refer to the NEDC and not the FTP-75 cycle that I refer to. What is meant is the following: Direct emissions from all vehicles in the FTP cycle are below the limits (on a per km basis) required by Euro IV regulations in the NEDC.

- Data availability for many components is poor. Detailed figures about material composition, energetic requirements or process-specific emissions have not been published. Moreover, for many of the future components today's models and manufacturing processes can hardly be considered representative.

In order to keep the time for data retrieval at an acceptable level the modules for the car components are very simple: they include a very coarse material breakdown that matches the specific weight of the device and an estimate for energy requirements that scales with weight. Emissions have been only assumed for car assembly (NMVOC from the paint shop). For the provision of materials the standard modules from [Frischknecht et al. 1996] were used, only for Platinum-group metals (PGM) and the proton-conducting membrane in the FC more detailed analyses were performed. All data for material production, energy provision and other basic processes (such as transport by rail, ship, and truck) refer to the situation in the mid-nineties and in Western Europe (where applicable). Site-specific data were mainly used for raw material extraction and processing, e.g. oil and gas extraction or production of platinum-group metals (PGM). in most cases the electricity mix is the one for the UCPTE as defined in [Frischknecht et al. 1996]. This implies that changes in these processes that will happen until 2010 are of minor importance for the overall balance only – an assumption that I think is rather realistic as these processes are rather mature.

Throughout the whole analysis, there are no spatial boundaries for emissions or resource consumption.

The depth and width of the analyses of single processes was mainly determined by the perceived potential impact of the process on the final result; in some cases, though, data availability posed additional constraints so that the analysis was less deep than desirable.

Data uncertainty has not been explicitly tracked; it has only been assessed qualitatively.

2.2.2.1 Allocation Procedure

Some of the processes in the ECOINVENT databank have multiple outputs. For the allocation methods applied there see [Frischknecht et al. 1996].

In the modules that were specifically elaborated for this study, the following multiple-output processes have been analysed:

Process	**Coupled Products**	**Allocation Method**
EtOH from wheat	EtOH, DDG	allocation by LHV
EtOH from sugar beet	EtOH, sugar beet pulp	allocation by LHV
MeOH from Wood (Biometh)	MeOH, electricity	allocation by exergy (HHV of MeOH)
Sulphuric acid	sulphuric acid, heat	substitution with typical energy mix according to [Patyk & Reinhardt 1997]
Refinery US / RUS	various oil derivatives	allocation by typical market price
PGM-production:		
Smelting	matte, sulphuric acid	substitution with sulphuric acid
Separation of PGM from Ni and Cu	PGM, Ni, Cu	substitution of Cu with predominant process; allocation among remaining metals by market price

Table 1: Allocation methods used in the LCA of powertrains and fuels.

The reason why in the separation step for PGM and other non-ferrous metals Cu is treated in another way is that PGM-producing mines contribute only on the order of 3-4% to the worldwide production of Cu (but nearly half of all Ni). Moreover, a rather detailed module for the predominant process for Cu production is available in [Frischknecht et al. 1996].

2.2.3 Impacts Selected for the Impact Assessment

In order to get an understanding of the important impacts associated impacts I will briefly outline how the legislation and scientific discussion of the environmental burdens have evolved over the last few decades.

At first, emissions of CO and lead-containing compounds were limited (the latter via limiting their concentration in the fuel). These emissions are **toxic to humans**; their **effect** is mainly **local**.

After the two oil crises in the seventies, the **use of scarce resources** (here: consumption of oil) became an important issue. This is an impact on a global scale.

In the eighties, evidence was growing that emissions from cars were partly responsible for the observed forest dieback, mainly via **acidification** (acid rain), a **regional effect**. First catalytic converters had to be introduced to meet stricter emission limits. Later on, emissions of NO_x and volatile organic compounds were linked to the **formation of ozone** that is now believed to be **toxic** for both **humans** and **ecosystems** and has also been related to **crop losses**. This impact can be classified as **regional**.

Finally, in recent years public and scientific interest has grown in the so-called **global warming**. This **global** effect is caused by greenhouse gases (GHG), mainly CO_2, which was formerly regarded as harmless. Another issue that has gained much attention lately are emissions of soot (mainly from diesel engines) that are suspicious of causing lung diseases and cancer, another **local-scale toxic effect on humans**.

This short outline can only show the major issues pursued in the time up to date, and it also reflects mainly European developments[10]. It contains the main impacts that are related to the use of cars, though, and is therefore a good starting point for the selection of impacts to be addressed in an LCA of vehicles.

The following impacts have been chosen to be included in the assessment:

- Use of non-renewable energetic resources

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[10] In the US, emission limits that required the installation of catalytic converters had been introduced nearly a decade earlier.

- Global warming
- Acidification
- Photochemical ozone creation
- Eutrophication by airborne emissions

Moreover, total emissions of NO_x and particulate matter (PM) are calculated.

Human toxicity was not included explicitly in this LCA although it is usually considered one of the most important impacts (see e.g. [Friedrich & Krewitt 1997, Nigge 2000]). The main reason for this decision is that many of the toxic effects take place on a very short range from the emission site. A detailed analysis of this impact would therefore require spatially disaggregated data to avoid significant distortions. This, however, is beyond the scope of this study.

Other possible impact classes considered at first were eutrophication by waterborne emissions and ozone depletion. But the LCA showed that due to poor data availability the results in these classes were very limited in their meaning. In a similar way, total copper requirements as a simple key indicator for resource depletion proved to be a somewhat doubtable measure because the results are dominated by the use of this metal in the vehicle. The results for these three impact classes are not presented in this work. They can be found in [Röder 2001].

The use of land is not included in this analysis. Up to date, most of the land use from the transportation sector is related to the infrastructure (roads and parking space) and is thus independent from the fuel and powertrain used. It is, however, an important aspect of biofuel production, but the effects of land use are local, and moreover the methods for aggregating different forms of land use are still at an early stage of development.

The following paragraphs give some background on the methodology chosen for every impact class. Detailed numbers for the weighing factors are represented in the appendix (Appendix 1).

Non-Renewable Energetic Resources: These are the sum of all waste heat emissions. The uptake of energy from the environment during the transformation of renewable forms of primary energy (PV, hydro power plant, biomass production etc.) is seen as a negative emission of waste heat. This methodological feature has some technical advantages compared to the explicit accounting for non-renewable energetic resources, especially for the assessment of large and complex systems[11]; yet one can easily see that both approaches yield the same result, provided that energy consumption is measured with respect to the HHV of all fuels. The use of energetic resources is often seen as a good indicator for the overall environmental performance of a process.

Greenhouse Gases (GHG): The Global Warming Potentials for a time horizon of 100 years (GWP_{100}) were taken from [IPCC 1996]. They include indirect effects only in the case of CH_4. Other indirect effects are not considered. In the latest IPCC assessment [IPCC 1996] no global warming potentials for the indirect effects of CO, NO_x and NMVOC are given any more because of difficulties to determine them. To have an idea of how large these effects are and in how far their consideration might change the results of the study I calculated them separately, using weighing factors from an earlier IPCC report [IPCC 1991].

Photochemical Ozone Creation Potential (POCP): Weighing factors have been taken from [Dinkel et al. 1996]. Differing from that source, no POCP has been assigned to NO_x because of the complex dependence of ozone formation from VOC and NO_x levels. Instead, total NO_x emissions have been calculated separately.

NO_x: NO_x emissions have been calculated separately as a complement to the POCP. Please note that NO_x also contributes to the categories of acidification, eutrophication and indirect global warming.

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[11] As an example take a look at the use of renewable and non-renewable hydrogen in a fuel cell with an assumed efficiency (HHV) of 50%:
If non-renewable energies are directly accounted for, the consumption of non-renewable energies during the utilisation phase of the cell is 2 kWh per kWh of electricity produced with non-renewable hydrogen and 0 kWh with renewable hydrogen.
When accounting for waste heat emissions, however, for both renewable and non-renewable hydrogen the waste heat emissions are 2 kWh per kWh of electricity produced. But in the case of renewable hydrogen these emissions are offset by the negative emissions, i.e. the uptake of heat from the environment, in the production of the fuel. In this way, the parameters of the fuel cell process are independent from the origin of the fuel, which prevents possible errors when analysing fuel switches, for instance.

Acidification Potential (AP): weighing factors have been assigned according to [Saur & Eyerer 1996]. The reference substance is SO_2, the weighing factors just represent the ability to release protons.

Eutrophication Potential (EP): weighing factors have been taken from [Saur & Eyerer 1996]. The reference substance is phosphate (PO_4^{3-}). The **intentional application** of fertilizers has not been included in this category. Only the shares of fertilisers transformed to gaseous substances and emitted to air are accounted for.

Particulate Matter (PM): This impact is the only purely local impact considered in this analysis. It was added because of the growing concern about it and the important role that transport (diesel engines) plays in this field. Alas, the notion particulate matter refers to a rather unspecified class of substances. It comprises everything from ordinary dust in careers to fine, lung-going soot loaded with hydrocarbons so the results for this impact category have to be interpreted carefully. It is highly preferable to classify particle emissions at least by their aerodynamic diameter[12], but data availability did not allow doing so in this work. Most references give only total particulate emissions. In some cases, additional data for particles with an aerodynamic diameter less than 10 µm (PM_{10}) are given, but detailed figures for even smaller particles ($PM_{2.5}$ and PM_1 with diameters smaller 2.5 µm and 1 µm, respectively) are nearly completely lacking.

[12] [Dockery et al. 1993] observed statistically significant and robust associations between air pollution and mortality that were strongest for air pollution with fine particulates.

2.3 Inventory

This section gives a short overview over the processes considered. A detailed description of inventory and impact assessment can be found in [Röder 2001].

2.3.1 Fuel Chains

2.3.1.1 Gasoline and Diesel

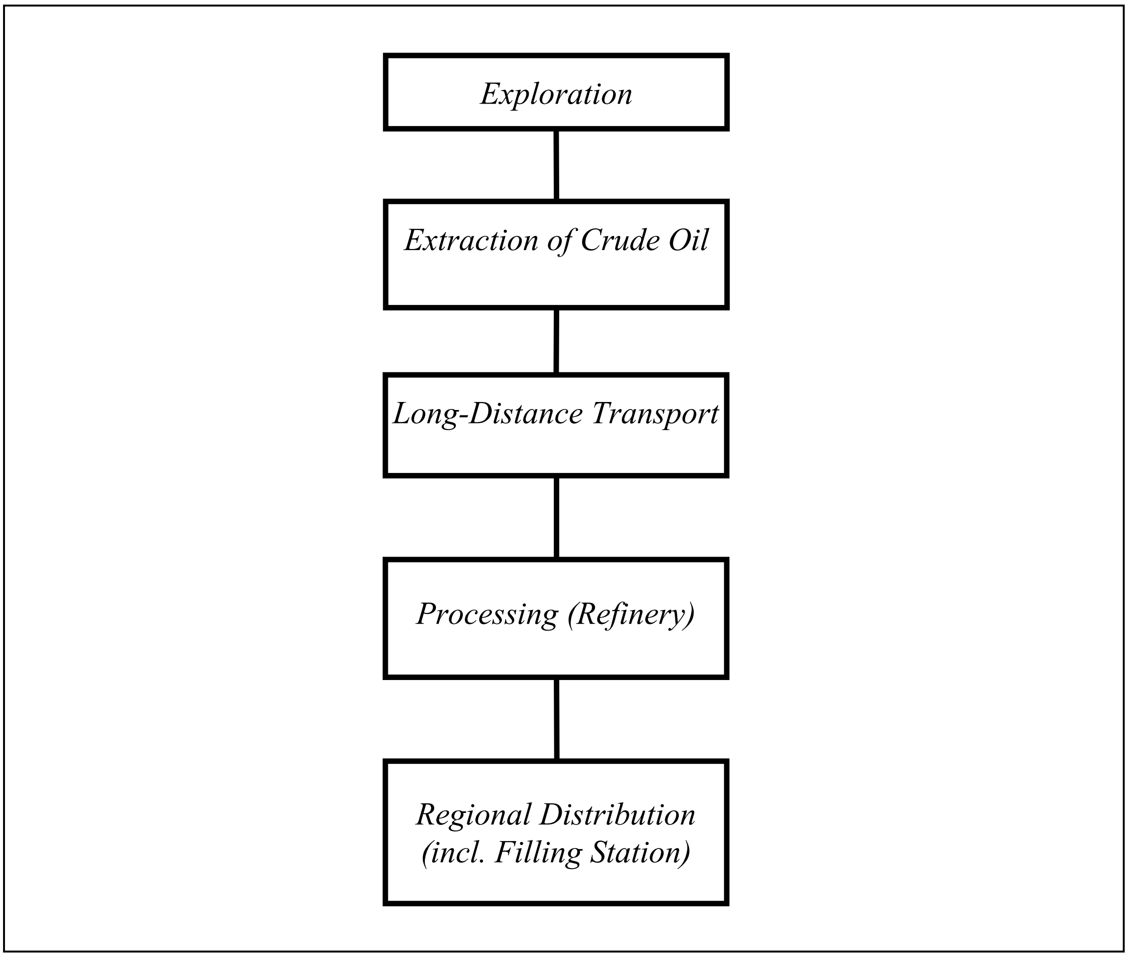

Figure 2: Fuel chain for gasoline and diesel fuel after [Frischknecht et al. 1996].

The main chain for gasoline and diesel fuel is represented in Figure 2. It has been analysed in [Frischknecht et al. 1996] and includes the most important additives. Changes were assumed in the production and distribution steps. In order to account for the production of low-sulphur gasoline and diesel (which is a prerequisite for further reduction of limited emissions) new modules for those fuels have been defined. In the production step, the focus is set on additional energy requirements for sulphur reduction that are based on [Greenergy 1999]; in the distribution module, evaporative emissions are significantly reduced by a lower Reid vapour pressure (RVP) (I assume the one for US reformulated gasoline (RFG)) and the universal use of gas recovery systems at the filling stations with a rather high control efficiency of 90%).

2.3.1.2 Compressed Natural Gas (CNG)

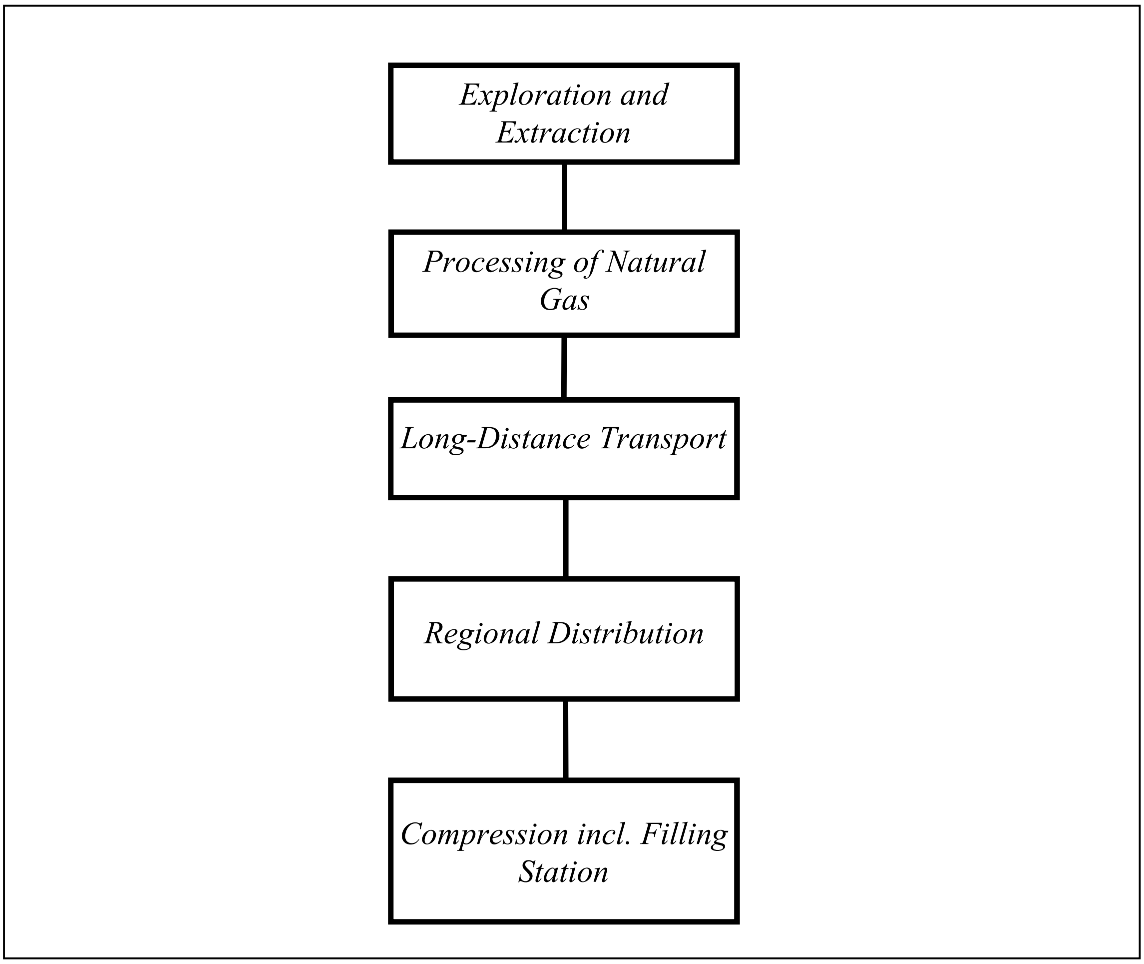

Figure 3: Fuel chain for CNG

A scheme of the fuel chain for compressed natural gas is shown in Figure 3. Up to the regional distribution step, it has been analysed in [Frischknecht et al. 1996]. I assume that compression is done at the filling station, which is directly connected to the high-pressure grid. In contrast to [Nigge 2000] I take an input pressure of 0.5 MPa (Nigge: 12 bar) and compression by NG turbines ($\eta = 34\%$) instead of electric compressors. The final pressure is assumed to be 25 MPa, 5 MPa more than in the on-board pressure vessel, to allow for fast filling. The compression work W has been calculated with the formula for adiabatic compression:

$$W = R_{NG} \cdot T \cdot Z \cdot \frac{\gamma_{NG}}{\gamma_{NG} - 1} \cdot \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma_{NG}-1}{\gamma_{NG}}} - 1 \right] \qquad \text{Eqn. 1}$$

where

R_{NG} = gas constant for natural gas

T = temperature

Z = compressibility factor of NG, $Z = Z(T,p)$

p_2 = final pressure

p_1 = initial pressure

γ_{NG} = ratio of specific heats for NG (1.307)

With $Z = 1$[13], the resulting compression work is 2.00% of the LHV of the compressed gas. With the turbine efficiency, the total energy input for compression is 58.8 GJ of natural gas per TJ of compressed gas.

Not included in this analysis are possible emissions (leakage) in the actual refuelling process.

[13] The compressibility factor Z of methane is smaller than 1 under the temperature and pressures considered here, so this calculation is a conservative estimate.

2.3.1.3 Methanol from Natural Gas

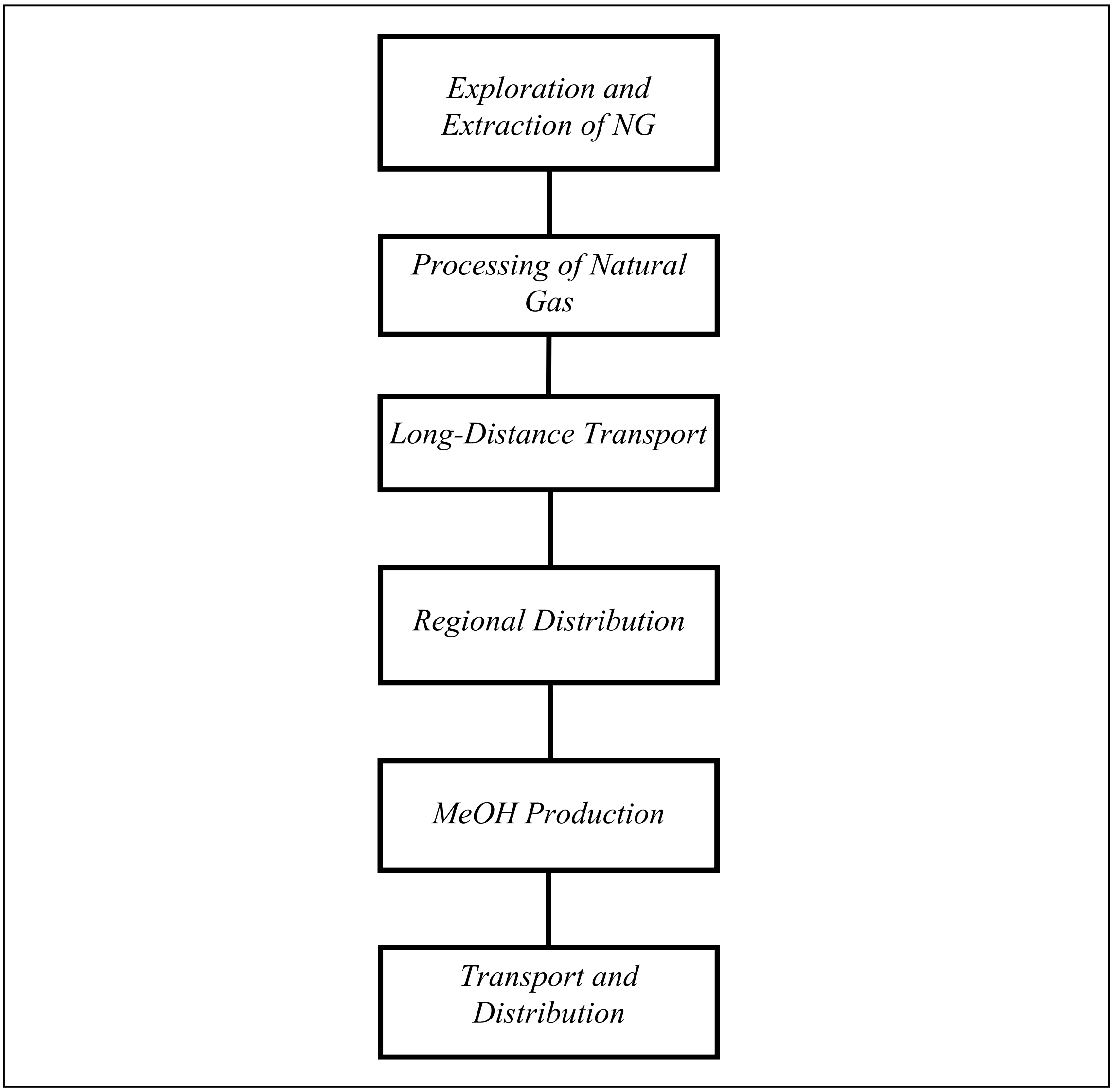

Figure 4: Fuel chain for MeOH from NG.

Methanol (MeOH) can be produced from various feedstock substances such as natural gas, oil, coal or biomass, and for most feedstocks different processes are available on the market (for an overview see e. g. [LeBlanc et al. 1994] or [Chauvel et al. 1985]). The most commonly used processes are via steam reforming or combined reforming of natural gas. Combined reforming has higher efficiencies than steam reforming and is analysed in this study. For this study I assume that MeOH is produced in Europe. Another option that is also proposed mainly for economic reasons is the production of MeOH from so-called remote natural gas; this gas is too far away from any potential market to be economically saleable, e.g. on some Caribbean islands or associated gas from oil extraction in the Middle East that is usually flared or vented. This MeOH would subsequently be shipped to Europe in large tankers (see, e.g., [Erdmann et al. 2000]). This route was also analysed in [Röder 2001]. Under the assumptions made (no credits for avoided flaring and venting) it has no ecological advantages over the other option, though. For the production of MeOH from wood see 2.3.1.5 "Biofuels".

The process chain for MeOH from natural gas "from cradle to tank" is shown in Figure 4. All steps up to the regional distribution are included in the module "Natural gas from HP grid in Europe" (Erdgas ab HD-Abnehmer Euro) in [Frischknecht et al. 1996]. The MeOH plant assessed represents the current state-of-the-art. Its efficiency is 70% (LHV), and the emission levels are very low compared to data quoted in literature so far [Höhlein 1999]. Plant infrastructure was assessed using data from a plant manufacturer [König 1998].

The analysis is restricted to pure MeOH. Additives that might become necessary for technical or safety reasons (dyes, odorants etc.) have not been considered; they would probably make up less than 1% of the final fuel.

Distribution of the fuel was derived from the corresponding modules for gasoline and diesel, taking into account MeOH-specific figures for properties such as density or vapour pressure.

2.3.1.4 Hydrogen

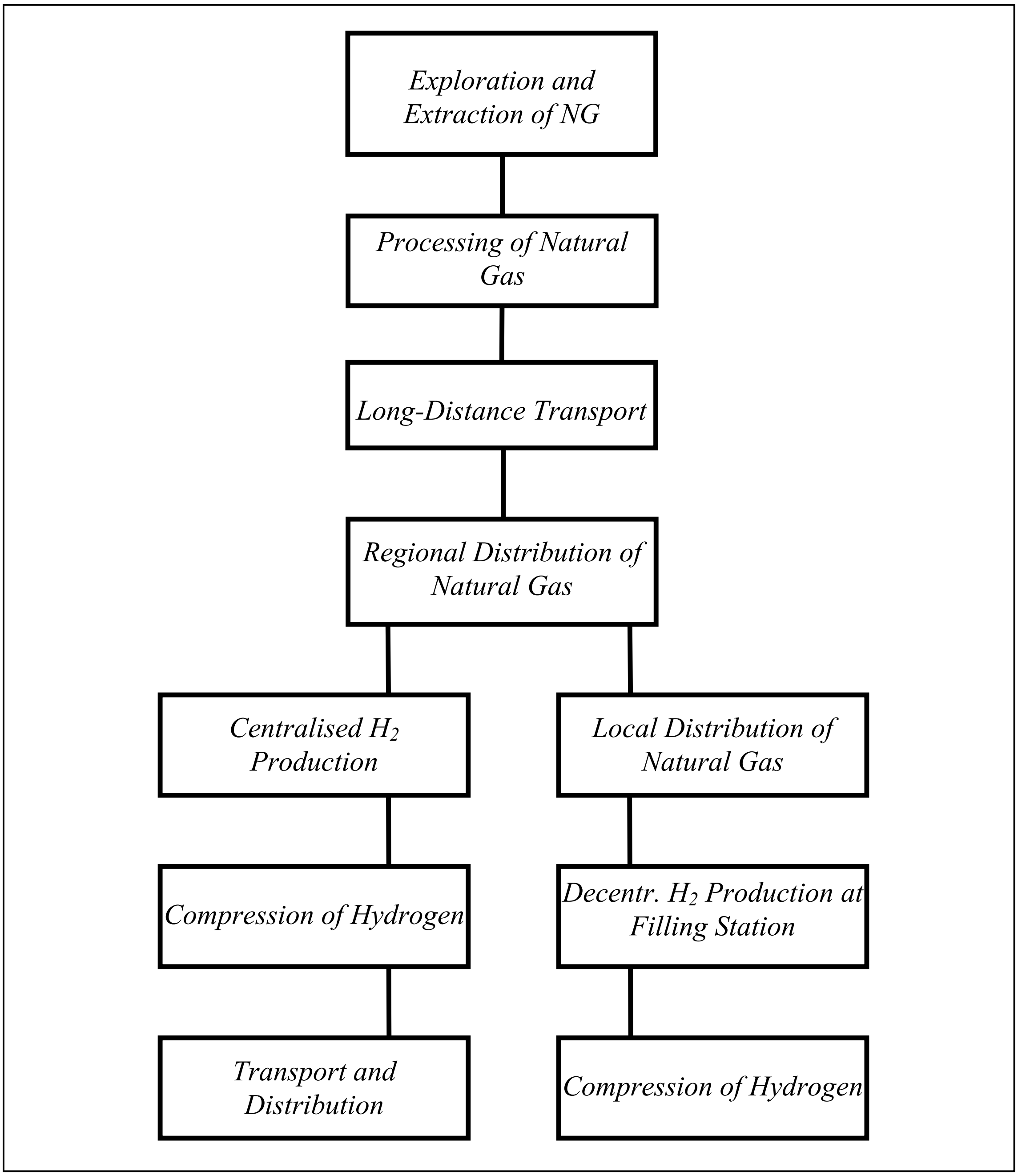

Figure 5: Fuel chain for compressed hydrogen from centralised and decentralised production.

This analysis refers mainly to small, decentralised units that include both hydrogen production (in a reformer or by water electrolysis) and filling station. The hydrogen produced at these units is compressed to 25 MPa to allow for fast filling of the 20 MPa pressure vessel on board the vehicle. The fuel chain is depicted in Figure 5 for the case of NG reforming. Once more, all the steps from exploration and extraction of NG to regional distribution have been taken from [Frischknecht et al. 1996]. The reformer unit has an efficiency of 79.8% [Ogden et al. 1996]. Emission factors for waste heat and CO_2 are calculated from the energy and carbon balance, respectively. Other emissions are estimated from values for a large-scale plant described in [Roesler & Zittel 1994]. Because of large similarities in the two processes, infrastructure requirements are derived from the NG-to-MeOH plant. Outlet pressure is 1.5 MPa. Under the assumption of adiabatic compression, the mechanical compression work W is then 3.13% of the LHV of the CH_2 (cf. Eqn. 1). This work is done by NG-fuelled turbines with an efficiency of 34%, so that per TJ of CH_2 92 GJ of NG have to be burned.

Hydrogen production in centralised plants requires a pipeline network or the use of relatively inefficient trucks[14] for local distribution. This option has also been analysed in the LCI, the results are not presented here, though. This fuel chain is, however, included in the MARKAL database (see Figure 32). The large centralised plant offers advantages in efficiency (81.2% based on LHV) and economics.

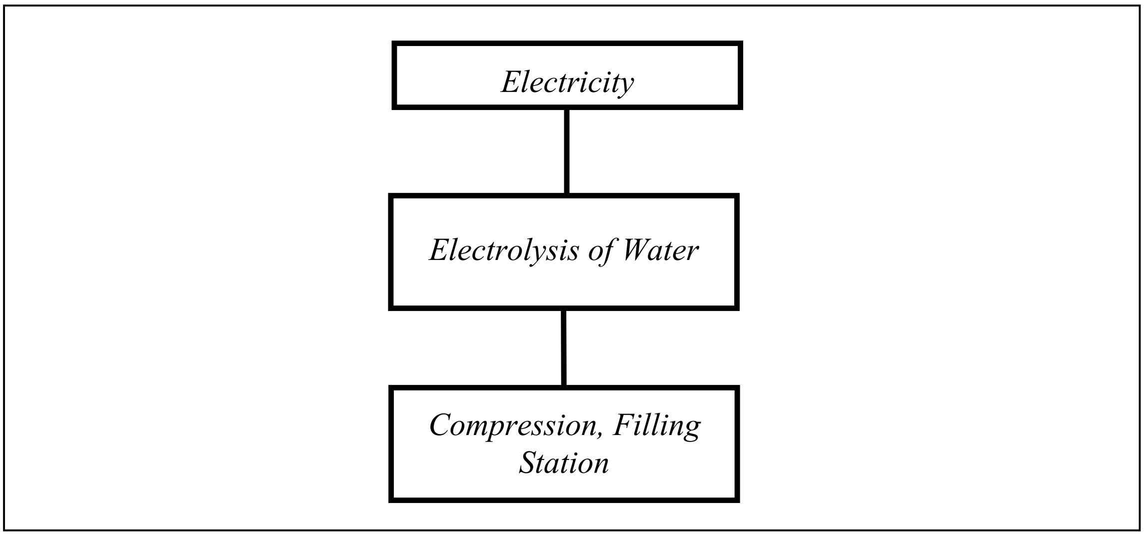

Figure 6: Fuel chain for compressed hydrogen from electricity. Not depicted in detail are the upstream steps of electricity production. All electrolysers are assumed to be decentralised.

[14] A truck trailer with a geometric volume of 22 m^3 and an operating pressure of 25 MPa has a maximum capacity of around 47 GJ of CH_2 (based on the LHV), corresponding to around 1.1 t of gasoline or diesel.

Another way of producing H_2 is by electrolysis of water. This alternative offers the potential of completely carbon-free fuel chains once an appropriate electricity source is available.

The electrolyser chain can be seen in Figure 6. The electrolyser is of an advanced pressurised alkaline type with an efficiency of 77% for the actual electrolyser and 96% for the rectifier. There are no direct emissions, and infrastructure requirements are taken from [Röder 1997]. With an outlet pressure of 3 MPa, the mechanical work for adiabatic compression is 2.35% of the LHV of the compressed gas, or 47 GJ_{el} per TJ of CH_2 produced (efficiency of electric compressor: 50% [Zittel & Wurster 1996]).

2.3.1.5 Biofuels

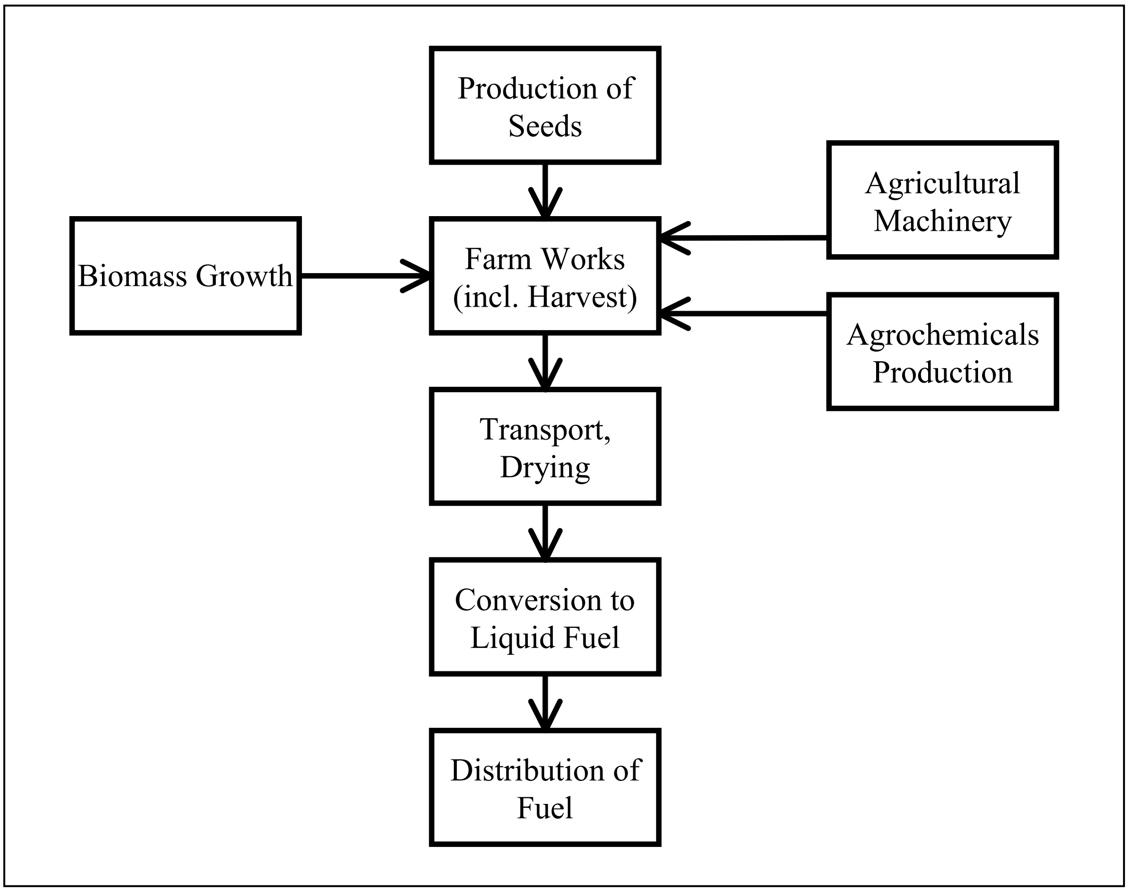

Figure 7: Schematic fuel chain for biofuels.

Figure 7 shows the schematic fuel chain for the production of biofuels. In this chapter only the steps from the main chain are outlined. For details on the side chains (biomass growth, production of agricultural machinery and chemicals) see [Röder

2001]. All biomass is grown without irrigation so the sometimes energy-intensive process of water provision is avoided.

Site dependency in biomass production is very pronounced. Soil fertility, topography, climate, production method (conventional or organic farming, for example) and other factors have a large influence on the inventory. Moreover, yield and requirements of some inputs (e.g. application of insecticides) show significant variations from year to year. Therefore, LCAs of biomass production often refer to a site that is considered typical for the region of interest and to an average year, especially in those studies that aim at supporting political decision-making. In sensitivity analyses, mainly the influence of the average yield is addressed. Examples of this type of study can be found in [Kaltschmitt & Reinhardt 1998, FAT/Carbotech 1997].

The production of biomass in this study was assessed for four commodities:

- winter rape (for production of RME),
- winter wheat (for production of EtOH),
- sugar beet (for production of EtOH),
- plantation wood (poplar for the production of MeOH). The production of wood in short rotation forestry (SRF) is still at an early stage of development. Hence the data for this crop are less reliable than those for the classical crops. In SRF, the lifetime of a plant is typically 20 years with harvest every four or five years.

Moreover, scrap wood was considered as a second feedstock commodity for the wood-to-MeOH process. Yet this process chain starts with the transport to the conversion plant, all previous have to be performed no matter whether the scrap wood is transformed into MeOH or landfilled or used in any other application. Nonetheless the scrap wood is credited the negative emissions during its growth phase because these emissions are still bound in it. The influence of this assumption has been tested in a sensitivity analysis (see section 2.4.8.5 "Scrap Wood Credits").

The assessment was restricted to an average site in Germany in 2010. The analysis is based on [Kaltschmitt & Reinhardt 1998], but supplemented with other data. I assume no fundamental changes until 2010; only the yield has been increased using data from

[Wintzer et al. 1993], see Table 2, and fertilizer requirements have been adjusted to these yields using empirical formulae.

Yield in 2010	$t_{dry\ matter}$/(ha*a)
Winter Rape	3.7
Winter Wheat	7.7
Sugar Beets	17.8
Poplar	12.0

Table 2: Yield of biomass commodities on average German sites in 2010 as assumed in the study.

The analysis of biomass production comprises the provision of seeds and saplings, the farm work (incl. manufacturing of tractors and other agricultural machinery), the production of fertilizers and pesticides, harvest, and emissions from the fields (N_2O and NO_x from fertilisers). In order to calculate the net environmental burdens induced by the cultivation of energy crops the corresponding inventory of a grass fallow (that is assumed to be replaced by the energy crops) has been subtracted. An important question is the emission of N_2O from nitrogen fertilizers applied; while emissions of NO_x are of minor importance, those of N_2O, a powerful greenhouse gas (GWP_{100} = 310), have a significant influence. Knowledge about these emissions is still very limited, and literature data about the fraction of the applied nitrogen emitted as N_2O differ by several orders of magnitude (cf. e.g. [Wintzer et al. 1993, Granli & Bockman 1994]). Basic mechanisms as well as more practical questions like dependence on soil, climate or crop are still subject to vivid discussions. To reflect this ongoing debate, two cases were considered: in the base case I use a conservative approach of 3% of the applied N emitted as N_2O (including indirect effects); in a sensitivity analysis this value is decreased to 1%. Both approaches are in line with [IPCC 1996] where a value of 2% ± 1% is considered representative for more than 90% of field situations.

The harvested biomass is then transported to the conversion plant and processed to a liquid fuel (RME from rapeseed, EtOH from wheat and sugar beet, MeOH from wood). The plants analysed have a moderate capacity so that they can be supplied on a regional scale.

Production of RME

The production of RME consists of three steps: extraction of the rapeseed oil, refining of the oil, and transesterification by addition of MeOH over a catalyst (NaOH). Rapemeal and glycerol are produced as by-products in the first and third step, respectively. The allocation is performed with the LHV of the commodities as allocation key. The parameters of the plant have been derived from data for existing facilities; in view of the development potential that has not been exploited yet, I assume a reduction of 15% for ancillary energy requirements (electricity and heat). The main input data are shown in Table 3 to Table 5.

		Rapeseed oil, unrefined
	Unit	1 t
Input		
Rapeseed	$t_{dry\ matter}$	2.27
Thermal Energy	MJ	1'217
Electricity	MJ	257
By-product		
Rapemeal	t	1.47
Allocation Key		LHV
Allocation Factor for Rapeseed Oil		60.6%

Table 3: Main input data for the rapeseed oil extraction step.

		Rapeseed oil, refined
	Unit	1 t
Input		
Rapeseed Oil, unrefined	t	1.04
Thermal Energy	GJ	277
Electricity	GJ	18

Table 4: Main input data for the rapeseed oil refining step.

		RME
	Unit	1 t
Input		
Rapeseed oil, refined	t	1.01
MeOH	t	0.109
Thermal Energy	MJ	1'156
Electricity	MJ	141
By-product		
Glycerol	t	0.093
Allocation Key		LHV
Allocation Factor for RME		96.1%

Table 5: Main input data for the transesterification step.

Production of EtOH

The production of EtOH from wheat and sugar beet takes place at a fermentation plant. In contrast to [Kaltschmitt & Reinhardt 1998] I assume a slightly better conversion rate (90% instead of 86%) and lower consumption of ancillary energy by 10% and 20% in the case of sugar beet and wheat, respectively. Both plants produce biogas that is used to reduce the requirements of fossil heat. The allocation between EtOH and by-products sugar beet pulp and DDG (distiller's dried grains), respectively, is done by LHV. The main input data are summarised in Table 6.

		EtOH from Sugar Beet	EtOH from Wheat
	Unit	1 t	1 t
Input			
Crop	$t_{dry\ matter}$	3.07	2.78
Thermal Energy		3'800	291
Electricity		9601	1605
By-product		Pulp	DDG
Yield	t	0.713	1.31
Allocation Key		LHV	LHV
Allocation Factor for EtOH		72.3%	56.1%

Table 6: Main input data for the production of EtOH from sugar beet and wheat, respectively.

Production of MeOH from Wood

For the conversion of wood to MeOH the Biometh process, which was developed at PSI, was chosen. In contrast to many other proposals this process was designed for a relatively small size that does not imply large transport distances. In a Biometh facility wood or other C-containing material such as plastic waste are first gasified; then heavy metals and other catalyst poisons such as H_2S and HCl are removed from the syngas. Finally, MeOH is synthesised and the remaining gas is burned in gas motors to produce electricity, and excess heat can be used for drying of wood or in other applications (when dry waste wood or plastic waste is used). In this study I assume that there is no purchaser of heat so that only electricity and MeOH production are taken into account; the allocation between these two commodities is done by exergy (HHV of MeOH: 22.4 GJ/t). The analysis is based on the future plant as described in [Röder 1997], but an efficiency increase of 20% (for MeOH and electricity) has been assumed. I consider this a conservative estimate. The main input data are shown in Table 7.

		MeOH from Wood
	Unit	1 t
Input		
Wood	$t_{dry\ matter}$	3.33
Thermal Energy	GJ	3.45 / 0*
By-product		
Electricity	GJ	4.49
Allocation Key		Exergy
Allocation Factor for MeOH		83.3%

Table 7: Main input data for the production of MeOH from wood; *: no energy needs for waste wood as feedstock.

Distribution of Biofuels

Modules for the distribution of all biofuels were derived from the corresponding modules for gasoline and diesel, considering fuel-specific properties.

2.3.2 Vehicles

For the LCA I assume that a car body of a small four-seater (comparable to a Renault Twingo or Volkswagen Lupo) is equipped with different powertrains, namely:

- cars with spark-ignited internal combustion engines (SI-ICE) fuelled with low-S gasoline, CNG, EtOH, MeOH, and CH_2. All these are so-called dedicated fuel vehicles that are optimised for a single fuel and thus exploit the fuel's potential.

- cars with compression-ignited internal combustion engines (CI-ICE) that can be fuelled with low-S diesel oil or RME.

- cars with a hybrid fuel cell (FC) powertrain fuelled with CH_2, MeOH and diesel or gasoline. The FC is always running on H_2, so MeOH and diesel have to be processed to a H_2-rich gas first.

