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The Future Role of Alternative Powertrains and Fuels in the German Transport Sector

A model based scenario analysis with respect to technical, economic and environmental aspects with a focus on road transport

Enver Doruk Özdemir

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The Future Role of Alternative Powertrains and Fuels in the German Transport Sector

A model based scenario analysis with respect to technical, economic and environmental aspects with a focus on road transport

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Enver Doruk Özdemir
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Hauptberichter:	Prof. Dr.-Ing. A. Voß
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Institut für Energiewirtschaft und Rationelle Energieanwendung, Stuttgart
Prof. Dr.-Ing. A. Voß
Abteilung Systemanalyse und Erneuerbare Energien (SEE)
Dr. sc. agr. L. Eltrop

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Nomenclature and abbreviations

bbl	Barrel
BCO	Bio crude oil
BEV	Battery electric vehicle
Bio-HC	Bio-hydrocarbon
BioKraftQuG	German biofuel quotas law
B-ISG	Belt driven integrated starter generator
BMELV	Federal Ministry of Food, Agriculture and Consumer Protection
BMU	Federal Environment Ministry
BMVBS	Federal Ministry of Transport, Building and Urban Development
BRD	Federal Republic of Germany
BTL	Biomass to liquid
CH_4	Methane
CHP	Combined heat and power
CI	Compression ignition
C-ISG	Crankshaft mounted integrated starter generator
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent (includes CO_2, CH_4 and N_2O)
conv	Conventional
CTL	Coal to liquid
DDGS	Distiller's dried grain and solubles
DME	Dimethyl ether
EEG	Renewable energy law (Germany)
EFLH	Equivalent full load hours
EFOM	Energy flow optimization model
EM	Electric motor
EOH	Ethanol
ETBE	Ethyl *tert*-butyl ether
EU	European Union
FAME	Fatty acid methyl ester (biodiesel)
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FCHEV	Fuel cell hybrid electric vehicle
FICFBG	Fast internal circulating fluidized bed gasification
FM Scenario	Free market scenario
FMM Scenario	Free market scenario with moderate fossil fuel price level
FMH Scenario	Free market scenario with high fossil fuel price level
FMV Scenario	Free market scenario with very high fossil fuel price level
FOM	Fixed operating & maintenance (costs)
FT	Fischer-Tropsch (synthesis)
FT-HC	Fischer-Tropsch hydrocarbons or synthetic diesel (BTL, GTL and CTL)
GDP	Gross domestic product
Gg	Giga grams
GHG	Greenhouse gas
GHG Scenario	Greenhouse gas restriction scenario
GM	General Motors
GTL	Gas to liquid
ha	Hectare

H_2	Hydrogen
HC	Hydrocarbons
HDV	Heavy duty vehicle
HEB	Hybrid electric bus
HEV	Hybrid electric vehicle
HEV CI	Hybrid electric vehicle with CI engine
HEV SI	Hybrid electric vehicle with SI engine
HVO	Hydrated vegetable oil
ICE	Internal combustion engine
ICE H_2	Internal combustion engine powered by hydrogen
ICEV	Internal combustion engine vehicle
IGCC	Integrated gasification combined cycle
kt	Kilo tons
LDV	Light duty vehicle
LHV	Lower heating value
MARKAL	Market Allocation (model)
MCFC	Molten carbonate fuel cell
MeOH	Methanol
MIT	Motorized individual transport
MTBE	Methyl *tert*-butyl ether
MTG	Methanol to Gasoline
N_2O	Nitrous oxide
Nm^3	Normal cubic meters (gas volume under normal conditions)
NO_x	Nitrogen dioxide (NO_2) and Nitric oxide (NO)
ORC	Organic Rankine cycle
PC	Passenger car
PEFC	Polymer electrolyte fuel cell
PEM	Proton exchange membrane
PHEB	Plug-in hybrid electric bus
PHEV	Plug-in hybrid electric vehicle
pkm	Person kilometer
PM	Particulate matter
PSA	Pressure swing adsorption
RME	Rape oil methyl ester (biodiesel)
SI	Spark ignition
SNG	Substitute natural gas (methane)
SOFC	Solid oxide fuel cell
SO_x	Sulfur oxides
SRC	Short rotation coppice
TCR scenario	Technology based cost reduction scenario
TIMES	The Integrated Markal Efom System
TIMES-D	TIMES Germany model
tkm	Ton kilometer
TTW	Tank to wheel
vkm	Vehicle kilometer
VOM	Variable operating & maintenance (costs)
WTT	Well to tank
WTW	Well to wheel
η	Specific energy consumption (per hundred vehicle kilometer)
η_{tkm}	Specific energy consumption (per hundred ton kilometer)
η_{pkm}	Specific energy consumption (per hundred person kilometer)

θ_{tkm}	Specific energy consumption (per offered ton kilometer)
θ_{pkm}	Specific energy consumption (per offered seat kilometer)
λ	Average occupancy level
x_j	Energy flows variable for different processes
j	The index for energy flow variable between 1 and n
c_j	The costs of energy flow variable
a_{ij}	The coefficient of energy flow variable in the equation i
i	The index for equations between 1 and m
b_i	The right hand side of the equation i

Abstract

The transport sector is facing the challenges of satisfying the ever increasing transport demand on the one hand and achieving greenhouse gas (GHG) emission reduction targets without compromising economic development on the other hand. There are various alternative fuels and powertrains which might play a role in the future of the German transport sector. Amongst these options, biofuels are considered to help lower GHG emissions. However, they are severely criticized to create an additional strain for the energy system and particularly for the transport sector with land area requirement for energy crop production, which may imply a competition with food production.

This study aims to assess the future role of alternative fuels and powertrains in the German transport sector in terms of their costs, efficiencies, GHG emissions and land area requirement for energy crops.

To fulfill this aim, a techno-economic analysis of all relevant fuels and powertrain options was performed and a model based approach was employed. The utilized model belongs to the TIMES (**T**he **I**ntegrated **M**ARKAL **E**FOM **S**ystem) family and is a bottom-up linear cost optimization energy system model. A scenario analysis was employed in order to assess the effect of different technological, economic, environmental and political conditions on the overall system.

The results of the scenario analysis indicated that the transport system will still be dominated by conventional powertrains in 2030. Alternative powertrains are projected to play only a secondary role until 2030. It is not expected that fuel cell or battery electric passenger cars will be introduced into the market until 2030 in Germany. Nevertheless, hybrid electric powertrains have to be used in the German passenger car sector under ambitious GHG emission reduction targets and high oil prices. The introduction of alternative powertrains (such as hybrid electric and fuel cell powertrain) is much more likely in the bus sector (especially for public buses) than in passenger cars or in the road freight sector.

Furthermore conventional fuels are expected to remain an important part of the German transport system until 2030. However, not only conventional fuels will be utilized in the future, but also biofuels and hydrogen are required.

It is concluded that the transport sector should not be the first sector to reduce GHG emissions within an overall GHG emission mitigation strategy. However, with the ambitious GHG emission reduction targets (such as self-commitment of the German government) some contributions should also come from the transport sector.

Kurzfassung

Der Transportsektor steht vor der Herausforderung, einerseits den steigenden Transportbedarf zu befriedigen und andererseits die Treibhausgasreduktionsziele zu erreichen, ohne seine wirtschaftliche Entwicklung zu gefährden. Verschiedene Alternativkraftstoffe und alternative Antriebssysteme könnten im zukünftigen Transportsektor Deutschlands eine Rolle spielen. Biokraftstoffe als eine dieser Optionen werden als Maßnahme zur Verringerung der Treibhausgasemissionen angesehen. Sie stehen jedoch in der Kritik, eine zusätzliche Belastung für das Energiesystem, insbesondere für den Transportsektor zu schaffen, wo der Flächenverbrauch für den Energiepflanzenanbau im Wettbewerb mit der Lebensmittelproduktion stehen könnte.

Diese Studie hat zum Ziel, die zukünftige Rolle von Alternativkraftstoffen und -antriebssystemen im deutschen Transportsektor hinsichtlich ihrer Kosten, Effizienz, Treibhausgasemissionen und Flächenverbrauchs für Energiepflanzen zu bewerten.

Um dieses Ziel zu erfüllen, wurde eine technisch-ökonomische Analyse aller relevanten Kraftstoff- und Antriebsoptionen durchgeführt und ein modellbasierter Ansatz angewendet. Das verwendete Modell gehört zur Familie der TIMES (**T**he **I**ntegrated **M**ARKAL **E**FOM **S**ystem) und ist ein bottom-up, lineares, kostenoptimierendes Energiesystemmodell. Eine Szenarioanalyse wurde zur Bewertung der Auswirkungen verschiedener technologischer, ökonomischer, politischer und Umweltfaktoren auf das Gesamtsystem eingesetzt.