In all cases, the power of the prime mover (ICE, electric motor) is 40 kW.

The powertrain in cars with ICE is conventional, i.e. the power from the engine is transferred to the wheels via a manual gearbox. A hybridisation with an electric motor is not assumed.

Such a hybridisation is much easier to accomplish in the case of a FC powertrain. A schematic structure of such a powertrain is depicted in Figure 8. The kingpin of this system is the fuel cell, a proton exchange membrane fuel cell (PEMFC), also called polymer electrolyte fuel cell (PEFC). In this fuel cell, the chemical energy stored in hydrogen is converted into electricity. If no hydrogen is stored on board the vehicle but MeOH or another hydrocarbon, this energy carrier first has to be converted into a hydrogen-rich gas in the fuel reformer. The electricity provided by the fuel cell is then used to propel the car via an electric motor and a transmission. The electric energy that the supercapacitor stores for short times can be fed from either the FC or the motor. The latter provides the possibility to recuperate energy when breaking the car or driving downhill.

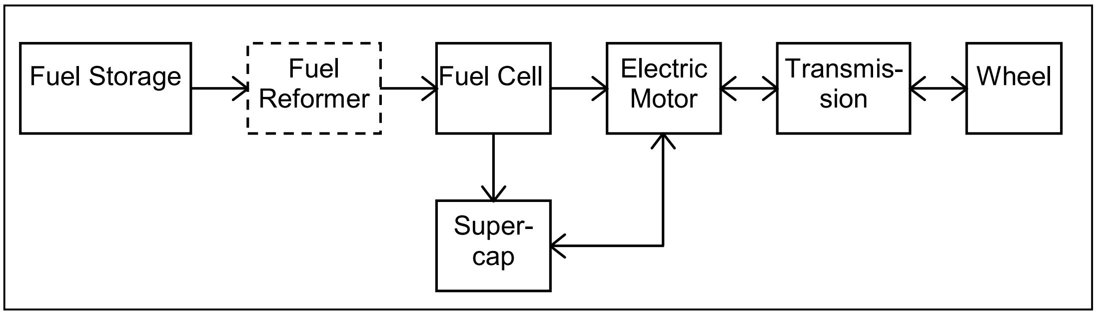

Figure 8: Example for powertrain structure of a fuel cell car; energy flows are denoted by arrowheads, components that are not necessary for all possible combinations are represented in dashed boxes; not represented are electronic devices.

In the context of this study, the total inventory of each vehicle is mainly determined by its fuel consumption, direct emissions, and manufacturing of the car. Maintenance and disposal play only a minor role, they are treated in a quite rough way. The transport of the car from the factory to the consumer was modelled assuming average distances for today's car park in Europe.

2.3.2.1 Consumption

The consumption of each vehicle type has been estimated using a simulation toolbox developed at ETH Zürich [Guzzella & Amstutz 1997]. The principles are described in the appendix (Appendix 2). The simulations have been run using the following characteristics:

ICE:

A detailed engine map determines the efficiency of a modern SI-engine. For the CI-engine I use a Willans-curve that fits a particular modern diesel engine. The efficiency of the transmission was taken to be 94%, the one for the electric generator 50%. In the cold start phase, the engine consumption at the beginning is set to be twice as much as according to the engine map. This increase is reduced with time, after 30 s the consumption is normal.

For SI-ICEs running on fuels others than gasoline (MeOH, EtOH, CNG, CH_2) an increase in efficiency by 15%, mainly due to the higher octane number, has been assumed (see [Dietrich et al. 1998]).

Fuel Cell Powertrain:

The fuel cell polarization curve represents an optimistic, but realistic assumption on efficiencies that are achievable in mass production by 2010. I use a λ_{H2} of 1.15, i.e. nearly 13% of the hydrogen are released to the environment unburned (or are oxidized in the catalytic burner of the reformer in the case of MeOH or diesel as on-board fuel) although higher utilization rates have been demonstrated (e.g. [Metkemeyer et al. 1997]: 97.4% without recirculation). I assume that recycling of mass flows can cover 50% of the compression work in the fuel cell system [Carpetis 1997]. The remaining compression work is done by small turbines with an overall efficiency of 52.5% (70% compressor, 75% electric motor). The engine map representing the efficiency of the engine/generator was derived from [Hauer 1999]. The efficiency of the power electronics is assumed to be 95%, which seems realistic after ongoing development work at PSI and ETHZ. For the transmission I use the same efficiency as for a multiple-speed gearbox i.e. 94%.

[Gao et al. 1999] have shown that with their reference car in most driving cycles nearly all of the total breaking energy can be used for energy recovery. For both the FTP75 and the ECE cycle they found that 100% of the braking energy could be taken up by the motor/alternator without any risk for driving stability, provided that an adequate braking controller (that does not exist yet) is used. Because these findings refer to a specific vehicle and to allow for an additional safety margin I assume that only 90% of the braking power are provided by the motor/alternator.[15]

Reformer System:

The on-board reformer system is not explicitly modelled in the simulation. A generic value is used for the total efficiency drop compared to a car driven on pure hydrogen. This means that the simulations are run with the vehicle mass of the MeOH or gasoline case, respectively, but the powertrain is modelled as if it ran on pure CH_2, and the resulting energy consumption is divided by the assumed average efficiency. After careful study of available literature and discussion with experts these efficiencies were set at 75.0% (for MeOH) and 68.6% (for diesel).

Results of the Simulations

Table 8 contains the weights and calculated energy consumption for all vehicles under consideration. As can be seen, the choice of the driving cycle has only a minor influence on the energy consumption: the difference is in the range of 2-3% for ICE-propelled cars and less than 1% for FC cars. All simulations have been run with full tanks and a payload of 140 kg. The driving cycles used are the full NEDC and the FTP-75 urban cycle. The following parameters have been applied to all vehicles:

rolling resistance coefficient: $\mu = 0.0075$[16]

air drag coefficient: $c_W = 0.25$

frontal surface: $A = 1.9\ m^2$

electricity consumption: $P_{el} = 500$ W

---

[15] This means that only 90% of the effective braking force (as calculated by the model) is "fed" into the powertrain. This energy flow is also subject to losses in the transmission and the alternator. Other restrictions that reduce the net recovery are the maximum power of the alternator and the capacity of the storage system (supercaps). Conventional friction brakes that have no effect on the model absorb the remaining 10% of the braking energy.

Powertrain	Vehicle Weight (kg)	Consumption (kWh / 100 km)	
		FTP-75	NEDC
ICE:			
Gasoline	669	40.0	41.1
CNG	720	35.5	36.3
MeOH	692	35.1	36.0
CH_2	766	36.1	36.8
EtOH	669	34.8	35.7
Diesel/RME	723	34.8	35.7
FC:			
MeOH	830	26.9	27.0
Diesel	827	29.3	29.5
CH_2	838	20.3	20.3

Table 8: Vehicle weight and consumption of cars with different powertrains and fuels.

Please note that with the volumes assumed for fuel storage the cars do not have the same range: while most ICE-powered cars offer ranges well in excess of 400 km (gasoline: 450 km, diesel: 580 km) and also the FC cars are acceptable in this respect (CH_2: 390 km, MeOH: 640 km), the CH_2-fuelled ICE car has a clear disadvantage with its low range of 220 km. This means that the equivalence of the functional unit is reduced.

2.3.2.2 Emissions

Substance	CO		HC		NO_x		HC+NO_x		PM
Engine Type	SI	CI	SI	CI	SI	CI	SI	CI	CI
	g/km		g/km		g/km		g/km		g/km
Euro IV Limit	1.00	0.50	0.10	-	0.08	0.25	-	0.30	0.025
Value Used in this Study	0.80	0.40	0.08	0.04	0.064	0.20	-	-	0.020

Table 9: Emission limits and emission factors for limited substances.

Future emission levels of cars depend on a variety of factors. The main driver for lower emissions in the past was legislation. The interaction between technical progress and legal requirements has led to the situation that now some of the environmental problems such as concentrations of CO in densely populated areas are now considered solved by many experts [Kolke 1998]. In the future, legislation will

[16] [OTA 1995] estimates that in 2005 the tire rolling resistance will be around 0.0065 and might decrease further to 0.005 in 2015. On the other hand they indicate that only 82% of the total rolling

continue to be the main determinant for emission levels. I assume that emissions of limited substances from all ICE-powered vehicles during their entire life are 80% of the so-called Euro IV emission standards that are mandatory for the EU from 2005 on, see Table 9. As a simplification I consider that with continuing catalyst development the influence of the fuel on emission levels decreases significantly. The only fuel-specific emission factors are:

- the profile of HC emission, see Table 10.
- emissions of CO from the CNG engine are lower.
- CH_2-engines do not emit any CO or HC, contributions from lubricants are neglected. Emissions of NO_x are very low (0.0016 g/km [Aceves & Smith 1996].

Emissions of waste heat, CO_2 and SO_2 were calculated from the energy, carbon and sulphur balance, respectively, see Table 11; emissions of unregulated substances were derived from [BUWAL 1998].

	Low-S Gasoline	MeOH	CNG	EtOH	Low-S Diesel	RME
1-3-Butadiene	0.6%	2.0%	0.1%	0.2%	1.5%	0.4%
Benzene	4.3%	0.3%	0.1%	1.1%	2.2%	5.6%
CH_4 Methane	12.7%	3.8%	89.6%	15.4%	3.6%	15.5%
Ethene	2.4%	1.0%	0.4%	2.3%	13.5%	2.4%
Formaldehyde	2.0%	17.3%	0.8%	2.3%	18.6%	25.4%
Other VOC	55.7%	58.0%	8.2%	66.3%	52.9%	21.3%
PAH Polycyclic Aromatic HC	0.0040%	0.0010%	0.0012%	0.0008%	0.051%	0.065%
Pentanes	7.1%	6.7%	0.0%	6.9%	0.1%	7.0%
Propene	2.5%	0.8%	0.1%	2.5%	4.6%	2.5%
Toluene	1.6%	9.0%	0.1%	0.3%	1.4%	9.9%
Xylenes	11.1%	1.0%	0.7%	2.7%	1.5%	9.9%

Table 10: Profile of HC emissions from ICEs by mass as a function of fuel. Source: [BUWAL 1998].

resistance is caused by the tires, with the rest stemming from brakes, seals, and bearings.

		CO_2	SO_2	Waste Heat
		kg	g	TJ
Low-S Gasoline	per t fuel	3'190	66.7	4.58E-02
Low-S Diesel	per t fuel	3'172	20.6	4.55E-02
CNG	per TJ	56'000	617	1.11
MeOH	per t fuel	1'375	10.3	2.24E-02
EtOH	per t fuel	1'913	26.0	2.99E-02
RME	per t fuel	2'823	64.9	3.93E-02
H_2	per TJ	0	0	1.18

Table 11: Emission factors of CO_2, SO_2 and waste heat for the different fuels. Waste heat emissions from CNG and H_2 are larger than 1 TJ / TJ_{fuel} because basis for all calculations is the LHV whereas waste heat emissions are computed using the HHV.

It has been shown that cars propelled by spark-ignited ICE can even fulfil the Californian SULEV emission requirements that are much stricter than those of Euro IV. This possibility, however, has not been included in this assessment for two reasons, namely the (assumed) lack of legislative pressure in Western Europe, and the lack of data concerning the technology to achieve such low emission levels (increased catalyst loading, for example).

A very important question is in how far the emission levels are representative for realistic driving patterns.

For FC cars, emissions of waste heat and CO_2 are the same as for ICEs. Only sulphur emissions I set to zero because this element is a serious poison for the reformer catalyst and therefore has to be removed from the fuel, either on-board or in previous steps of the chain. Other emission data have been taken from literature, see Table 12. These values have been obtained for static operation, under dynamic conditions an increase is to be expected; on the other hand the devices analysed are still at a very early stage of development, and the corresponding optimisation potential should at least partly compensate this increase.

Fuel		Gasoline / Diesel	MeOH
Reference		Mitchell et al. 1999	Höhlein & Biedermann 1996
CO	kg / t fuel	0.109	0.021
NMVOC	kg / t fuel	0.142	0.021
NO_x	kg / t fuel	0.025	0.0042

Table 12: Emission factors for reformer operation.

2.3.2.3 Manufacturing of Cars

The production of cars was analysed in less detail than the fuel chain. Reasons for this were limited time and data availability in combination with the perception that in general the fuel chains and direct emissions contribute much more to the impact categories than the production of the vehicle.

2.3.2.3.1 General Remarks

Whenever Al is used, I assume it to be 50% primary (virgin) and 50% secondary (recycled) metal; for platinum-group metals (PGM; Pt, Rh, Pd) I count 71% of the input as secondary. For all other metals recycling shares are incorporated in the basic modules from [Frischknecht et al. 1996] (steel: 0%-20%, Cu: 40%).

The energy consumption for the production (12 MJ of final energy/kg) has been taken from [Frischknecht et al. 1996], the share has slightly been modified to 45% electricity and 55% thermal energy (48% NG and 7% oil).

Transport of the manufactured car from the car plant to the vendor is also included in the calculations. The distances assumed were estimated from the average situation in Western Europe in the beginning of the 90s.

2.3.2.3.2 Car Body

The car body definition in this LCA comprises all components of the car that are identical for all powertrain configurations analysed plus all structural reinforcements that are induced by higher powertrain weight. This means, for instance, that for a conventional vehicle only the fuel tank, the engine system, and the gearbox are excluded from the car body.

The mass of the car body is assumed to be 560 kg; the construction is based on carbon steel, but a relatively large amount of Al (93 kg) is included. Reinforcement structures are assumed to be made entirely of steel. The weight of the reinforcement is calculated as 30% of the powertrain mass exceeding the mass of the lightest powertrain, the gasoline-fuelled ICE.

2.3.2.3.3 Fuel Storage

As typical for a tank for normal liquid fuels a specific weight of 0.08 kg/l of capacity and HDPE as material were taken. A differentiation between sizes or fuels (MeOH is a corrosive for many plastics) was not deemed necessary.

Gaseous fuels are assumed to be stored in pressure vessels with a specific weight of 0.55 kg/l of capacity. They are made of aluminium (36%) and epoxy fibres (64%); due to lack of data, the latter are replaced by a common plastic commodity in the calculations.

2.3.2.3.4 Internal Combustion Engine

The specific weights of the SI-ICE and the CI-ICE are 2 kg/kW and 3 kg/kW, respectively. The displacement and weight of the ICE running on H_2 was increased by 10% to account for the lower energy content of the fuel/air-mixture [Dietrich et al. 1998]. For all engines I assume that nearly 40% of the material are aluminium.

Because of the carbon-free fuel, hydrogen engines might be able to comply with stringent emission legislation without a catalytic converter. For all other fuels I assume a PGM loading in the converter of 10 mg / kW, which reflects already some reduction potential compared to today's situation. The average composition is shown in Table 13. This mix is used for the inventory of the SI-engine, the CI-engine has a Pt-only catalyst [Johnson Matthey 2000].

PGM	Use in Automotive Industry 1997 ('000 oz)	Share (weight basis)
Pt	1'830	33.6%
Pd	3'200	58.7%
Rh	418	7.7%

Table 13: Average PGM-mix in the automotive industry. Source: [Johnson Matthey 1999].

Moreover, an electronic motor controller has been included in the inventory.

2.3.2.3.5 Gearbox and Transmission

The gearbox connected to the ICE has a specific mass of 0.75 kg/kW of which 80% are steel, 15% aluminium and 5% gearbox oil. The same material composition, but with a specific mass of 0.3 kg/kW, is used for the single-stage transmission in the fuel cell powertrain.

2.3.2.3.6 Reformer

The reformers have an assumed specific mass of 1.5 kg/kW_{FC} (MeOH) and 2.0 kg/kW_{FC} (gasoline/diesel). Estimates concerning material composition and mass of active components in both the reformer unit and the subsequent gas clean-up are very uncertain. As of today's knowledge MeOH would be reformed over a catalyst with no noble metals (Zn and Cu), whereas for the reforming of higher hydrocarbons Rh, a PGM, is necessary. As a very rough estimate I use 0.6 g Rh/kW_{FC} over the entire life of the vehicle. Gas clean-up is assumed to be performed by a Pd/Ag-membrane system that needs 0.4 g Pd/kW_{FC}. All PGMs in the reformer are assumed to be 25% primary and 75% secondary.

2.3.2.3.7 Fuel Cell System

The total weight of the fuel cell system was set to be 3 kg/kW_{el}. I assume that bipolar plates are made from low-alloy steel; if, however, graphite is used, environmental burdens from the production of these components would rise significantly [Pehnt 2001]. The Pt loading used in this study is 0.4 g/kW_{el}. The analysis made here is quite coarse; a detailed LCA of a PEM-fuel cell system will soon be available (cf. [Pehnt 2001]).

2.3.2.3.8 Electric Motor

As a reasonable value for the specific mass of the electric motor 0.8 kg/kW were taken. This figure does not include controller or other electronic devices. The electric motor consists mainly of steel (nearly 75%), aluminium (16.5%) and copper (9%).

2.3.2.3.9 Electronic Devices

Due to lack of data about both specific production processes and the actual composition of the electronics used in both powertrains a general module has been introduced for all electronic devices. This general module for electronic devices cannot, of course, represent the heterogeneity of electronic components. It consists mainly of a general material composition (aluminium, copper, nickel, plastics and silicon).

2.3.2.3.10 Supercapacitors

Supercapacitor technology is still at an early stage of development, so once more the inventory is very simplified. The most important materials are activated carbon, the electrolyte with a dissolved salt, aluminium, HDPE and small amounts of PTFE.

2.3.2.4 Maintenance and Disposal

These processes have only a very small influence on the LCI, as has been shown in e.g. [Schuckert 1996]. For maintenance some rough estimates of energy and material requirements were used, the disposal of cars at the end of their life was completely neglected.

2.4 Classification and Interpretation

Numerical results for selected emissions (CO_2, CH_4, N_2O, SO_2, NO_x, NMVOC (sum), NH_3 and PM) and the impact classes analysed are included in the appendix.

Throughout the section the following numbers have been used for denomination of the different fuel chains:

Number:	Powertrain:
ICE:	
1	Gasoline-SI
2	Diesel - CI
3	MeOH from NG - SI
4	CNG - SI
5	CH_2 from NG - SI
6	CH_2 from NPP - SI
7	CH_2 from PV CH - SI
8	MeOH from Poplar - SI
9	MeOH from Waste Wood - SI
10	EtOH from Sugar Beet - SI
11	EtOH from Wheat - SI
12	RME - CI
FC:	
13	Diesel (Gasoline) - Reformer
14	MeOH from NG - Reformer
15	CH_2 from NG - direct
16	CH_2 from NPP - direct
17	CH_2 from PV CH - direct
18	MeOH from Poplar - Reformer
19	MeOH from Waste Wood - Reformer

Table 14: Numbers used for denomination of different powertrains.

2.4.1 Non-Renewable Energetic Resources

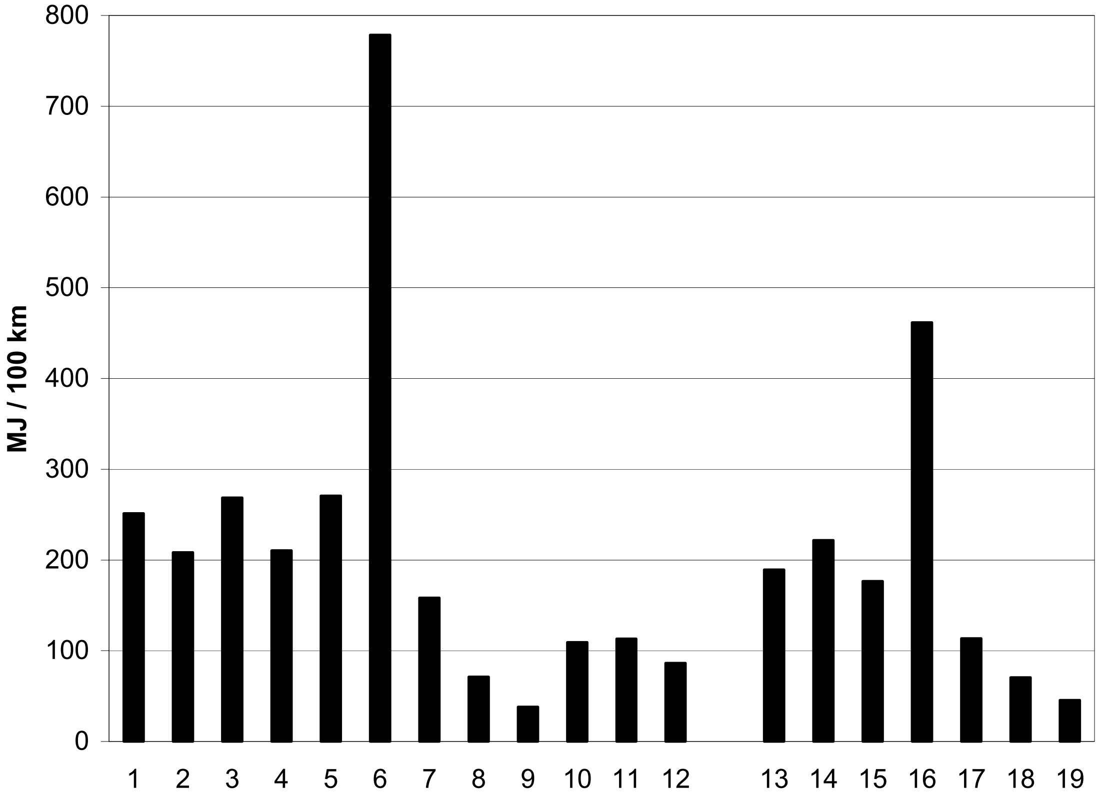

Figure 9: Total emissions of waste heat (= use of non-renewable energetic resources). For explanation of numbers see Table 14.

If one looks at cars running on non-renewable fuels first, one sees the following: Over the whole life cycle the diesel car (2) uses some 17% less energy than the gasoline car (1). Similar reductions (16%) are reached with CNG (4). With ICE-cars fuelled with MeOH (3) or CH_2 from NG (5) the emissions are higher than the reference case by 7% and 8%, respectively. Energy use by the FC car running on middle distillates (13) and MeOH from NG (14) are some 25% and 12%, respectively, lower than that of the reference case, the FC car with CH_2 from NG (15) uses 30% less energy. The largest use of non-renewable energy is caused by the two alternatives involving nuclear power: the relatively low efficiency of the NPP and the large number of conversion steps in the fuel chain drive the energetic requirements for the ICE car (6) to more than three times those of the gasoline car, waste heat emissions from the FC car (16) amount to some 180% of the base case figures.

All alternatives using renewable primary energy (PV, biofuels) use significantly less energy than the reference vehicle: reductions range from 37% (ICE, CH_2 from Swiss PV, (7)) to nearly 85% (ICE, MeOH from waste wood, 19).

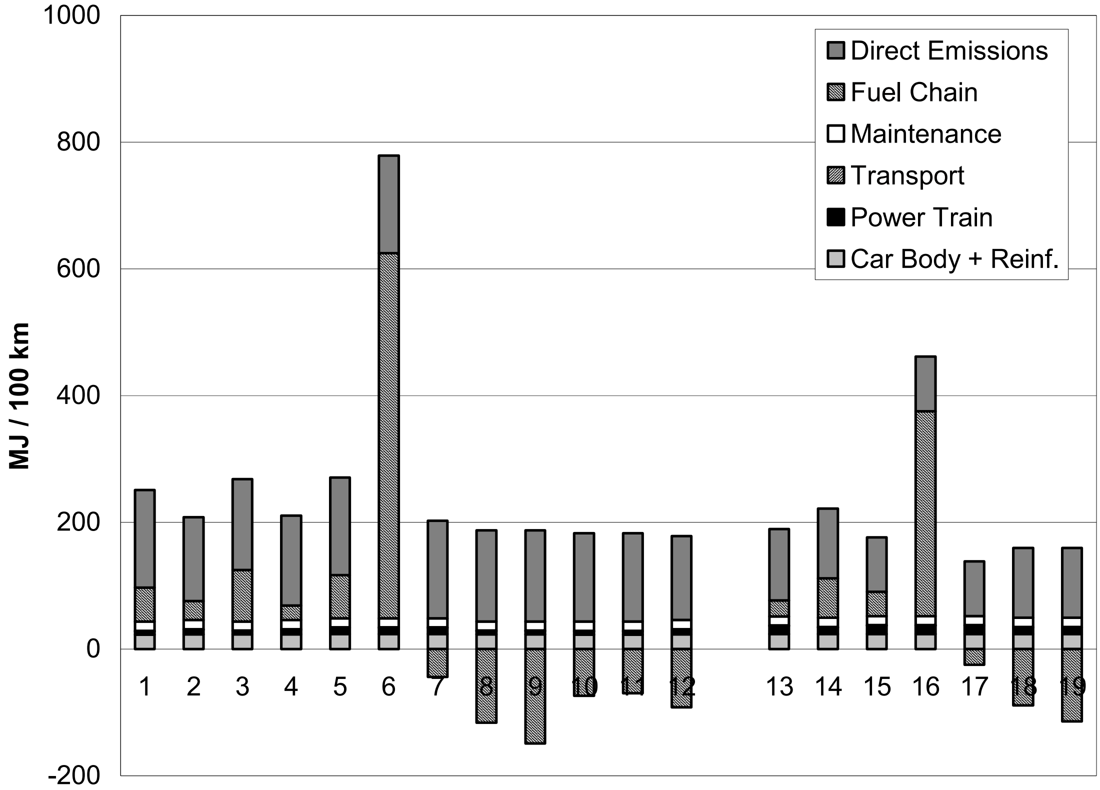

Figure 10: Waste heat emissions by origin. For explanation of numbers see Table 14.

A more detailed analysis of waste heat emissions shows that for fossil fuels the direct emissions are predominant, whereas the credits from the fuel chain lead to a significant reduction of total energy use in the case of biofuels. Systems involving CH_2 from PV get only small credits from the fuel chain because of the high energetic requirements for the production of the power plant and the relatively low yield under Swiss conditions. The use of non-renewable energetic resources for the production of CH_2 from NPP has already been explained before.

Although the energetic requirements for the production of the powertrain show large differences, their influence on the final result is small.

2.4.2 Emissions of Greenhouse Gases (Global Warming Potential, GWP)

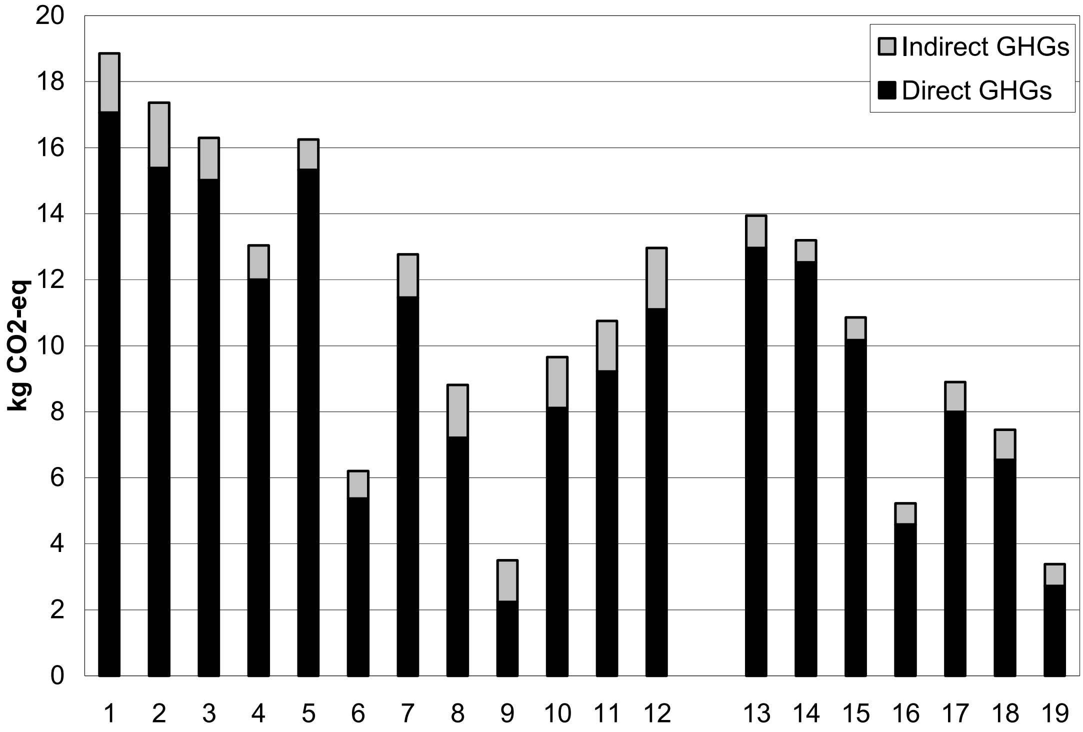

Figure 11: Emissions of GHGs per km. Direct GHGs are weighted according to [IPCC 1996], indirect gases according to [IPCC 1991]. For explanation of numbers see Table 14.

Figure 11 shows emissions of direct and indirect GHGs per km. The latest IPCC report [IPCC 1996] no longer recommends weighing factors for indirect GHGs because of the difficulties to assess their effect. Using weighing factors from [IPCC 1991], I have included them nonetheless in the figure to show that total GHG emissions are dominated by emissions of direct GHGs. One can also see that in general emissions of indirect GHGs from ICEs are higher than those from FCs. This is to a large part due to the direct emissions formed in the combustion process (NO_x and, for C-containing fuels, NMVOC and CO). Yet because of the weak basis of the GWP for NO_x, CO and NMVOC one can only say that the results of my calculations suggest that including these indirect effects would slightly favour FC cars. The following comments refer to direct GHGs only.

Gasoline cars (1) cause most GHG emissions; diesel cars offer overall reductions of around 10% (2), an effect of better engine efficiency and lower energy requirements in the refinery step.

Cars with ICEs fuelled with fuels derived from NG (MeOH (3), CNG (4), CH_2 (5)) show smaller overall emissions than the reference case. The reduction potentials range from around 10% in the case of CH_2 and 12% with MeOH to 30% with CNG. This result is not surprising, if one looks at the main conversion steps in the fuel chains: CNG only has to be compressed, while the other fuels have to be converted with a considerable energy loss (around 20% plus compression energy in the case of H_2, 30% in the case of MeOH). Engine efficiency is equal for all the three fuels.

With CH_2 from NPP (6) total GHG-emissions are only 32% of the reference case, with most of the emissions stemming from production and maintenance. Total emissions with CH_2 from Swiss PV (7) are two thirds of those from the reference car, only slightly less than with CNG. The results for this solar fuel seem to be rather disappointing, but one must not forget that these calculations are based on production processes typical for the mid-nineties. A sensitivity analysis with future PV plants is shown in Section 2.4.8.4 "Future PV Plants".

Biofuels also offer significant overall reduction potentials. Under the assumptions made here, with EtOH from wheat (11) and RME (12) reductions of 35% and 30%, respectively, could be achieved, compared to the base case. Even more promising are EtOH from sugar beets (46%, (10)) and MeOH from wood (58% for poplar chips (8), around 87% for waste wood (9) as feedstock). The balance for all biofuels is better than that for CNG, the best-performing fossil alternative.

A FC car fuelled with diesel (or another middle distillate) (13) is 24% less GHG-intensive than the reference case, with MeOH from NG (14) the reduction is 27%. This is less than the ICE car running on the same fuel, but more than the CNG car. Considering the large uncertainties concerning efficiencies (especially for the on-board reforming of MeOH and other hydrocarbons), these differences are not significant. The least emissions with NG as primary energy carrier can be achieved when fuelling a FC car with CH_2 (40% reduction, (15)). Even larger reductions might be possible when fuelling the FC car with CH_2 from NPP (73%, (16)), CH_2 from

Swiss PV (53%, (17)) or MeOH from poplar chips (62%, (18)) and waste wood (84%, (19)).

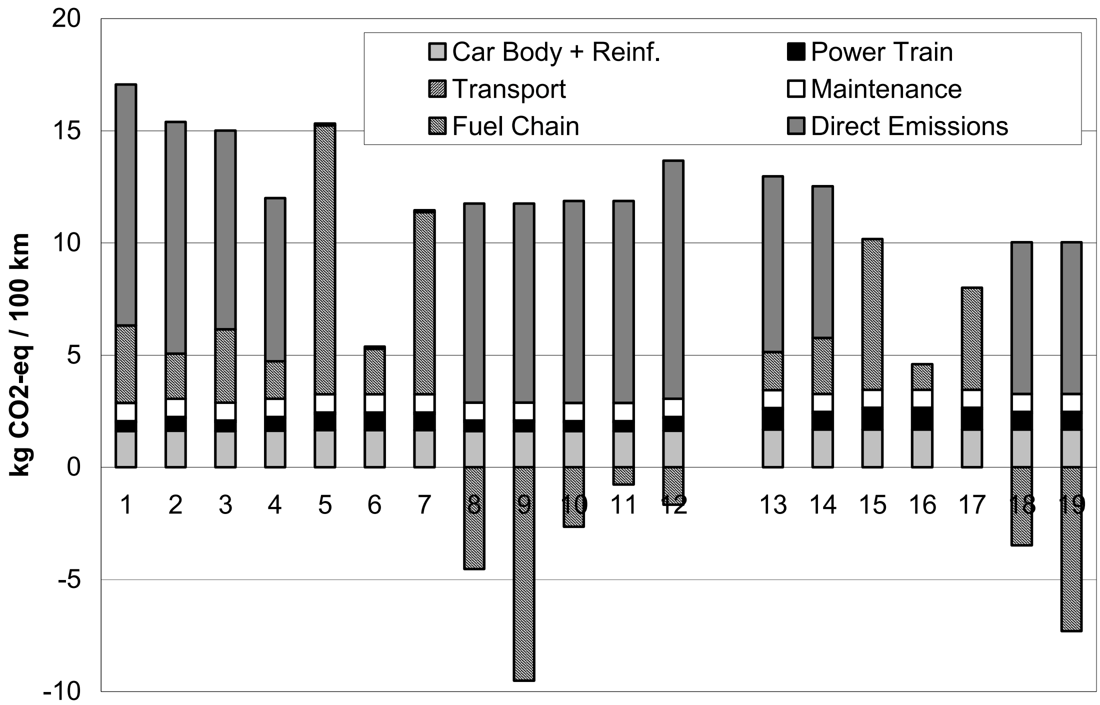

Figure 12: Emissions of direct GHGs by origin. For explanation of numbers see Table 14.

Figure 12 shows the emissions of direct GHGs by origin. The absolute contribution of the production of the car body (including the necessary reinforcement for heavier powertrains) is, as expected, nearly the same for all vehicles. The manufacturing of the powertrain shows large differences: the diesel cars are handicapped by the relatively large mass of the engine, all vehicles running on gaseous fuels have a material intensive pressure vessel, and in the case of FC cars the reformer (where applied), electric motor, power electronics and especially the PEMFC contribute significantly to GHG emissions.

The transport of the car from the production site to the customer can be neglected, although the data taken for this study include a significant share of vehicles from overseas.

GHG emissions from the maintenance of the cars are nearly independent from the type of powertrain. This is in part due to the fact that because of lack of disaggregated data all energy requirements for the maintenance of the whole car have been attributed to the car body. This means that all vehicles have been charged with the requirements for the maintenance of a conventional powertrain as well. However, the effect on the final result (FC cars promise to be less maintenance-intensive than ICE cars) should be small.

In the case of fossil fuels, the majority of GHG emissions stems from the fuel as such, i.e. the sum of fuel chain and direct emissions. The distribution between fuel and direct emissions reflects the carbon content of the final fuel: while for diesel the contribution from the fuel chain is fairly small, hydrogen causes no CO_2 emissions when being burned. The small contributions from direct emissions in the case of hydrogen-fuelled ICE cars (which are hardly visible in the graph) are emissions of N_2O.

Despite of the higher carbon content of the fuel, the diesel car performs better than the gasoline car because of its superior engine efficiency and the smaller emissions from the refinery that have to be credited to the fuel.

As one would expect, contributions from the fuel chain are very small in the case of CH_2 from NPP, they represent around two fifths of the total emissions. In the case of CH_2 from Swiss PV the fuel production is much more GHG-intensive because of the production processes for the PV plant (see also 2.4.8.4 "Future PV Plants").

All biofuels have a negative GHG-balance from cradle to tank, i.e. the uptake of CO_2 from the air is larger than the emission of GHG during farming, conversion and transport. This finding, however, is very sensitive to changes in the underlying assumptions. EtOH from wheat, for instance, has a positive cradle-to-tank balance if no by-product credit is assumed in the conversion step. But even in this case a car fuelled with EtOH from wheat has less total emissions than the reference case. This is mainly caused by the efficiency of the ICE that can be noticeably higher if optimised for alcohols. Another factor is the slightly smaller carbon intensity (per unit of energy) of EtOH compared to gasoline.

In the case of MeOH from waste wood nearly all direct emissions are offset by the negative GHG-balance of the fuel. The other biofuels (EtOH from sugar beet, MeOH from poplar chips, RME) are in-between these two extremes. All these calculations have been made assuming that 3% of all fertilizer-N is released as N_2O. A sensitivity analysis with a smaller emission factor has been carried out as well, see Section 2.4.8.1 "Lower N_2O Emissions from Fertilizers".

The results show clearly that the answer to the question whether the FC is superior to the ICE depends also on the fuel (or the primary energy carrier) that is used: While for fossil primary energy carriers the higher efficiency of the FC powertrain leads to overall reductions of GHG-emissions compared to the ICE, this picture can be inverted if a fuel that is nearly GHG-free over the complete life cycle (such as MeOH from waste wood) is considered. In this case the higher emissions from the powertrain production outweigh the relatively small reductions achievable by lower fuel consumption.

2.4.3 Photochemical Ozone Creation Potential (POCP)

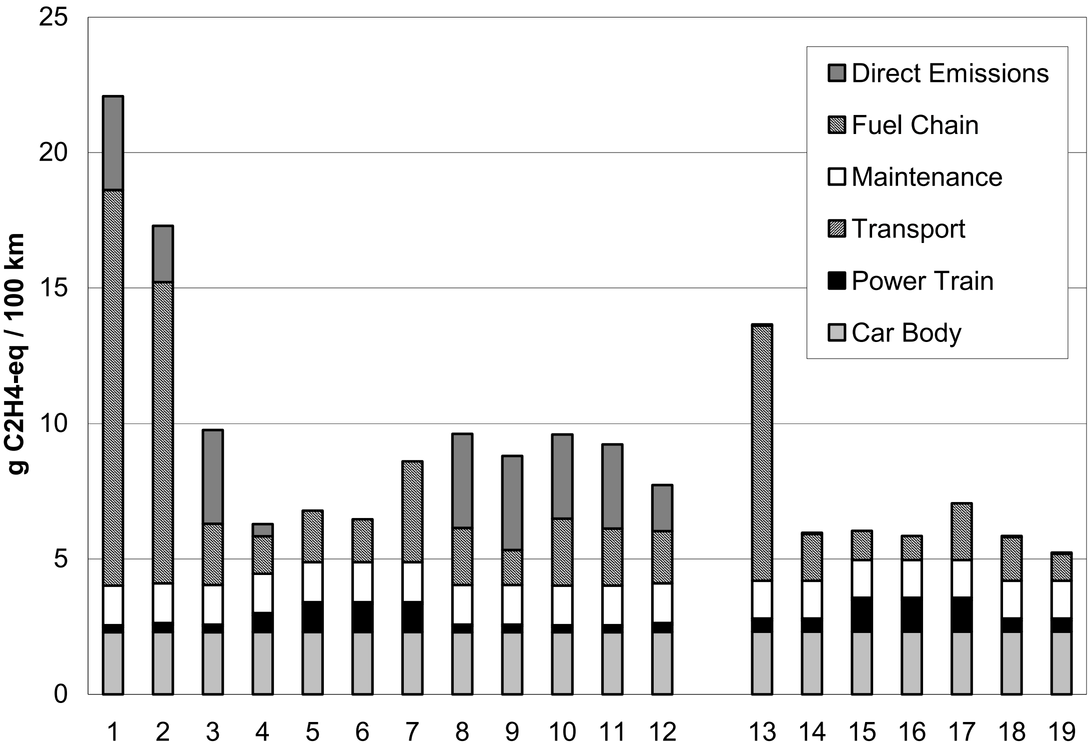

Figure 13: Emissions of ozone forming substances. For explanation of numbers see Table 14.

The two conventional systems, ICEs run on gasoline (1) and diesel (2), and the FC car fuelled with middle distillates (13), have by far the highest emissions of VOC, which are the only substances that have a POCP. These high emissions stem mainly from the fuel chain from well to tank. Only a small part (on the order of 10% to 20%) of the VOC emissions from these chains are emitted in the refinery or during the distribution of the fuels, the predominant fraction is emitted in the extraction step. This has to be kept in mind because photochemical creation is a regional, not a global impact. A correction of the data used here is, however, very difficult because the other fuel chains also involve remote releases of VOC. If one neglects totally the extraction of crude oil, the gasoline-fuelled ICE car would still be the largest polluter with more than 10 g C_2H_4-eq / 100 km, the diesel-fuelled ICE car would cause emissions of around 7 g C_2H_4-eq / 100 km.

Other fuel chains show reduction potential between nearly 50% and around 75% compared to the reference vehicle (with complete fuel chain).

Another two points are worth mentioning:

Maintenance has a relatively large importance for this impact category. Around 50% of these emissions come from the manufacturing of rubber for the tires. Since the value for rubber use is only a rough estimate, the according figures might be wrong. The contribution to the total (in absolute terms) is the same for all different vehicles, so there is no effect on the final ranking.

There are big differences in the contributions from the powertrain. Vehicles running on gaseous fuels have very large contributions from these modules. This is due to the relatively high VOC-emissions from the production of PE(HD), which I use as a substitute for aramid fibres and epoxy resin. Replacing the module for PE(HD) with other plastics might have a significant impact on the results for POCP from the pressure vessel production and the powertrain, but for the whole vehicle these effects would be small.

2.4.4 Total NO_x-Emissions

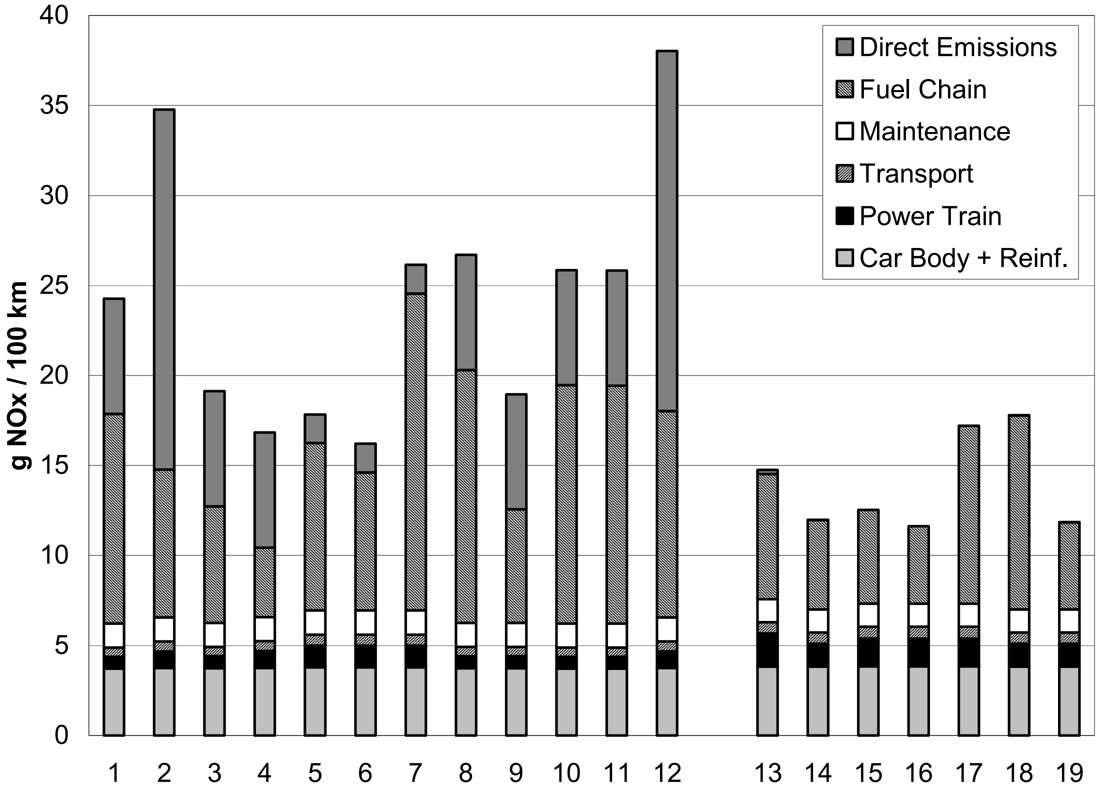

Figure 14: Total NO_x-emissions. For explanation of numbers see Table 14.