Die Ergebnisse der Szenarioanalyse zeigen, dass das Transportsystem 2030 noch von konventionellen Antrieben dominiert sein wird. Alternativantriebe werden bis 2030 voraussichtlich nur eine sekundäre Rolle spielen. Es wird nicht erwartet, dass Brennstoffzellen oder batteriebetriebene PKW vor 2030 in den deutschen Markt eingeführt werden. Dessen ungeachtet müssen bei ambitionierten Treibhausgasreduktionszielen und hohen Ölpreisen hybride, elektrische Antriebe im deutschen PKW-Sektor eingesetzt werden. Die Einführung alternativer Antriebssysteme (wie elektrohybride und Brennstoffzellenantriebe) ist im Bussektor (vor allem öffentliche Busse) viel wahrscheinlicher als im PKW- oder Straßengüterverkehr.

Es wird erwartet, dass konventionelle Kraftstoffe weiterhin ein wichtiger Teil des deutschen Transportsystems bis 2030 bleiben. Trotzdem werden zukünftig neben konventionellen Kraftstoffen allein auch Biokraftstoffe und Wasserstoff benötigt.

Daraus folgt, dass der Transportsektor nicht der erste Sektor zur Reduzierung der Treibhausgasemissionen innerhalb der gesamten Emissionsvermeidungsstrategie sein sollte.

Bei den ehrgeizigen Emissionsreduktionszielen (wie der Selbstverpflichtung der deutschen Regierung) sollten trotzdem einige Beiträge auch aus dem Transportsektor kommen.

1 Introduction

1.1 Problem statement

Being mobile is an important element for many people in Germany (Infas and DIW, 2004). The demand for transport increased drastically both for passengers and freight in the last century in Germany as well as worldwide.

The activity in passenger transport is measured with the unit of passenger kilometer (pkm, one kilometer traveled by one person). The total traveled pkm in Germany increased from 738.4 Giga passenger kilometer (Gpkm) in 1980 (BMU, 1997) to 1087.6 Gpkm in 2005 (DIW, 2011).

In the 20th century the shares of means of transport changed drastically as well. Although more or less the transport activities of all types of means of transport increased in the last century, the overwhelming increase in motorized individual transport (MIT) resulted in a decrease of shares of other means of transport (Figure 1). The stock of passenger cars in Germany for 1000 inhabitants is 559 in 2005, which makes it the third car intensive country in the EU27 after Luxembourg and Italy (DIW, 2011).