A striking result from the analysis of life-cycle NO_x-emissions is the large importance of direct emissions from CI-engines: the diesel (2) and the RME car (12) cause the highest emissions (43% and 57% above the reference case), followed by ICE-cars fuelled with biofuels (8, 10, 11) (exception: MeOH from waste wood), CH_2 from PV (7), and gasoline (1). Lowest emissions for ICE-cars are caused by the CNG-car (31% less than reference car, (4)). Fuel cell cars offer reductions of between 27% (MeOH from poplar chips, (18)) and around 50% (MeOH from NG (14) and waste wood (19), H_2 from NG (15) and NPP (16)), compared to the reference car.

Once more the influence of the production of the fuel cell powertrain is clearly visible although its meaning for the final result is fairly small.

The contribution from transporting the vehicle from the car plant to the vendor is much larger than for most other impact categories. However, for the final results it is meaningless.

2.4.5 Acidification Potential (AP)

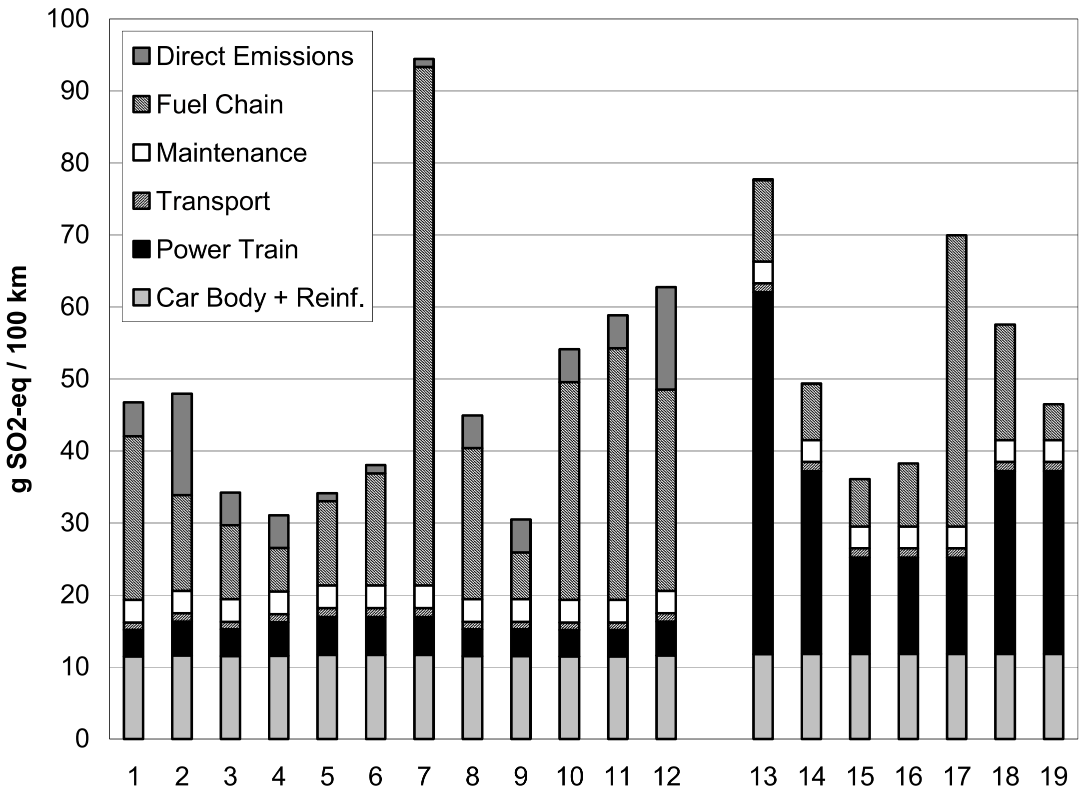

Figure 15: Emissions of acids to air over the whole life cycle. For explanation of numbers see Table 14.

Acid emissions for the reference case are 47 g SO_2-eq / km, of which around 50% are from production and distribution of the fuel. For diesel (2), overall emissions are only slightly (on the order of 2.5%) higher. Smaller emissions from the fuel chain (esp. at the refinery) are more than offset by substantially larger direct emissions, mainly NO_x. NG-derived fuels promise (with ICE) reductions between 27% (MeOH (3), CH_2 (5)) and 33% (CNG, (4)). Although direct emissions are very low for CH_2 from NPP (6), the overall reduction is only on the order of 19% because of significant contributions from fuel chain and production of powertrain (pressure vessel instead of tank). With hydrogen from PV plants (7), acid emissions are more than twice as high as in the reference case. This is mainly due to the high consumption of electricity for the production of PV plants (UCPTE mix), but a considerable share comes from the Ni in the electrolyser: A low capacity factor and the sole availability of data for the production of Ni from sulphidic ores (as a co-product of PGM mining) drive its contribution to about 15% of the fuel chain. This share would probably be lower if one considered as well Ni production from oxidic ores. See also 2.4.8.4 "Future PV Plants").

The use of biofuels in ICEs leads to significant reductions only for MeOH from waste wood (35%, (9)); for RME (12) and EtOH from wheat (11) the emissions are higher by about 34% and 26%, respectively. The transformation of N-fertilisers to NH_3 and NO_x is the main contributor to the large emissions in the fuel chain. The uncertainty concerning the conversion rates is high, though.

For FC cars, the importance of the fuel chain is much less pronounced than for ICE cars. This can be explained on the one hand by the smaller fuel consumption, on the other hand by the large emissions caused by the production of the powertrain. These are dominated by the SO_2 emissions connected with the production of PGM. This can also be seen when hydrogen- and methanol-fuelled cars are compared with each other: the additional use of a PGM (Pd for the reformer) causes significantly higher emissions. Especially the diesel FC vehicle is penalised by the large Rh requirements assumed. If these were significantly lower (on the order of 1 g / vehicle instead of nearly 20 g / vehicle), total acid emissions would be only slightly higher than those from the MeOH-fuelled FC car.

As the Russian chain dominates acid emissions from PGM-production, a sensitivity analysis has been carried out that assumes the installation of flue gas controls with a control efficiency of 90% (which is below BAT) for the Russian smelters.

2.4.6 Eutrophication Potential (EP)

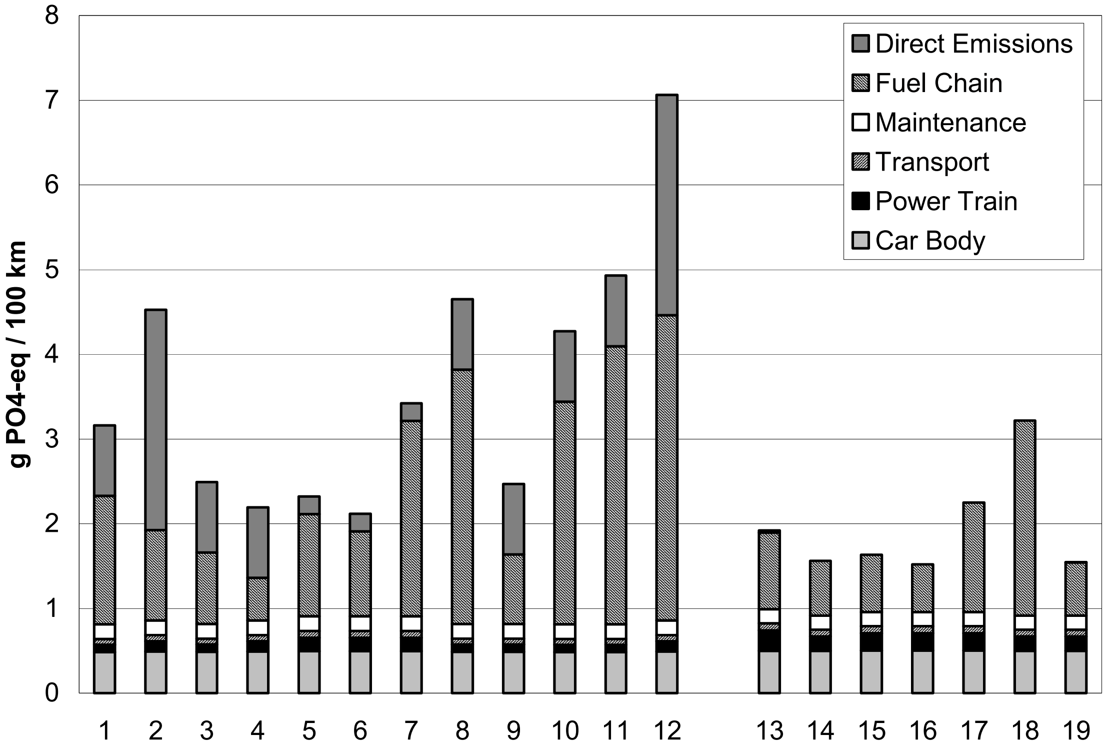

Figure 16: Emissions of eutrophying substances to air. For explanation of numbers see Table 14.

Airborne emissions of substances causing eutrophication are dominated by the fuel chain and direct emissions. The largest direct emissions come from CI-engines (mainly NO_x (2, 12)); above-average emissions from fuel chains can be noticed for the biofuels (use of fertilizer, (8, 10-12, 18) and CH_2 from PV (electricity consumption during manufacturing of PV plant, (7, 17)). Most promising variants for the reduction of these emissions are FC cars running on MeOH from NG (14) and waste wood (19) as well as CH_2 from NG (15) and NPP (16) with reduction potentials of some 50%. Even the least favourable fuel analysed here for FC cars, MeOH from poplar chips (18), has nearly the same emissions (+2%) as the gasoline car (1). The highest emissions can be found for ICE cars fuelled with RME (225% compared to reference car, (12)), EtOH from wheat (157% (11)), MeOH from poplar chips (147% (8)) and diesel (143% (2)). Considerable reductions using ICE cars are possible with CH_2 from nuclear power (33% (6)), CNG (31% (4)), MeOH from waste wood (22% (9)) and from NG (21% (3)).

A significant share of the emissions from the FC powertrain stems from the production of PGM. Their contribution to the results for the whole car is not crucial, though.

2.4.7 Particulate Matter (PM)

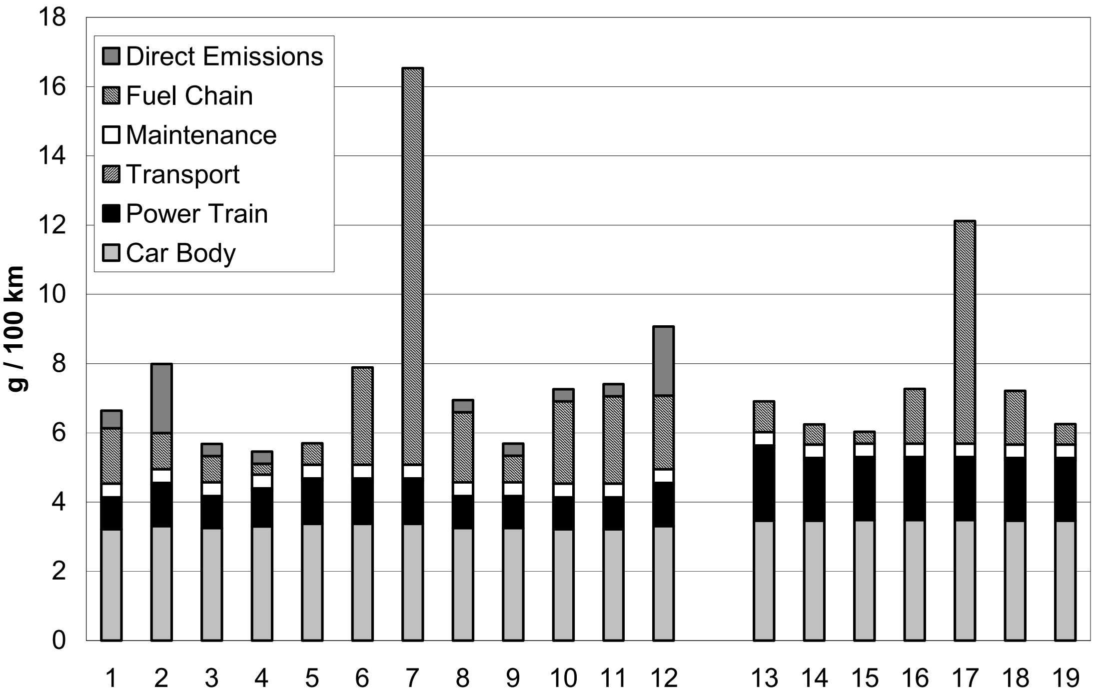

Figure 17: Particle emissions. For explanation of numbers see Table 14.

The total emissions of PM have been summed up and shown here as well but one must be aware of the fact that it might not be appropriate to sum up particles just by their mass. The generic term "particulate matter" includes as well soot emitted by combustion engines that is lung-going and often loaded with other pollutants as well as simple dust from stone-crushing operations. It would be desirable to classify PM at least by their size, but sufficient data is not available and even then the loading with pollutants could not be taken into account.

The largest emissions of particulate matter are caused by the PV-chains (7, 17). These result from the large use of electricity that has been considered to be UCPTE-average. Construction of car body and powertrain has high emissions, with the high emissions from the FC-powertrain being a consequence of increased use of metals.

2.4.8 Sensitivity Analyses

In this section some sensitivity analyses have been carried out for parameters with either exceptional uncertainty (N_2O emissions from fertilizers) or large potential for improvement (SO_2 emissions from Russian PGM-smelters, PV plants), and where a change within the possible ranges might have a considerable influence on at least one of the impact categories analysed.

2.4.8.1 Lower N_2O Emissions from Fertilizers

For the sensitivity analysis I have assumed a lower emission factor for emissions of N_2O from nitrogen fertilizers. The emission factor is 0.01 kg N_2O-N / kg fertilizer-N applied (base case: 0.03 kg N_2O-N / kg fertilizer-N). This change has only an effect on GHG-emissions of biofuel chains.

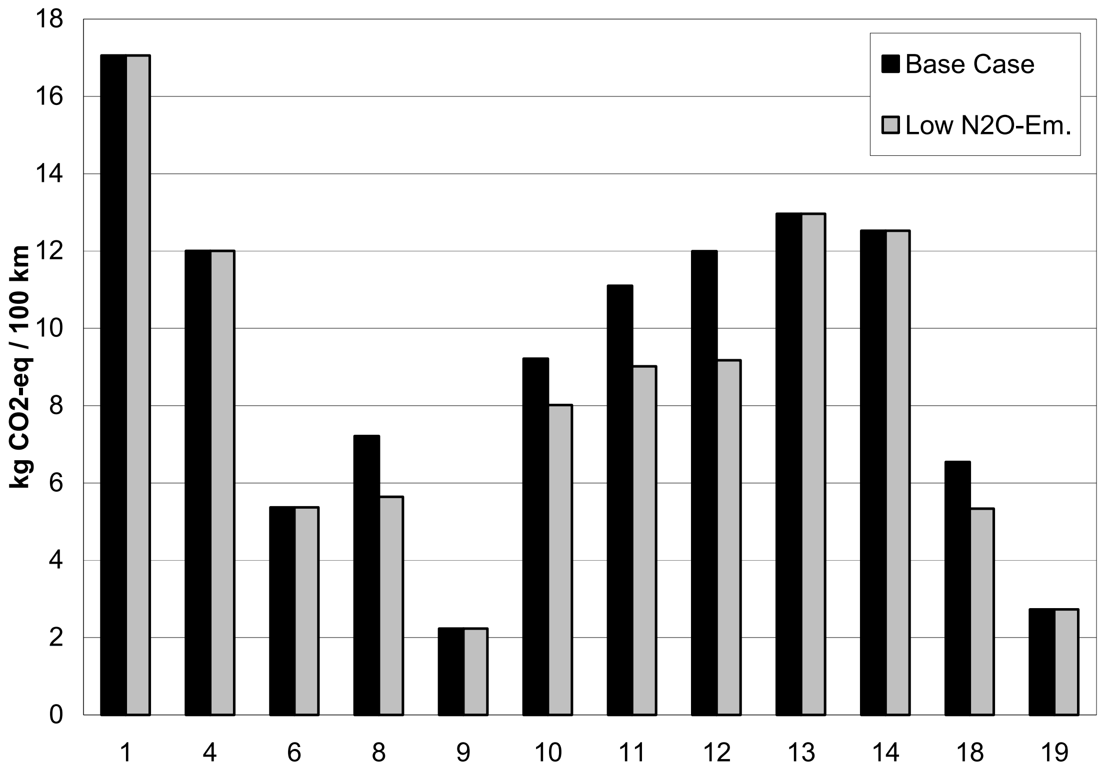

Figure 18: Emissions of direct GHGs in the base case and assuming lower N_2O-emissions from fertilizers. For explanation of numbers see Table 14.

The lower laughing gas emissions lead to substantial reductions for all biofuels (except for MeOH from waste wood, where no fertilizer is applied). They range from 13% (EtOH from sugar beet, ICE car) to more than 23% (RME, ICE). Under these assumptions EtOH from wheat is around 48% better than the reference vehicle. RME leads to emissions 46% below the reference powertrain. Total emissions for the ICE-car fuelled with MeOH from poplar are now only about 5% higher than those for the ICE car fuelled with CH_2 from NPP. The FC car running on MeOH from poplars performs not much better (5%), a result of the efficiency losses in the reformer system. The total emissions amount to 31% of the gasoline car.

This sensitivity analysis shows the large influence of the assumed nitrogen conversion rate on the results. Although the advantage of the biofuels becomes more pronounced with a smaller conversion rate the overall ranking is more or less unaffected.

2.4.8.2 Influence of PGM-Production

2.4.8.2.1 Lower SO_2-Emissions from Russian PGM-Smelters

In this analysis I have assumed that the SO_2 emissions from Russian PGM-smelters are reduced by 90% to 2'950 kg SO_2 / kg PGM. This control efficiency is still rather low compared to the BAT.

In relation to the base case, the AP from the production of PGM and Ni is reduced by: 77% (Ni), 68% (Pt), 85% (Pd), 73% (Rh). The significant reductions for Ni also affect the fuel chains of electrolytic H_2 because of noticeable requirements for the assumed electrolyser type.

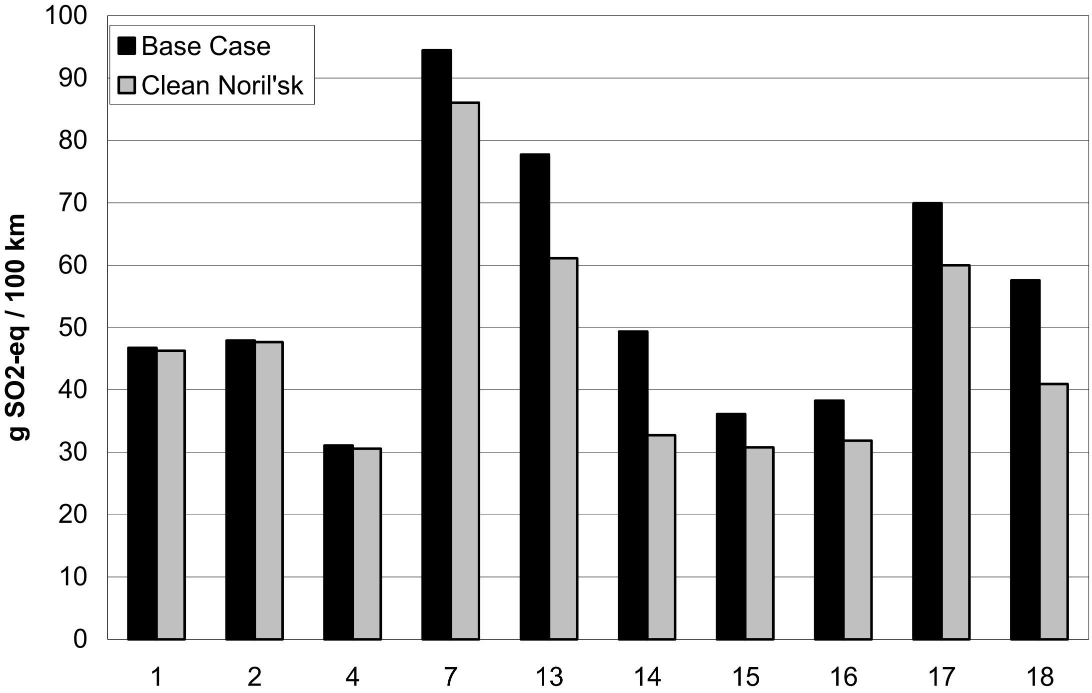

Figure 19: Acid emissions in the base case and with a possible SO_2-control in Russian PGM-smelters. For explanation of numbers see Table 14.

The reduction in the case of ICEs (catalytic converter, Ni in electronics) running on fossil fuels is negligible. They are on the order of 1%. In the case of CH_2 from Swiss PV the reductions resulting from the lower SO_2 emissions connected to the production of Ni for the electrolyser are clearly visible. They amount to 9%. For fuel cell cars reductions are considerable: depending on powertrain design (Pd in MeOH-reformer) and contributions from the fuel chain they range from 14% (CH_2 from PV) to 34% (MeOH from NG). Total emissions are still considerably higher than those from the CNG chain, but for most fuels they are lower than those from the gasoline or diesel car.

2.4.8.2.2 Varying Assumptions on PGM Production

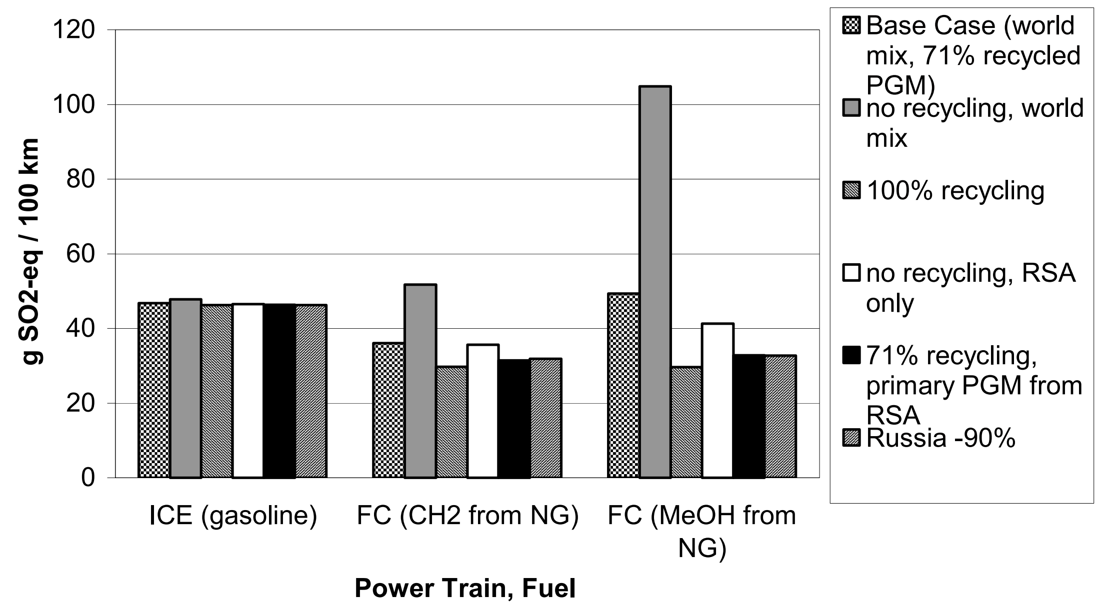

Figure 20: Influence of assumptions on PGM production on emissions of acid precursors from various powertrain configurations and fuels on life-cycle emissions of acid gases.

Some more detailed conclusions concerning the role of PGM production can be drawn from Figure 20. It shows total emissions of acid precursors for selected combinations of powertrains and fuels for different assumptions on PGM production:

- The base case is characterised by the 1999 world mix for primary PGM, a share of 71% of secondary metals, and technology as applied currently (i.e., no flue gas desulphurisation in Russia).
- The second case differs from the base case in that the world mix for primary PGM is replaced by average South African production.
- In the third case only primary metals from South Africa are considered.
- The fourth case assumes today's world mix for primary metals and no secondary PGM.

- The fifth case assumes the same production structure as the base case, but here Russian smelters are equipped with flue gas desulphurisation like in the previous section.[17]

For ICE cars the influence of PGM production is very small, the difference between the highest figure (case 2) and the lowest (case 5) is only 3.4%. Due to higher Pt requirements in the fuel cell car, in the case with on-board storage of CH_2 the maximum (case 2) is 65% larger than the minimum (case 4). For the MeOH-fuelled car with additional Pd in the gas clean-up of the reformer unit (membrane) the maximum (case 2) exceeds the minimum (case 5) by 220%. This significant difference is explained by the high share of Russian Pd on the world market; accordingly, the emission figures for Pd are more affected by changes in Russian technology than those for other PGM.

The results of these sensitivity analyses underline the importance of PGM production for the life-cycle balances. PGM loadings, the recycling share, the physical origin of the metals and the equipment of Russian smelters with control devices are critical parameters for the overall performance of the FC vehicle in the impact category "Acidification".

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[17] This leads also to lower SO_2-emissions from Ni production.

2.4.8.3 Influence of Fuel Cell Parameters

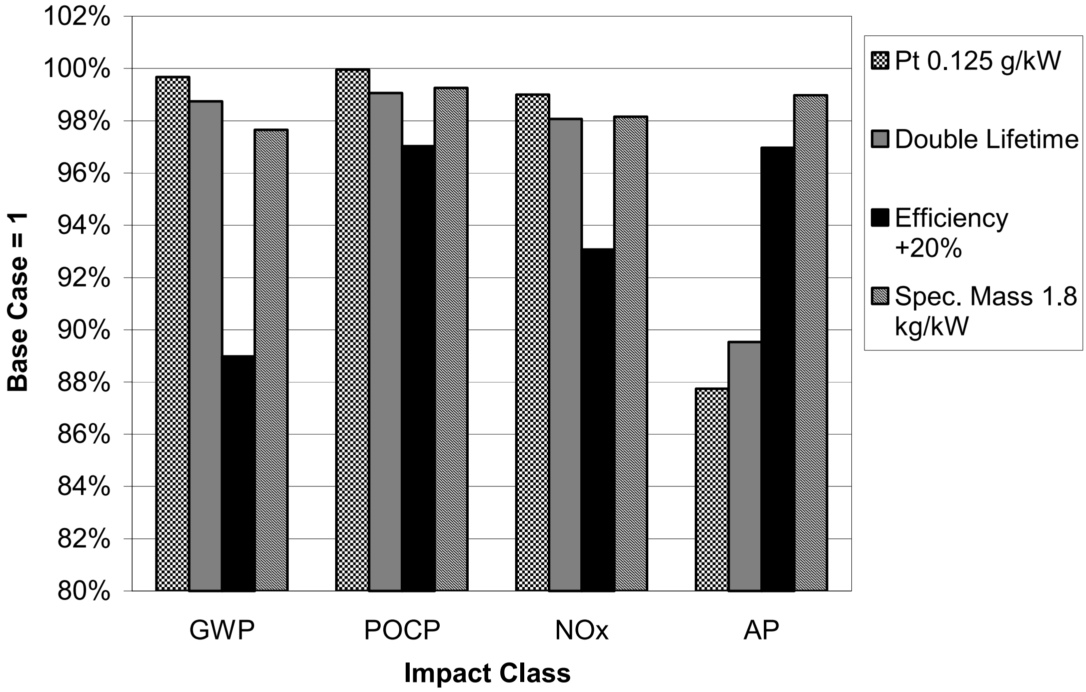

Figure 21: Sensitivity analysis in several fuel cell parameters. See text for details.

The influence of fuel cell parameters has been analysed in a series of sensitivity analyses. The base case is the fuel cell car fuelled with CH_2 from natural gas. The following parameters were varied to reflect optimistic assumptions on achievable goals for fuel cells:

- Pt requirement 0.125 g/kW$_{el}$ (base case: 0.4 g/kW$_{el}$).
- Double lifetime (i.e. one fuel cell can subsequently be used for two cars).
- Higher efficiency (+20% relative to base case).
- Specific mass of 1.8 kg/kW$_{el}$ (base case: 3 kg/kW$_{el}$); the sensitivity analysis considers both reduced requirements for fuel cell production and lower consumption due to reduced vehicle weight.

The results are represented in Figure 21. Highest reductions are achievable for the impact class of acidification, above all with assumptions that affect the specific Pt requirements per km driven (lower Pt loading, higher lifetime). A 20% increase in efficiency reduces GHG emissions to some 89%; with less carbon-intensive fuel chains, relative reductions would be even smaller. The effect of a reduced specific mass is relatively small. It is most pronounced for global warming.

All these analyses have a preliminary character; they assume that all the different goals can be achieved without any major changes in design and production of the cell. They especially neglect possible trade-offs between the parameters analysed. Longer lifetime or better efficiency, for instance, might require higher Pt loadings, and lower specific mass might induce a shorter lifetime of the system. But even under consideration of all these differences it becomes clear that these fuel cell parameters play a significant role for the overall ecological performance of the vehicle.

2.4.8.4 Future PV Plants

The calculations for these plants follow directly [Dones et al. 1996] for the future (available in 2030) m-Si 3 kWp rooftop plants, but they have been made consistent with the modules in [Frischknecht et al. 1996] (same electricity mix, capacity factor). Moreover I have assumed that no inverter is used because the electrolyser uses DC.

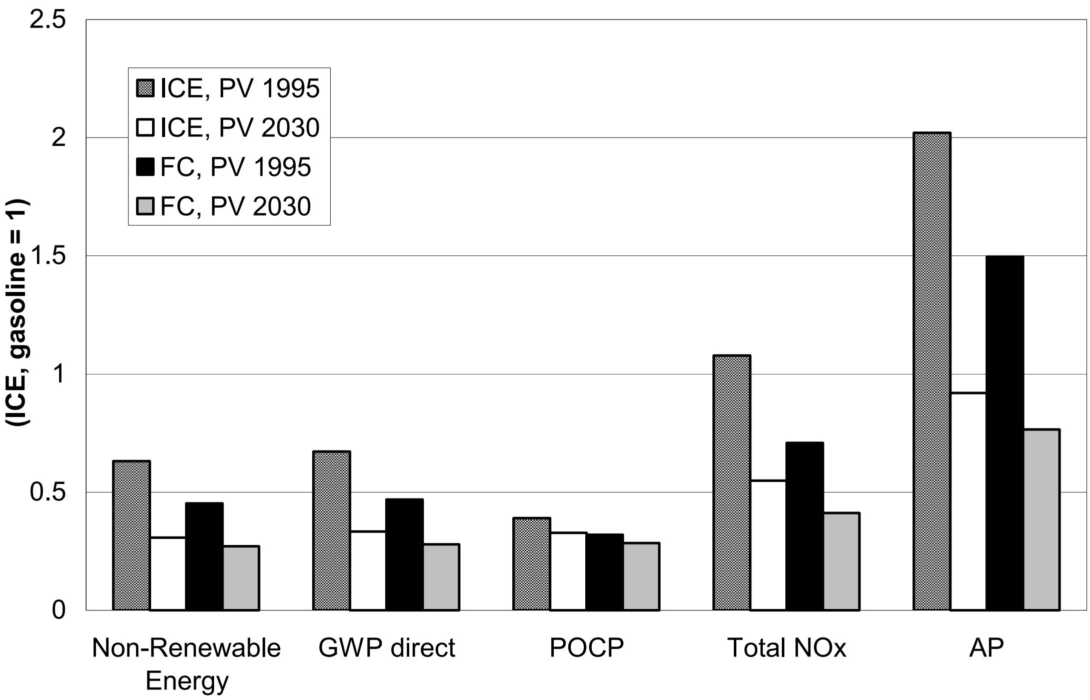

Figure 22: Comparison of vehicles running on CH_2 from different PV technologies. All values are normalized to the corresponding values for the reference vehicle with gasoline-fuelled ICE.

The assumption of a future PV power plant leads to significant reductions for nearly all impacts analysed. Relatively small reductions are observed for the POCP (16% for the ICE, 11% for the FC). In most impact categories the reduction potential with future PV plants is around 50% for the ICE and 40% for the FC. In the case of the AP, reductions of 55% and 49%, respectively, are achievable.

Because of the generally larger relative contribution of the fuel chain in the case of the ICE, the reductions are less pronounced for the FC car.

This sensitivity analysis shows the large improvement potential for PV-derived H_2. It proves that the relatively bad performance of this fuel in some impact categories (especially AP) is just a consequence of today's state-of-the-art of the production process but is not intrinsic to the technology.

2.4.8.5 Scrap Wood Credits

In the base case scrap wood is credited its full energy and carbon content as negative emissions of waste heat and CO_2, respectively. This is based on the idea that most of these negative emissions would be released again if the would was to decay in a landfill. One might, however, argue that at least part of these credits should be allocated to the primary use of the wood. The results of a sensitivity analysis for GHG emissions in the worst case (i.e. no credits for scrap wood) are shown in Figure 23.

Under this assumption the high carbon content of wood (on a per-energy basis) and the relatively low efficiency of the Biometh process drive total GHG emissions from the fuel chain and fuel combustion to around 250 kg CO_2-eq / GJ MeOH (for comparison: the corresponding figures for NG and light fuel oil are less than 70 kg / GJ and 90 kg / GJ, respectively). The vehicles fuelled with MeOH from scrap wood are now emitting much more emissions than any other alternative analysed. This worst case approach (no credits for scrap wood) seems to be not appropriate for most situations; nonetheless, even with a 50% credit for scrap wood overall GHG emissions would be near those from the gasoline ICE vehicle.

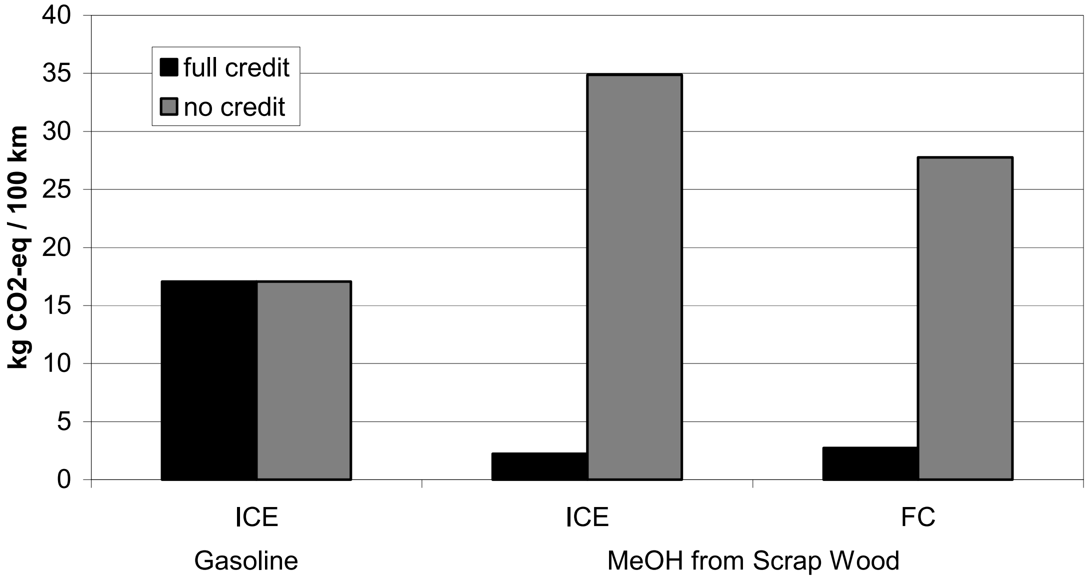

Figure 23: Life-cycle GHG-emissions from vehicles fuelled with MeOH from scrap wood under different assumptions concerning credits of negative emissions during the growth phase of wood, compared to a gasoline ICE vehicle.

This sensitivity analysis shows how different assumptions concerning allocations of (positive or negative) emissions can completely change the ranking of different alternatives. It underlines the necessity to clearly document all assumptions made in an LCA.

2.4.9 Conclusions from the LCA

The results show the reduction potentials of some alternative technologies, compared to the optimised state-of-the-art of today's standard technologies. The ranking of options is, however, not unanimous across impact categories: While in some impact categories (such as NO_x) the FC car seems to have a clear advantage over the conventional ICE technology, the situation is quite reverse with acidification (where the situation is further complicated by significant improvement possibilities in the production of PGM). A similar picture appears for the different fuels: while biofuels in general offer reduction potentials for GHG, their production causes large emissions of eutrophying substances. All these results are summarized in the following table. Please note that the possible errors are much larger than the form of the representation (in %) might suggest.

	Non-renewable Energy	GWP direct	POCP	Total NOx	AP	EP (Air)	PM
ICE:							
Gasoline	100%	100%	100%	100%	100%	100%	100%
Diesel	83%	90%	78%	143%	103%	143%	120%
MeOH from NG	107%	88%	44%	79%	73%	79%	86%
CNG	84%	70%	28%	69%	66%	69%	82%
CH2 from NG	108%	90%	31%	73%	73%	73%	86%
CH2 from NPP	310%	31%	29%	67%	81%	67%	119%
CH2 from PV	63%	67%	39%	108%	202%	108%	249%
MeOH from Poplar	28%	42%	44%	110%	96%	147%	105%
MeOH from Waste Wood	15%	13%	40%	78%	65%	78%	86%
EtOH from Sugar Beet	43%	54%	43%	107%	116%	135%	109%
EtOH from Wheat	45%	65%	42%	106%	126%	156%	112%
RME	34%	70%	35%	157%	134%	223%	137%
FC:							
Diesel	75%	76%	62%	61%	166%	61%	104%
MeOH from NG	88%	73%	27%	49%	106%	49%	94%
CH2 from NG	70%	60%	27%	52%	77%	52%	91%
CH2 from NPP	184%	27%	26%	48%	82%	48%	109%
CH2 from PV	45%	47%	32%	71%	150%	71%	183%
MeOH from Poplar	28%	38%	26%	73%	123%	102%	109%
MeOH from Waste Wood	18%	16%	24%	49%	99%	49%	94%

Figure 24: Environmental indicators, aggregated over the whole life cycle, normalised to corresponding value of ICE-propelled car running on gasoline. All figures refer to the base case (gasoline ICE).

The LCA unveils that for many technologies and impact categories indirect processes like the manufacturing of the car or the provision of the fuel play an important, in some cases even a dominant role. This underlines the importance of taking the whole life cycle of vehicles into account in a comparison of their environmental performance. On the other hand the rankings of technologies in the various impact classes shows that the simultaneous mitigation of different emissions will probably call for a compromise. Therefore, a thorough evaluation of the total environmental impact of cars must not be restricted to a single impact class or indicator such as total energy use or emissions of GHG.

3 Costs of Fuels and Vehicles

In this chapter the methodology of the cost calculation is presented and the results are discussed. The calculations also include hypothetic emission taxes to account for external effects.

3.1 Methodology for Cost Calculation

The total costs c_{tot} of all commodities and services have been calculated in a straightforward way as the sum of capital, fuel and O&M costs:

$$c_{tot} = c_{cap} + c_{fuel} + c_{O\&M}$$

where

$$c_{cap} = \frac{a \cdot INV}{CF}$$

with a the annuity factor for the given discount rate and the technical lifetime of the technology, INV its specific investment cost, and CF its capacity factor, i.e. yearly production divided by the theoretic maximum production (8'760 h at full capacity);

$$c_{fuel} = \sum_i cons_i \cdot pr_i$$

with $cons_i$ the specific consumption of the i-th fuel, energy carrier, feedstock or other ancillary that is not included in the O&M costs, and pr_i its price;

$$c_{O\&M} = \frac{FIXOM}{CF} + VAROM$$

with $FIXOM$ the fix O&M costs, CF the capacity factor and $VAROM$ the variable O&M costs of the plant.

The costs do not include any taxes or insurance fees. Infrastructure costs for the road network are not incorporated in the calculations (in analogy to the LCI) either. The omission of these costs is based on the idea that the wear and tear of the road infrastructure depends only to a small degree on the type of the powertrain and therefore is irrelevant for the comparison. Moreover, total infrastructure costs for the region analysed is very difficult to estimate, in contrast to the investment costs of the car body that are included in the calculation.

3.2 External Costs

The cost calculation as defined in the previous section include only so-called private or internal costs, i.e. "costs borne by those responsible for them" [Seethaler 1999]. Damage costs from emissions are not included, for they are usually not borne by the polluter but by others. These costs are external costs or externalities. In general, external cost can be defined as "economic cost not normally taken into account in markets or in decisions by market players" [ECMT 2001].

The effects of external costs on a market are depicted in Figure 25, following [Endres 1994, Biz/ed 2001]. For a more detailed introduction cf. any textbook on microeconomics, e.g. [Mas-Colell et al. 1995]. The diagram shows the market for a single good. The considerations can easily be generalised. Consider e.g. the good as emission permits with manufacturers forming the demand curve and society as the supplier.

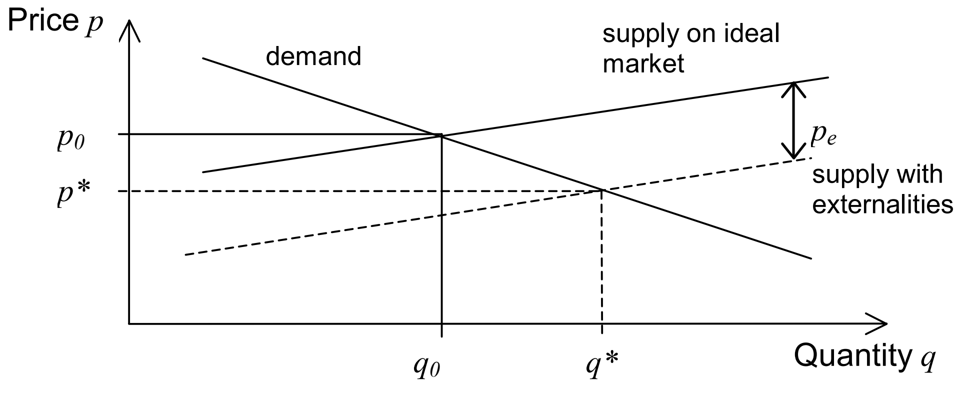

Figure 25: Effects of externalities on a market, after [Endres 1994, Biz/ed 2001]. See text for details.

The picture schematically shows supply and demand curves for a homogeneous good. The situation on an ideal market is represented by the solid curves for demand and supply. These curves represent the marginal social benefit (demand) and the marginal social cost (supply). The optimum equilibrium for society is where marginal costs and benefits are equal, i.e. at the intersection of the two curves in (q_0, p_0). With externalities p_e[18], however, the marginal *private* costs (represented by the dotted line) are lower than the marginal social costs by p_e, and a free market will relax to the non-optimal equilibrium (q^*, p^*). Therefore, with negative externalities the market tends to over-produce a good.

External benefits (i.e. benefits that are not cleared on a market) shift the supply curve down and lead as well to a non-optimal equilibrium. However, external benefits are much less frequent than external costs because usually the supplier tries to get compensated for any benefit he creates.

To reduce losses for society, the following basic economic instruments can be distinguished [Pillet et al. 1993][19]:

Instruments that will theoretically lead to the optimum are:

- **Pigovian tax** [Pigou 1920]: This tax is equal to the external costs of an activity. This approach requires enormous amounts of information about "the unknown value of marginal net damages" [Baumol & Oates 1971] and is therefore of little practical relevance only.

- **Individual Bargaining** [Coase 1960]: The polluter and all those that bear the external costs have to find an agreement on compensations or acceptable levels of activity. Because of the numerous interactions between a polluter and individual economic subjects this approach is also not practical in most cases.

In addition, there are so-called "second-best" approaches; they are based on the idea of aggregate acceptability standards:

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[18] For sake of simplicity marginal external costs have been assumed to be constant.

[19] Please note that the broadly used technical regulations (e.g. allowable emission levels per vkm) are not economic instruments.

- In the **pricing-and-standards approach** [Baumol & Oates 1971] taxes are determined in a way that they will lead to a new equilibrium where the amount of a noxious activity equals the aggregate standard.

- **Tradable pollution permits** [Dales 1968] are emitted by an authoritative body; their sum equals the aggregate acceptability standard.

It is important now to see that one can apply either a tax or a cap on a substance (or a substance class). A combination of both (for the same substance) is redundant.

In this study both taxes and caps are used, but in a simplified form. The taxes for various pollutants and GHG do in general not equal the (marginal) external costs caused by these emissions, neither are they derived from a pricing-and-standards approach. The caps (that apply only to chapter4 "Analysis with MARKAL") are also voluntarily chosen. The taxes and caps used in this work should not be seen as a representation of the situation on the real market, but rather as a means to understand how the ranking of different technologies would change if these taxes or caps were introduced.[20]

This introduction into external costs is not exhaustive. It shall just provide the basic ideas to understand the limitations of the very simple model for the internalisation of external costs that I have used in my analysis.

3.3 Emission Tax Approach

In order to integrate economic and ecological data, virtual emission taxes were applied; these were derived from damage cost estimates. This simplified approach is very transparent, but it has also severe drawbacks:

- Damage cost estimates have only been published for single substances, but not for the impact categories used in the LCI; approximations for these categories cannot be derived in a straightforward way either because most of these single substances

[20] In theory, this approach requires that there are no technical regulations concerning substances that are subject to a tax or a cap. For practical reasons I assume, however, that all vehicles fulfil Euro IV emission level requirements.

contribute to various categories. The only exception are GHG, but there, on the other hand, estimates for damages from CO_2 vary in an exceptional way. Thus, the data from the LCI had to be de-aggregated to represent emissions of NO_x, SO_2, NMVOC and PM.

- The approach does not consider in any way the specific situation of the actual emissions. In state-of-the-art models to calculate external costs from electricity generation such as the impact pathway analysis, dependence on site, time, climate, background concentrations, population distribution, as well as non-linear dose-response functions are applied (see, e.g., [Friedrich & Krewitt 1997]). These multiple dependencies underline that the approach chosen in this study can at best be called a rough estimate of the damage actually done. The main reason for choosing this method in spite of these disadvantages is simply that at the time being there is no other model available that allows for a detailed calculation of damage costs from the transport sector.

- The idea of comprehensive emission taxation is very unrealistic; even if a system to control all emission sources were available, its cost (and the expenses for the corresponding administration) would be prohibitively high.

The virtual emission taxes used here should therefore not be regarded as the actual damage assignable to the use of a vehicle, but rather as an indicator of this damage under the assumption of a high valuation of environmental qualities and health. In order to fulfil this purpose, rather high tax rates have been chosen. For the "classical" pollutants SO_2, NO_x, NMVOC and PM the upper limit for the estimates in [Infras/Econcept/Prognos 1996] are used. The reference distinguishes between seasons for some of the pollutants; I take the arithmetic average in these cases. Also, I reduce the estimate for PM to 10 Fr/kg (from 18 Fr/kg) because part of the PM emissions accounted for in the LCI are simply dust that is much less harmful than the combustion products for which the original estimate was derived. For GHG I use the upper limit foreseen by a Swiss legal motion to reduce CO_2-emissions [Beusch 1999]; it is applied to all greenhouse gases, see Table 15. The table also contains information on maximum tax rates applied today in OECD countries according to [OECD 2001] and maximum prices for credits paid in the US [Airtrends 2001]. Average credit prices are significantly lower. Credits for CO_2 emissions are traded at prices varying from a few Rp / t up to around 30 Fr/t [Brodmann 2001].

Substance	Unit	**Tax Rate in this Study**	Maximum Taxes OECD today	Maximum Price for Credits
SO_2	Fr/kg	**34**	2.8	0.4
NO_x	Fr/kg	**35**	7.4	40
PM	Fr/kg	**10**	--	40
NMVOC	Fr/kg	**18**	0.1	8
GHG	Fr/t CO_2-eq	**210**	--	--

Table 15: Assumed emission taxes compared to today's tax rates and prices for emission rights. Please note that these do not represent actual damage costs. For references see text.

Four tax regimes have been considered: no emission taxes, taxes on pollutants (SO_2, NO_x, PM, and NMVOC), a mere GHG tax, and a combined tax on both pollutants and GHG.

No tax has been applied for the use of scarce resources such as non-renewable energy; there is in fact a market for these resources, so that prices should reflect threatening scarcity. According to the Hotelling Rule the (real) price for non-renewable resources should grow with the (real) discount rate.[21] It is a fact that prices for most raw materials (including fossil fuels) have not shown this growth in the past. This, however, does not automatically imply market failure (and, consequently, externalities). The issue of scarce resources is addressed in a sensitivity scenario with much higher prices for fossil fuels.

3.4 Scenario Description

In order to examine the influence of boundary conditions, several alternative scenarios have been developed. In the Base Case scenario, fuel prices have been taken to remain constant, and the data used to calculate emission taxes correspond to the base case of the LCI. In a second scenario called Expensive Fossils, much higher prices for fossil fuels and Uranium are assumed, while a third scenario called Emerging Technologies analyses the results of more optimistic assumptions concerning the development of emerging technologies such as the fuel cell, hydrogen distribution, or photovoltaic electricity production. Finally, the fourth scenario combines higher prices for non-renewable energies and optimistic assumptions for emerging technologies. It is therefore called the Expensive Fossils / Emerging Technologies scenario.

The cost data used for the different processes are presented in Appendix 1 "Cost Figures Used". They have been derived from an extensive literature overview. For details see [Röder 2001].

The following parameters have been used in all scenarios:

Discount Rate	5%
Vehicle Lifetime	10 y / 150'000 km

Table 16: Basic parameters for all scenarios.

The discount rate is in real terms, i.e. after correction for inflation. It represents a realistic long-term rate, averaged over the whole national economy; a private investor would use a larger rate to compensate for the risk he bears, among other reasons.

In the Base Case scenario, the prices for natural gas and oil are the average prices in the years 1997 to 1999 according to [BP Amoco 2000], the one for Uranium as nuclear fuel has been provided by an expert [Krakowski 2001], see Table 17. Emission taxes are calculated according to the base case results of the LCI. In another scenario called Expensive Fossils, the estimates from [van Walwijk et al. 1998] for the long term (i.e. for the period 2010 to 2020) have been used.

Fuel Prices	Base Case	Expensive Fossils
Crude Oil	3.85 Fr/GJ	12.0 Fr/GJ
Natural Gas	3.04 Fr/GJ	12.7 Fr/GJ
Uranium	2.40 Fr/GJ_{el}	2.40 Fr/GJ_{el}

Table 17: Prices for fossil fuels and uranium in the different scenarios.

[21] Simply said, the Hotelling Rule is based on the assumption that non-renewable resources are a capital

The changes in the scenarios favouring emerging technologies are shown in Table 18. Moreover, the following two assumptions have been made in these two scenarios:

- The tank-to-wheel efficiency of all FC powertrains is supposed to be higher by 20%.
- The LCI of photovoltaic plants refers to the "future" case in the LCI.

		Base Case	Emerging Technologies
Cost of Biomass:			
Rapeseed	Fr/t	535	400
Wheat	Fr/t	267	200
Sugar Beet	Fr/t	175	130
Plantation Wood	Fr/t	235	150
Waste Wood)[1]	Fr/t	0	-10
Conversion of Biomass:			
Wheat-to-EtOH Plant	Fr/(GJ/a)	38	30
Sugar Beet-to-EtOH Plant	Fr/(GJ/a)	38	30
Hydrogen T&D:			
Investment	Fr/(GJ/a)	30	20
Variable O&M	Fr/GJ	13.8	9
Electrolysis incl. H_2-Station			
Investment	Fr/(GJ/a)	64.4	40
Fix O&M	Fr/(GJ/a)	1.3	0.9
Variable O&M	Fr/GJ	9	7
NG-to-H_2-Reformer, Small Scale, incl. Filling Station:			
Investment	Fr/(GJ/a)	64.4	48
Variable O&M	Fr/GJ	14	11
Photovoltaic Plant:			
Investment	Fr/kW	5'500	2'000
Fix O&M	Fr/kW	96	15
Cost of Powertrain Components:			
Pressure Vessel	Fr/l	14	12
MeOH Reformer	Fr/kWel	28	25
HC Reformer	Fr/kWel	38	35
Fuel Cell	Fr/kW	80	50
Electric Motor	Fr/kW	34+341/P	27

Table 18: Cost assumptions for 2010 in the scenarios.)[1]: The costs for waste wood at the plant are estimated under the assumption that the only alternative to the use in the Biometh-plant is their costly disposal in either a landfill or an incinerator.

stock that has to have the same profit as any other investment.

The cost numbers for the fuel cell powertrain also refer to mass production of further developed components. To show their influence on the total cost of the vehicle, an additional calculation with much higher investment costs (fuel cell: 250 Fr/kW$_{el}$, MeOH reformer: 50 Fr/kW$_{el}$, diesel reformer: 70 Fr/kW$_{el}$) has been carried out. These figures do not represent today's state-of-the-art; they are an estimate of costs achievable in first small series production at around 2005. The estimate is based on [Röder 2001] and is restricted to these three main components.

3.5 Results

3.5.1 The Base Case Scenario

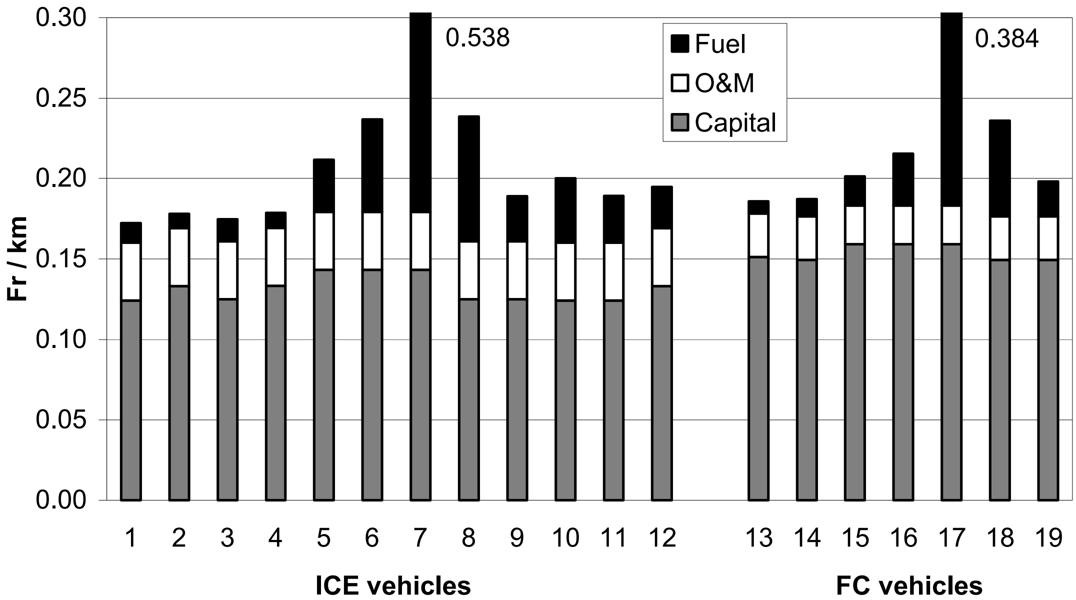

Figure 26: Internal cost of different powertrain / fuel combinations in the base case and without emission taxes. For explanation of numbers see Table 19.

Figure 26 and Table 19 show internal costs of different powertrain / fuel combinations. In most cases, capital costs clearly dominate the picture, whereas fuels from fossil primary energy carriers make up only a small part of the total cost.[22] The smallest costs are achieved with the standard gasoline car, followed by ICE vehicles fuelled by MeOH and CNG. It is surprising that the total costs (as calculated in this

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[22] Please remember that the costs do not include any fuel tax or insurance fees.

model) are relatively close to each other: most combinations are within 5 Rp/km from the gasoline car, even those with CH_2 from NG. FC cars are penalized by their higher investment and therefore higher capital costs. Due to their lower O&M cost and fuel consumption they are, however, almost competitive to ICE cars running on the same fuel. With expensive fuels such as electrolytic CH_2, especially from PV, they are noticeably less expensive. A sensitivity analysis where the discount rate for either the vehicles only or for all processes was set to 3% led to smaller costs and slightly narrowed the gaps between the different alternatives, but the main conclusions remain unaffected.

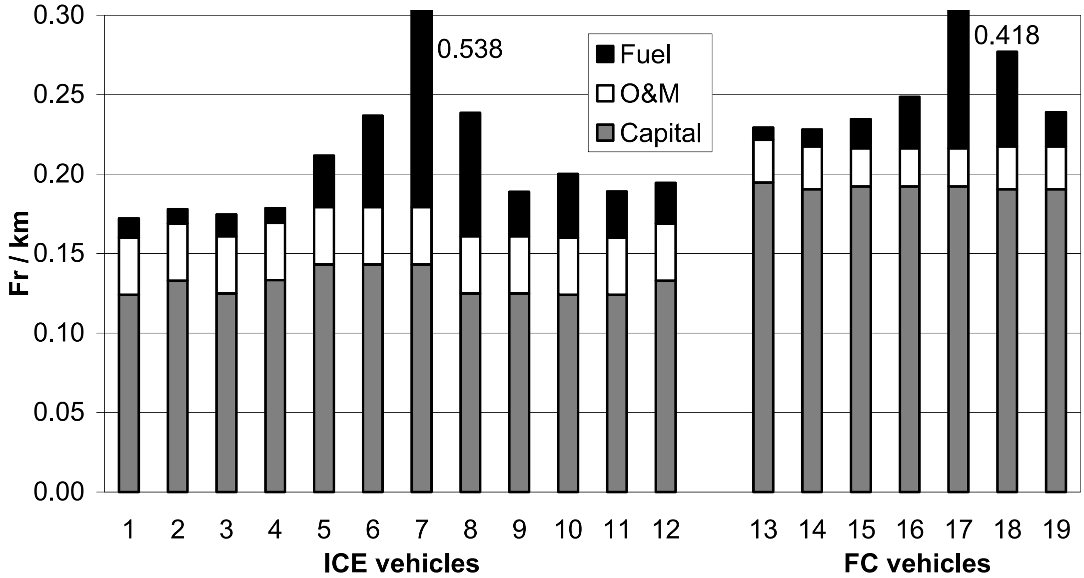

Figure 27: Internal cost of different powertrain / fuel combinations under the assumption of higher costs for FC powertrain components. For explanation of numbers see Table 19.

However, under the assumption of much higher costs for the fuel cell powertrain (250 Fr/kW_{el} for the fuel cell, 50 Fr/kW_{el} for the MeOH reformer and 70 Fr/kW_{el} for the diesel reformer), there is a noticeable cost gap between ICE vehicles and FC cars, see Figure 27. The higher investment costs drive up total FC vehicle costs by 3.3 Rp/km (CH_2) to 4.4 Rp/km (diesel). Since the focus of this study is on the comparison of mature technologies in widespread use, this scenario is not analysed in detail. The results, however, show that the high initial investment costs for the new technologies might be a serious obstacle for their introduction. In chapter 4 "Analysis with MARKAL" this effect is included in the analysis by making investment costs of emerging technologies dependent on their own success in the market.

No	Base Case	Net Private Costs	Costs with Pollutant Taxes	Costs with GHG Tax	Costs with Pollutant and GHG Taxes
No		Rp98/km	Rp98/km	Rp98/km	Rp98/km
	ICE:				
1	Gasoline	17.2	20.0	21.2	24.0
2	Diesel	17.8	20.6	21.5	24.2
3	MeOH from NG	17.5	19.3	20.9	22.7
4	CNG	17.9	19.4	20.6	22.1
5	CH2 from NG	21.2	22.8	24.6	26.2
6	CH2 from NPP	23.7	25.5	25.0	26.8
7	CH2 from PV	**53.8**	**57.7**	**56.5**	**60.4**
8	MeOH from Poplar	**23.9**	**25.9**	**25.7**	**27.7**
9	MeOH from Waste Wood	18.9	20.5	19.6	21.3
10	EtOH from Sugar Beet	20.0	22.4	22.3	24.7
11	EtOH from Wheat	18.9	21.3	21.6	24.0
12	RME	19.5	22.0	22.4	24.9
	Fuel Cell:				
13	Diesel	18.6	22.0	21.5	24.9
14	MeOH from NG	18.7	20.8	21.5	23.6
15	CH2 from NG	20.1	21.8	22.4	24.0
16	CH2 from NPP	21.5	23.2	22.6	24.3
17	CH2 from PV	**38.4**	**41.3**	**40.3**	**43.2**
18	MeOH from Poplar	23.6	**25.9**	25.2	27.4
19	MeOH from Waste Wood	19.8	21.8	20.5	22.5

Table 19: Cost calculation for different combinations of powertrains and fuels with and without assumed emission taxes. The least expensive alternatives are shaded, the most expensive ones printed in bold.

Under the assumption of emission taxes the picture changes slightly (Table 19, Figure 28): With pollutant taxes as defined above, MeOH- and CNG fuelled ICE vehicles turn out to be the least expensive variants, followed by the gasoline-fuelled car. Here, the environmentally benign character of the natural gas chain has its effect, whereas the low (or even zero in the case of CH_2) emissions from the FC vehicles are outweighed by high emissions during their production phase. The CNG car is still among the least expensive alternatives when applying a tax on greenhouse gases, but vehicles fuelled with MeOH from waste wood perform even better. Under the combined tax regime, the situation is nearly the same as with a GHG tax only. With increasing taxes other biofuels, mainly EtOH from wheat, become more and more interesting and finally outrank gasoline.

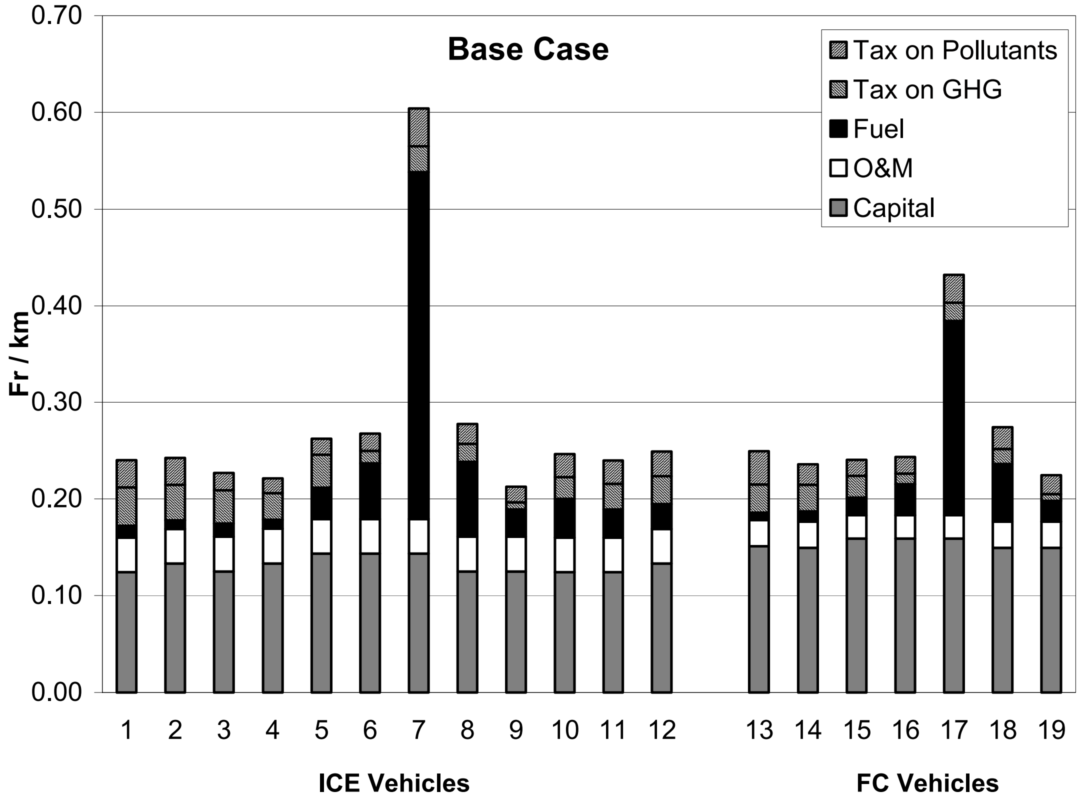

Figure 28: Cost for different combinations of powertrains and fuels in detail. Base Case. For explanation of numbers see Table 19.

3.5.2 The Expensive Fossils Scenario

	Expensive Fossils	Net Private Costs	Costs with Pollutant Taxes	Costs with GHG Tax	Costs with Pollutant and GHG Taxes
No		Rp98/km	Rp98/km	Rp98/km	Rp98/km
	ICE:				
1	Gasoline	18.7	21.6	22.7	25.5
2	Diesel	19.0	21.8	22.6	25.4
3	MeOH from NG	19.1	20.9	22.5	24.3
4	CNG	19.1	20.6	21.8	23.3
5	CH2 from NG	22.8	24.5	**26.2**	**27.9**
6	CH2 from NPP	23.7	25.5	25.0	26.8
7	CH2 from PV	**53.8**	**57.7**	**56.5**	**60.4**
8	MeOH from Poplar	**24.1**	**26.1**	25.9	**27.9**
9	MeOH from Waste Wood	18.9	20.5	19.6	21.3
10	EtOH from Sugar Beet	20.3	22.7	22.6	24.9
11	EtOH from Wheat	19.2	21.6	21.9	24.3
12	RME	19.6	22.2	22.5	25.1
	Fuel Cell:				
13	Diesel	19.6	23.0	22.5	25.9
14	MeOH from NG	19.9	22.0	22.7	24.8
15	CH2 from NG	21.0	22.7	23.3	25.0
16	CH2 from NPP	21.5	23.2	22.6	24.3
17	CH2 from PV	**38.4**	**41.3**	**40.3**	**43.2**
18	MeOH from Poplar	23.8	26.0	25.3	27.6
19	MeOH from Waste Wood	19.8	21.8	20.5	22.5

Table 20: Cost calculation for different combinations of powertrains and fuels with and without assumed emission taxes. The least expensive alternatives are shaded, the most expensive ones printed in bold.

In the scenario with higher expenses for non-renewable energy carriers the ranking of the alternatives changes slightly (Table 20, Figure 29): Without emission taxes, the gasoline car is still the least-cost vehicle, but an entire set of other technologies is very close: ICE vehicles fuelled with MeOH from both waste wood and NG, diesel, CNG, and EtOH from wheat are all within a margin of only 0.5 Rp/km. The difference between the gasoline car and the cheapest FC vehicle (fuelled with diesel in both scenarios) decreases from 1.4 Rp/km to 0.9 Rp/km. When applying taxes, in all cases (only pollutants; only GHG; combined tax strategy) the MeOH fuelled ICE car is the least expensive one. The CNG car is also very attractive in all these cases, but as soon as the GHG-tax of 210 Fr/t CO_2-eq is applied, it is outrun by the FC vehicle fuelled with MeOH from waste wood. In the case where all taxes are applied once more biofuels such as EtOH from wheat become quite attractive. In general, the gaps between the different alternatives narrow, but electrolytic hydrogen still remains too expensive to be competitive.

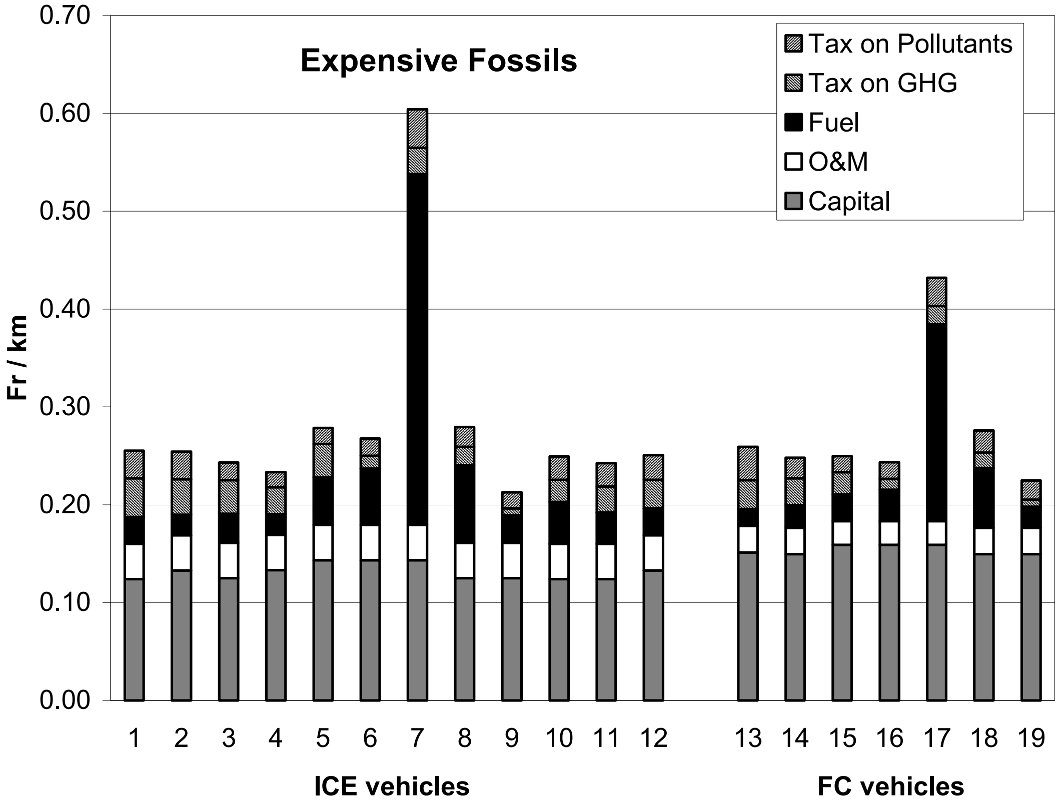

Figure 29: Cost for different combinations of powertrains and fuels in detail. Expensive fossils case. For explanation of numbers see Table 20.

3.5.3 The Emerging Technologies Scenario

	Emerging Technologies	Net Private Costs	Costs with Pollutant Taxes	Costs with GHG Tax	Costs with Pollutant and GHG Taxes
No		Rp98/km	Rp98/km	Rp98/km	Rp98/km
	ICE:				
1	Gasoline	17.2	20.0	21.2	24.0
2	Diesel	17.8	20.6	21.5	24.2
3	MeOH from NG	17.5	19.3	20.9	22.7
4	CNG	17.9	19.4	20.6	22.1
5	CH2 from NG	20.6	22.3	24.0	25.7
6	CH2 from NPP	**23.0**	**24.8**	**24.3**	**26.1**
7	CH2 from PV	**32.2**	**35.3**	**33.5**	**36.6**
8	MeOH from Poplar	22.0	24.1	23.9	25.9
9	MeOH from Waste Wood	18.7	20.3	19.4	21.1
10	EtOH from Sugar Beet	19.5	21.8	21.7	24.1
11	EtOH from Wheat	18.3	20.7	21.0	23.4
12	RME	18.8	21.4	21.7	24.3
	Fuel Cell:				
13	Diesel	17.1	20.4	19.6	22.9
14	MeOH from NG	17.2	19.2	19.6	21.6
15	CH2 from NG	18.0	19.6	20.0	21.6
16	CH2 from NPP	19.2	20.8	20.2	21.8
17	CH2 from PV	**23.4**	**25.8**	**24.5**	**26.8**
18	MeOH from Poplar	20.1	22.3	21.5	23.7
19	MeOH from Waste Wood	18.0	19.9	18.7	20.6

Table 21: Cost calculation for different combinations of powertrains and fuels with and without assumed emission taxes. The least expensive alternatives are shaded, the most expensive ones printed in bold.

In the Emerging Technologies scenario, FC vehicles are much more promising candidates. Even without emission taxes, FC vehicles running on diesel or MeOH from NG are competitive with the standard gasoline car, and both CH_2 from NG and MeOH from waste wood are less than 1 Rp/km more expensive. Under the assumption of pollutant taxes, the ranking is led by four alternatives that are within a band of 0.5 Rp/km: ICE vehicles fuelled with CNG and MeOH from NG, and FC vehicles running on MeOH from NG and CH_2 from NG. The diesel-fuelled FC car, however, is penalised mainly by its very high emissions of SO_2 that stem from the large amounts of PGM in the powertrain, particularly the reformer unit. With a GHG tax, once more MeOH from waste wood turns out to be the most favourable fuel, but in this scenario the FC vehicle performs better than the ICE car. FC vehicles occupy the following places in the ranking. Under a combined tax CH_2 from nuclear electricity is on the edge of being competitive, provided it is used in a FC vehicle.

On the other end of the ranking, still solar hydrogen is the worst choice under the assumptions made. But the gap is closing considerably. Provided that the PV plants were producing 1'375 kWh/(kW$_p$*a) instead of 1'000 kWh/(kW$_p$*a) – a reasonable assumption for Southern Europe - the private costs of FC cars running on electrolytic CH_2 from PV would be lower by 1.7 Rp/km.

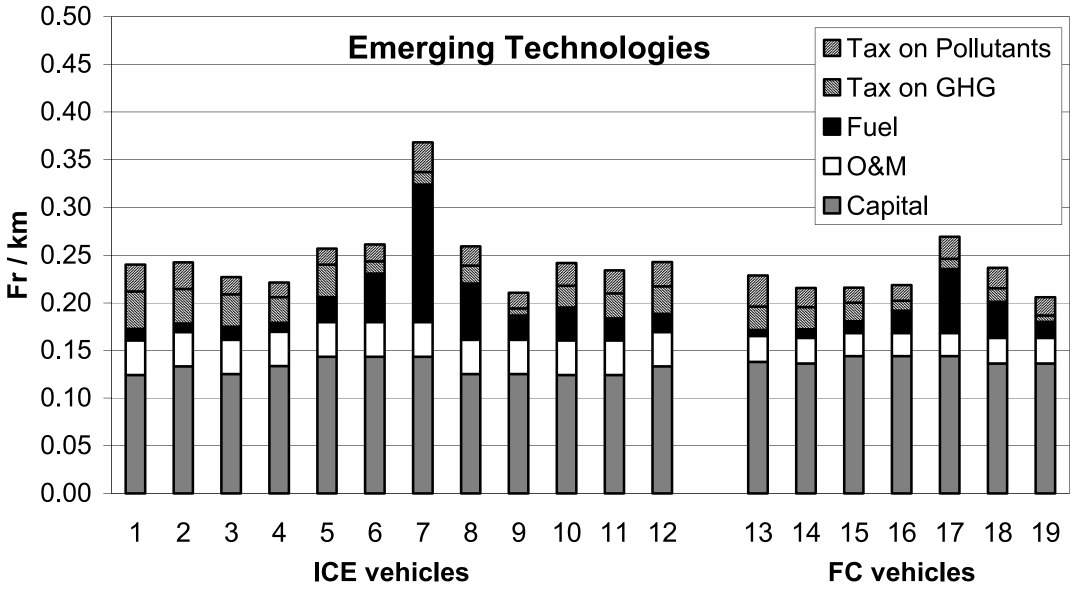

Figure 30: Cost for different combinations of powertrains and fuels in detail. Emerging Technologies case. For explanation of numbers see Table 21.

3.5.4 The Expensive Fossils / Emerging Technologies Scenario

No	**Emerging Technologies** / **Expensive Fossils**	Net Private Costs	Costs with Pollutant Taxes	Costs with GHG Tax	Costs with Pollutant and GHG Taxes
		Rp98/km	Rp98/km	Rp98/km	Rp98/km
	ICE:				
1	Gasoline	18.7	21.6	22.7	25.5
2	Diesel	19.0	21.8	22.6	25.4
3	MeOH from NG	19.1	20.9	22.5	24.3
4	CNG	19.1	20.6	21.8	23.3
5	CH2 from NG	22.2	23.9	**25.6**	**27.3**
6	CH2 from NPP	**24.1**	**25.9**	**25.4**	**27.2**
7	CH2 from PV	**32.4**	**35.5**	**33.7**	**36.8**
8	MeOH from Poplar	22.2	24.3	24.1	26.1
9	MeOH from Waste Wood	18.7	20.3	19.4	21.1
10	EtOH from Sugar Beet	19.8	22.2	22.1	24.5
11	EtOH from Wheat	18.6	21.0	21.3	23.7
12	RME	19.0	21.5	21.9	24.4
	Fuel Cell:				
13	Diesel	18.0	21.2	20.5	23.7
14	MeOH from NG	18.2	20.2	20.6	22.6
15	CH2 from NG	18.8	20.4	20.8	22.4
16	CH2 from NPP	19.2	20.8	20.2	21.8
17	CH2 from PV	**23.4**	**25.8**	24.5	26.8
18	MeOH from Poplar	20.2	22.4	21.7	23.8
19	MeOH from Waste Wood	18.0	19.9	18.7	20.6

Table 22: Cost calculation for different combinations of powertrains and fuels with and without assumed emission taxes. The least expensive alternatives are shaded, the most expensive ones printed in bold.

This scenario is even more dominated by FC vehicles and alternative fuels than the one before; due to the higher efficiency of the FC powertrain, these vehicles are less affected by more expensive fossil energy carriers than ICE cars. Under any tax regime the FC vehicle running on MeOH from scrap wood is the cheapest option. With a GHG tax or a combined tax strategy the 2nd best alternative is its ICE counterpart. As the availability of this particular fuel is limited, other fuels become very interesting: without any tax, diesel would be the least expensive choice, whereas pollutant taxes favour MeOH from NG. With a GHG tax or the combined tax strategy, finally, CH_2 from nuclear electricity would be the fuel of choice. One must, however, not forget that much of the pollutant emissions from the diesel FC car are a consequence of the relatively large Rh requirements assumed for the reformer in this study. If the reformer were realised at significantly lower Rh loadings this would considerably improve the position of diesel fuel in this scenario.

In this scenario, the FC vehicle running on PV H_2 is relatively close to competitiveness. Assuming an annual PV electricity production of 1'375 kWh/kW$_p$, which can be expected in Southern Europe, the costs for this type of vehicle and fuel are still lower by 1.7 Rp/km, enough to compete with the conventional gasoline and diesel ICE cars under a GHG tax or combined taxes.

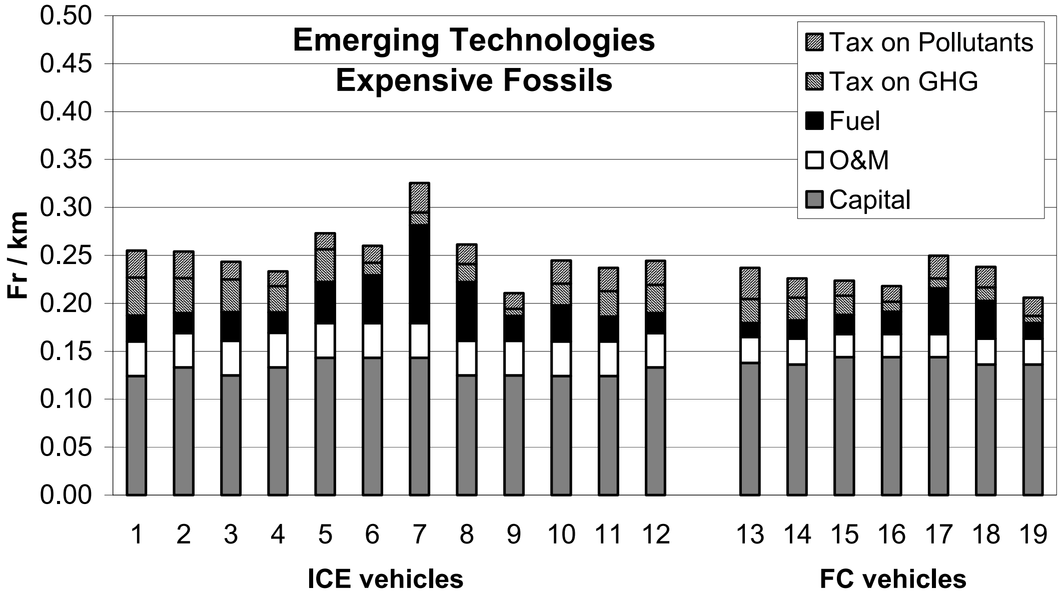

Figure 31: Cost for different combinations of powertrains and fuels in detail. Emerging Technologies and High Cost for Fossil Fuels case. For explanation of numbers see Table 22.

3.6 Conclusions

Under present conditions and without emission taxes the conventional technologies and fuels are the least expensive alternative. Even with quite optimistic assumptions concerning costs and efficiencies of alternative technologies, such as the fuel cell powertrain, the production of biomass or the distribution of hydrogen, fossil fuels still have an advantage over renewable energy sources. In such a case the fuel cell powertrain becomes competitive due to its high efficiency. High prices for fossil fuels on the other hand favours renewable energy carriers, and biofuels in ICE vehicles are on the edge of competitiveness. When relatively high emission taxes are applied, fossil fuels are penalised by these taxes. There is also a tendency that fuel cell vehicles perform better (in comparison to ICE cars) with GHG taxes, whereas taxes on other pollutants have rather an influence on the ranking of the fuels but not on the ranking of powertrain configurations.

Although the findings of this chapter are based on a thorough and comprehensive analysis of data, they are still limited. The analysis includes only internal costs and some proxy for external costs. All data are subject to uncertainties (that cannot be quantified, though), especially parameters characterising emerging technologies; other important factors such as additional externalities (e.g. noise, large parts of human and ecotoxicity, waste production) or factors that a potential car buyer will explicitly consider, like safety, ease and time of refuelling, driving comfort, are not included. In view of the relatively small difference that the cost analysis in this chapter shows, these factors might become decisive. Moreover, issues such as availability of some resources (especially biomass) and the influence of technological learning cannot be adequately answered in this static analysis. They are addressed in the following chapter.

4 Analysis with MARKAL

4.1 The MARKAL Model

The initial MARKAL model was developed in a joint effort by Brookhaven National Laboratory in the USA and Kernforschungsanlage Jülich in Germany in the late 70s as a tool to evaluate the possible role of new technologies in energy systems [Fishbone et al. 1983]. Since then it has been gradually improved and has become one of the most appropriate least-cost analysis models. It is especially suited to study the impacts of policies to respond to the thread of climate change on the energy system of an economy. In short words, it is an energy systems planning model that finds the optimal development 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). This chapter shall provide some background information to understand the basic principles of this optimisation tool.

4.1.1 Linear Programming (LP) and MARKAL

An optimisation problem in an n-dimensional variable $\mathbf{x} = (x_1,...,x_n)^T$ can be generally written as

$$\min[z = z(x_1,...x_n)] \qquad \text{Eqn. 2}$$

subject to

$$f_i(\mathbf{x}) \geqq b_i, \qquad i = 1,\ldots, m$$

$$u_j \geq x_j \geq l_j \qquad j = 1,\ldots, n$$

z is called the **objective function**. In the case of an energy or transportation system z might be total costs, emissions of a specific substance or the amount of employment created by the system, for example, or a combination of them. u_j, l_j, f_i and b_i are used to set **constraints** that define the space of allowed or **feasible solutions**. These constraints may include restricted availability of resources or maximum allowable emission levels[23]. If both z and $\mathbf{f}$ are linear in $\mathbf{x}$, i.e.

$$z = \mathbf{cx} = \sum_{j=1}^{n} c_j x_j \qquad \text{Eqn. 3}$$

$$\mathbf{f} = \mathbf{Ax} \Leftrightarrow \forall i : f_i = \sum_{j=1}^{n} a_{ij} x_j$$

and all l_j are non-negative,

$$\mathbf{l} \geq \mathbf{0}$$

the optimisation problem is called a linear programme. In this case the problem can be solved in a straightforward way by using standard algorithms. Non-linearities call for much more sophisticated solvers and need much more computing time.

The problem mentioned above, the optimisation of a regional or national energy system over several time periods, typically involves constraint matrices **A** that are very large (containing several thousand rows and columns) and sparse (typically less than 1% of the entries are non-zero). Writing out all the relation and vector names and coefficients in a form intelligible to the optimiser program is a very tedious task. MARKAL is a tool that allows entering the necessary data in a much user-friendlier way and, moreover, translates the output of the optimisation calculation in a report that is much easier to understand and interpret.

The MARKAL model has found widespread use in the past decades. It has been constantly extended and optimised. MARKAL is a demand-driven model, i.e. the (end-use) demand in any time period is given as an external parameter, and the system has to cover this demand by use of the technologies that the model user defines. Later developments allow incorporating an elastic demand, i.e. the demand changes with the marginal cost to satisfy this demand [Berger et al. 1992, Loulou & Lavigne 1996], or

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[23] Please note that a quantity should not be both constrained and part of the objective function. In such a case the problem would be very susceptible to be overdetermined. See also 3.2 "External Costs".

even coupling with a macroeconomic general equilibrium model [Manne & Wene 1992, Kypreos 1996].

4.1.2 Endogenous Technological Learning (ETL)

Another important improvement concerns the description of technological learning: Empirical knowledge shows that experience is one of the main drivers for any development (see e.g. [IEA 2000]). This experience, in its turn, can only be gained when the technology is installed and used already at an early stage of its development. In the basic version of the MARKAL model, however technological learning is an exogenous process, i.e. the development of a technology is only determined by time but not by the evolution of the system. This means that a technology matures no matter whether it is installed or not. This can lead to significant distortions of the results, be it that the exogenous learning assumed does not exploit the full improvement potential of a technology, be it that the model chooses a technology at an advanced stage of development although the costs to reach this stage are actually prohibitively high.

The concept of technological learning describes the relation between the cumulative installed capacity or another measure for the experience already gained and the associated improvement of technological parameters.

The most important effect of technological learning is on specific investment costs *INV*. It is usually described as a so-called learning curve of the following shape:

$$INV(CC) = INV_0 \cdot (CC / CC_0)^f \qquad \text{Eqn. 4}$$

where

CC = cumulative capacity at a given time

INV_0 = specific investment costs at starting point

CC_0 = cumulative capacity at starting point

f = parameter describing the ability to learn

An equivalent formulation of this behaviour is that specific investment costs are reduced to a fraction *pr* every time the cumulative capacity doubles. *pr* is called the progress ratio. The following relation links *f* and *pr*:

$$pr = 2^{f} \qquad \text{Eqn. 5}$$

This term "progress ratio" is used in this text from now on.

Implementing these equations into MARKAL transforms technological learning from an exogenous to an endogenous process. This means, however, that the utility function (that is, usually the discounted cost of the total system over the entire time modelled) is not linear any more. Moreover, because the system has a positive return of scale the problem becomes non-convex. Such a problem, however, cannot be solved directly by commercial solvers. The only way out is to linearise the learning curve by e.g. MIP (Mixed Integer Programming); in this case the learning curve is approximated by piecewise constant investment costs, see [Barreto 2001].

4.1.3 Introducing Environmental Aspects into MARKAL

MARKAL provides the user with the possibility to include environmental indicators such as emissions in the process database. Similar to cost data, environmental indicators can be proportional to investments, to the installed capacity, or to the activity of a process. This gives the possibility to distinguish between emissions during the manufacturing of e.g. cars and their use phase. The amounts of these indicators produced per year are summed up and reported. These environmental burdens can be considered in the optimisation process in various ways; the most important two are (cf. also 3.2 "External Costs"):

1. Any of the environmental burdens can be subject to a tax. This tax is then included in the objective function that has to be optimised.

2. For any environmental burden (or a linear combination of burdens) caps can be introduced. These caps create additional constraints the model has to respect.

Moreover, environmental indicators can be explicitly included in the objective function.