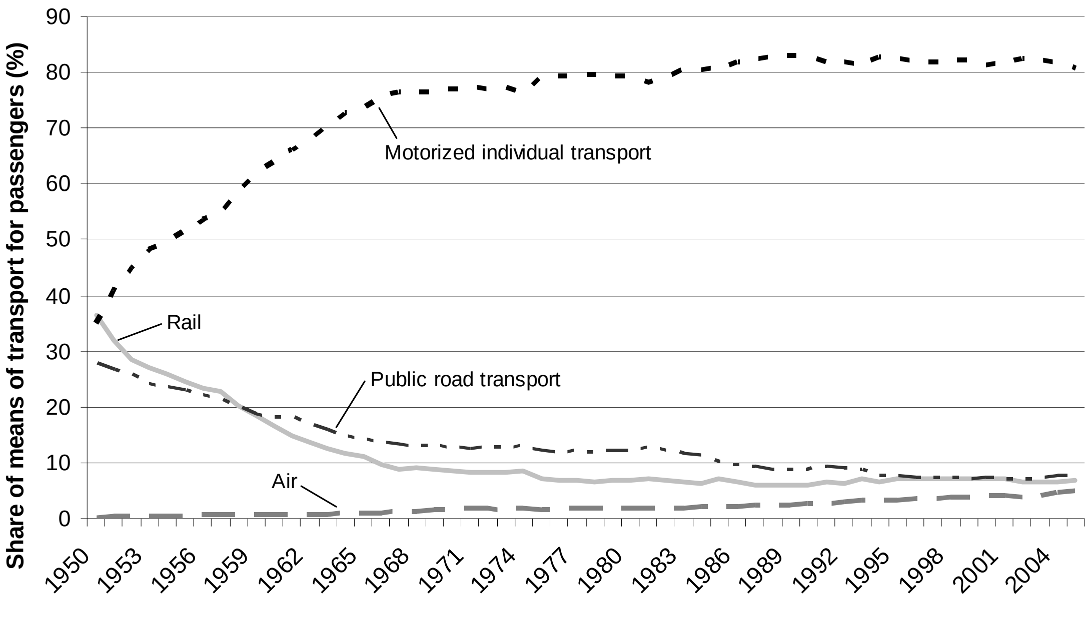

Figure 1: Share of means of transport for passengers in Germany (West Germany until 1990 and BRD after 1991) (Gesis, 2007)

The activity in freight transport is measured in ton kilometer (tkm, one km travel of a good of one ton). The freight transport gives a similar picture like the passenger transport (Figure 2). The activity of freight transport increased sharply from the 90’s on where the main increase happened in the road freight transport. This increase is due to the reunification of Germany and opening of new trade routes in the previous Eastern Bloc.

The road freight transport has more than doubled in the last decade of the 20th century. The inland vessel transport stayed almost constant and the transport via rail increased almost 50% within the past 25 years. Although the air traffic is at first sight negligible, it is the most energy intensive means of transport and its demand increased from 0.8 Gtkm in 2000 to 1.4 Gtkm in 2008 (DIW, 2011).

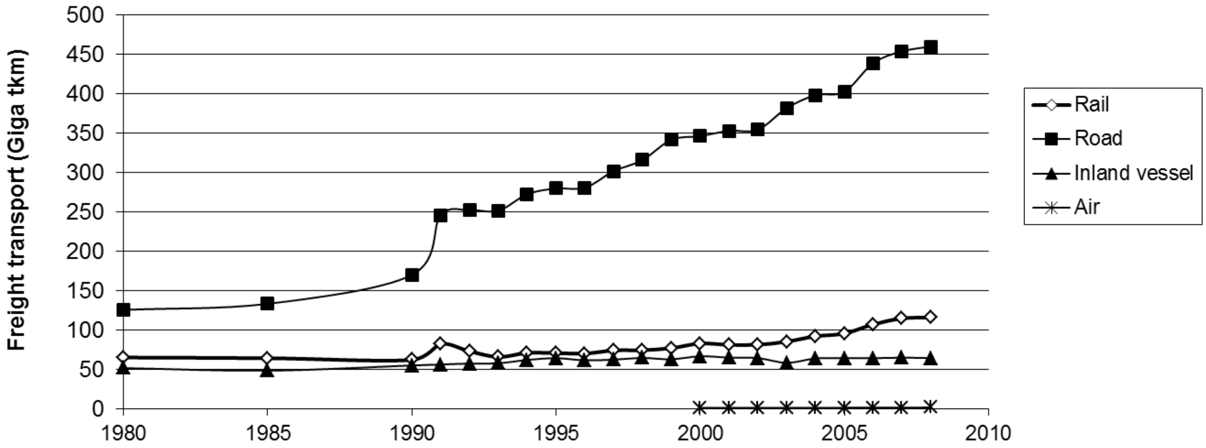

Figure 2: Freight transport in Germany (West Germany until 1990 and BRD after 1991) (DIW, 2011)

The increase in energy related greenhouse gases (GHG) are one of the concerns which arise from the increasing transport demand. One of the proposed solutions to this increase is the use of renewable energy for the transport sector, particularly biofuels.

The discussion about biofuels is intensified as the wheat, rice, and plant oil prices increased sharply over a short period (Stein, 2007; Boddiger, 2007; Clayton, 2008; Muller et al., 2008). One of the causes of the food price increases is the expansive pressure on agricultural land due to world population growth and the increased consumption of animal products in the diets of people especially in developing countries, which comes together with their income growth (Johansson et al., 2007). Moreover, the increased biomass utilization in the energy sector - especially for biofuel production - does not release (but may add additional) pressure on productive land (Özdemir et al., 2009). Thus, the biofuels, which are seen as one of the solutions to the GHG emission problem, have been criticized severely due to its land area requirement and related problems.

Achieving reduction targets for GHG emissions, while meeting the ever increasing transport demand without compromising economic development is the main challenge of the transport sector. Furthermore, another strain for the energy system and particularly for the transport sector is the land area requirement for energy crops.

1.2 The political and legal framework of the German transport sector and opportunities for alternative fuels in Germany

There are efforts from politics in Germany as well as at the EU level to enable utilization of alternative fuels which help to abate the GHG emissions.

Two recent laws in Germany, the energy tax law[1] and biofuel quota law[2], that came into effect as from 2007 have a very broad influence on the market position of biofuels (UFOP, 2007). The former defined the framework of the tax reductions in biofuels for the transport sector (Table 1). It becomes clear that biodiesel (B100) and vegetable oil loose most of their tax reduction privileges until the year 2012 gradually. On the other hand, ethanol (E85) will enjoy its tax exemption at least until 2015.

Table 1: Tax rates (EURcent/l) for various fuels between 2006 and 2015 (UFOP, 2007)

EURcent/l	Diesel	Gasoline	Biodiesel[3] (B100[4])	Biodiesel (blending)	Vegetable oil[5]	Ethanol (E85[6])	Ethanol (blending[7])
Aug 2006	47.04	65,45	9.00	15.00	0.00	0.00	Not known
2007	47.04	65,45	8.86	47.04	2.07	0.00	65,45
2008	47.04	65,45	14.88	47.04	9.86	0.00	65,45
2009	47.04	65,45	21.41	47.04	18.46	0.00	65,45
2010	47.04	65,45	27.42	47.04	26.44	0.00	65,45
2011	47.04	65,45	33.33	47.04	33.33	0.00	65,45
2012	47.04	65,45	45.06	47.04	45.06	0.00	65,45
2013	47.04	65,45	45.06	47.04	45.06	0.00	65,45
2014	47.04	65,45	45.07	47.04	45.07	0.00	65,45
2015	47.04	65,45	45.07	47.04	45.07	0.00	65,45

The latter of the two laws determines the blending quota for the German fuel sector (see Table 2). The mineral oil companies are forced with this law to blend a certain amount of biofuel with their fossil products. After the year of 2010, only the total quota is rising but not the quota for diesel or gasoline, which means that it is left to the companies to decide which product to blend with more biofuel. Thus, the aim is to substitute the fossil fuels efficiently in economic terms.

[1] Energiesteuergesetz (accepted on 15.07.2006 updated on 18.12.2006)
[2] Biokraftstoffquotengesetz (accepted on 18.12.2006)
[3] The agriculture and forestry sectors are exempted from this tax (UFOP, 2007).
[4] B100 refers to 100% biodiesel. On the other hand, B5 or B20 would mean 5% or 20% of biodiesel blending by volume in the conventional diesel respectively.
[5] The agriculture and forestry sectors are exempted from this tax (UFOP, 2007).
[6] E85 contains 85% anhydrous ethanol and 15% gasoline by volume
[7] Blending of ethanol up to 10% by volume

Table 2: Blending quota (share of energy content) for the German transport sector (UFOP, 2007)

Year	Total quota	Diesel quota	Gasoline quota
2007	-	4.4%	1.2%
2010	6.25%	4.4%	3.6%
2015	8.00%	4.4%	3.6%

On the other hand, the federal immission control law[8] was updated on 11.08.2009. The updated law reduced total and gasoline quotas for the years between 2010 and 2014 to 6.25% and 2.8% respectively. Furthermore, the structure of the law is changed principally after the year 2015, when the *decarbonisation* amount, which is the reduction of GHG emissions, is counted instead of energy content of the blended fuel. Decarbonisation of the transport fuels should be at least 3.0%, 4.5%, and 7.0% according to this law after 2015, 2017, and 2020 respectively. Although it is not defined clearly by the policy makers how this law is operationalized, the government will probably provide official GHG values for the different fuel production pathways and then the oil companies will be free to choose the blended biofuel among the alternatives as long as the overall emissions are below the defined values for corresponding years. However, as the approach and operationalization of the law is not clear yet, decarbonisation strategy is not considered and only the existing blending quota values (presented in Table 2) are investigated in this study.

Furthermore, the binding targets of the EU for share of biofuels use in member countries are 5.75% and 10% for the years of 2010 and 2020 respectively (EU, 2006). The comparison of these targets with Table 2 shows that the German government aims to go beyond the EU targets for the year 2010.