The fact that the volume of a market and the price for the good or service determine each other becomes particularly apparent in an LP model like MARKAL: the Pigou tax (which is actually the price for the emission right) on a substance and the emission cap for the same substance are so-called dual variables: applying a Pigou tax determines the volume q of a market, and for a fixed cap q^* the model calculates a shadow price p_{shadow} that equals the Pigou tax which corresponds to q^*, and that is defined as the marginal abatement cost $p_{shadow} = -\left.\frac{\partial Cost}{\partial q}\right|_{q^*}$ with $Cost$ the total cost of the system. Therefore, if an emission or class of emissions is to be regulated within the MARKAL framework, it should be either subject to a Pigou tax or constrained by a cap, but not both at the same time.

Technical regulations such as limited emission factors are not explicitly modelled in MARKAL. They are included in the specific emission factors of the technologies.

4.2 Input Data for the MARKAL Model

4.2.1 Geographic Setting and Timeframe

The region analysed in the study is the WEU region according to [Nakicenovic et al. 1998], i.e. OECD Europe plus Turkey. The time frame for the study is 2030, thereby allowing significant changes in the structure of the car sector to take place (first fuel cell cars are announced to be available from 2004 on, and the typical lifetime of a car is 10 years). It was, however, not possible to foresee all technological developments for the whole timeframe so the technological parameters here refer to the state of the art in 2010 as described in the previous chapters. As I suppose that all these technologies have similar improvement potentials I expect that the relative superiority of one technology over another one under given conditions should not be affected by further development of both technologies.

The time horizon of the scenario runs is 2050, but results are presented up to 2040; this avoids typical end-of-simulation effects.[24]

The total simulation time is divided into periods of five years. They start in 1995, but the vehicle distribution for the first two periods is fixed. 80% of the demand is covered by conventional gasoline vehicles, the rest by conventional diesel cars. Thus, actual development starts in 2005.

The timescale given in the results should not be seen as an exact measure. Even with actual development matching perfectly the technology characterisation used here, structural changes might in reality take place much faster or slower than in the model.

4.2.2 Technology Characterisation

The system analysed includes only the passenger car sector. The autonomous demand for electricity was kept to an absolute minimum. It was dimensioned in a way that under any circumstance the coupled production of electricity can be used and thus be credited.

The structure of the system modelled in MARKAL is shown in Figure 32 (except for vehicles). The system analysed in the MARKAL model contains more different options than were presented in the chapters on LCI and the cost analysis. Especially more process chains can be identified for the production and distribution of hydrogen. The characterisation of each technology contains both economic parameters (e.g. investment costs, efficiency etc.) and ecological data (emissions of GHG, SO_2, NO_x, NMVOC, and PM on a life cycle basis; these data are split up in emissions proportional to investments (production of device) and those proportional to activity (use of device)).

The higher complexity of the system (network of technologies instead of independent chains) and the fact that the model does not distinguish commodities by feedstock or production process allows additional alternatives to be considered, e.g. the production of RME using MeOH from scrap wood (instead of MeOH from NG).

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[24] Such effects arise from the fact that at the end of the timeframe the optimisation procedure might not consider the whole lifetime of a process. For example, in a CO_2-constraint scenario this means that

On the other hand it is more difficult now to assign specific processes to each other (e.g. when hydrogen from both central and decentralised steam reforming is used in more than one type of powertrains).

The following types of powertrains were considered:

- gasoline SI-ICE
- CNG SI-ICE
- MeOH SI-ICE
- EtOH SI-ICE
- CH_2 SI-ICE
- diesel SI-ICE
- RME SI-ICE[25]
- diesel FC (with reformer)
- MeOH FC (with reformer)
- CH_2 FC

In order to have a more detailed representation, the vehicle market was divided in three classes: small cars, compact cars, and mid-class vehicles. Other classes such as upper class cars or SUV (sport utility vehicles) were neglected because of their rather small share. The technology characterisation (costs, efficiencies, emissions) was taken from the LCI and cost analysis, respectively, but for modelling reasons the lifetime of all cars and all classes was assumed to be 180'000 km instead of 150'000 km in the previous

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processes with higher emissions during the installation phase but lower life-cycle emissions due to better performance during utilisation is handicapped.

[25] This distinction is artificial for many of today's CI engines are able to run on diesel, RME, or a mixture of both without any modification. It is, however, not possible to model fuel-dependent emission profiles within MARKAL. The effect of this distinction on the final outcomes of the runs should be small, though.

chapters. All powertrain technologies are available from 2005 on. For the two starting periods (1995 and 2000), additional powertrain types, namely existing gasoline and diesel cars, have been defined. These are vehicles available today (2000), fulfilling Euro IV (gasoline) and Euro III (diesel) regulations, respectively. Their consumption is quite low, but they do not represent BAT.

Most technology parameters are assumed to undergo no changes from 2005 to 2050; the only exceptions are investment costs for technologies with ETL (cf. 4.2.2.1.4 "Endogenous Technological Learning (ETL)"), the consumption of vehicles and the ecological performance of PV systems that I assume to improve gradually until 2030 when the state of the art as described in 2.4.8.4 "Future PV Plants" is reached. This simplification looks quite radical but there are some arguments that justify it:

- For all technologies an advanced state-of-the-art is assumed such that only relatively moderate improvements can be expected. PV, however, is an outstanding exception to that rule.
- Much of the improvement potential for the fuel consumption of cars is not related to the powertrain and thus affects all alternatives in the same way.
- In the time after 2030 no technological changes are assumed so that the model can find some kind of steady-state solution until the 2040 period; the extension of the runs to 2050 excludes effects from the analysis that might occur at the end of the simulated time.

4.2.2.1.1 Car Fuel Consumption

The consumption of all vehicles has been estimated for the model year 2030 using the QSS toolbox (see Appendix 2 "The QSS Toolbox"). The parameter changes are shown in Table 23. All assumptions for future power trains are based on and consistent with [Dietrich et al. 1998, Weiss et al. 2000, Dietrich 2001].

Parameter	2005	2030
c_W	0.25	0.22
RRC	0.008	0.006
Weight	various	-10%
Efficiency SI-ICE Powertrain	--	+15%
Efficiency CI-ICE Powertrain	--	+12%
Efficiency FC Powertrain (w/o Reformer)	--	+15%
Efficiency MeOH Reformer	75%	82%
Efficiency Diesel Reformer	69%	75%

Table 23: Parameters determining the reduction in consumption between 2005 and 2030. c_W: air resistance coefficient; RRC: rolling resistance coefficient.

The resulting reductions are around 16% for CI-ICE vehicles, 18% for SI-ICE vehicles, 20% for CH_2-FC vehicles, and 27% for reformer FC vehicles.

All other vehicle parameters (direct emissions, vehicle production) have been left unchanged.

4.2.2.1.2 PV Systems

In order to address large regional differences, three PV technologies have been defined that only differ in their average yield: 15.7% (corresponding to 1375 kWh/(kW_p*a)) in P, E, GR, and TR, 11.8% (1034 kWh/(kW_p*a)) in F, CH, A, and I, and 9.4% (823 kWh/(kW_p*a)) in other countries. These values have been estimated from data in [European Commission 1996] and calibrated with a yield of 1'000 kWh/(kW_p*a) (11.4%) in Switzerland. These yields clearly characterize above-average sites; this has been taken into account in the calculation of resource availability (see 4.2.2.1.7 "Restriction of Resource Availability").

The only plants considered are rooftop systems or equivalent facilities that are directly connected to an electrolyser.

4.2.2.1.3 Scenario Definition

I distinguish between scenarios and cases. Their definitions are taken from the cost analysis. The four scenarios are defined by the following settings:

Price for fossil fuels: In the base case, prices are assumed to remain constant at a level that corresponds to the average price between 1997 and 1999. In the alternative case, they are going to escalate significantly until 2020.

Assumptions on emerging technologies: In a scenario with more optimistic assumptions on emerging technologies, the efficiency of the FC powertrains is higher by 20%, and costs for many technologies are lower. Cost reductions are assumed to gradually take place between 2005 and 2015, whereas the efficiency is not time-dependent.

For every scenario four cases were defined that differ in their tax regimes. Taxes can be applied to both classical pollutants and to GHG. In order to keep the complexity of the study at a reasonable level only four different alternatives have been assumed:

- no emission taxes.
- taxes on classical pollutants.
- taxes on GHG.
- taxes on both classical pollutants and GHG.

All taxes apply from the first period without any phasing in.

For details see chapter 3 "Costs of Fuels and Vehicles". Moreover, all scenarios have been run with and without endogenous technological learning (see below).

The real discount rate in all runs is 5%/a.

4.2.2.1.4 Endogenous Technological Learning (ETL)

In an alternative set of runs, some key technologies are allowed to learn and thus reduce their investment costs with increased cumulative capacity. These technologies are the polymer electrolyte fuel cell, the photovoltaic system, and the Biometh plant. The parameters used for ETL are shown in Table 24. The cumulative capacities as well as the investment costs in 2005 are estimated; the capacity of 10 MW for the PEM fuel cell corresponds to around 200 vehicles (if non-vehicle applications are neglected), the one for PV was taken from [Barreto 2001], and the cumulative capacity for the Biometh process is around one demonstration plant as described in [Biometh 1996]. The progress ratios are taken from [Seebregts et al. 1999]. The floor costs describe the minimum achievable cost for the technology; please note that they are lower than even the optimistic estimates without learning. In the case of PV, one has to add the costs for the balance of the plant; these I assume to decrease in time and independently from the installation of the technology from 1'486 Fr/kW in 2000 to 282 Fr/kW in 2030, see also [Seebregts et al. 1999].

The same parameters are used in all scenarios. This means that in the Base Case and Expensive Fossils scenarios (with moderate assumptions for emerging technologies) the endogenous learning mechanism can lead to substantial cost reductions compared to the case without learning.

	Cumulative Capacity in 2005	Investment Cost in 2005	Progress Ratio	Floor Cost
PEMFC	0.01 GW	1500 Fr/kW	0.82	40 Fr/kW
PV*	0.5 GW	5944 Fr/kW	0.82	1000 Fr/kW
Biometh	0.2 PJ/a	160 Fr/(GJ/a)	0.9	75 Fr/(GJ/a)

Table 24: Parameters for the modelling of endogenous technological learning. *: Without balance of plant.

In the cases with endogenous technological learning also the costs for biomass decrease with time. For these costs, no **endogenous**, but exogenous learning was assumed; the reason is that most of this reduction I assume to be connected to generic developments in agriculture that do not depend on the amount of bio**fuels** produced.[26] The future values are those assumed in the scenarios with more optimistic assumptions on emerging technologies, but they are only reached in 2025.

4.2.2.1.5 Growth Constraints on Technologies

Growth constraints have only been defined for the vehicles, but not for other processes. This is a very strong simplification since the infrastructure requirements for the

[26] This reasoning might not hold true for SRF. However, there are no data available that allow deriving progress ratios for this culture.

distribution of alternative fuels are often seen as the major bottleneck for the introduction of a new technology. However, infrastructure requirements are not linear in the quantity of the distributed fuel; already a small number of cars needs a nation-wide fuel infrastructure network.

When the model selects a powertrain for the first time, its capacity is usually restricted to 5% of the demand in the corresponding class in 2005. Exceptions are the advanced gasoline and diesel cars (20% each), and the fuel cell vehicles as an emerging technology (1.25% if first introduced in 2005, 5% if first introduced in 2010 or later)[27]. After being introduced for the first time, the capacity of the powertrain technologies are allowed to grow with a maximum growth rate of 32.6% per year (corresponding to 310% in 5 years) and a minimum growth rate (that defines how fast a technology can fade out of the market) of -25% (-76% in 5 years).

4.2.2.1.6 LDV Transport Demand

The base case projections for transportation demand were derived from the so-called efficiency scenario in [Diekmann 1995]; they were calibrated to match the data from [Schäfer 2000] for the geographic region analysed (OECD Europe plus Turkey) in 1995 and extrapolated beyond 2010 assuming a substantial saturation effect, see Table 25. [Diekmann 1995] projects already rather moderate growth, cf. overview in [GVF 1995], but in the MARKAL model used here and under the assumption of no caps for emissions its influence on the result is rather small:

- The maximum share of fuels with limited availability (biofuels, hydrogen from wind and solar electricity) is inverse proportional to the total demand.
- If the market is too small, learning processes cannot take place.

With a GHG cap, however, the ratio of total allowable emissions to total demand defines the maximum allowable average emissions per vkm, so the demand is a very important parameter. Therefore, a second demand development was defined for sensitivity analyses. It is taken from [Schäfer 2000]; these projections show only a slight saturation effect (see annual growth rate in Table 25).

Year	Base Case		High Demand Scenario	
	bln vkm/a	annual growth	bln vkm/a	annual growth
1995	2'371	--	2'371	--
2000	2'623	2.04%	2'668	2.38%
2005	2'739	0.87%	2'975	2.20%
2010	2'855	0.83%	3'298	2.09%
2015	2'912	0.40%	3'584	1.67%
2020	2'969	0.39%	3'872	1.56%
2025	3'026	0.38%	4'141	1.36%
2030	3'055	0.19%	4'404	1.24%
2035	3'084	0.19%	4'611	0.92%
2040	3'112	0.18%	4'795	0.79%
2045	3'141	0.18%	4'946	0.62%
2050	3'169	0.18%	5'069	0.49%

Table 25: Demand projections used in the model.

The distribution among the three vehicles classes was derived from data in [BFS 1999] and [BUWAL 1995] under the assumption that the classification made here by vehicle size matches relatively well the distribution by engine displacement (<1'400 cm^3, 1'400 – 2'000 cm^3, >2'000 cm^3). The resulting distribution (20% small cars, 55% compact cars, 25% middle class cars) was taken to be representative for the whole region of interest and for all periods.

4.2.2.1.7 Restriction of Resource Availability

Availability constraints have been introduced for waste wood, arable land, and photovoltaics (available rooftop area). For the first two quantities no geographic differentiation was assumed, the restrictions in the following paragraphs refer to the

[27] An additional constraint ensures that the model will in most cases install not more than one new technology (i.e. a powertrain not based on gasoline or diesel ICE) in 2005.

whole region analysed. The site-dependence of electricity production from PV was modelled by dividing the region into three subregions with different yields (annual electricity production per kW_p, see also 4.2.2.1.2 "PV Systems").

Waste wood: total availability of this resource was estimated at 36 mln t per year. This is an extrapolation from [Riegger 2000], assuming that per capita yields of waste wood are homogeneous in time and space.

Agricultural land: land use is restricted to 3 mln ha in 2005 and rises to 8 mln ha from 2015 on. This appears to be quite low (see, e.g., [Flaig & Mohr 1993] who estimate a total area of 16.2 mln ha for the EU in 2005, considering competing land uses like natural habitat areas, growth of crops for the chemical industry or reforestation), but it is based on the assumption that more than half of the available land is used for the production of energy crops that are used outside the LDV sector.

Photovoltaics: With the available roof surface estimates from [European Commission 1996], I assessed maximum capacity for each region assuming that not more than 25% of the rooftops can be used for production of H_2 for mobile applications and assuming efficiencies of 10% (1995) and 15% (2030). The resulting potentials are shown in Table 26.

	Available Surface	Installable Power	
		1995	2030
	km^2	GW	GW
Region I	489	48.9	73.4
Region II	315	31.5	47.3
Region III	202	20.2	30.3

Table 26: Available rooftop surface and corresponding installable PV power in the three regions (Region I: B, D, DK, IRL, IS, LUX, NL, N, S, SF, UK, Region II: A, CH, F, I, Region III: E, GR, P, TR).

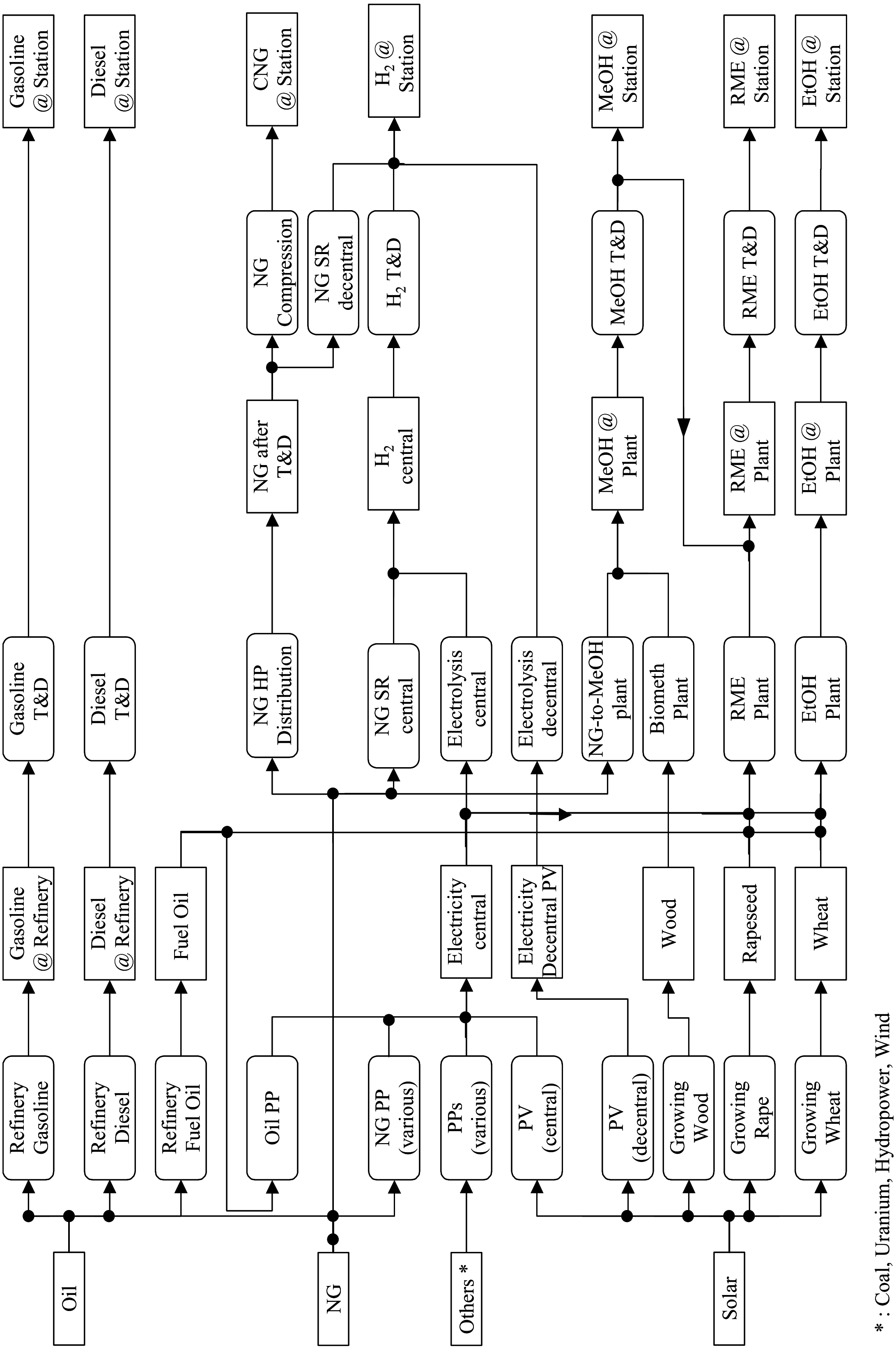

Figure 32: Structure of the energy and transportation system modelled in MARKAL. Not shown are the collection of scrap wood and the vehicles.

4.3 Results of the MARKAL Runs

In this chapter the results from the MARKAL runs are presented. Although many of the parameters are subject to significant errors, already some very important conclusions can be drawn.

A Remark on the Patterns in the Figures:

The following pattern system was applied to all figures in this section:

The basic pattern stands for the fuel:

- gasoline (vertical)
- diesel (horizontal)
- CNG (downward diagonal)
- MeOH (upward diagonal)
- RME (horizontal brick)
- EtOH (diamond)
- CH2 (grid)

In the graphs representing vehicle technologies dark patterns (thick lines) stand for conventional ICE cars, light patterns (thin lines) for advanced ICE vehicles, and dashed or dotted patterns for FC vehicles.

In the graphs showing energy consumption these features represent different feedstocks or primary energy sources, respectively.

4.3.1 The Base Case Scenario

4.3.1.1 The Base Case Scenario without Taxes

The base case scenario is defined by constant prices for non-renewable primary energy carriers and rather conservative assumptions on costs for emerging technologies. In the absence of ecologically motivated taxes, the model chooses the advanced gasoline car as soon as it is available (2005), see Figure 33. This result could be expected from the cost analysis, see 3 "Costs of Fuels and Vehicles". This new technology could even be introduced at a still faster pace, but it is limited by a growth constraint. That is why other technologies (Advanced diesel car, MeOH ICE car) are introduced for a transition period: under the circumstances given these technologies are more expensive than the advanced gasoline car but offer cost advantages compared to the conventional vehicles. This transitional pattern is, of course, not very realistic. The introduction of an alternative fuel for only a short period is very unlikely to happen.

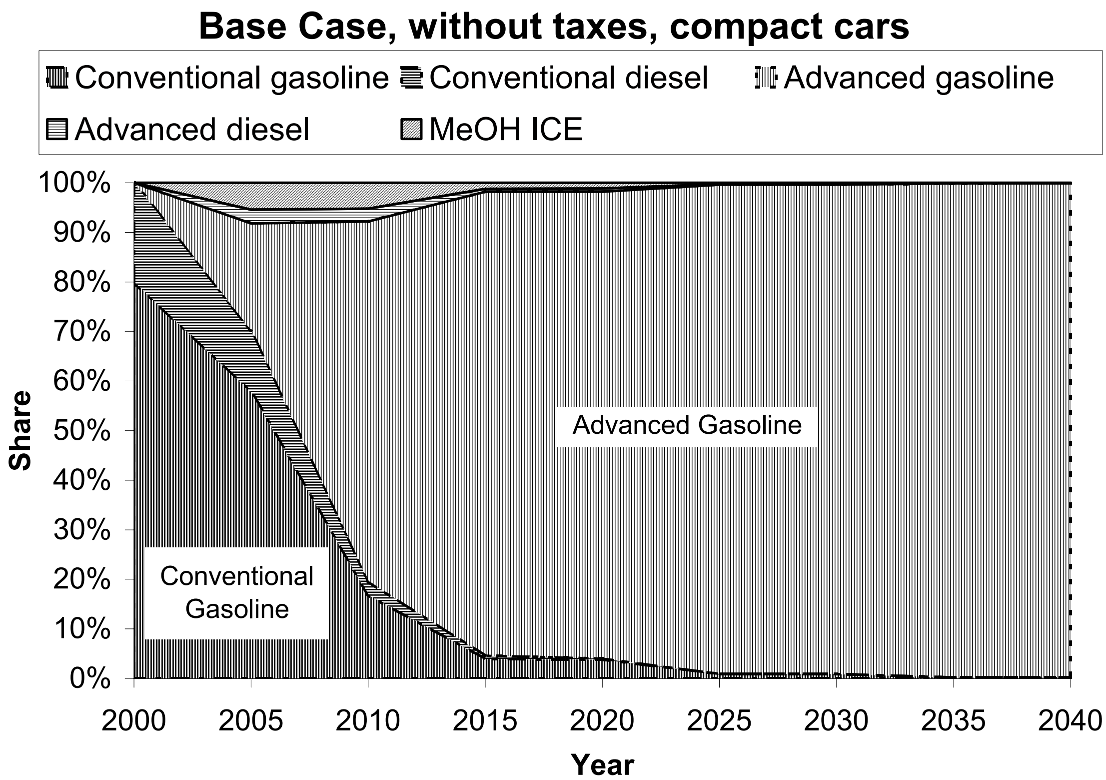

Figure 33: Distribution of vehicle types in operation in the base case without taxes, compact cars, OECD Europe plus Turkey.

The model does not consider the advanced diesel vehicle (except for a transition period) because its higher capital charges offset the lower consumption and therefore running costs offered by this technology. A different use pattern (higher annual mileage, for instance) might favour the diesel powertrain.

The development in the other sectors (small cars, mid-class cars) is similar to the one depicted in Figure 33, but in the mid-class sector neither the advanced diesel car nor the MeOH ICE car are introduced.

Total energy consumption in the car sector is shown in Figure 34. Between 2005 and 2010 consumption decreases significantly because of the wide introduction of a more efficient powertrain technology. Afterwards, consumption decreases slower because of smaller fractions of the old technology to be replaced. Finally, after 2030 the technologies remain unchanged, so the rising demand leads to a small increase. This specific pattern is triggered by two central assumptions: a moderate, even low demand projection, and a technical development (efficiency increases) that stops in 2030.

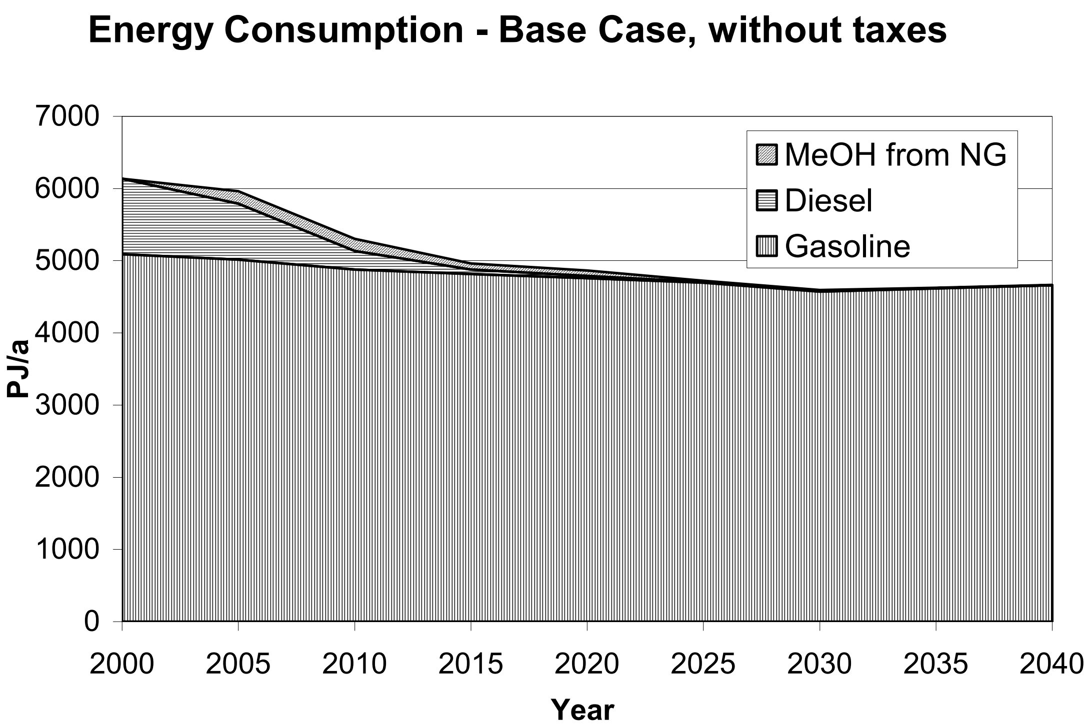

Figure 34: Consumption of final energy in the car transport sector in the base case scenario without taxes, OECD Europe plus Turkey.

The consumption of gasoline remains fairly constant over the time span considered. Diesel, however, fades out completely. MeOH is only introduced for a transition period. Its share remains small.

Figure 35 shows total GHG, NO_x, and NMVOC emissions from the car transport sector compared to the demand. In general, the emissions are in line with total energy consumption: they decrease until 2030 with the maximum reduction happening between 2005 and 2010, and rise slightly towards the end. Emissions of GHG are in this case more or less proportional to the consumption. The reduction potential for NO_x is slightly larger and the one for NMVOC is smaller, respectively, because the gasoline vehicle substitutes for its diesel counterpart.

SO_2, and PM are not shown because their development pattern resembles much that of the emissions shown here.

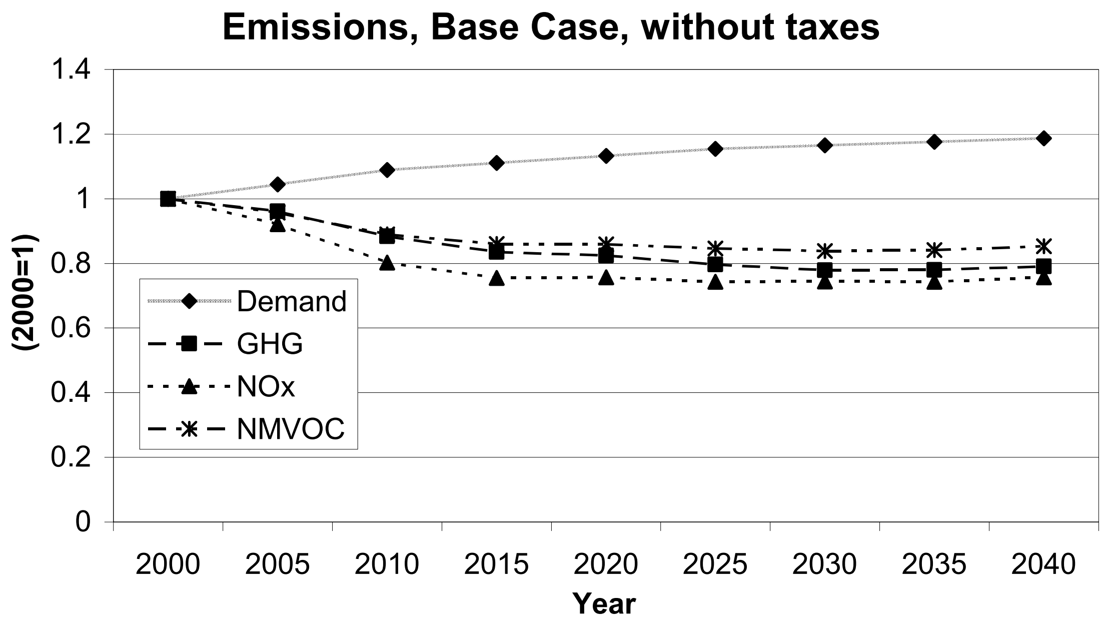

Figure 35: Emissions from the car transport sector in the base case without taxes, normalised to emissions in 2000, OECD Europe plus Turkey.

Finally, Figure 36 shows a proxy for the average costs of driving (in Rp / km). These approximated costs were obtained by dividing total yearly costs in one period by the corresponding demand. The results would equal actual costs if installations of vehicles were distributed evenly among periods. In the model runs, however, investments show small oscillations. These lead to higher estimates for the average costs in periods with larger investments (2000, 2010, 2020, 2030, 2040) and lower estimates in the other periods[28].

Despite of these oscillations one can distinguish a trend towards slightly smaller costs due to the higher efficiency of the future vehicles. The effect, however, is rather small (on the order of 1 Rp/km or 5% between 2000 and 2040).

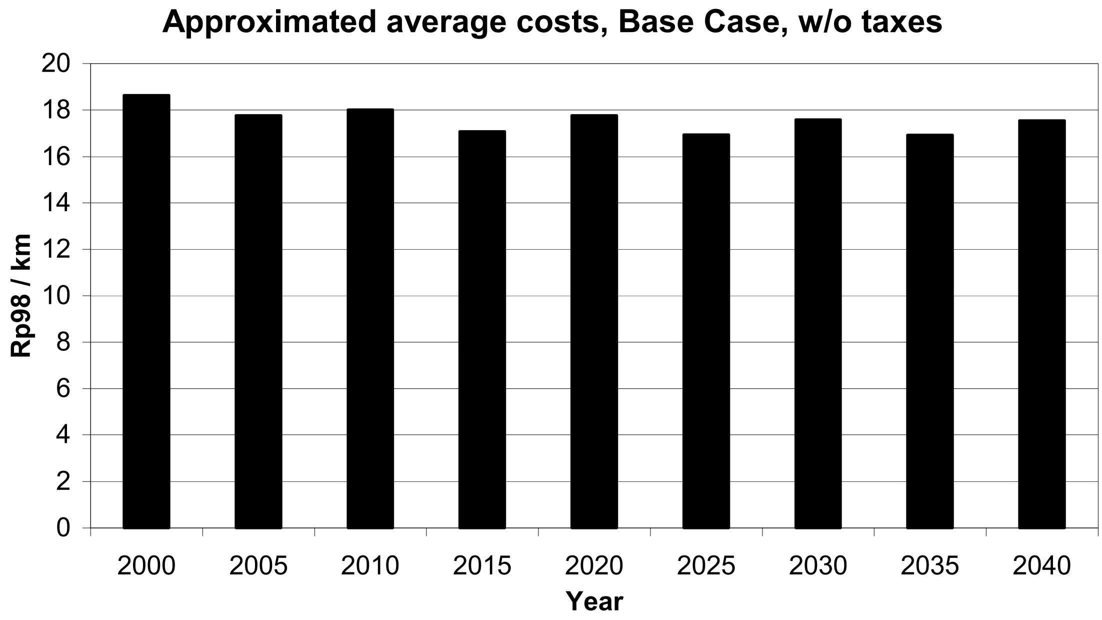

Figure 36: Approximated average costs in the Base Case scenario without taxes, OECD Europe plus Turkey. The oscillations are a modelling artefact, see text for details.

4.3.1.2 The Base Case Scenario with Pollutant Taxes

When applying pollutant taxes in the base case, the model chooses the MeOH ICE vehicle that leads to smaller total pollutant emissions, see Figure 37; like in the case without taxes (and even to a larger extent), this new technology is restricted to a specific growth potential and cannot replace the conventional vehicles at once. In this case, however, the gap is filled by advanced diesel and gasoline cars. This kind of transitional use of a technology, however, differs from the one that occurs in the Base Case without taxes: here, the model replaces the conventional cars with their further developed versions. The model uses the existing infrastructure as long as the new technology

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[28] The inclusion of a small electricity sector in the model can be neglected.

cannot cover the whole demand. In the other two sectors (small cars, mid-class cars), however, the CNG vehicle is introduced for a transition period.

This means that for the transition period the model structure and the parameters chosen produce a result that is **qualitatively** realistic, but the **quantitative** development of the car sector in time is probably not modelled correctly.

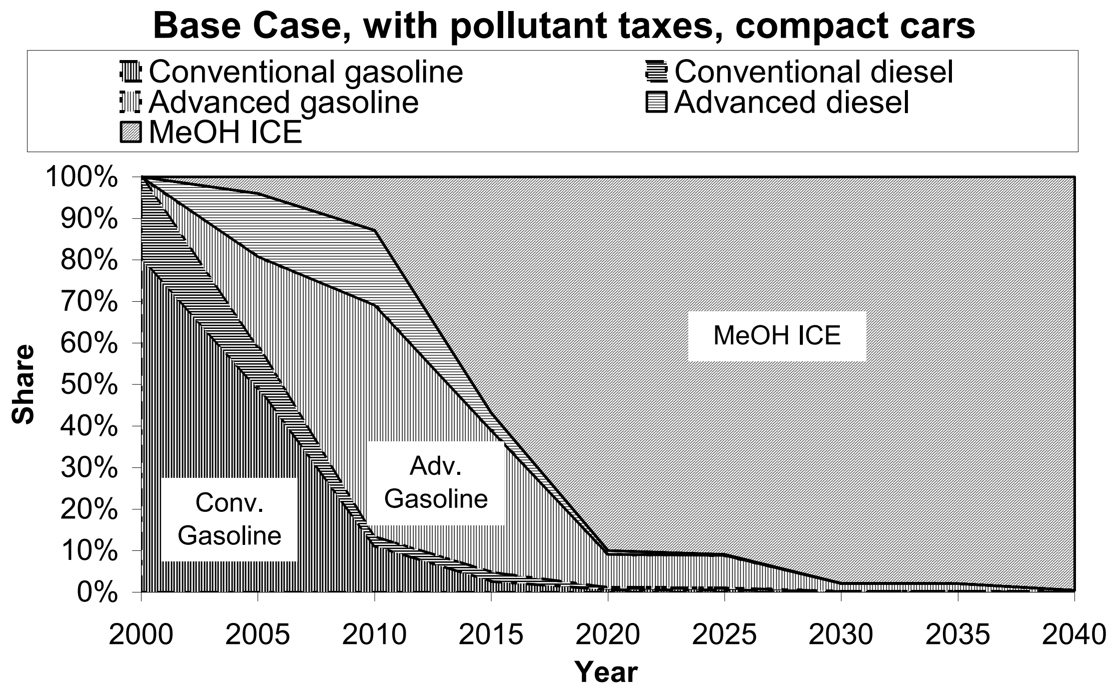


Figure 37: Distribution of vehicle types in operation in the base case with taxes on pollutants (SO_2, NO_x, NMVOC, PM), compact cars, OECD Europe plus Turkey.

Figure 38 shows the corresponding consumption of final energy. As in the case without taxes total consumption reaches its minimum in 2030 and then slowly begins to rise again. However, due to the higher efficiency of the MeOH ICE the drop in final energy demand is much more pronounced. Of course, the traditional motor fuels are gradually replaced by MeOH.

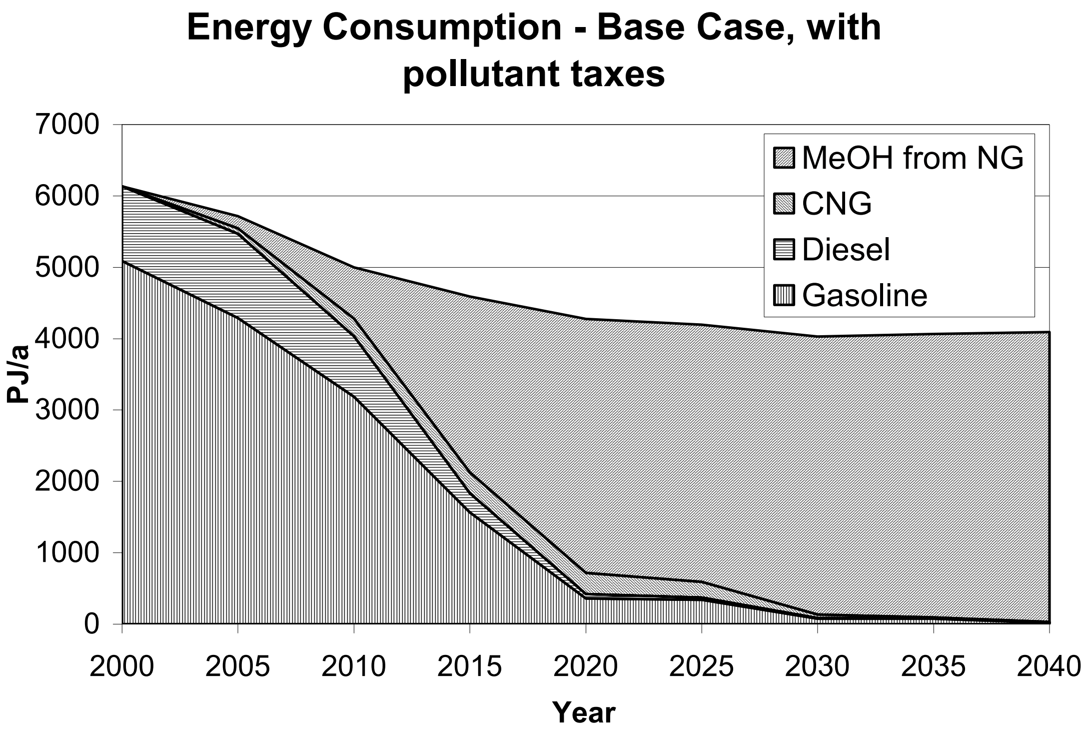


Figure 38: Consumption of final energy in the car transport sector in the base case scenario with pollutant taxes, all classes, OECD Europe plus Turkey.

4.3.1.3 The Base Case Scenario with a GHG Tax

When a greenhouse gas tax of 210 Fr98/t CO_2-eq is applied to the base case scenario, the results become even more complex, and a fairly large variety of technologies is introduced.

The most interesting and illustrative example is the compact car class, see Figure 39. Although FC vehicles dominate the market in the end, they are not introduced in the first period available (2005), but only in 2015. The reason for this lies in the structure of the model: there is a limit for the weighted sum of all new technologies (i.e. all technologies except for the conventional and advanced gasoline and diesel cars), and the weighing factor for FC vehicles in this sum is four (ICE: one). This makes it more attractive for the model to first introduce ICE cars running on alternative fuels and postpone the breakthrough of the FC technology. This rivalry between alternative technologies is indeed realistic (e.g. for scarce R&D money), its meaning, however, seems to be overemphasized in the current state of the model.

Another interesting feature of the results of this run is that the new technology favoured in 2005 is the MeOH ICE vehicle; this way, the system exploits its possibility to use the nearly GHG-neutral Biometh process for the conversion of scrap wood. As soon as FC vehicles are available to use this MeOH, the use of MeOH ICE cars fades out.

The results in the other sectors show similar patterns; the main difference is that in the mid-class sector the FC vehicle is introduced later and that, correspondingly, ICE vehicles still dominate the market in 2025. This reflects the fact that the consumption advantage of the FC powertrain over the ICE decreases (in relative terms) with increasing vehicle size.

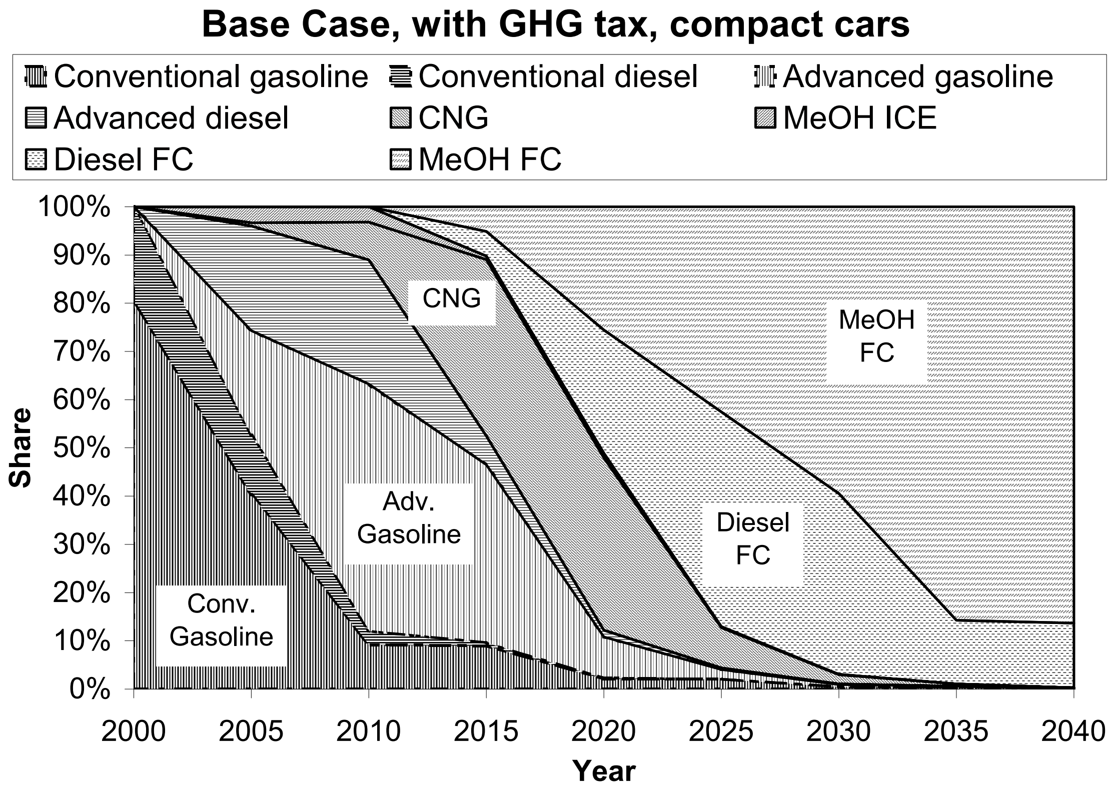


Figure 39: Distribution of vehicle types in operation in the base case with a GHG tax, compact cars, OECD Europe plus Turkey.

The choice of the FC vehicle is an first effect that could not be expected from the static cost analysis in Chapter 3 "Costs of Fuels and Vehicles" where it was outperformed by ICE cars running on CNG and MeOH from waste wood. The lower floor costs that can be reached with endogenous technological learning and the larger improvement potential for the efficiency (cf. 4.2.2.1.1 "Car Fuel Consumption") make the FC a very attractive option in the long run.