The Federal Environment Ministry (BMU) and Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) met with interest groups from automobile, mineral oil, biofuel and agriculture sectors and developed a common strategy for biofuels (BMU et al., 2007). The so called roadmap for biofuels mentions four crucial points for the future strategy in Germany:

- Increasing biofuel blending limits
- Increasing biofuel targets
- Securing the sustainability of biofuels and successive increase of GHG efficiency
- Promoting second generation biofuels

Researchers as well as politicians increasingly focus on electricity as a transport fuel. There are many programs (e.g. BMU, 2009b; BMVBS, 2009) to support the research,

[8] Bundesimmissionschutzgesetz (BImSchG)

demonstration and market penetration of electric mobility which are sponsored by the German government.

Besides the utilized fuel, the emissions from motorized vehicles are also regulated. The history of automotive emission regulation in the EU is summarized by Vogel et al. (2005). The first uniform set of automotive emission standards was initiated in 1987 in the EU. Later these standards are renewed and strengthened several times. The EURO4 regulation restricts the emissions of CO[9], HC[10], NO_x[11], and PM[12] differentiated for powertrain and vehicle type (EC, 2003). The EU has prepared EURO5 and EURO6 regulations which have stricter restrictions particularly for NO_x and PM. EURO5 came into effect on 01.09.2009 and EURO6 regulation will come into force on 01.09.2014 (EC, 2007).

1.3 Existing studies for system analysis of the transport sector

There are several studies that performed an energy system analysis for the transport sector. An overview of the selected studies is presented in Table 3.

IFEU (2005) describes the conventional powertrains in terms of energy efficiency, GHG emissions, and pollutants. However, an economic analysis is not included in the study.

Similar to IFEU (2005), the HBEFA (2004) also analyzed conventional powertrains for their energy consumption and emissions. The detailed results of this study are based on experimental measurements separately for transport sections (e.g. passenger car, public bus or heavy duty vehicle), vehicles with different emission regulations (e.g. EURO1-5), road type (e.g. highway or street), and traffic situation (e.g. free driving or congestion). Although the conventional powertrains are investigated in detail for their energy consumption and various emissions, alternative powertrains and an economic analysis are not included in the study.

The Concawe (2009) study examines different fuel production pathways and powertrains for passenger transport only. In the study the efficiencies, costs, and GHG emissions are investigated for the year 2010. However, an integrated assessment with the help of a system model is lacking in this study. Furthermore, the future developments of the technologies are not investigated.

Remme (2006) modeled the German energy system with the help of the TIMES model. The model has very detailed technological description especially for the conventional technologies in the sectors of heating systems, electricity generation, and refineries. Although

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[9] Carbon monoxide
[10] Hydrocarbons
[11] Nitrogen dioxide (NO_2) and Nitric oxide (NO)
[12] Particulate matter

the transport system is also modeled in this study, only few fuel and powertrain alternatives were considered.

Table 3: Overview of selected studies for energy system analysis

Study	Analysed energy carriers, technologies, and sector	Analysed aspects	Integration of different aspects by model type	Spatial scope	Temporal scope until
IFEU, 2005*	Conventional fuels and powertrains for • Transport	• Energy efficiency • GHG emissions • Pollutants	No integration	Germany	2030
HBEFA, 2004	Conventional fuels and powertrains for • Transport	• Energy efficiency • GHG emissions • Pollutants	No integration	Germany	2020
Concawe, 2009	Alternative fuels for • Motorized individual transport	• Energy efficiency • Costs • GHG emissions	No integration	EU	2010
Remme, 2006	Renewable and fossil energy mainly for • Electricity	• Energy efficiency • Costs • GHG emissions	TIMES	Germany	2050
König, 2009	Biomass for • Electricity • Heat • Transport	• Energy efficiency • Costs • GHG emissions • Land area for biofuels	TIMES	Germany	2030
Gül, 2008	Biofuels and hydrogen for • Motorized individual transport	• Energy efficiency • Costs • GHG emissions	MARKAL	EU29 Global	2100

*) There is an update of this study on 26.03.2010 (IFEU, 2010)

König (2009) builds upon the work of Remme (2006) and investigates mainly the bioenergy pathways in the German context. The main research question is to find out the role of biomass in the German energy system. Although biofuels (biodiesel, bioethanol, BTL, and SNG) are investigated in this study, the focus is not on the transport system, alternative energy carriers (such as hydrogen, hydrated vegetable oils etc) and powertrains (such as fuel cell and hybrid technologies etc).

Gül (2008) aims to assess the role of hydrogen and biofuels in the motorized individual transport separately for EU29 and for the globe. The energy efficiencies, costs, and GHG emissions of alternative fuel pathways are investigated in the study. The hydrogen infrastructure is modeled in detail and many fuel and powertrain alternatives are investigated. Although the study is very detailed for the motorized individual transport, the rest of the transport system is not modeled. Furthermore, only the oil prices and the fuel cell costs are varied in the study. The effect of different battery and gasifier costs are not investigated. Lastly, the land area requirement of biofuels is not quantified. Instead, a fix biofuel potential is taken from literature and the production is limited with this value.

To sum up, there are several existing studies that performed a system analysis of the transport sector. However, the German transport sector is not modeled in detail for the alternative fuels and powertrains in terms of their costs, GHG emissions, and land area requirement for biofuels. Moreover, the effect of future costs of different fuel production pathways and powertrains are also not investigated with a special focus on road transport.

1.4 Aim of the study

This study aims to assess the role of alternative fuels and powertrains in the German transport sector (with a special focus on road transport) in future (until 2030) in terms of their

- costs,
- GHG emissions and
- land area requirement for energy crops.

It is expected that the findings of this study have significant contributions to understand the influence of the existing policies for the German transport sector (such as blending quota) on the costs, GHG emissions and land area requirement for energy crops and to suggest improvements for the existing policies.

1.5 Methodology and structure of the study

An energy system analysis is a complex task especially if one considers technological diversity and their future developments. Thus, in this work a model based approach is employed. The utilized model belongs to the TIMES (**T**he **I**ntegrated **M**ARKAL **E**FOM **S**ystem) family and is a bottom-up linear optimization energy system model. The model comprises of the German energy system; however, in this study the focus is on the road transport. The pre-existing model from Remme (2006) is extended, updated, and improved in this work. The scenario analysis method is employed in order to assess the effect of different conditions on the overall system (Voß, 1982 and Remme, 2006).

As mentioned in chapter 1.4, costs, GHG emissions, and land area requirement of energy crops are examined in this study. The costs are categorized as investment costs, fixed operating maintenance (FOM) costs, and variable operating maintenance (VOM) costs. The VOM costs are further divided into feedstock costs and other VOM costs. The costs of different fuel production pathways and powertrains are determined for present and future (2030) with the help of an extensive literature review. Moreover, the future costs of different fuel production pathways and powertrains are varied in order to see their effects on the results.

The major energy related greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are investigated in this work. These emissions are further summarized by carbon dioxide equivalent emissions (CO_{2eq}). The CO_{2eq} emissions include CO_2, CH_4, and N_2O with corresponding CO_2 equivalent factors of 1.0, 23.0, and 296.0 respectively (IPCC 2001).

The required land area for energy crops is measured in million hectares (ha) of arable land. Today's yields of energy crops are taken from literature and expected future yields are estimated for each crop.

It is intended to analyze different powertrains in chapter 2 in terms of their "tank to wheel" characteristics. These characteristics include energy consumption, onboard GHG emissions, investment costs and FOM costs of vehicles. An analysis based on a broad literature review is made to characterize different powertrains.

Chapter 3 deals with the different fuel production pathways. Complementary to chapter 2, in this chapter the characteristics of different fuel production pathways are investigated from raw material to the fuel station. This analysis includes energy efficiency, costs, and GHG emissions of fuel production pathways, which is based on an extensive literature review.

Chapter 4 presents the method and tools for the system analysis. First a brief overview of energy models is given. Secondly, the utilized model TIMES is explained in detail and the modifications, updates, and improvements on the pre-existing model are presented.

The scenario analysis is presented in chapter 5. In this chapter, first the key modeling assumptions for the scenarios are presented. Moreover, the specific assumptions for each scenario and their results are depicted.

Lastly, the findings are summarized in chapter 6. Furthermore, suggestions for future research are mentioned.