The consumption of final energy (Figure 40) also shows some new patterns that are mainly an effect of the introduction of new technologies in two "waves" (first the advanced ICE vehicles, then the FC powertrain). The consumption of diesel oil has a first minimum in 2015 (fade out of diesel ICE cars) and then rises again due to the introduction of the diesel FC vehicle. It remains at a low, but constant level in the last period to exploit the existing infrastructure. MeOH from scrap wood is introduced as soon as possible and contributes a constant share afterwards.

The absolute reduction from period to period shows a first local maximum between 2005 and 2010 and a second local maximum between 2015 and 2020. Energy consumption is still slightly decreasing after 2030 because the introduction of the FC technology is not complete yet. Total demand of final energy in 2040 is still much lower than in the other cases, an effect of the high efficiency of the FC powertrain.

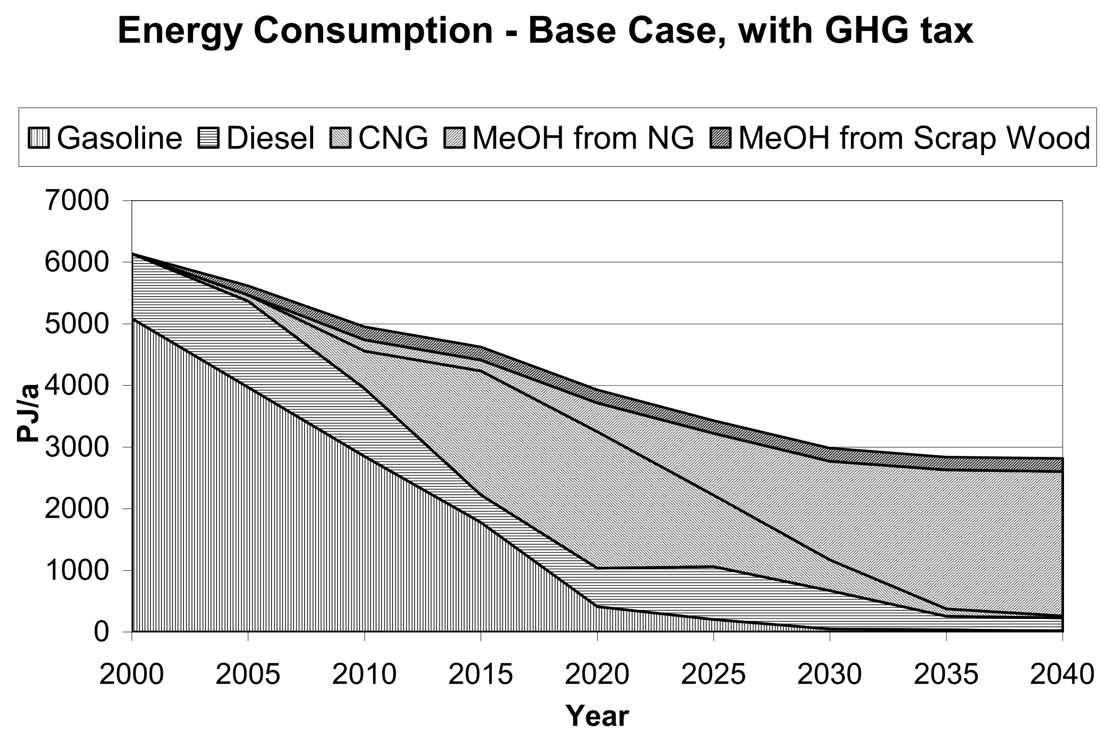


Figure 40: Consumption of final energy in the car transport sector in the base case scenario with a GHG tax, all classes, OECD Europe plus Turkey.

The approximated costs in Figure 41 were derived in the same way as those in Figure 36 and they show a similar oscillatory pattern.

The average tax revenues show how efficient the GHG taxes work in order to reduce these emissions. But it is interesting to see that the total cost without taxes is decreasing as well. In 2040, they are even lower than in the case without taxes (16.7 vs. 17.5 Rp / km). This result is contradictory only at first sight: the total discounted costs of this run are higher than those in the run without taxes. The lower costs towards the end are outweighed by higher investments into the FC technologies in the early periods up to 2020.

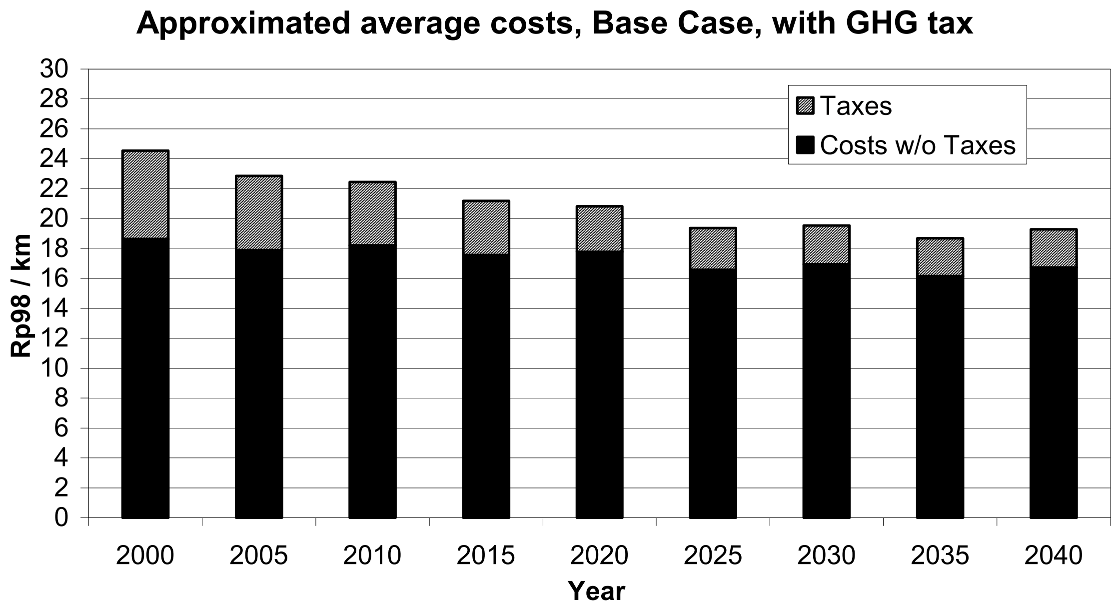


Figure 41: Approximated average costs in the Base Case scenario with GHG tax, all classes, OECD Europe plus Turkey. The oscillations are a modelling artefact, see text for details.

4.3.1.4 The Base Case Scenario with Pollutant and GHG Taxes

In this case the MeOH FC vehicle and the CNG car finally dominate the market, with the FC vehicle being more successful in the small car sector and the CNG car dominating the mid-class (in the compact car class the FC vehicle is decreasing, but the CNG car still covers 70% of the demand). This reflects the fact that the efficiency advantage of the FC vehicle decreases with increasing car size.

4.3.1.5 Summary of Tax Effects in the Base Case Scenario

The effect of taxes on total emissions in the base case scenario is shown in Figure 42 to Figure 46.

The introduction of pollutant taxes reduces emissions of NO_x by 21% in 2040, compared to the situation without taxes. In combination with a GHG tax an even higher effect (34%) could be achieved, but largest reductions occur with a mere GHG tax (36%). This result shows the tradeoffs between GHG and pollutant mitigation: the FC vehicle offers largest reductions of GHG emissions, but the high SO_2 emissions from its powertrain production make the model choose the more NO_x-intensive ICE under a combined tax regime.

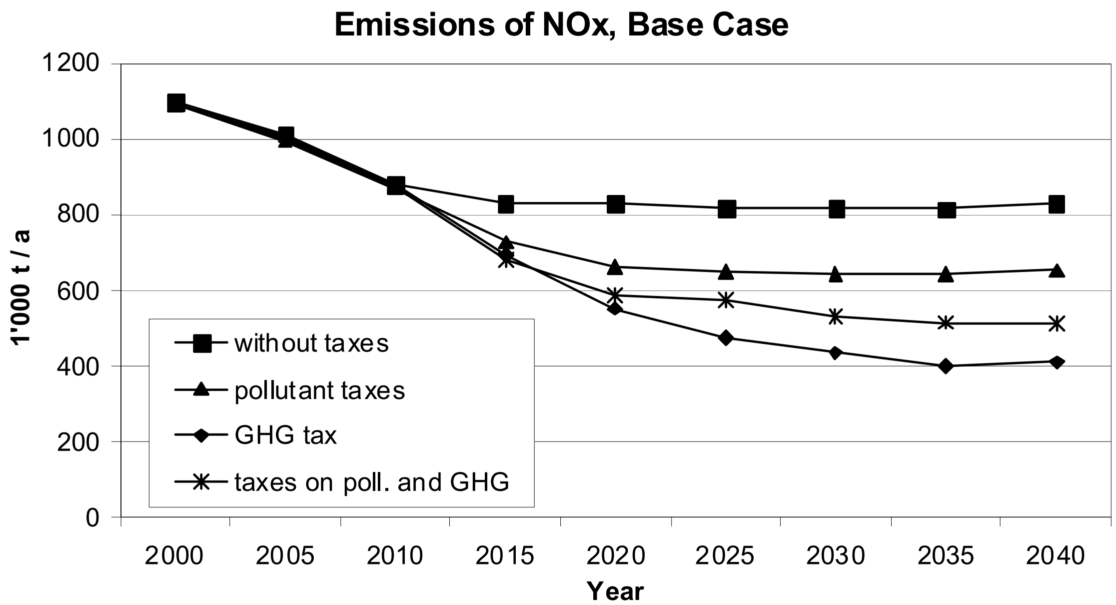


Figure 42: Emissions of NO_x in the base case under different tax regimes, all classes, OECD Europe plus Turkey.

The first significant differences between the different tax regimes can be observed in 2015. Up to this period the assumptions made for the LCI (same specific emissions for all ICE vehicles) lead to a common pattern. With all tax regimes a general pattern can be recognized that is typical for all emissions analysed here: The introduction of new technologies that offer a quite radical reduction leads to decreasing emissions in the first periods, but then the higher demand begins to outweigh the effect of replacing the remaining conventional technology, and emissions rise again. Usually, the minimum is achieved in 2035. Only in the case with a combined tax there is still a small decrease from 2035 to 2040 (introduction of the MeOH FC vehicle is not complete yet).

Emissions of SO_2 rise significantly in the case of a mere GHG tax where the PGM-intensive fuel cell vehicles are introduced. Under this tax regime, emissions of SO_2 would rise by 33% in 2040, compared to reductions by 42% (pollutant taxes) and 21% (combined tax strategy), respectively, in the other cases. With combined taxes, emissions of SO_2 begin to rise considerably in the last periods when FC vehicles are introduced to a greater extent.

Please note that these emissions show an oscillatory pattern, especially when FC vehicles are applied. This reflects the fluctuations in the production of vehicles and are therefore a modelling artefact (cf. 4.3.1.1 "The Base Case Scenario without Taxes").

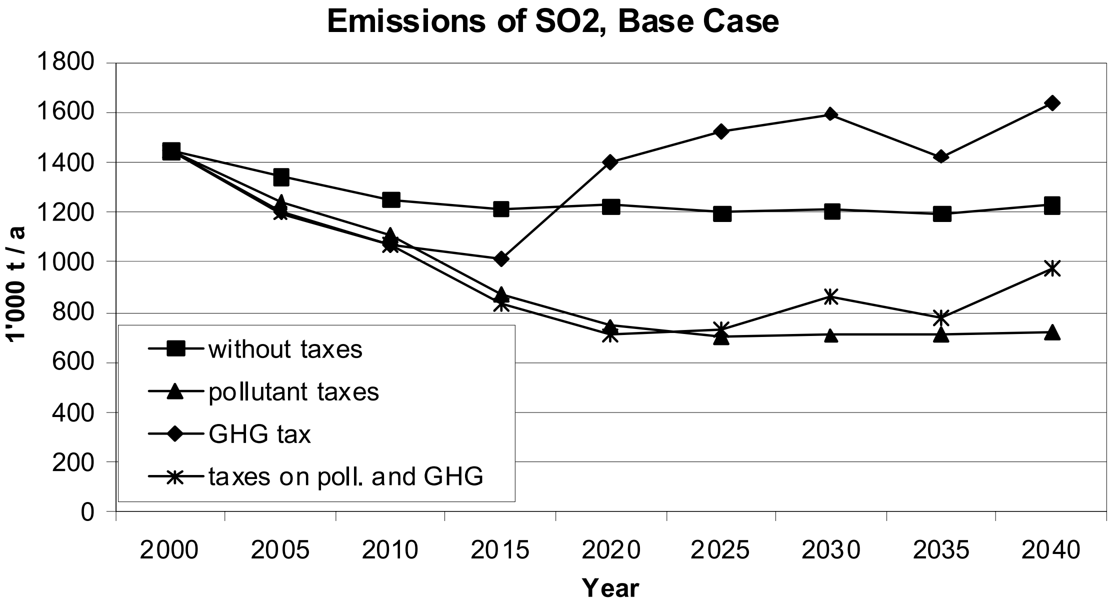


Figure 43: Emissions of SO_2 in the base case under different tax regimes, all classes, OECD Europe plus Turkey.

Large reductions are possible for organic compounds: a GHG tax or the combined tax strategy would reduce these emissions by some 70%. Even mere pollutant taxes would more than half them.

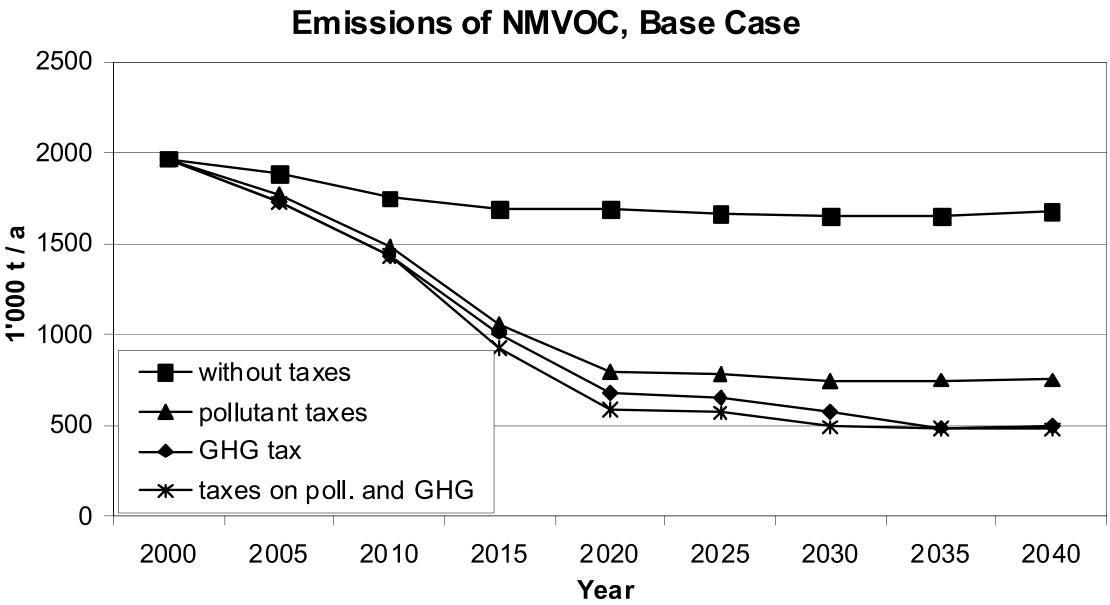


Figure 44: Emissions of organic compounds in the base case under different tax regimes, all classes, OECD Europe plus Turkey.

The taxes applied here lead to relatively low reductions of PM emissions; they range from 8% (GHG tax) to 18% (pollutant taxes) in 2040. On the other hand one must not forget that the introduction of the fuel cell eliminates fine and ultrafine soot particles that are emitted directly on the road by ICEs and the hazardous nature of which is subject to a controversial scientific discussion at the time being. This underlines once more the limitations of using the generic notion of particulate matter instead of a more detailed concept. At least a classification by particle sizes should be performed as soon as corresponding data are available.

The influence of oscillating car production volumes is clearly visible in these emissions as well.

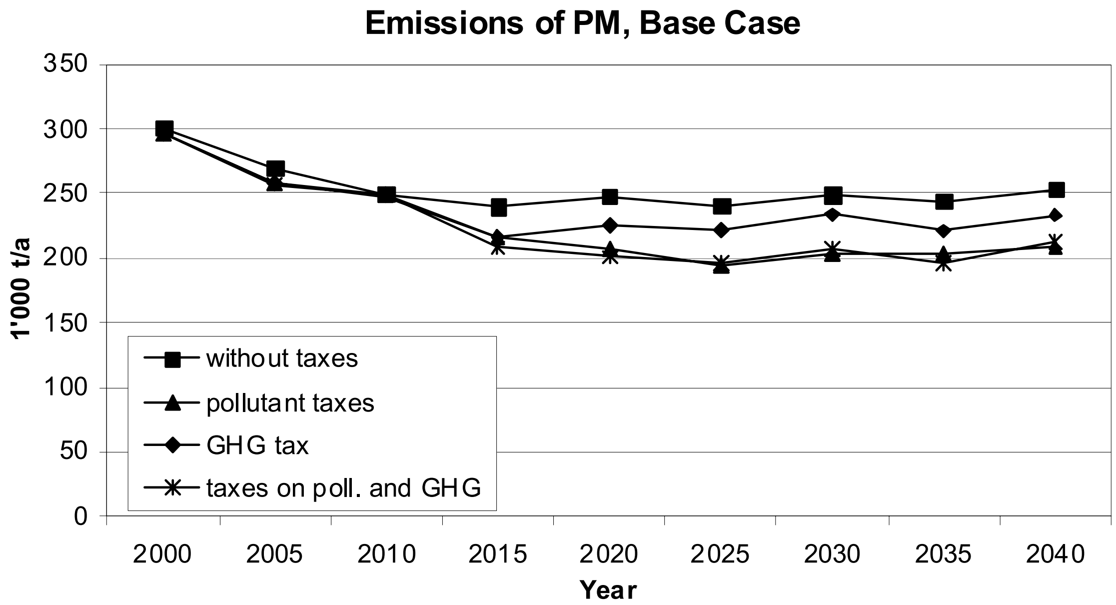


Figure 45: Particle emissions in the base case under different tax regimes, all classes, OECD Europe plus Turkey.

Emissions of greenhouse gases can also be efficiently mitigated by taxes. Pollutant taxes alone lead to reductions of 11%, the GHG tax and combined taxes reduce emissions by more than one third (36% and 34%, respectively).

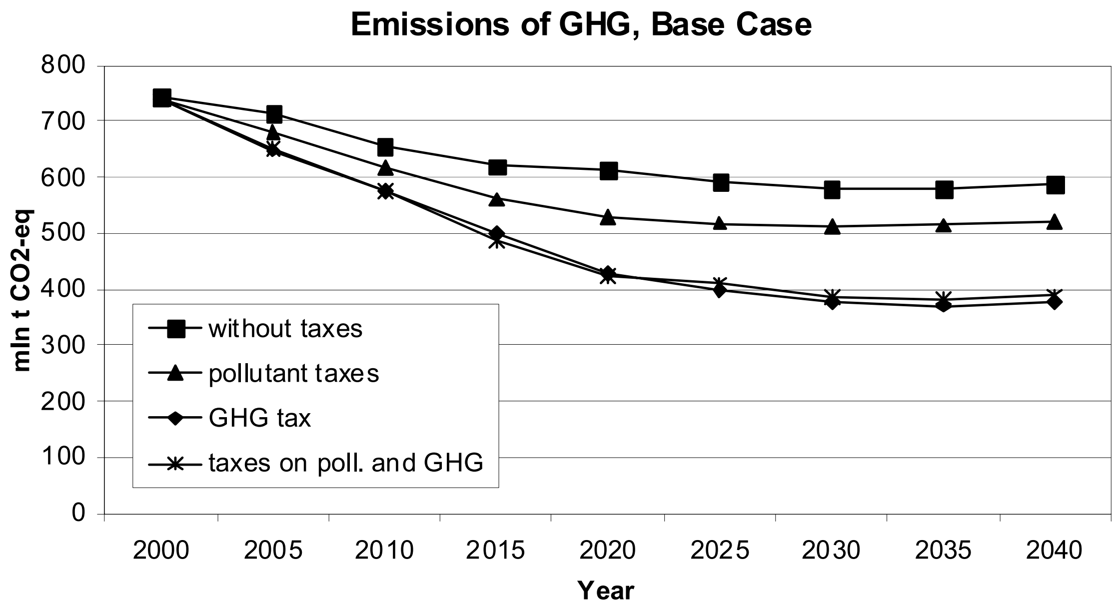
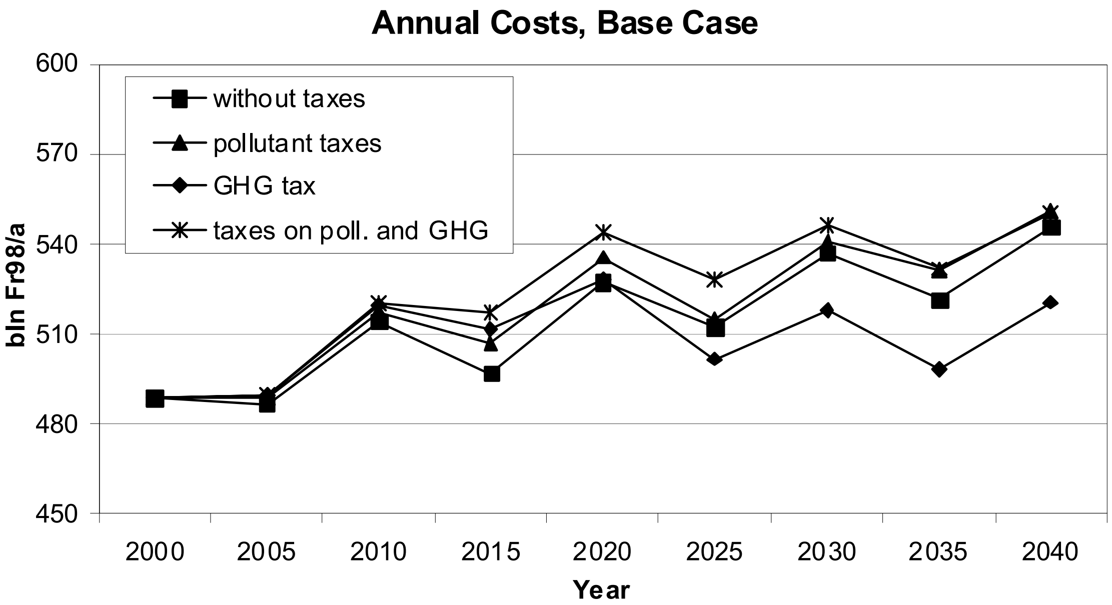


Figure 46: Greenhouse gas emissions in the base case under different tax regimes, all classes, OECD Europe plus Turkey.

Finally, Figure 47 shows annual undiscounted costs under the four tax strategies. The taxes are not included in the cost because they can be refunded to society, e.g. as lower income taxes or social security fees. As a consequence, total system costs are only little affected although the tax rates applied are rather high: In 2040, the worst of the cases analysed (pollutant taxes) causes an increase of total system cost by 1.0% over the case without environmental taxes. When considering that many costs such as infrastructure expenditures or insurance fees have not been taken into account in this analysis, the relative increase appears to be even lower.

Figure 47: Costs in the Base Case under different tax regimes, all classes, OECD Europe plus Turkey. Taxes are excluded from the cost calculation.



An interesting effect can be observed under the GHG tax: From 2025 on total annual system costs are even lower than in the case without taxes. This is an effect of the endogenous technological learning mechanism: At first, the model has to invest into the development of the FC, but afterwards it profits from the possibility to achieve cheaper transportation. Absolute gains in the time after 2015 seem to more than offset initial investments, but one must not forget that the optimisation function is defined as total discounted costs; this means that costs in earlier periods have a heavier weight. This is the reason why the model does not introduce the fuel cell even without a GHG tax. Thus, this case can serve as an example on how a particular tax induces developments that would probably pay out even without such a tax if only the time horizon were long or the discount rate small enough.

The effects of different taxation strategies on emissions are summarised in Table 27, Table 28 resumes the influence on the technology choice. The differences between different substance classes are clearly visible: The largest reductions (compared to the case without taxes) are possible for organic compounds, the lowest ones for particles.

Base Case	**Taxes on**	**--**	**Pollutants**	**GHG**	**Pollutants + GHG**
GHG	mln t CO_2-eq	588	521	377	388
	)[1]	100%	89%	64%	66%
NO_x	1'000 t	832	654	412	513
	)[1]	100%	79%	50%	62%
SO_2	1'000 t	1230	719	1634	973
	)[1]	100%	58%	133%	79%
NMVOC	1'000 t	1681	753	497	480
	)[1]	100%	45%	30%	29%
PM	1'000 t	253	208	233	212
	)[1]	100%	82%	92%	84%
Cost	bln Fr98	546	551	521	550
	)[1]	100%	101%	95%	101%
Tax Revenues	bln Fr98	0	63	79	143
per km					
w/o taxes	Rp98/km	17.5	17.7	16.7	17.7
with taxes	Rp98/km	17.5	19.7	19.3	22.3

Table 27: Emissions and costs in the base case in 2040 with different taxes, all classes, OECD Europe plus Turkey.)[1]: normalised to values without taxes.

The results show that the conventional gasoline car is the technology of choice if circumstances remain similar to those prevailing today. Constant pollutant taxes over the whole life cycle would favour MeOH-fuelled ICE vehicles, whereas under a mere GHG tax the FC vehicle and the production of MeOH from scrap wood would become competitive. Finally, under a combined tax strategy the market is dominated by CNG and MeOH FC vehicles.

	Taxes on:			
Base Case	**--**	**Pollutants**	**GHG**	**Pollutants and GHG**
Sector	**Dominating Technology**			
Small Cars	Gasoline ICE (100%)	MeOH ICE (98%)	MeOH FC (99%)	MeOH FC (93%), CNG ICE (7%)
Compact Cars	Gasoline ICE (100%)	MeOH ICE (100%)	MeOH FC (86%), Diesel FC (13%)	CNG ICE (70%), MeOH FC (29%)
Mid-Class Cars	Gasoline ICE (100%)	MeOH ICE (100%)	MeOH FC (98%)	CNG ICE (100%)
Fuels	Gasoline (100%)	MeOH from NG (99%)	MeOH from NG(83%), Diesel (8%), MeOH from Scrap Wood (8%)	CNG (77%), MeOH from NG (17%), MeOH from Scrap Wood (6%)

Table 28: Dominating powertrains and fuels in 2040 in the Base Case scenario with different taxes, OECD Europe plus Turkey. Market shares are given in brackets. Technologies with a small share that are limited by resource availability are included as well.

4.3.1.6 Conclusions Concerning Model Features

The analysis of the base case already shows some patterns that are characteristic for many of the runs done with the model:

1. New technologies are usually introduced at the maximum rates possible; in later periods their growth is restricted by the residual volumes of other technologies. This is mainly due to the fact that the infrastructure problem could not be adequately addressed in the model.

2. Because of the simple demand structure (only differentiation by vehicle size) in most cases one technology proves superior and finally dominates the market segment. A more differentiated approach (different driving patterns, driving styles, yearly mileage, preferences for qualities like driving comfort or ease of refill) might force the model to choose a wider variety of technologies.

3. In some cases second best technologies are introduced for an intermediate phase only because of growth restrictions for the best (i.e. cheapest) available technology. This pattern is very unlikely to happen in reality.

4. The results so far show that by 2040 in most cases the transportation sector has developed into the structure that is the cheapest under the given circumstances. This structure can therefore be considered a good approximation of a hypothetic steady state.

This shows that although the results in 2040 indicate which technologies are favoured in the long run, the actual development pathway followed by the model is of minor relevance only. Therefore, the analysis of the other scenarios is restricted to the situation in 2040; results for other periods are only considered in order to solve ambiguities.

4.3.2 The Expensive Fossils Scenario

Without any taxes, the model chooses the diesel-fuelled fuel cell car for the small and compact car class, cf. Table 29. This is an effect of the learning mechanism with floor costs well below the costs assumed in the static cost calculation; otherwise, the gasoline ICE car would dominate these classes like in the Base Case scenario without taxes (cf. 3.5.2 "The Expensive Fossils Scenario"). The same effect drives in the FC vehicle fuelled with MeOH from scrap wood. In the mid-class sector ICE vehicles running on biofuels are the least expensive option, due to learning effects (exogenous learning for the cost of wheat production, endogenous learning for the Biometh plant). As biomass-derived fuels are restricted by the availability of land and scrap wood, the rest of the demand in this sector is covered by the technology that performs best in the static analysis, too, the gasoline-fuelled ICE car.

These results show already how the consideration of learning mechanisms influences the results of the model runs. Similar observations can be made in the case with a GHG tax. Here the MeOH fuel cell car, the EtOH ICE car and the diesel fuel cell car phase in although they could not be expected from the static analysis.

The case with mere pollutant taxes (pollutant taxes only, combined taxes) is dominated by the CNG ICE powertrain with small complements by biofuels. In the base case scenario with pollutant taxes only, the MeOH ICE car was dominating all vehicle classes, but the lower conversion efficiency of the NG-to-MeOH process compared to CNG production makes it less attractive under higher prices for fossil fuels.

Under the combined tax regime CNG is the fuel of choice in the mid-class sector whereas virtually all small cars are FC vehicles running on CH_2 from nuclear energy. Both these technologies hold a significant market share in the compact car class (and the results do not show which one would be favoured in the long run); they are complemented by biofuels. The diesel FC is not introduced by the model, its high PGM loadings for the reformer make it unattractive.

	Taxes on:			
Expensive Fossils	**--**	**Pollutants**	**GHG**	**Pollutants and GHG**
Sector	**Dominating Technology**			
Small Cars	Diesel FC (70%), MeOH FC (30%)	CNG ICE (100%)	Diesel FC (98%)	CH_2 FC (99%)
Compact Cars	Diesel FC (97%)	CNG ICE (56%), EtOH ICE (34%), MeOH ICE (10%)	Diesel FC (99%)	EtOH ICE (44%), CH_2 FC (35%), MeOH FC (14%), CNG ICE (6%)
Mid-Class Cars	EtOH ICE (75%), Gasoline ICE (24%)	CNG ICE (100%)	EtOH ICE (74%), MeOH FC (23%)	CNG ICE (99%)
Fuels	Diesel (56%), EtOH from Wheat (28%), Gasoline (11%), MeOH from Scrap Wood (5%)	CNG (77%), EtOH from Wheat (17%), MeOH from Scrap Wood (5%)	Diesel (64%), EtOH from Wheat (29%), MeOH from Scrap Wood (6%)	CNG (42%), EtOH from Wheat (28%), CH_2 from Nuclear (23%), MeOH from Scrap Wood (6%)

Table 29: Dominating powertrains and fuels in 2040 in the Expensive Fossils scenario with different taxes, OECD Europe plus Turkey. Market shares are given in brackets. Technologies with a small share that are limited by resource availability are included as well.

Table 30 shows total emissions and costs in the Expensive Fossils scenario. It is apparent that -compared to the Base Case Scenario- without any taxes the higher fuel prices lead to significantly lower emissions of the substances analysed here (at a surprisingly small cost premium of 2.1%). The exceptions are SO_2 and PM where the production of the FC vehicles boasts emissions. For SO_2, the increase is very high (+66%), while that for PM is not significant (+1%).

Because of this lower baseline the reduction potential of the taxes is considerably lower. Only for SO_2 this potential is much higher because FC vehicles are already introduced in the case without taxes.

An interesting result can be seen when pollutant taxes are applied: Although ICE vehicles emit more NO_x than FC cars; the model chooses them because of the large reductions in SO_2 emissions possible. This explains why the application of these taxes leads to a small increase in NO_x emissions.

Another result worth mentioning is that emissions under a GHG tax are higher than in the corresponding case of the Base Case scenario. The reason is the following: in the Base Case the FC vehicle running on MeOH from NG dominates the market under a GHG tax. It is, however, more handicapped by higher prices for fossil primary energy carriers than the diesel FC car because its well-to-wheel efficiency is worse. Thus, the diesel FC car replaces the MeOH FC vehicle to a large extent in the Expensive Fossils scenario. This, however, leads to the higher emissions in the model.

While the higher prices for fossil primary energy carriers have only a small effect in the case without taxes (+0.4 Rp/km compared to the Base Case scenario) the increase of net cost is more pronounced with taxes (+0.8 - +1.3 Rp/km). This is equivalent to a larger effect of taxes on net costs.[29]

Tax revenues reflect the emissions of substances that are subject to taxation.

[29] The lower net costs with a GHG tax compared to the corresponding cases without such a tax is once again offset by higher costs in earlier periods, cf. 4.3.1.5 "Summary of Tax Effects in the Base Case Scenario".

Expensive Fossils	Taxes on	--	Pollutants	GHG	Pollutants + GHG
GHG	mln t CO_2-eq	400	387	379	284
	)^{1}	68%	74%	101%	73%
	)^{2}	100%	97%	95%	71%
NO_x	1'000 t	584	618	554	505
	)^{1}	70%	94%	134%	98%
	)^{2}	100%	106%	95%	87%
SO_2	1'000 t	2039	717	2119	834
	)^{1}	166%	100%	130%	86%
	)^{2}	100%	35%	104%	41%
NMVOC	1'000 t	934	535	864	492
	)^{1}	56%	71%	174%	103%
	)^{2}	100%	57%	92%	53%
PM	1'000 t	255	208	257	218
	)^{1}	101%	100%	110%	103%
	)^{2}	100%	82%	101%	86%
Cost	bln Fr98	557	592	554	575
	)^{1}	102%	108%	106%	104%
	)^{2}	100%	106%	99%	103%
Tax Revenues	bln Fr98	0	58	80	117
	)^{1}	--	92%	101%	82%
per km					
w/o taxes	Rp98/km	17.9	19.0	17.8	18.5
with taxes	Rp98/km	17.9	20.9	20.4	22.2

Table 30: Emissions and costs in the Expensive Fossils scenario in 2040 with different taxes, all classes, OECD Europe plus Turkey.)^{1}: normalised to values in the base case scenario with same tax strategy;)^{2}: normalised to values without taxes.

4.3.3 The Emerging Technologies Scenario

The assumption of lower costs for new technologies leads to significant changes compared to the Base Case scenario: without taxes, the diesel FC car is introduced in the small and compact car classes; with mere pollutant taxes, the CNG car replaces the MeOH ICE vehicle in the small car class due to the reduced costs for the tank; with a combined tax, the dominance of the fuel cell in the small sectors becomes more pronounced, and reduced electrolysis costs make hydrogen from nuclear power competitive. Only the case with a pure GHG tax is a little more difficult to analyse: the slight shift towards the diesel FC cannot be explained with the changes in the assumptions (both MeOH and diesel FC vehicles have the same absolute cost reduction); these results indicate that these two technologies have nearly the same costs in this specific case.

	Taxes on:			
Emerging Technologies	**--**	**Pollutants**	**GHG**	**Pollutants and GHG**
Sector	**Dominating Technology**			
Small Cars	Diesel FC (99%)	CNG ICE (99%)	Diesel FC (98%)	CH_2 FC (63%), MeOH FC (35%)
Compact Cars	Diesel FC (97%)	MeOH ICE (98%)	MeOH FC (99%)	MeOH FC (93%), CNG ICE (7%)
Mid-Class Cars	Gasoline ICE (99%)	MeOH ICE (100%)	MeOH FC (98%)	CNG ICE (100%)
Fuels	Diesel (58%), Gasoline (42%)	MeOH from NG (84%), CNG (16%)	MeOH from NG (75%), Diesel (17%), MeOH from Scrap Wood (8%)	CNG (45%), MeOH from NG (41%), CH_2 from NG (5%), MeOH from Scrap Wood (7%), CH_2 from Nuclear (2%)

Table 31: Dominating powertrains and fuels in 2040 in the Emerging Technologies scenario with different taxes, OECD Europe plus Turkey. Market shares are given in brackets. Technologies with a small share that are limited by resource availability are included as well.

The emissions in the Emerging Technologies scenario reflect the changes depicted above: in the cases with pure pollutant taxes or pure GHG tax they are mostly the same as in the corresponding cases of the Base Case scenario; only for NMVOC differences in excess of 3% can be observed. In the other two cases the increased use of fuel cells leads to higher emissions of SO_2 (under the combined tax regime the introduction of the less PGM-intensive CH_2 FC car partly offsets this effect) and more or less pronounced reductions of emissions of GHG, NO_x, and NMVOC.

Total net costs are lower than in the Base Case. Only under pure pollutant taxes there is nearly no effect because there are only minor changes in the technology use.

Emerging Technologies	Taxes on	--	Pollutants	GHG	Pollutants + GHG
GHG	mln t CO_2-eq	474	504	377	371
	)[1]	81%	97%	100%	96%
	)[2]	100%	107%	80%	78%
NO_x	1'000 t	588	642	418	454
	)[1]	71%	98%	101%	88%
	)[2]	100%	109%	71%	77%
SO_2	1'000 t	2100	714	1653	1086
	)[1]	171%	99%	101%	112%
	)[2]	100%	34%	79%	52%
NMVOC	1'000 t	1196	703	542	473
	)[1]	71%	93%	109%	98%
	)[2]	100%	59%	45%	40%
PM	1'000 t	256	208	235	217
	)[1]	101%	100%	101%	102%
	)[2]	100%	81%	92%	85%
Cost	bln Fr98	516	552	505	527
	)[1]	95%	100%	97%	96%
	)[2]	100%	107%	98%	102%
Tax Revenues	bln Fr98	0	61	79	141
	)[1]	--	98%	100%	99%
per km					
w/o taxes	Rp98/km	16.6	17.8	16.2	16.9
with taxes	Rp98/km	16.6	19.7	18.8	21.5

Table 32: Emissions and costs in the Emerging Technologies scenario in 2040 with different taxes, all classes, OECD Europe plus Turkey.)[1]: normalised to values in the base case scenario with same tax strategy;)[2]: normalised to values without taxes.

4.3.4 The Expensive Fossils / Emerging Technologies Scenario

In the final scenario with both higher prices for fossil fuels and more optimistic assumptions on emerging technologies the FC is the dominating technology. In the case without any taxes the diesel FC car covers nearly all the demand, also in the mid-class category, where the model chooses ICE vehicles in all the other scenarios. The only exception is a small market share that is occupied by MeOH from scrap wood. When introducing pollutant taxes, the diesel FC is replaced by less PGM-intensive alternatives like the MeOH FC or the CNG ICE. It is the only scenario where the FC is introduced under this tax regime.

Under a pure GHG tax the model chooses the FC car fuelled with CH_2 from nuclear power for the small and the mid-class car sector. In the compact car sector the diesel FC and vehicles running on biomass-derived fuels are used. With the combined tax regime, finally, the CH_2 FC dominates the market; only MeOH from scrap wood is competitive.

Expensive Fossils	**Taxes on:**			
Emerging Technologies	**--**	**Pollutants**	**GHG**	**Pollutants and GHG**
Sector	**Dominating Technology**			
Small Cars	Diesel FC (99%)	MeOH FC (73%), CH_2 FC (25%)	CH_2 FC (99%)	CH_2 FC (99%)
Compact Cars	Diesel FC (98%)	MeOH FC (90%), CNG (10%)	Diesel FC (78%), MeOH FC (14%), EtOH ICE (8%)	CH_2 FC (85%), MeOH FC (14%)
Mid-Class Cars	Diesel FC (75%), MeOH FC (25%)	CNG (100%)	CH_2 FC (98%)	CH_2 FC (99%)
Fuels	Diesel (91%), MeOH from Scrap Wood (7%)	CNG (46%), MeOH from NG (44%), MeOH from Scrap Wood (6%), CH_2 from NG (3%)	Diesel (47%), CH_2 from Nuclear (38%), MeOH from Scrap Wood (8%), EtOH from Wheat (7%)	CH_2 from Nuclear (89%), MeOH from Scrap Wood (9%)

Table 33: Dominating powertrains and fuels in 2040 in the Expensive Fossils / Emerging Technologies scenario with different taxes, OECD Europe plus Turkey. Market shares are given in brackets. Technologies with a small share that are limited by resource availability are included as well.

Without taxes, emissions of most substances are significantly smaller than in the Base Case. SO_2 emissions, on the other hand, are more than twice as high, because most of the vehicles are PGM-intensive diesel FC cars. This explains also why in this scenario any tax regime offers a significant reduction potential for SO_2.

It is worth mentioning that emission levels for GHG are exceptionally low, especially in the case of a combined tax regime. However, with the extensive use of MeOH from scrap wood and CH_2 from nuclear power the system is close to its limits in this respect.

Exp. Fossils, Emerging Technologies	Taxes on	--	Pollutants	GHG	Pollutants + GHG
GHG	mln t CO_2-eq	391	381	263	143
	)[1]	67%	73%	70%	37%
	)[2]	100%	97%	67%	37%
NO_x	1'000 t	488	457	404	297
	)[1]	59%	70%	98%	58%
	)[2]	100%	94%	83%	61%
SO_2	1'000 t	2521	1089	1657	1025
	)[1]	205%	152%	101%	105%
	)[2]	100%	43%	66%	41%
NMVOC	1'000 t	951	474	655	394
	)[1]	57%	63%	132%	82%
	)[2]	100%	50%	69%	41%
PM	1'000 t	259	215	247	235
	)[1]	102%	103%	106%	111%
	)[2]	100%	83%	95%	91%
Cost	bln Fr98	531	560	537	540
	)[1]	97%	102%	103%	98%
	)[2]	100%	105%	101%	102%
Tax Revenues	bln Fr98	0	64	55	85
	)[1]	--	101%	70%	59%
per km					
w/o taxes	Rp98/km	17.1	18.0	17.2	17.4
with taxes	Rp98/km	17.1	20.0	19.0	20.1

Table 34: Emissions and costs in the Expensive Fossils / Emerging Technologies scenario in 2040 with different taxes, all classes, OECD Europe plus Turkey.)[1]: normalised to values in the base case scenario with same tax strategy;)[2]: normalised to values without taxes.

4.3.5 Influence of the Progress Ratio

The influence of parameters characterizing the endogenous technological learning process was analysed in MARKAL runs where the progress ratio for the FC technology was 0.86 (instead of 0.82), a rather high value. This means that the learning process is significantly slower. With this high value, in many cases the FC vehicles are replaced by either the advanced gasoline car (in runs without taxes) or the CNG car (with any tax). Only in five runs (Expensive Fossils scenario with either no tax or GHG tax, Emerging Technologies scenario with GHG tax, Expensive Fossils/Emerging Technologies scenario with GHG tax or combined taxes) the FC is still introduced; the outcomes are not much affected by the slower learning process, only in the Expensive Fossils/Emerging Technologies scenario with combined taxes the FC is only introduced for a short transition period in only in the small car sector.

These results show that the progress ratios a crucial factor that is decisive for the introduction of the FC under certain circumstances.

4.3.6 Effects of a Cap on Greenhouse Gas Emissions

4.3.6.1 Description of Scenarios Analysed

As already explained earlier (3.2 "External Costs"), the optimal quantity of emissions can be obtained by either a tax or by limiting emissions to this optimal value. The latter approach has been used for GHG in a second series of runs with the MARKAL model. The results, however, are to be interpreted with much more care than when using the pure tax approach. While there are recommendations by various bodies concerning upper limits for worldwide GHG emissions and there are also suggestions of how to distribute these emissions by regions, it is difficult to devote a share of this total to the sector analysed here. Moreover, the effect of technological development beyond the state-of-the-art projected here should have a larger influence on the resulting technology park than in the case with emission taxes. This concerns both the evolution of technologies already included in the database as well as the development of new technologies.

The analysis is restricted to the Base Case scenario, i.e. constant prices for fossil primary energy carriers as well as moderate assumptions on the efficiency of the fuel cell powertrain and the costs of emerging technologies. All runs use endogenous technological learning and an elastic demand, i.e. higher transport costs (compared to the baseline without any taxes or restrictions) lead to demand decreases. The demand elasticity was –0.2, i.e. a price increase by 1% will lower the demand by 0.2%, and the maximum effect was restricted to 20% of the baseline demand. Due to modelling characteristics (threshold for reductions) this feature has only an effect in the radical reduction scenario.

The baseline for the emission caps (691 mln t CO_2-eq per year for the whole system) is the arithmetic mean of GHG emissions in 1995 and 2000 in the Base Case without any taxes[30]. Please note that these emissions are not representative for real world emissions because the vehicles in the model are assumed to have a rather low consumption compared to the total class they are representing. In the first case (stabilisation of emissions), emissions are restricted to that value from 2005 on; in the second and third case the emission cap is linearly reduced by 20% (moderate reduction) and 50% (radical reduction), respectively, starting in 2005, and is held constant afterwards. All emission caps are arbitrarily chosen, they just represent three different degrees of the need to mitigate GHG emissions.

All runs have been performed with the reference demand and the higher demand as defined in 4.2.2.1.6 "LDV Transport Demand"; the results presented here are a selection that represents the most important findings.

The analyses refer mainly to the total market rather than to the various classes if not stated otherwise. In the aggregation process, the classes are weighted with the mileage.

4.3.6.2 The Stabilisation Scenario

With the reference demand the GHG Stabilisation scenario is not a real constraint for the model: under the assumptions made total GHG emissions in the Base Case scenario are well below the caps for all periods (except 2005 in the case without taxes). As a consequence, without a pollutant tax the model chooses the advanced gasoline car, and with pollutant taxes the MeOH ICE vehicle covers all the demand by 2040.

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[30] Emissions in 1995 and 2000 differ significantly because in 1995 there is virtually no production of vehicles in the model.

The distribution of vehicle types under the assumption of the higher demand is shown in Figure 48 and Figure 49. Without pollutant taxes, the model is forced to introduce both the MeOH ICE and the diesel FC in significant amounts. With pollutant taxes, the MeOH ICE and the CNG car dominate the market. In this case the MeOH ICE car at first reaches a market share of 80% (in 2020) and is then step-by-step replaced by the CNG vehicle. In contrast to the temporary introduction of technologies in the runs without caps this pattern is quite realistic: the model uses the cheaper MeOH car as long as possible and introduces the CNG car only to the extent necessary to fulfil the GHG constraint.[31]

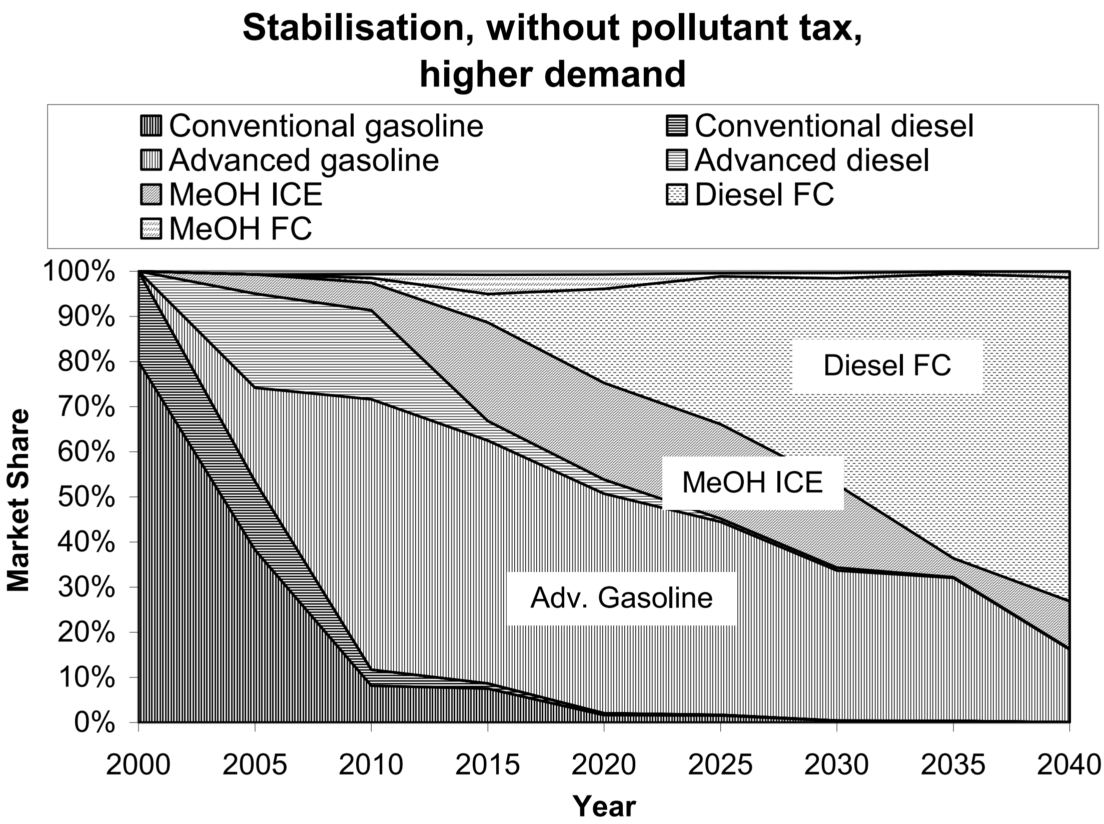

Figure 48: Distribution of vehicle types in operation in the GHG Stabilisation scenario without pollutant taxes and with higher demand, all classes, OECD Europe plus Turkey.

[31] Please note that because of the growing demand the GHG Stabilisation scenario implies a reduction of specific emissions.

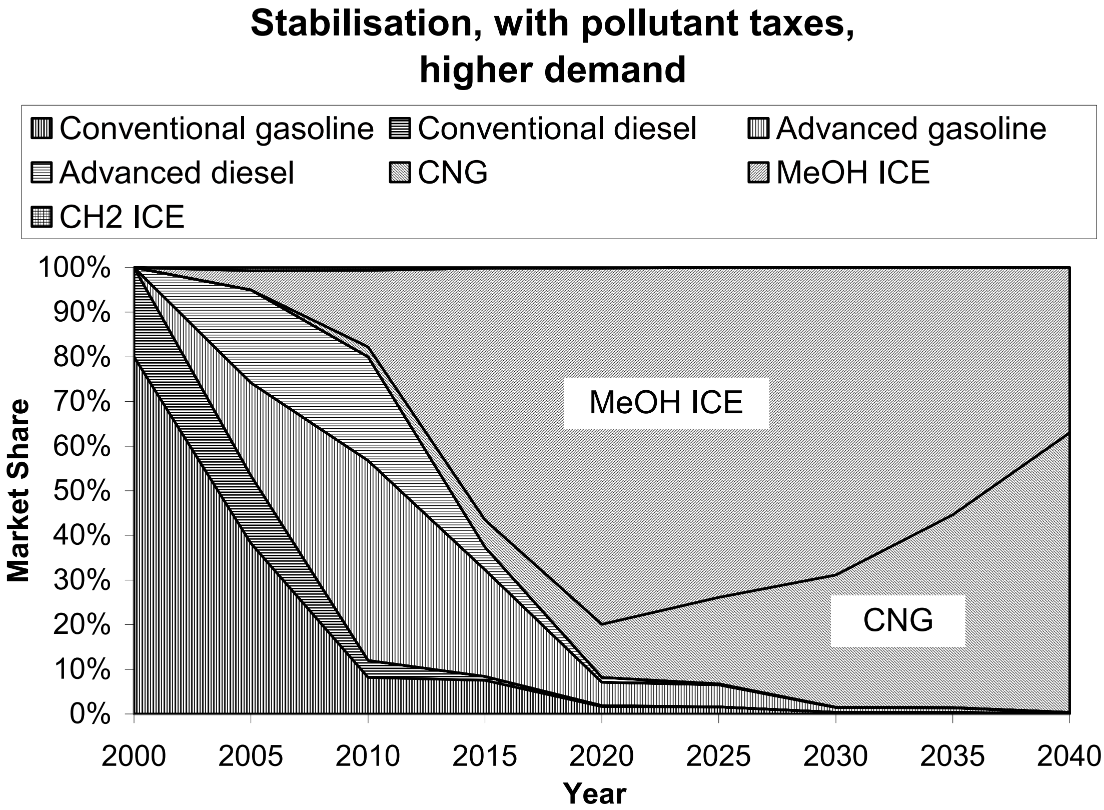

Figure 49: Distribution of vehicle types in operation in the GHG Stabilisation scenario with pollutant taxes and with higher demand, all classes, OECD Europe plus Turkey.

4.3.6.3 The Moderate Reductions Scenario

In the Moderate GHG Reductions scenario with reference demand, the evolution is similar to that in the stabilisation scenario: without pollutant taxes, the use of MeOH ICE and CNG cars rises from 2025 on to reach around one third of total market share in 2040. With pollutant taxes, the unconstrained solution already fulfils the caps so that the results are virtually the same as in the Stabilisation scenario.

When assuming the higher demand, the diesel ICE gains a larger market share in early periods. Later on, the results differ more significantly: without pollutant taxes, the diesel FC dominates the market only for an intermediate time; it is replaced mainly by the MeOH FC, but also the EtOH ICE and the CH_2 FC gain larger market shares (on the order of 10% each) in 2040. With pollutant taxes the demand in 2040 is covered by the CNG car (around 73%), the CH_2 FC vehicle and the MeOH FC vehicle.

4.3.6.4 The Radical Reductions Scenario

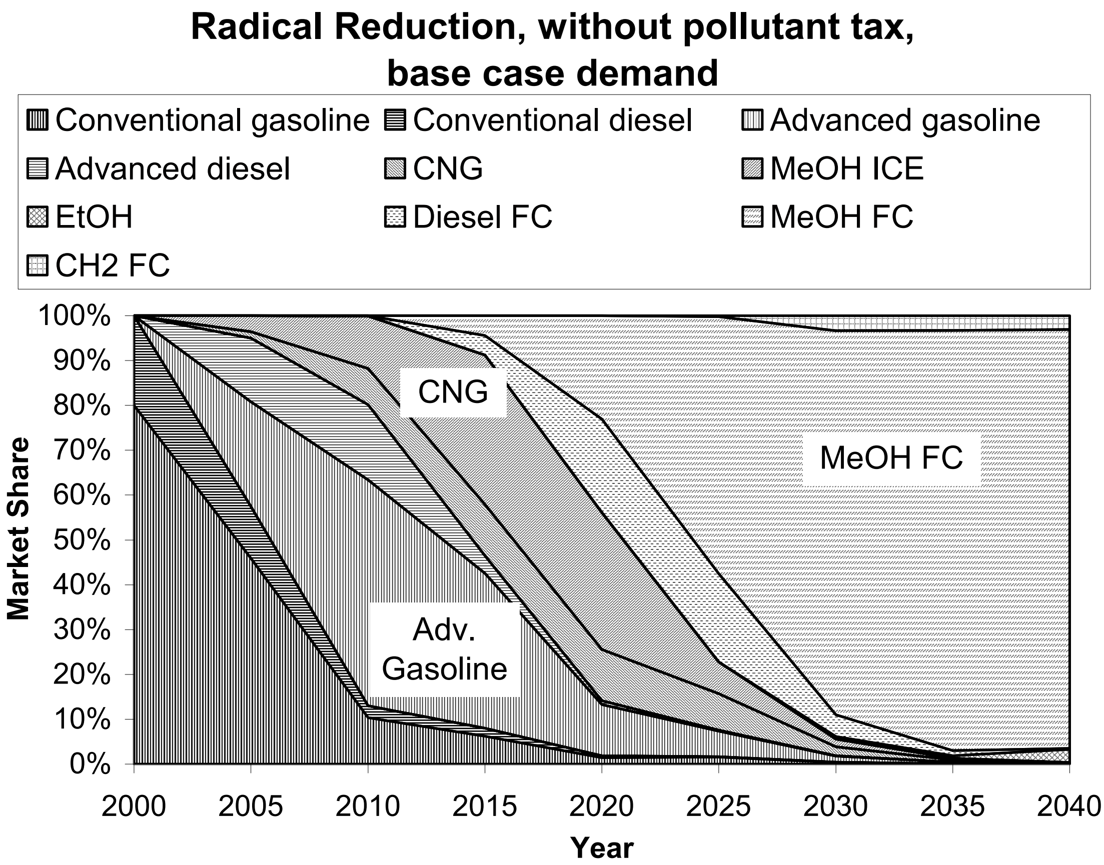

Figure 50: Distribution of vehicle types in operation in the Radical GHG Reduction scenario without pollutant taxes, all classes, OECD Europe plus Turkey.

With the reference demand and without pollutant taxes (Figure 50) advanced gasoline and diesel ICE cars as well as MeOH ICE, CNG, and diesel FC cars are introduced for a transition period. In 2040, the MeOH FC vehicle has a market share of 93%. With pollutant taxes, this share is reduced to 33%. The MeOH FC is mainly replaced by the CNG ICE car (57%); in order to comply with the GHG constraint, the model is also forced to introduce a larger share of FC vehicles running on CH_2 from nuclear power (9%).

The demand reduction due to the elasticity of demand is around 5% in the case without taxes and some 6.5% with taxes.

With higher demand, the model is forced to increase the share of FC cars running on nuclear CH_2 significantly. Their market share amounts to 56% in the case without taxes and 64% with taxes, respectively. In both cases, around 1'100 TWh of nuclear electricity are produced in 2040, the equivalent of some 110 modern NPP blocks.

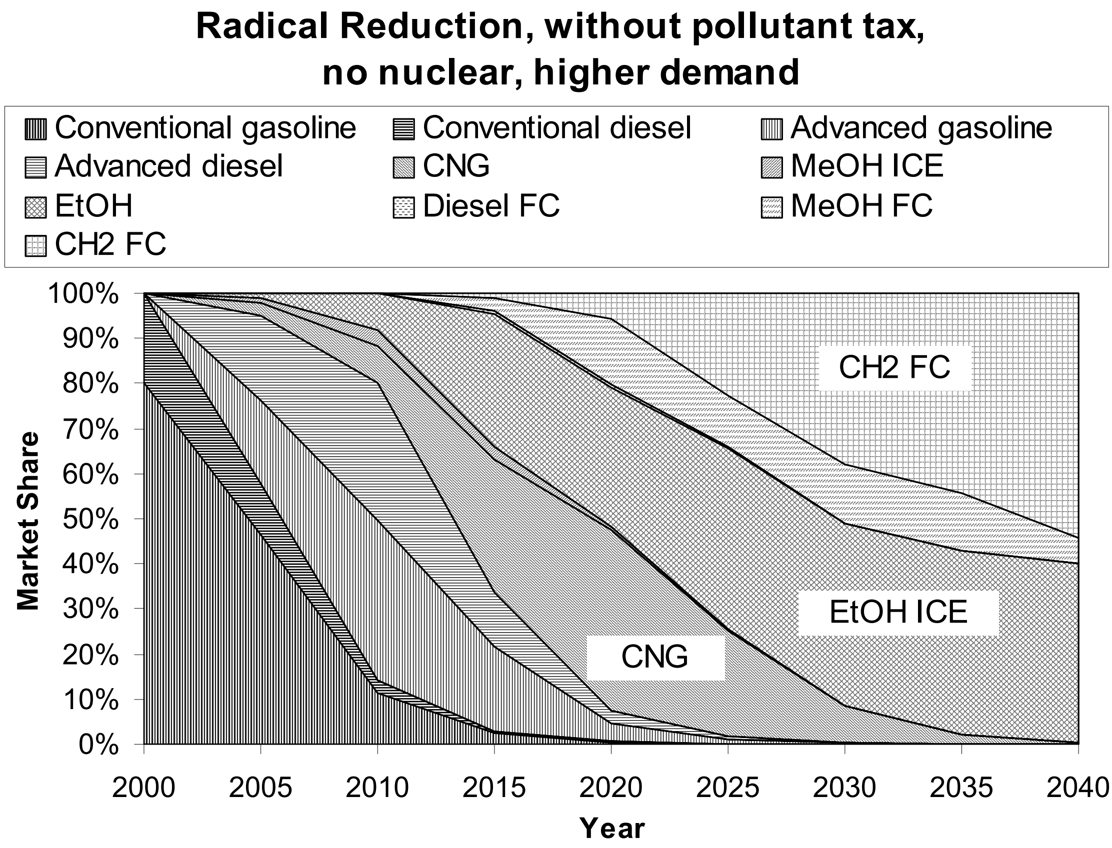

Figure 51: Distribution of vehicle types in operation in the Radical GHG Reduction scenario without pollutant taxes and no nuclear power plants, all classes, OECD Europe plus Turkey.

Replacing this considerable contribution from NPPs with other energy sources is not easy. With the availability of renewable energies as defined in section 4.2.2.1.7 "Restriction of Resource Availability" the model does not find a feasible solution, i.e. without NPPs there is no possibility to cover the higher demand without violating the GHG constraint. Even if one assumes that the availability of land rises to 20 mln ha from 2030 onwards, that twice as much scrap wood and rooftop area (for the production of hydrogen from PV electricity) is available, around 1'500 PJ of electricity from wind turbines are needed; this is more than even optimistic estimates for the on-shore potential of this technology in Western Europe (see e.g. [Wolf et al. 2000]). Thus a large fraction of this energy has to be produced offshore where both economic and LCI data used here are probably at best a very rough approximation. Nonetheless the results from these runs lead to interesting new insights, see Figure 51.

The technologies to cover final demand in 2040 are the CH_2 FC car (54%), the EtOH ICE car (40%) and the MeOH FC car (6%). The fuels are all produced from so-called renewable sources: hydrogen from wind (90%) and PV (10%), EtOH from sugar beets and MeOH from scrap wood. Sugar beets are used although this feedstock leads to noticeably higher costs than wheat because it offers the potential to produce more EtOH per unit of arable land.

The demand in 2040 is reduced by around 13% compared to the base case.

The results for 2040 change only slightly with the introduction of pollutant taxes. The strict GHG constraint reduces the set of feasible solutions to such an extent that only little variations are possible.

4.3.6.5 The Costs of Mitigating GHG

To have an idea of the costs for mitigating GHG emissions, Table 35 summarises the total system costs for various scenarios. All figures are for cases with reference demand and without pollutant taxes. The reference case is the Base Case scenario without any taxes, see 4.3.1.1 "The Base Case Scenario without Taxes". The first figure in each row is the total discounted system cost; this is the quantity to be minimised in the optimisation process. The second number is the arithmetic means of undiscounted annual system cost in 2035 and 2040[32]; this figure is less representative for the entire case, but it can help to derive some important findings and put the numbers in a more intelligible perspective. It also offers a valuable check because the first periods (where the different scenarios differ relatively slightly in their boundary conditions) contribute more than the later ones.

[32] This operation eliminates the effects of oscillatory investment volumes.

Reference Demand		Total Discounted Cost	Cost in 2035 / 2040 (undiscounted)
No Constraint	bln Fr98	10'190	534
	)[1]	100.0%	100.0%
Stabilisation	bln Fr98	10'190	533
	)[1]	100.0%	100.0%
Moderate Reduction	bln Fr98	10'210	535
	)[1]	100.2%	100.3%
Radical Reduction	bln Fr98	10'360	491
	)[1]	101.7%	91.1%

Table 35: Total discounted system costs and system costs in 2040 for GHG reduction scenarios without pollutant taxes and with reference demand, all classes, OECD Europe plus Turkey.)[1]: Compared to unconstrained reference case.

As already mentioned above already in the unconstrained case emissions drop significantly by 2040. Thus in the Stabilisation and the Moderate Reductions scenarios only minor changes are necessary to comply with the imposed constraints and, hence, costs are only slightly affected. In the radical reduction scenario total discounted costs rise by 1.7%. Overall costs in 2040, however, are lower by nearly 9%. This significant reduction has two reasons: on the one hand, earlier investments into learning technologies (especially the FC) lead to lower specific costs, and on the other hand, the demand is reduced due to the assumed elasticity of this quantity with respect to price.[33] The marginal cost for GHG abatement in the radical reduction case is around 350 Fr/t CO_2-eq in the last two periods, around 1.7 times the GHG tax rate assumed in this study.

[33] The demand is lower in spite of lower specific costs because the elasticity refers to the **marginal** price, not the average price.

Higher Demand		Total Discounted Cost	Cost in 2035 / 2040 (undiscounted)
No Constraint	bln Fr98)[1]	12'360 100.0%	818 100.0%
Stabilisation	bln Fr98)[1]	12'530 101.4%	796 97.2%
Moderate Reduction	bln Fr98)[1]	13'080 105.8%	802 98.0%
Radical Reduction	bln Fr98)[1]	13'120 106.1%	786 96.1%
Radical Reduction, no nuclear power plants	bln Fr98)[1]	13'230 107.0%	760 92.8%

Table 36: Total discounted system costs and system costs in 2040 for GHG reduction scenarios without pollutant taxes and with higher demand, all classes, OECD Europe plus Turkey.)[1]: Compared to unconstrained reference case.

When referring to the cases with higher demand, the cost premium is significantly higher: already in the Stabilisation scenario it amounts to 1.4% of the total costs, with marginal abatement costs in excess of 160 Fr/t CO_2-eq in 2040. In the Moderate Reduction scenario the total costs rise by 5.8% compared to the unconstrained case, and marginal abatement costs reach nearly 580 Fr/t CO_2-eq in 2040. However, this run is exceptional in that it shows very large fluctuations in investments: in 2035 these costs are only 60 Fr/t CO_2-eq.

In the Radical Reduction scenario the additional costs for GHG abatement amount to 6.1%, at a marginal abatement cost of 350 Fr/t CO_2-eq in the last periods. Finally, the premium reaches 7% if no nuclear power plants are allowed in the Radical Reduction scenario[34], and marginal abatement costs climb to around 1'500 Fr/t CO_2-eq – an unrealistically high value. However, the fact that total costs are only slightly higher than

[34] In the case without NPP the availability of renewable energy sources is roughly twice as high as in the case with NPP. Assuming this higher availability in all runs would probably increase the gap between these two cases. The difference between the Radical Reduction scenario without NPP and the

in the case with nuclear power plants indicates that most of the reductions could be achieved at much lower specific costs.

The reduced costs in the last periods indicate that the difference between constrained and unconstrained cases would be further reduced if one chose a longer time horizon for the study.

4.4 Analysis of the Results and Conclusions

The conclusions that can be drawn from these results can be grouped in two categories: conclusions concerning the applicability and appropriateness of the approach and those concerning the evaluation of the different technologies analysed.

4.4.1 The Approach Used

The basic concept of the approach was the adaptation of the MARKAL model to two non-standard features:

1. the integration of LCI data into the MARKAL model; compared to most other MARKAL applications this means the introduction of the cradle-to-grave concept (including the production of vehicles and fuel chain infrastructure) as well as a significant expansion of environmental parameters (i.e. emitted substances or substance classes).

2. the analysis of the LDV market in a large region (Western Europe); this market differs significantly in its structure from the energy market that is usually explored with this model.

Both aims could be accomplished in a rather straightforward way. Life-cycle emissions were represented by splitting them up in those proportional to the production of vehicles or process infrastructure and those proportional to actual use[35]. This concept worked out

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unconstrained Reference Case would remain the same, however, for in the Reference Case none of these renewable energy sources are used

[35] Emissions from disposal were negligible for most of the processes under consideration. They were included in the figures for production.

properly. The main methodological problem is the simple representation of the LDV sector: Total demand was split up in three categories (small cars, compact cars, mid-class cars). The dynamics of the market are nearly unconstrained, only the growth (and decline) of vehicle technologies was restricted. This very simple model could not produce realistic dynamics of the market development: In some runs the cheapest technology cannot replace the conventional powertrain to the desired extent, and so additional technologies are introduced that fade out after a few periods. Under GHG constraints, however, the development path is much more realistic, mainly, because the effective pressure gradually phases in and so the system has time to evolve. Nonetheless the introduction of new technologies is a weak point in the model. One must not forget that the hurdles from placing the required infrastructure for an alternative fuel are quite low in the model.

Another shortcoming is that the model treats all vehicles as having the same use for the driver or owner. Factors like driving comfort (including refilling time), safety issues or the image of a car are not considered at all although they might be decisive for the customer's purchasing decision.

When analysing the consequences of an emission cap, the standalone model for the LDV sector is handicapped by the need to allocate an appropriate share of emissions to this sector. In the existing form the model can tell which technologies to use in order to obtain reductions of emissions (mainly GHG) in the transport sector if they are necessary. It does not tell whether these reductions are necessary to reach a certain emission level. An extension to include at least the whole energy sector and the most important transport modes would solve this problem.

But despite all these drawbacks the MARKAL model with LCI data has proven to be already a very useful tool for the assessment of different powertrains and fuels. Although the dynamics in the transition phase are for sure not realistic, the resulting distribution in around 2040 represents a good evaluation of which technologies are favoured by the market under given boundary conditions and assuming that qualities not considered in this study (such as driving comfort or image) are of minor importance for the ranking of different technologies. Compared to an analysis based on static cost calculations (with or without environmental taxes) it allows considering features such as restricted resource availability, exogenous and endogenous technological learning, elastic demand functions or sector-wide emission caps. All these additional effects influence the output of the model in a very distinguished way.

The disadvantages mentioned above are not inherent to the model but are insufficiencies of the representations of demand and supply side chosen here and can thus be overcome by refining the model (see section 4.4.3 "Improving the Model").

4.4.2 Evaluation of Technologies

Table 37 presents an overview over the results of the various runs.

The results of the various runs show how parameters such as fossil fuel prices or the valuation of health and environment (that are implicitly expressed in the pollutant and GHG taxes applied) influence the ranking of technologies in the cost analysis.

Cars with ICE powertrain:

Gasoline: The gasoline ICE car is the dominant technology under today's boundary conditions and still holds significant market shares under rising prices for fossil fuels or with optimistic assumptions on emerging technologies (at least in the mid-class sector where the energetic superiority of the FC powertrain is less pronounced). It also has the potential to meet relatively weak GHG reduction aims, but is replaced by alternative technologies under more stringent caps. Pollutant taxes make this fuel rather unattractive; especially emissions from the fuel chain would have to be considerably reduced in order to make this alternative competitive.

Diesel oil: In none of the runs made here the diesel ICE car holds a significant market share in 2040. Only in some GHG cap scenarios it is of intermediate importance. As was already said before a different use pattern (higher mileage) might make this car superior to the gasoline vehicle in the Base Case without taxes. It would also profit from cheap technologies to efficiently reduce direct emissions of NO_x and PM, and from emission reductions in the oil chain.

	Pure Tax Approach																GHG Caps													
Scenario	Base Case				Expensive Fossils				Emerging Techno-logies				Exp. Foss. Emerging Techn.				Stab Ref		Stab Hi		Mod Ref		Mod Hi		Rad Ref		Rad Hi		Rad Hi no Nuke	
Taxes	no	po	gh	co	no	po	gh	co	no	po	gh	co	no	po	gh	co	no	po	no	po	no	po	no	po	no	po	no	po	no	po
ICE:																														
Gasoline	x				x				x								x	(x)	x	(x)	x	(x)			(x)	(x)			(x)	
Diesel																							(x)	(x)			(x)	(x)		(x)
CNG				x		x		x		x		x		x						x	x			x		x	(x)	x	(x)	(x)
MeOH from NG		x								x								x	x	x	x	x		(x)	(x)	(x)				
MeOH from Poplar																														
MeOH f. Scrap Wood						x																			(x)	(x)	(x)			
EtOH f. Sugar Beet																													x	x
EtOH f. Wheat					x	x	x	x							x								x							
RME																														
CH_2 f. NG																														
CH_2 f. NPP																														
CH_2 f. Wind, PV																														
FC:																														
Diesel			x		x		x	x	x		x		x		x				x				(x)							
MeOH from NG			x	x							x	x		x									x		x	x	x			
MeOH f. Poplar																														
MeOH f. Scrap Wood			x	x	x		x	x			x	x	x	x	x	x							x	x	x	x	x	x	x	x
CH_2 f. NG														x																
CH_2 f. NPP												x			x	x								x		x	x	x		
CH_2 f. Wind, PV																													x	x

Table 37: Summary of results for OECD Europe plus Turkey. **x** stands for a technology that has a significant market share (> 5% of all classes) in 2040, (x) for a technology that is only introduced for a transition period and gains a market share of at least 20% of all classes at any time. The abbreviations in the "Scenario" line read: Stab – Stabilisation, Mod – Moderate Reduction, Rad – Radical Reduction, Ref – reference demand, Hi – higher demand, no Nuke – no nuclear power plants. The abbreviations in the "Taxes" line stand for: no – no taxes, po – pollutant taxes, gh – GHG tax, co – combined taxes.

CNG: The high efficiency of the CNG powertrain (compared to gasoline), small pollutant emissions in the fuel chain and the low carbon intensity of the primary energy carrier make this fuel attractive under a large variety of boundary conditions; it is introduced by the model especially in runs with pollutant taxes or combined taxes. It is very effective to mitigate GHG emissions, too: it is the only ICE vehicle running on fossil fuels that has a significant market share in 2040 in any of the radical reduction scenarios. The question whether the CNG ICE is cheaper than the FC depends, however, to a significant extent on two parameters: the cost and (with pollutant taxes) the PGM requirements of the FC powertrain.
These findings are representative for the so-called dedicated-fuel vehicle only; a flexible-fuel vehicle with a gasoline backup cannot be optimised for the higher octane number of NG and therefore has a lower efficiency.

MeOH from NG: Due to its lower investment cost the MeOH vehicle outperforms the CNG car in some cases with pollutant taxes; it also proves a cost-effective technology for moderate GHG mitigation; at significantly higher prices for fossil fuels, however, it becomes more expensive than the CNG car due to the lower efficiency of MeOH production compared to NG compression.

MeOH from Poplar: This technology is not chosen by the model in any run. Its costs are prohibitively high. Because of its large reduction potential for GHG and the high yield per ha of arable land it might become competitive under an extreme GHG cap scenario that goes beyond the reductions in the Radical Reductions scenario defined here. However, it is likely that it would then be used preferably in a FC vehicle.

MeOH from Scrap Wood: This fuel is only burned in ICE cars as long as no FC vehicles are available that use MeOH at a much higher efficiency. Only in one case where the market is not large enough for FC vehicles to move down on the experience curve the ICE vehicle running on MeOH from scrap wood is still present in 2040.

EtOH from Sugar Beet: This fuel is only used in the two runs with radical reduction of GHG and no nuclear power plants. The model prefers it in these runs to EtOH from wheat mainly because sugar beet offers a much higher yield (l EtOH per ha). The slightly better GHG balance with this feedstock plays only a minor role.

EtOH from Wheat: EtOH from wheat offers significant reductions of GHG at medium prices. It is favoured by increased prices for fossil energy and GHG taxes. However, emissions of classical pollutants are relatively high. The potential for EtOH from wheat, however, is a complex function of many factors: minimum achievable biomass costs, available arable land, competing forms of land use, or restrictions implied by crop rotation, to name just a few.

RME: Under the assumptions made the MARKAL model does not choose RME in any run. The costs of this fuel are too high in comparison to the possible emission reductions. Alternative uses of rapeseed oil, e.g. as tractor fuel (without transesterification) have not been assessed in this study.

Hydrogen: Whenever the model introduces hydrogen this is used in FC vehicles. In addition, the calculations in chapter 3 "Costs of Fuels and Vehicles" show that due to its high costs hydrogen cannot compete with other ICE fuels. If the FC turns out to be prohibitively expensive hydrogen as a motor fuel will probably only be competitive in as case of extreme GHG emission reductions.

Fuel Cell Vehicles:

General: Despite the high initial investments necessary to drive the FC down the experience curve this technology is introduced in many model runs: although even in later periods investment costs are higher than those for ICE cars, the better efficiency and (to a smaller extent) the negligible direct emissions of classical pollutants make the FC powertrain very attractive. However, if the ambitious, but realistic floor costs cannot be reached in the long run or the learning process proceeds considerably slower than assumed in these runs, the situation might be completely different.
Another important parameters in all runs involving pollutant taxes are the PGM requirements of the powertrains: both specific loadings and the production of the metals have a considerable optimisation potential that might drive down life-cycle SO_2 emissions significantly. On the other hand one must not forget that the shares of around 70% recycled material are a very ambitious goal, even in the long run.

Diesel: The diesel FC car enters the market in many runs; due to the very high PGM loadings assumed here it is, however, particularly penalised by a tax on SO_2 emissions.

Its ability to reduce GHG emissions (compared to the gasoline ICE car) is moderate, too.

MeOH from NG: This fuel is used in FC vehicles especially under GHG and combined taxes, but also in scenarios with GHG caps that call for a significant, but not yet drastic reduction of specific emissions.

MeOH from Poplar: Even when used in a FC powertrain this fuel is too expensive to be competitive in any of the cases considered here. MeOH from poplar has to be considered an option for extreme GHG reduction scenarios only where it is likely to be used in a FC powertrain (see above).

MeOH from Scrap Wood: This powertrain / fuel combination turns out to be the most widely used of all alternatives analysed. It combines a large GHG reduction potential with moderate emissions of classical pollutants and attractive costs. Nonetheless one has to keep in mind that this GHG reduction potential is a result of crediting the carbon uptake during biomass growth completely to the scrap wood: if a significant share of the CO_2 credits is allocated to the primary use of the wood, total CO_2 and GHG emissions might be even higher than those from the gasoline ICE car (cf. 2.4.8.5 "Scrap Wood Credits").

Hydrogen: CH_2 is nearly exclusively produced from nuclear power or (if no NPP are available) from wind and PV electricity. The model profits from the ability of these fuels to significantly reduce specific GHG emissions (all cases where electrolytic CH_2 is introduced have either a tax or a cap on GHG emissions). Only in one case it turns out to be preferable to produce CH_2 from NG in central stations. Because of the model's limited availability to represent development and market penetration processes in a realistic way this does not necessarily mean that small-scale production of CH_2 from NG does not make sense in niche markets or for a transitional period. However, the results imply that in the long run the large advantage of hydrogen is the possibility to produce it from nearly GHG-free energy carriers such as nuclear power or renewable energies.

4.4.3 Improving the Model

Most of the drawbacks mentioned above (section 4.4.1 "The Approach Used") can be overcome by further developing the model. In the area of technology characterisation the long-term improvement potentials should be assessed not only for the powertrains, but also of some other processes like crude oil refining or fuel production from biomass. With this data a gradual improvement of technologies (either time-dependent or by ETL) can be modelled. Moreover, alternative technologies should be considered. Additional powertrain configurations might include parallel and series hybrid ICE vehicles, but depending on the purpose of the study one might also think of more detailed distinctions; FC cars running on carbonaceous fuels might be equipped with different reformers and gas clean-up systems, those fuelled with CH_2 with different technologies for fuel storage.

Additional technologies for fuel production might include facilities to convert coal and NG into liquid fuels (especially if the availability of crude oil is restricted), but also other renewable energy sources like wood-to-hydrogen processes or the possibility to import solar hydrogen from Northern Africa. If the whole energy sector (i.e. electricity, process heat, residential heating, and the most important transport modes) were included it would also make sense to extend the distribution step to a pipeline net for hydrogen.

The extension of the analysis to the whole energy and transport sector would also solve the problem of assigning appropriate emissions rights or resources to particular sectors; the model would automatically find the optimal solution for the total system. The integration of the whole energy market with LCI data, however, is quite a tedious task: In order to avoid double counting all energy requirements during infrastructure and car production have to be explicitly included in the model and subtracted from the corresponding demand projections.

Another promising option is a more detailed representation of biomass production that takes into account that yields vary with time and space, that there might be limitations imposed by crop-rotation rules or overall optimisation potentials by varying fertiliser use (N_2O emissions from nitrogen fertilisers). Yet the biomass share of total energy demand is relatively small, so these improvements might be only important for analyses focusing on the production of biomass.

Other improvements concern the internal structure of the model. I already mentioned the need to refine the demand side of the model. For example the demand for LDV transportation services is much more inhomogeneous than the three demand sectors (corresponding to three classes of vehicle size) suggest. Other classifications might refer to the average yearly mileage, the wish to drive a more powerful car than those assumed in this study, or the preference for a specific powertrain for reasons of convenience and/or image (that can be expressed as a willingness to pay a higher price for this powertrain).

Closely related is the development and implementation of features that allow better modelling of the introduction of alternative fuels and new powertrains (market penetration models).

Another important aspect is the representation of data uncertainty. Further development of the approach might address this problem in an integrated way, e.g. by using stochastic models.

5 Summary of Results and Outlook

The study has assessed car powertrains and fuels on three different levels: at first, a conventional Life-Cycle Assessment (LCA) has been carried out. In a second step data from the LCA and costs have been combined by application of hypothetical emission taxes. Finally, all these data have been included into an energy-planning model called MARKAL that allows considering additional aspects such as restricted resource availability or learning curves.

The LCA shows that many alternative technologies offer the potential to reduce most emissions, compared to the gasoline- or diesel-fuelled car with combustion engine. It also shows some weak points of alternative technologies, such as high emissions of classical pollutants from most biofuel chains, high SO_2 emissions from the production of the fuel cell powertrain, or high energetic requirements to produce today's photovoltaic cells. The fuel cell proves to be superior to the internal combustion engine in most cases: higher emissions in the production phase are more than outweighed by the higher efficiency of this powertrain. Only in cases of fuels with very small emissions over the whole life cycle (provision and combustion) the fuel cell is at a slight disadvantage.

In sensitivity analyses the influence of data uncertainty and the state-of-the-art, but also of assumptions that the LCA practitioner has to make, has been analysed.

The results of the LCI show also that the data available today on emissions of particulate matter are not sufficient to represent these emissions in an adequate way. A more detailed distinction of these emissions, at least by size, is necessary.

The static cost analysis shows that in a business-as-usual scenario (no emission taxes, constant prices for fossil primary energy carriers) alternative technologies will hardly find their way into market. With emission taxes and/or increasing prices for fossil fuels the gasoline and diesel car become less attractive. Promising candidates are then mainly the natural gas vehicle and the fuel cell car, especially in combination with methanol that is produced from scrap wood. Hydrogen, however, becomes competitive only under a combination of favourable assumptions.

The runs with MARKAL refine the results of the static cost analysis. They show that with escalating prices for fossil primary energy carriers biofuels become competitive. The fuel cell vehicle is introduced under varying boundary conditions; its biggest advantage over the internal combustion engine is its high efficiency that makes it environmentally friendlier in the case of emission-intensive fuels and much less costly when fuelled with fuels that are nearly emission-free (and generally expensive). In particular, it proves to be superior when hydrogen is used to fuel the vehicles.

If there is one general statement that considers all the findings from the various chapters, then it is probably the following one: The ranking of different technologies is a very complex function of technological, economic, ecological, and societal parameters. Not only improvements or setbacks in the development of technologies make a re-assessment necessary, but also new scientific results or changes in society's value system.

This conclusion has a very practical meaning. It underlines the necessity to develop different alternatives, not to focus on one or two technologies only. Of course, limited availability of resource (i.e. money) makes it necessary to restrict research, development and demonstration to the most promising technologies, so the technologies should be regularly assessed.

The method developed in this thesis, the integration of life-cycle assessment and energy-planning models, can significantly enhance understanding potentials of competing technologies. It offers the possibility to include various aspects (e.g. costs, life-cycle emissions, resource availability and competing uses, learning potentials) in a consistent way. To make proper use of it the following points have to be respected:

- The model does not make decisions; it finds optimal solutions with respect to a specific objective function in specific scenarios and boundary conditions. Both objective function and scenarios are defined by the decision maker; they represent his value system and/or his estimates of boundary conditions.

- The model is especially suited for problems with the following characteristics:
  - + national or international level; otherwise, some features, in particular the model for endogenous technological learning, will not lead to useful results,
  - + time horizon of at least some 20 years; this corresponds to two vehicle generations, and in a shorter time it is difficult to obtain meaningful results with this approach,
  - + large influence of the decisions to be made on the total economic system; otherwise a less complex (and less data-intensive) model will provide results much faster.

  In other cases the model can be used as well but one cannot exploit all its potential, and a less sophisticated (and thus less time-consuming) approach might be preferable.

Although there is still a large optimisation potential the approach used has proven to be a valuable tool to support decision-making.

The most promising directions for the further development of this approach are:

- The extension to cover the total transport, the electricity and the heat sector. This step is particularly important for more detailed analyses of the effect of greenhouse gas caps because it allows allocating emissions to the different sectors in the most efficient way.
- The consideration of additional technologies. An alternative powertrain that is worth being included is the hybrid drivetrain where both an electric motor and an internal combustion engine are used in either parallel or serial configuration. Other interesting technologies are the production from alternative fuels such as hydrogen or methanol from fossil energy carriers others than natural gas, carbon sequestration technologies, or alternative forms of solar energy, e.g. the import of electricity or hydrogen that was produced in large plants in the Sahara.

Finally, a competing use for scrap wood should be included to verify the very good performance of the scrap-wood-to-methanol process.

- The refining of the demand side of the model. A more heterogeneous demand that better reflects the car driver's personal conditions (e.g. yearly mileage) and preferences (e.g. for a car that is more comfortable to drive) could offer additional insights concerning the long-term potential of technologies in the market.

Of course, changing the focus of the study might lead to different developments of the approach. A correct modelling of the dynamics, for instance, requires a sophisticated market penetration model the different fuels and powertrains, and a shift of the focus towards biomass-derived fuels needs a more detailed and regionally differentiated representation of agricultural processes.

The analyses presented in this work are based on today's knowledge. New developments in the spheres of legislation or technology, but also changing prices for fossil fuels or other resources, might call for an up-date of these analyses. A complete reassessment should be envisaged for the time when first practical experience with series-produced fuel cell vehicles (start of production is announced for 2004/05) is available.

Appendix 1 Weighing Factors for the Impact Assessment

		GWP_{100}
		kg CO_2-eq.
Direct Effects:		
C_2F_6	kg	9200
CF_4	kg	6500
CH_4 Methane*	kg	21
CO_2 Carbon Dioxide	kg	1
Methylene Chloride	kg	9
H 1211 Halon**	kg	4900
H 1301 Halon	kg	5400
N_2O Laughing Gas	kg	310
R11 CFC	kg	3800
R113 CFC	kg	4800
R114 CFC	kg	9300
R115 CFC	kg	9300
R12 CFC	kg	8100
R13 CFC	kg	11700
R134a HFC	kg	1300
R141b HCFC	kg	630
R142b HCFC	kg	1800
R22 CFC	kg	1500
SF_6	kg	23900
Carbon Tetrachloride	kg	1400
$CHCl_3$ Chloroform	kg	4
Indirect Effects:		
CO Carbon Monoxide	kg	3
NMVOC	kg	11
NO_x Nitrogen Oxides	kg	40

Table 38: Global Warming Potentials used in this study. *: includes indirect effects; **: taken from [Saur & Eyerer 1996].

		POCP
		kg C_2H_4-eq
Acetaldehyde	kg	0.527
Acetic Acid	kg	0.416
Acetone	kg	0.178
Acroleine	kg	0.443
Alcanes	kg	0.398
Aldehydes	kg	0.443
Alkenes	kg	0.906
Aromatic HC	kg	0.761
BaP Benzo(a)pyrene	kg	0.761
Benzaldehyde	kg	-0.334
Benzene	kg	0.189
1,3-Butadiene	kg	0.906
Butane	kg	0.3625
Butene	kg	0.9755
C_2F_6	kg	0.021
Carbon Tetrachloride	kg	0.021
CF_4	kg	0.021
$CFCl_3$	kg	0.021
CH_3Br	kg	0.021
CH_4 Methane	kg	0.007
Chloroform	kg	0.001
Cycloalkanes	kg	0.398
Ethane	kg	0.082
Ethanol	kg	0.268
Ethene	kg	1
Ethine	kg	0.168
Ethylbenzene	kg	0.593
Ethylen Dichloride	kg	0.021
Ethylene Oxide	kg	0.416
Formaldehyde	kg	0.421
H 1211 Halon	kg	0.021
H 1301 Halon	kg	0.021
Heptane	kg	0.529
Hexachlorobenzene HCB	kg	0.021
Hexane	kg	0.421

Table 39: Values for POCP used in this Study. Source: [Dinkel et al. 1996].

		POCP
		kg C_2H_4-eq
Methanol	kg	0.123
Methylene Chloride	kg	0.01
MTBE	kg	0.416
NMVOC	kg	0.416
PAH Polycyclic Aromatic HC	kg	0.761
Pentachlorobenzene	kg	0.021
Pentachlorophenol PCP	kg	0.021
Pentane	kg	0.352
Phenol	kg	0.761
Propane	kg	0.42
Propene	kg	1.03
Propionaldehyde	kg	0.603
Propionic Acid	kg	0.416
R11 CFC	kg	0.021
R113 CFC	kg	0.021
R114 CFC	kg	0.021
R115 CFC	kg	0.021
R12 CFC	kg	0.021
R13 CFC	kg	0.021
R134a HFC	kg	0.021
R141b HFC	kg	0.021
R142b HFC	kg	0.021
R22 HCFC	kg	0.021
Styrene	kg	0.416
Toluene	kg	0.563
Vinyl Chloride	kg	0.021
Xylenes	kg	0.851

Table 39: cntd.

		AP
		SO_2-eq
Carbon Tetrachloride	kg	0.83
H_2S Hydrogen Sulfide	kg	1.88
HCl Hydrochloric Acid	kg	0.88
Hexachlorobenzene HCB	kg	0.67
HF Hydrofluoric Acid	kg	1.6
NH_3 Ammonia	kg	1.88
NO_x as NO_2	kg	0.7
SO_2	kg	1

Table 40: Values for AP used in this study. Source: [Saur & Eyerer 1996], own calculations

		EP (Air)
		kg PO_4^{3-}-eq
NH_3 Ammonia	kg	0.33
Nitrates	kg	0.42
NO_x as NO_2	kg	0.13
P Phosphorus	kg	3.06

Table 41: EP for airborne emissions as used in this study. Source: [Saur & Eyerer 1996].

Appendix 2 The QSS-Toolbox

This text gives only a short introduction into the QSS-toolbox (quasistationäre Simulation) developed by L. Guzzella and A. Amstutz at ETH Zürich [Guzzella & Amstutz 1997]. The basic principle is to reverse physical flows of energy, force and angular momentum: starting from a given driving cycle the model computes acceleration, angular momentum at wheel, transmission, motor, and finally consumption of fuels in engines, motors and reformers in discrete time steps (normally 1 second).

The following formula symbols are used in Figure 52 to Figure 54 for physical quantities:

eta	efficiency
P	power
T	angular momentum
U	voltage
v	velocity
w	angular velocity
V, W	average consumption
x_tot, S_F	distance

A "d" denotes a derivative with respect to time.

The following letters describe at which device the quantities are taken:

rad	wheel
GT, G	gearbox/transmission
VM	internal combustion engine
EM	electric motor
BZ	fuel cell
SC	supercapacitor
H2	tank

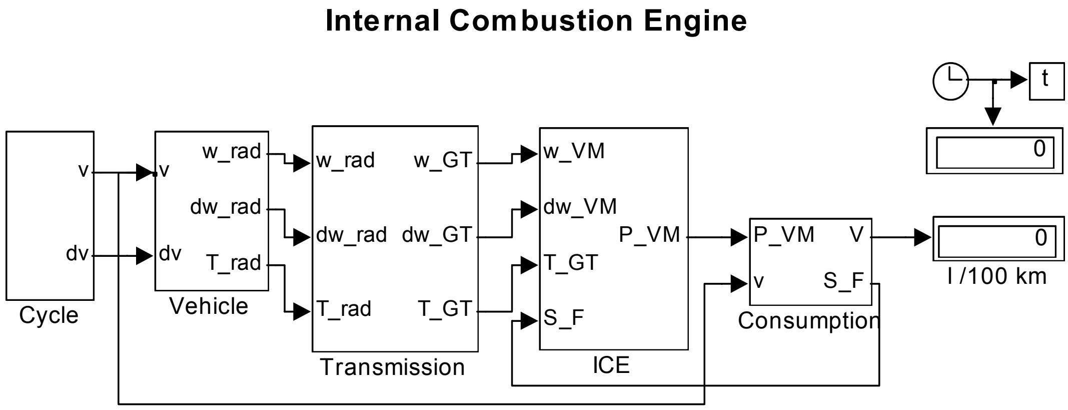

Figure 52: Top level of the model for an ICE-driven car. Cf. text for details.

Figure 52 shows the top level of a model for an ICE-driven car. Data flow is from left to right: for each time step, in the block "Cycle" the speed (v) and the acceleration (dv) are provided. The "Vehicle" block transforms this into angular velocity and acceleration and torque at wheel (w_rad, dw_rad and T_rad, respectively). In the following "Transmission" block the corresponding values at the power input of the gearbox are calculated. The gear that is chosen is either prescribed by the cycle (NEDC) or chosen by a function inside the "Transmission" block (FTP cycle). The "ICE" block uses this information together with the engine map to calculate the fuel consumption P_VM. In the "Consumption" block P_VM is summed up over all time steps and then divided by the total driven distance (sum of v times length of time step). The final block "l/100 km" is just a display, like the block in the upper right corner that shows the simulation time. The model stops automatically when the test cycle is run through.

Each of the blocks can be represented in a similar diagram. As an example, Figure 53 shows the structure of the "Transmission" block. On the extreme left the input values are shown, on the extreme right output values. The "Mux" block builds a vector of angular speed at wheel w_rad and torque at wheel T_rad which serves as input for the MATLAB-function "find_gear". This simple function determines the gear from these variables. The output is the transmission ratio for that time step. In the bottom line first the reciprocal value of this ratio is calculated and then divided by the gearbox efficiency eta_G. In the rectangular blocks on the right (marked with a cross) the input values are multiplied to give the output of the whole "transmission" block.

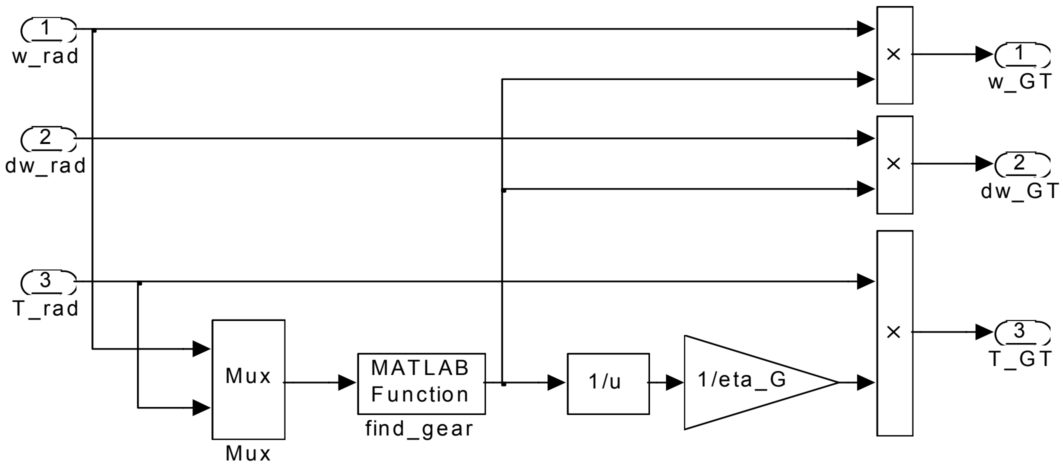

Figure 53: Details of the "Transmission" block (simplified).

Figure 54 shows the top level of a fuel cell vehicle model (without reformer).

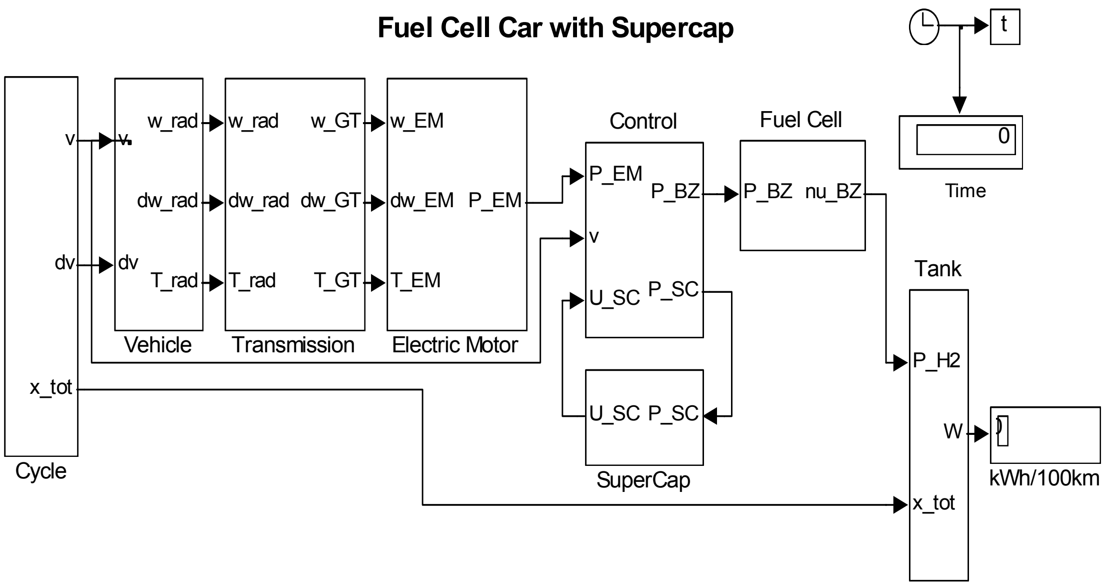

Figure 54: Top level for model of fuel cell car with supercapacitor (simplified).

Appendix 3 Numerical LCA Results

The results are for a small car at around 2010. The second line represents the numbers that are also used for the denomination of powertrain / fuel combinations in chapters 2 "LCA of Different Powertrains" and 3 "Costs of Fuels and Vehicles".

Non-Renewable Energy	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
MJ/100 km	1	2	3	4	5	6
Car Body	2.28E+01	2.32E+01	2.30E+01	2.32E+01	2.35E+01	2.35E+01
Power Train	5.15E+00	7.11E+00	5.22E+00	7.37E+00	9.64E+00	9.64E+00
Transport	8.36E-01	9.04E-01	8.45E-01	9.06E-01	9.77E-01	9.77E-01
Mainten.	1.46E+01	1.46E+01	1.46E+01	1.46E+01	1.46E+01	1.46E+01
Fuel Chain	5.37E+01	2.98E+01	8.11E+01	2.28E+01	6.81E+01	5.76E+02
Direct Em.	1.54E+02	1.33E+02	1.44E+02	1.42E+02	1.54E+02	1.54E+02
Total	2.51E+02	2.08E+02	2.68E+02	2.10E+02	2.70E+02	7.79E+02

Table 42: Life-cycle waste heat emissions for the powertrain / fuel combinations assessed.

Non-Renewable Energy	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
MJ/100 km	7	8	9	10	11	12
Car Body	2.35E+01	2.30E+01	2.30E+01	2.28E+01	2.28E+01	2.32E+01
Power Train	9.64E+00	5.22E+00	5.22E+00	5.15E+00	5.15E+00	7.11E+00
Transport	9.77E-01	8.45E-01	8.45E-01	8.36E-01	8.36E-01	9.04E-01
Mainten.	1.46E+01	1.46E+01	1.46E+01	1.46E+01	1.46E+01	1.46E+01
Fuel Chain	-4.40E+01	-1.16E+02	-1.49E+02	-7.39E+01	-6.98E+01	-9.21E+01
Direct Em.	1.54E+02	1.44E+02	1.44E+02	1.40E+02	1.40E+02	1.33E+02
Total	1.58E+02	7.12E+01	3.82E+01	1.09E+02	1.13E+02	8.62E+01

Table 42: cntd.

Non-Renewable Energy	FC Diesel	FC MeOH from NG	FC CH_2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
MJ/100 km	13	14	15	16	17	18	19
Car Body	2.39E+01	2.39E+01	2.40E+01	2.40E+01	2.40E+01	2.39E+01	2.39E+01
Power Train	1.25E+01	1.02E+01	1.27E+01	1.27E+01	1.27E+01	1.02E+01	1.02E+01
Transport	1.04E+00	1.02E+00	1.07E+00	1.07E+00	1.07E+00	1.02E+00	1.02E+00
Mainten.	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.43E+01
Fuel Chain	2.53E+01	6.22E+01	3.82E+01	3.23E+02	-2.47E+01	-8.90E+01	-1.14E+02
Direct Em.	1.12E+02	1.10E+02	8.62E+01	8.62E+01	8.62E+01	1.10E+02	1.10E+02
Total	1.89E+02	2.22E+02	1.77E+02	4.62E+02	1.14E+02	7.06E+01	4.53E+01

Table 42: cntd.

Global Warming	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
kg CO_2-eq/100 km	1	2	3	4	5	6
Car Body	1.61E+00	1.63E+00	1.62E+00	1.63E+00	1.65E+00	1.65E+00
Power Train	3.96E-01	5.49E-01	4.00E-01	5.53E-01	7.16E-01	7.16E-01
Transport	5.70E-02	6.16E-02	5.77E-02	6.18E-02	6.66E-02	6.66E-02
Mainten.	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.14E-01	8.14E-01
Fuel Chain	3.45E+00	2.01E+00	3.26E+00	1.67E+00	1.20E+01	2.03E+00
Direct Em.	1.07E+01	1.03E+01	8.87E+00	7.28E+00	9.30E-02	9.30E-02
Total	1.71E+01	1.54E+01	1.50E+01	1.20E+01	1.53E+01	5.37E+00

Table 43: Life-Cycle GHG emissions for the powertrain / fuel combinations assessed..

Global Warming	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
kg CO_2-eq/100 km	7	8	9	10	11	12
Car Body	1.65E+00	1.62E+00	1.62E+00	1.61E+00	1.61E+00	1.63E+00
Power Train	7.16E-01	4.00E-01	4.00E-01	3.96E-01	3.96E-01	5.49E-01
Transport	6.66E-02	5.77E-02	5.77E-02	5.70E-02	5.70E-02	6.16E-02
Mainten.	8.14E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01
Fuel Chain	8.11E+00	-4.54E+00	-9.52E+00	-2.66E+00	-7.70E-01	-1.67E+00
Direct Em.	9.30E-02	8.87E+00	8.87E+00	9.00E+00	9.00E+00	1.06E+01
Total	1.15E+01	7.22E+00	2.24E+00	9.22E+00	1.11E+01	1.20E+01

Table 43: cntd.

Global Warming	FC Diesel	FC MeOH from NG	FC CH_2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
kg CO_2-eq/ 100 km	13	14	15	16	17	18	19
Car Body	1.68E+00	1.68E+00	1.69E+00	1.69E+00	1.69E+00	1.68E+00	1.68E+00
Power Train	8.87E-01	7.16E-01	8.93E-01	8.93E-01	8.93E-01	7.16E-01	7.16E-01
Transport	7.07E-02	6.97E-02	7.30E-02	7.30E-02	7.30E-02	6.97E-02	6.97E-02
Mainten.	7.96E-01	7.96E-01	7.96E-01	7.96E-01	7.96E-01	7.96E-01	7.96E-01
Fuel Chain	1.70E+00	2.50E+00	6.72E+00	1.14E+00	4.55E+00	-3.48E+00	-7.30E+00
Direct Em.	7.83E+00	6.76E+00	0.00E+00	0.00E+00	0.00E+00	6.76E+00	6.76E+00
Total	1.30E+01	1.25E+01	1.02E+01	4.59E+00	8.00E+00	6.54E+00	2.73E+00

Table 43: cntd.

Ozone Formation	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
g C_2H_4-eq/100 km	1	2	3	4	5	6
Car Body	2.29E+00	2.30E+00	2.29E+00	2.30E+00	2.31E+00	2.31E+00
Power Train	1.93E-01	2.60E-01	2.17E-01	6.25E-01	1.02E+00	1.02E+00
Transport	6.71E-02	7.25E-02	6.78E-02	7.26E-02	7.83E-02	7.83E-02
Mainten.	1.46E+00	1.46E+00	1.46E+00	1.46E+00	1.47E+00	1.47E+00
Fuel Chain	1.46E+01	1.11E+01	2.25E+00	1.38E+00	1.91E+00	1.58E+00
Direct Em.	3.46E+00	2.08E+00	3.47E+00	4.46E-01	0.00E+00	0.00E+00
Total	2.21E+01	1.73E+01	9.76E+00	6.29E+00	6.79E+00	6.46E+00

Table 44: Life-cycle emissions of ozone-forming substances for the powertrain / fuel combinations assessed.

Ozone Formation	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
g C_2H_4-eq/100 km	7	8	9	10	11	12
Car Body	2.31E+00	2.29E+00	2.29E+00	2.29E+00	2.29E+00	2.30E+00
Power Train	1.02E+00	2.17E-01	2.17E-01	1.93E-01	1.93E-01	2.60E-01
Transport	7.83E-02	6.78E-02	6.78E-02	6.71E-02	6.71E-02	7.25E-02
Mainten.	1.47E+00	1.46E+00	1.46E+00	1.46E+00	1.46E+00	1.46E+00
Fuel Chain	3.72E+00	2.10E+00	1.29E+00	2.47E+00	2.10E+00	1.93E+00
Direct Em.	0.00E+00	3.47E+00	3.47E+00	3.11E+00	3.11E+00	1.70E+00
Total	8.60E+00	9.61E+00	8.80E+00	9.59E+00	9.22E+00	7.73E+00

Table 44: cntd.

Ozone Formation	FC Diesel	FC MeOH from NG	FC CH_2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
g C_2H_4-eq/100 km	13	14	15	16	17	18	19
Car Body	2.31E+00	2.31E+00	2.32E+00	2.32E+00	2.32E+00	2.31E+00	2.31E+00
Power Train	3.98E-01	4.01E-01	1.16E+00	1.16E+00	1.16E+00	4.01E-01	4.01E-01
Transport	8.31E-02	8.19E-02	8.58E-02	8.58E-02	8.58E-02	8.19E-02	8.19E-02
Mainten.	1.40E+00	1.40E+00	1.40E+00	1.40E+00	1.40E+00	1.40E+00	1.40E+00
Fuel Chain	9.41E+00	1.72E+00	1.07E+00	8.88E-01	2.09E+00	1.61E+00	9.90E-01
Direct Em.	4.68E-02	4.30E-02	0.00E+00	0.00E+00	0.00E+00	4.30E-02	4.30E-02
Total	1.37E+01	5.96E+00	6.03E+00	5.85E+00	7.05E+00	5.85E+00	5.23E+00

Table 44: cntd.

NO_x	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
g/100 km	1	2	3	4	5	6
Car Body	3.72E+00	3.76E+00	3.73E+00	3.75E+00	3.79E+00	3.79E+00
Power Train	6.65E-01	9.23E-01	6.73E-01	9.37E-01	1.22E+00	1.22E+00
Transport	5.12E-01	5.53E-01	5.18E-01	5.55E-01	5.98E-01	5.98E-01
Mainten.	1.34E+00	1.34E+00	1.34E+00	1.34E+00	1.34E+00	1.34E+00
Fuel Chain	1.16E+01	8.20E+00	6.46E+00	3.84E+00	9.29E+00	7.66E+00
Direct Em.	6.40E+00	2.00E+01	6.40E+00	6.40E+00	1.60E+00	1.60E+00
Total	2.43E+01	3.48E+01	1.91E+01	1.68E+01	1.78E+01	1.62E+01

Table 45: Life-Cycle NO_x emissions for the powertrain / fuel combinations assessed.

NO_x	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
g/100 km	7	8	9	10	11	12
Car Body	3.79E+00	3.73E+00	3.73E+00	3.72E+00	3.72E+00	3.76E+00
Power Train	1.22E+00	6.73E-01	6.73E-01	6.65E-01	6.65E-01	9.23E-01
Transport	5.98E-01	5.18E-01	5.18E-01	5.12E-01	5.12E-01	5.53E-01
Mainten.	1.34E+00	1.34E+00	1.34E+00	1.34E+00	1.34E+00	1.34E+00
Fuel Chain	1.76E+01	1.40E+01	6.30E+00	1.32E+01	1.32E+01	1.14E+01
Direct Em.	1.60E+00	6.40E+00	6.40E+00	6.40E+00	6.40E+00	2.00E+01
Total	2.62E+01	2.67E+01	1.90E+01	2.59E+01	2.58E+01	3.80E+01

Table 45: cntd.

NO_x	FC Diesel	FC MeOH from NG	FC CH2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
g/100 km	13	14	15	16	17	18	19
Car Body	3.83E+00	3.83E+00	3.84E+00	3.84E+00	3.84E+00	3.83E+00	3.83E+00
Power Train	1.84E+00	1.28E+00	1.56E+00	1.56E+00	1.56E+00	1.28E+00	1.28E+00
Transport	6.35E-01	6.26E-01	6.55E-01	6.55E-01	6.55E-01	6.26E-01	6.26E-01
Mainten.	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00
Fuel Chain	6.95E+00	4.96E+00	5.21E+00	4.30E+00	9.88E+00	1.08E+01	4.83E+00
Direct Em.	2.25E-01	2.07E-02	0.00E+00	0.00E+00	0.00E+00	2.07E-02	2.07E-02
Total	1.47E+01	1.20E+01	1.25E+01	1.16E+01	1.72E+01	1.78E+01	1.19E+01

Table 45: cntd.

AP	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
g SO_2-eq/100 km	1	2	3	4	5	6
Car Body	1.15E+01	1.16E+01	1.15E+01	1.16E+01	1.17E+01	1.17E+01
Power Train	3.70E+00	4.75E+00	3.73E+00	4.66E+00	5.27E+00	5.27E+00
Transport	1.03E+00	1.11E+00	1.04E+00	1.11E+00	1.20E+00	1.20E+00
Mainten.	3.14E+00	3.14E+00	3.14E+00	3.14E+00	3.15E+00	3.15E+00
Fuel Chain	2.27E+01	1.33E+01	1.03E+01	6.03E+00	1.17E+01	1.56E+01
Direct Em.	4.70E+00	1.41E+01	4.55E+00	4.56E+00	1.12E+00	1.12E+00
Total	4.67E+01	4.79E+01	3.42E+01	3.11E+01	3.41E+01	3.80E+01

Table 46: Life-Cycle emissions of airborne acids for the powertrain / fuel combinations assessed.

AP	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
g SO_2-eq/100 km	7	8	9	10	11	12
Car Body	1.17E+01	1.15E+01	1.15E+01	1.15E+01	1.15E+01	1.16E+01
Power Train	5.27E+00	3.73E+00	3.73E+00	3.70E+00	3.70E+00	4.75E+00
Transport	1.20E+00	1.04E+00	1.04E+00	1.03E+00	1.03E+00	1.11E+00
Mainten.	3.15E+00	3.14E+00	3.14E+00	3.14E+00	3.14E+00	3.14E+00
Fuel Chain	7.20E+01	2.10E+01	6.50E+00	3.02E+01	3.49E+01	2.80E+01
Direct Em.	1.12E+00	4.55E+00	4.55E+00	4.59E+00	4.59E+00	1.42E+01
Total	9.45E+01	4.49E+01	3.05E+01	5.41E+01	5.88E+01	6.28E+01

Table 46: cntd.

AP	FC Diesel	FC MeOH from NG	FC CH_2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
g SO_2-eq/100 km	13	14	15	16	17	18	19
Car Body	1.18E+01	1.18E+01	1.18E+01	1.18E+01	1.18E+01	1.18E+01	1.18E+01
Power Train	5.02E+01	2.54E+01	1.34E+01	1.34E+01	1.34E+01	2.54E+01	2.54E+01
Transport	1.28E+00	1.26E+00	1.32E+00	1.32E+00	1.32E+00	1.26E+00	1.26E+00
Mainten.	3.02E+00	3.02E+00	3.02E+00	3.02E+00	3.02E+00	3.02E+00	3.02E+00
Fuel Chain	1.13E+01	7.86E+00	6.58E+00	8.75E+00	4.04E+01	1.61E+01	4.98E+00
Direct Em.	1.58E-01	1.45E-02	0.00E+00	0.00E+00	0.00E+00	1.45E-02	1.45E-02
Total	7.77E+01	4.94E+01	3.61E+01	3.83E+01	6.99E+01	5.76E+01	4.65E+01

Table 46: cntd.

EP (Air)	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
g PO_4^{3-}-eq/100 km	1	2	3	4	5	6
Car Body	4.86E-01	4.91E-01	4.88E-01	4.90E-01	4.95E-01	4.95E-01
Power Train	8.70E-02	1.21E-01	8.81E-02	1.23E-01	1.59E-01	1.59E-01
Transport	6.67E-02	7.20E-02	6.74E-02	7.22E-02	7.79E-02	7.79E-02
Mainten.	1.74E-01	1.74E-01	1.74E-01	1.74E-01	1.75E-01	1.75E-01
Fuel Chain	1.51E+00	1.07E+00	8.41E-01	5.00E-01	1.21E+00	1.00E+00
Direct Em.	8.32E-01	2.60E+00	8.32E-01	8.32E-01	2.08E-01	2.08E-01
Total	3.16E+00	4.52E+00	2.49E+00	2.19E+00	2.32E+00	2.12E+00

Table 47: Life-Cycle emissions of eutrophying substances for the powertrain / fuel combinations assessed.

EP (Air)	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
g PO_4^{3-}-eq/100 km	7	8	9	10	11	12
Car Body	4.95E-01	4.88E-01	4.88E-01	4.86E-01	4.86E-01	4.91E-01
Power Train	1.59E-01	8.81E-02	8.81E-02	8.70E-02	8.70E-02	1.21E-01
Transport	7.79E-02	6.74E-02	6.74E-02	6.67E-02	6.67E-02	7.20E-02
Mainten.	1.75E-01	1.74E-01	1.74E-01	1.74E-01	1.74E-01	1.74E-01
Fuel Chain	2.31E+00	3.00E+00	8.19E-01	2.63E+00	3.28E+00	3.60E+00
Direct Em.	2.08E-01	8.32E-01	8.32E-01	8.32E-01	8.32E-01	2.60E+00
Total	3.42E+00	4.65E+00	2.47E+00	4.27E+00	4.93E+00	7.06E+00

Table 47: cntd.

EP (Air)	FC Diesel	FC MeOH from NG	FC CH_2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
g PO_4^{3-}-eq/ 100 km	13	14	15	16	17	18	19
Car Body	5.00E-01	5.00E-01	5.01E-01	5.01E-01	5.01E-01	5.00E-01	5.00E-01
Power Train	2.41E-01	1.67E-01	2.04E-01	2.04E-01	2.04E-01	1.67E-01	1.67E-01
Transport	8.27E-02	8.15E-02	8.53E-02	8.53E-02	8.53E-02	8.15E-02	8.15E-02
Mainten.	1.66E-01	1.66E-01	1.66E-01	1.66E-01	1.66E-01	1.66E-01	1.66E-01
Fuel Chain	9.04E-01	6.45E-01	6.78E-01	5.62E-01	1.29E+00	2.30E+00	6.28E-01
Direct Em.	2.93E-02	2.68E-03	0.00E+00	0.00E+00	0.00E+00	2.68E-03	2.68E-03
Total	1.92E+00	1.56E+00	1.63E+00	1.52E+00	2.25E+00	3.22E+00	1.55E+00

Table 47: cntd.

Total PM	ICE Gasoline	ICE Diesel	ICE MeOH from NG	ICE CNG	ICE CH_2 from NG	ICE CH_2 from NPP
g/100 km	1	2	3	4	5	6
Car Body	3.22E+00	3.30E+00	3.25E+00	3.30E+00	3.37E+00	3.37E+00
Power Train	8.67E-01	1.19E+00	8.69E-01	1.04E+00	1.25E+00	1.25E+00
Transport	5.42E-02	5.86E-02	5.48E-02	5.87E-02	6.33E-02	6.33E-02
Mainten.	3.97E-01	3.97E-01	3.97E-01	3.97E-01	3.98E-01	3.98E-01
Fuel Chain	1.60E+00	1.04E+00	7.50E-01	3.13E-01	6.13E-01	2.80E+00
Direct Em.	5.00E-01	2.00E+00	3.50E-01	3.50E-01	0.00E+00	0.00E+00
Total	6.64E+00	7.99E+00	5.68E+00	5.46E+00	5.69E+00	7.88E+00

Table 48: Life-Cycle particle emissions for the powertrain / fuel combinations assessed.

Total PM	ICE CH_2 from PV	ICE MeOH from Poplar	ICE MeOH from Scrap Wood	ICE EtOH from Sugar Beet	ICE EtOH from Wheat	ICE RME
g/100 km	7	8	9	10	11	12
Car Body	3.37E+00	3.25E+00	3.25E+00	3.22E+00	3.22E+00	3.30E+00
Power Train	1.25E+00	8.69E-01	8.69E-01	8.67E-01	8.67E-01	1.19E+00
Transport	6.33E-02	5.48E-02	5.48E-02	5.42E-02	5.42E-02	5.86E-02
Mainten.	3.98E-01	3.97E-01	3.97E-01	3.97E-01	3.97E-01	3.97E-01
Fuel Chain	1.14E+01	2.02E+00	7.64E-01	2.37E+00	2.52E+00	2.12E+00
Direct Em.	0.00E+00	3.50E-01	3.50E-01	3.50E-01	3.50E-01	2.00E+00
Total	1.65E+01	6.95E+00	5.69E+00	7.26E+00	7.41E+00	9.07E+00

Table 48: cntd.

Total PM	FC Diesel	FC MeOH from NG	FC CH_2 from NG	FC CH_2 from NPP	FC CH_2 from PV	FC MeOH from Poplar	FC MeOH from Scrap Wood
g/100 km	13	14	15	16	17	18	19
Car Body	3.46E+00	3.47E+00	3.48E+00	3.48E+00	3.48E+00	3.47E+00	3.47E+00
Power Train	2.11E+00	1.74E+00	1.75E+00	1.75E+00	1.75E+00	1.74E+00	1.74E+00
Transport	6.72E-02	6.62E-02	6.93E-02	6.93E-02	6.93E-02	6.62E-02	6.62E-02
Mainten.	3.87E-01	3.87E-01	3.87E-01	3.87E-01	3.87E-01	3.87E-01	3.87E-01
Fuel Chain	8.81E-01	5.75E-01	3.44E-01	1.57E+00	6.42E+00	1.55E+00	5.86E-01
Direct Em.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	6.90E+00	6.24E+00	6.03E+00	7.26E+00	1.21E+01	7.21E+00	6.25E+00

Table 48: cntd.

Appendix 4 Cost Figures Used

This appendix gives an overview over the economic data used in this study. For details see [Röder 2001].

When no availability or capacity factor is given, investment cost and fix O&M refer to the net capacity of the process.

Biomass Cost:

		Fr98
Winter Rape	t	535
Sugar Beet	t	175
Winter Wheat	t	267
Plantation Wood	t	235
Waste Wood	t	0

Table 49: Assumed biomass costs.

Biomass Processing:

Input Commodity	Life-time	Input Biomass	Input Hexane	Input Electr.	Input NG	Investment	Fix O&M	Var O&M incl. By-product credits
		t dry matter	GJ / GJ_{out}	GJ / GJ_{out}	GJ / GJ_{out}	Fr98/ (GJ/a)	Fr98/ (GJ/a)	Fr98/ GJ
Wheat	20	0.0598	0.0621	0.0412	0.1863	38	5	-6.02
Sugar Beet	20	0.0856	0.0611	0.0284	0.1832	38	5	4.11

Table 50: Economic data for biomass-to-EtOH plants.

Input Commodity	Lifetime	Input Biomass	Input NG	Investment	Fix O&M	Var O&M (incl. By-product credits)
		t dry matter / GJ_{out}	GJ / GJ_{out}	Fr98/ (GJ/a)	Fr98/ (GJ/a)	Fr98/GJ
Plantation Wood	20	0.169	0.172	100	7.88	1.39
Waste Wood	20	0.169	--	100	7.88	1.11

Table 51: Economic data for the wood-to-MeOH plant.

Input Commodity	Life-time	Input Biomass	Input MeOH	Input Hexane	Input Electr.	Input NG	Invest-ment	Fix O&M	Var O&M (incl. By-product credits)
		t dry matter / GJ_{out}	GJ / GJ_{out}	GJ / GJ_{out}	GJ / GJ_{out}	GJ / GJ_{out}	Fr98 / (GJ/a)	Fr98 / (GJ/a)	Fr98 / GJ
Rape Seed	20	0.0376	0.0558	0.0182	0.0099	0.0547	13	3	-6.79

Table 52: Economic data for the RME plant.

Electrolysis incl. Filling Station:

	Lifetime	Electricity	Investment	Fix O&M	Var O&M (incl. By-product credits)
	a	GJ_{in}/GJ_{out}	Fr98/ (GJ/a)	Fr98/ (GJ/a)	Fr98/GJ
Electrolysis	20	1.665	64.2	1.32	9.01

Table 53: Economic data for filling stations with decentralised electrolyser.

Refinery Processes, Low-Sulphur Commodities

Commodity	Lifetime	Input Crude Oil	Input NG	Capacity Factor	Investment	Fix O&M	Var O&M
	a	GJ / GJ_{out}	GJ / GJ_{out}		Fr98/ (GJ/a)	Fr98/ (GJ/a)	Fr98/GJ
Diesel	30	1.067		90%	4.59	0.183	0.918
Gasoline	30	1.167	0.0147	90%	5.74	0.304	1.37

Table 54: Economic data for the production of low-S fuels from crude oil.

Electricity Production:

	Capacity Factor	Lifetime	Investment	Fix O&M
		a	Fr98/kW	Fr98/(kW*a)
Existing coal plant	0.85	25	1884	107
PFBC	0.8	25	2463	116
GCC	0.9	25	722	26.0
GT	0.95	25	580	44.6
Oil plant	0.8	30	1051	75.3
NPP	0.8	40	4147	112
PV	0.094 / 0.118 / 0.157*	30	5500	96.0
Wind turbine	0.25	30	1594	66.7

Table 55: Economic data for power plants. PFBC: Pressurised Fluidised Bed Combustion (Advanced Coal Plant), GCC: Gas-fired Combined Cycle plant, GT: Gas Turbine. *: Northern / Central / Southern Europe.

Centralised Processing of NG:

Product	Lifetime	Input	Capacity Factor	Investment	Var O&M
	a	GJ_{in}/GJ_{out}		Fr98/(GJ/a)	Fr98/GJ
CH_2	20	1.328	90%	14.5	0.82
MeOH	20	1.429	90%	20	0.8

Table 56: Economic data for the production of CH_2 and MeOH in centralised plants.

Distribution of NG:

	Price Premium
	Fr98/GJ
T&D of NG (to decentralised CNG or H_2 station)	1.04

Table 57: Costs for distributing NG in a pipeline network.

Decentralised NG Processing with Integrated Filling Station:

Product	Lifetime	Input	Investment	Var O&M
	a	GJ_{in}/GJ_{out}	Fr98/(GJ/a)	Fr98/GJ
CNG	20	1.036	7.85	2.46
CH_2	20	1.397	64.6	14

Table 58: Economic data for processing NG in decentralised CNG and CH_2 stations.

T&D of Liquid Fuels:

Fuel	Losses	T&D cost (without losses)
		Fr98/GJ
Gasoline	0.5%	1.72
Diesel	0.0%	1.67
RME	0.0%	1.93
EtOH	0.0%	2.67
MeOH	0.0%	3.73

Table 59: Economic data for transport and distribution of liquid fuels.

Hydrogen T&D:

	Lifetime	Losses	Investment	Var O&M
	a		Fr98/(GJ/a)	Fr98/GJ
Hydrogen T&D	20	1.0%	30	13.8

Table 60: Economic data for transport and distribution of CH_2 from centralised plants.

Investment Cost for Powertrains

Components:

Component	Unit	Cost
Fuel Storage		Fr98
Tank	l	4
Pressure Vessel	l	14
ICE Powertrain		
SI for gasoline, CNG, MeOH, EtOH	kW	50
SI for CH_2	kW	55
CI	kW	75
Manual Gearbox	per system kW	240 1.66
FC Powertrain		
MeOH Reformer	kWel	28
Gasoline Reformer	kWel	38
FC	kWel	80
SC	kWel	8
Electric Motor	per system kW_{mech}	341 34
Transmission	per system kW_{mech}	120 0.83

Table 61: Cost of powertrain components. For details see [Röder 2001].

Vehicles:

Class Powertrain Fuel		Small Car SI-engine Gasoline	Small Car SI-engine EtOH	Small Car SI-engine MeOH	Small Car SI-engine CNG	Small Car SI-engine CH_2	Small Car CI-engine Diesel
Mech. Power	kW	40	40	40	40	40	40
FC Power	kW	0	0	0	0	0	0
SC Power	kW	0	0	0	0	0	0
Tank f. Liquid Fuels	l	20	20	40	0	0	20
Pressure Vessel	l	0	0	0	80	147	0
Costs:							
Tank	Fr98	80	80	160	1'120	2'646	80
ICE & Transm.	Fr98	2'306	2'306	2'306	2'306	2'513	3'306
Reformer	Fr98	0	0	0	0	0	0
FC	Fr98	0	0	0	0	0	0
SC	Fr98	0	0	0	0	0	0
El. Motor & Transm.	Fr98	0	0	0	0	0	0
Total Powertrain	Fr98	2'386	2'386	2'466	3'426	4'564	3'386
Body	Fr98	12'000	12'000	12'008	12'017	12'033	12'018
Total Car	Fr98	14'386	14'386	14'474	15'443	16'596	15'404

Table 62: Investment costs for the vehicles analysed. See [Röder 2001] for details.

Class		Small Car	Small Car	Small Car	Compact Car	Compact Car	Compact Car
Powertrain		FC	FC	FC	SI-engine	SI-engine	SI-engine
Fuel		CH_2	MeOH	Gasoline / Diesel	Gasoline	EtOH	MeOH
Mech. Power	kW	40	40	40	55	55	55
FC Power	kW	28	28	28	0	0	0
SC Power	kW	28	28	28	0	0	0
Tank f. Liquid Fuels	l	0	40	20	30	30	60
Pressure Vessel	l	147	0	0	0	0	0
Costs:							
Tank	Fr98	2'646	160	80	120	120	240
ICE & Transm.	Fr98	0	0	0	3'081	3'081	3'081
Reformer	Fr98	0	784	1'064	0	0	0
FC	Fr98	2'240	2'240	2'240	0	0	0
SC	Fr98	224	224	224	0	0	0
El. Motor & Transm.	Fr98	1'854	1'854	1'854	0	0	0
Total Powertrain	Fr98	6'376	5'262	5'462	3'201	3'201	3'321
Body	Fr98	12'055	12'052	12'051	17'000	17'000	17'011
Total Car	Fr98	18'431	17'314	17'513	20'201	20'201	20'333

Table 62: cntd.

Class		Compact Car	Compact Car	Compact Car	Compact Car	Compact Car	Compact Car
Powertrain		SI-engine	SI-engine	CI-engine	FC	FC	FC
Fuel		CNG	CH_2	Diesel	CH_2	MeOH	Gasoline/ Diesel
Mech. Power	kW	55	55	55	55	55	55
FC Power	kW	0	0	0	39	39	39
SC Power	kW	0	0	0	39	39	39
Tank f. Liquid Fuels	l	0	0	30	0	60	30
Pressure Vessel	l	120	220	0	220	0	0
Costs:							
Tank	Fr98	1'680	3'080	120	3'080	240	120
ICE & Transm.	Fr98	3'081	3'356	4'456	0	0	0
Reformer	Fr98	0	0	0	0	1'078	1'463
FC	Fr98	0	0	0	3'080	3'080	3'080
SC	Fr98	0	0	0	308	308	308
El. Motor & Transm.	Fr98	0	0	0	2'377	2'377	2'377
Total Powertrain	Fr98	4'761	6'436	4'576	8'845	7'083	7'348
Body	Fr98	17'025	17'046	17'024	17'079	17'073	17'071
Total Car	Fr98	21'786	23'483	21'601	25'924	24'156	24'418

Table 62: cntd.

Class Powertrain Fuel		Middle-Class Car SI-engine Gasoline	Middle-Class Car SI-engine EtOH	Middle-Class Car SI-engine MeOH	Middle-Class Car SI-engine CNG	Middle-Class Car SI-engine CH_2	Middle-Class Car CI-engine Diesel
Mech. Power	kW	85	85	85	85	85	85
FC Power	kW	0	0	0	0	0	0
SC Power	kW	0	0	0	0	0	0
Tank f. Liquid Fuels	l	35	35	70	0	0	35
Pressure Vessel	l	0	0	0	140	250	0
Costs:							
Tank	Fr98	140	140	280	1'960	3'500	140
ICE & Transm.	Fr98	4'631	4'631	4'631	4'631	5'056	6'756
Reformer	Fr98	0	0	0	0	0	0
FC	Fr98	0	0	0	0	0	0
SC	Fr98	0	0	0	0	0	0
El. Motor & Transm.	Fr98	0	0	0	0	0	0
Total Powertrain	Fr98	4'771	4'771	4'911	6'591	8'556	6'896
Body	Fr98	25'000	25'000	25'013	25'029	25'054	25'037
Total Car	Fr98	29'771	29'771	29'924	31'620	33'610	31'933

Table 62: cntd.

Class Powertrain Fuel		Middle-Class Car FC CH_2	Middle-Class Car FC MeOH	Middle-Class Car FC Gasoline/ Diesel
Mech. Power	kW	85	85	85
FC Power	kW	60	60	60
SC Power	kW	60	60	60
Tank f. Liquid Fuels	l	0	70	35
Pressure Vessel	l	250	0	0
Costs:				
Tank	Fr98	3'500	280	140
ICE & Transm.	Fr98	0	0	0
Reformer	Fr98	0	1'666	2'261
FC	Fr98	4'760	4'760	4'760
SC	Fr98	476	476	476
El. Motor & Transm.	Fr98	3'422	3'422	3'422
Total Powertrain	Fr98	12'158	10'604	11'059
Body	Fr98	25'105	25'109	25'109
Total Car	Fr98	37'263	35'712	36'168

Table 62: cntd.

Appendix 5 Abbreviations

η	"eta", formula symbol for efficiency
a	year (lat. *annum*)
AP	acidification potential
BAT	best available technology
CF	capacity factor
CH_2	compressed hydrogen
CHPP	combined heat and power plant
CI	compression ignition
CNG	compressed natural gas
CO	carbon monoxide
CO2	carbon dioxide
CVT	continuous variable transmission
DC	direct current
DDG	dried distiller's grains
EP	eutrophication potential
ETH	Swiss Federal Institute of Technology (German *Eidgenössische Technische Hochschule*)
ETL	endogenous technological learning
EtOH	ethanol
EU	European Union
FC	fuel cell
Fr	Swiss Franc
FTP	federal test procedure
GCC	gas combined cycle (plant)
GHG	greenhouse gas
GT	gas turbine
GWP	global warming potential
GWP_{100}	GWP calculated for a time horizon of 100 years
HC	hydrocarbons
HHV	higher heating value
ICE	internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

kWh	kilowatt-hour
LCA	life-cycle assessment
LCI	life-cycle inventory
LDV	light-duty vehicle
LHV	lower heating value
low-S	low sulphur
MARKAL	MARKet ALlocation, energy-planning model
MeOH	methanol
MTBE	methyl-tertiary butyl ether
NEDC	New European Driving Cycle
NG	natural gas
NMVOC	non-methane volatile organic compounds
NO_x	nitrogen oxides
NPP	nuclear power plant
O&M	operation and maintenance
OECD	Organization for Economic Cooperation and Development
PAH	polycyclic aromatic hydrocarbons
PC	personal computer
PFBC	pressurised fluidised bed combustion
PGM	platinum-group metals
PM	particulate matter
PM_x	particulate matter with an aerodynamic diameter smaller x µm
POCP	photochemical ozone-creation potential
PP	power plant
PSI	Paul Scherrer Institute
PTFE	poly tetra fluor ethylene
PV	photovoltaic
QSS	as-if-stationary simulation (German *Quasistationäre Simulation*)
R&D	research and development
RFG	reformulated gasoline
RME	rapeseed methyl ester
Rp	Swiss Rappen (1/100 Fr)
RUS	Russia
RVP	Reid vapour pressure
SI	spark ignition
SO_2	sulphur dioxide
SRF	short-rotation forestry

T&D	transport and distribution
UCPTE	Union pour la Coordination de la Production et du Transport de l'Electricité (European Electricity Network)
US	United States
vkm	vehicle kilometre
VOC	volatile organic compounds
w/o	without
WEU	Western Europe (here: OECD Europe plus Turkey)

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