2 Description and analysis of alternative powertrains in the German transport sector

This chapter is dedicated to alternative powertrains that are commercially[13] available or expected to be available in the future in Germany. This chapter is concerned with technical, environmental and economic aspects of powertrains for tank to wheel (TTW). TTW refers to the activities after the fuel is filled at the tank station (Messaoudene et al., 2010). Therefore, the activities of fuel production and supply are not considered in this chapter and mentioned in chapter 3.

Chapters 2.1 to 2.7 introduce powertrain technologies and present the state of the art of each powertrain. The technology description is followed by the calculations for the fuel consumption and direct greenhouse gas emissions per vehicle kilometer (vkm).

To calculate the fuel consumption and direct greenhouse gas emissions per vkm for the conventional technologies the existing and expected vehicle fleet characteristics are determined based on IFEU (2005) and matched with the fuel consumption and emission inventory of HBEFA (2004). For all non-conventional powertrain alternatives the changes relative to the conventional powertrain technology for fuel consumption and emissions are determined with the help of an extensive literature survey.

Chapter 2.8 introduces the investment cost calculation of each powertrain technology. In this chapter, previously presented powertrain technologies are compared for passenger cars, buses, and freight trucks in terms of their investment costs and energy consumption per 100 vkm.

The German transport system depends mainly on the internal combustion engine. Thus, in this chapter the two most common internal combustion engines (spark ignition and compression ignition) types are explained first. The other powertrain alternatives follow these.

2.1 Spark ignition engines

Spark ignition (SI or Otto cycle) engines like all internal combustion engines (ICEs) consists of a combustion chamber and a reciprocating piston. The four stroke internal combustion engines have intake, compression, expansion, and exhaust phases, which are also applicable to other internal combustion engines.

[13] Commercial production is defined as the production by permanently established plants which are operated on a regular basis in a market environment by applying business methodology.

The spark ignition engine is highly popular for motorized individual transport. In 2005, 36.3 million out of 45.4 million passenger cars in Germany have spark ignition engines (DIW, 2011). Furthermore, almost all of the motorcycles are equipped with this engine type. On the other hand, the spark ignition engines cover only a niche in the market for small trucks and small aircrafts. Spark ignition powered aircrafts are not investigated further in this study.

In this section, only gasoline fuel is investigated. Other fuels that might be used in spark ignition engines are examined in chapter 3.

2.1.1 Passenger cars

The emission level regulations are the standards defined by the legislator. The EURO1 regulations were introduced in the early 1990s (Council Directive, 1991). Each new coming regulation (e.g. EURO2, EURO3. etc.) builds upon previous ones with additional emission restrictions (see section 1.2). Although the regulations define the restrictions for pollutants, there is a clear correlation between the emission regulation of the vehicle and its energy consumption. Therefore, it is quite common to distinguish the existing passenger car fleet for its emission regulation levels to estimate the tank to wheel energy consumption and emission values of conventional engines (among others Goyns and Özdemir, 2011; Smit et al., 2007; IFEU, 2005; HBEFA, 2004).

The assumed development of emission regulation level shares for passenger cars with spark ignition engines are taken from IFEU (2005). In IFEU[14] (2005), only the regulations EURO1 to EURO4 until the year 2020 are considered. Therefore, in the present study the emission regulation level development is updated for EURO5 and 6 cars and extended to the year 2030 (Figure 3). As the post EURO6 regulations are not known yet (Delphi, 2011), it is assumed in this study that all the post EURO6 vehicles will have similar characteristics as the EURO6 vehicles.

The results show that the passenger cars with EURO4 spark ignition engine will have the highest share in the transport sector between 2010 and 2025. The vehicles with EURO6 regulation are expected to dominate starting from the year 2025. The increase of vehicles with new emission regulations will have an impact on the energy consumption and emission per vkm of the fleet.

The TTW energy consumption and GHG emission factors (CO_2 and CO_{2eq}) are calculated with the help of the HBEFA (2004) database for the emission levels EURO1 to 4. The EURO5 and EURO6 emission levels are obtained with the assumptions that the energy

[14] IFEU (2010) is an updated study of IFEU (2005) and considers the emission levels EURO5 and 6. The results of the share of EURO5 and 6 vehicles in 2030 for this study and IFEU (2010) for are quite similar for all type of vehicles.

efficiencies (and correspondingly the CO_2 emissions) are 1% higher (lower) than their predecessors.

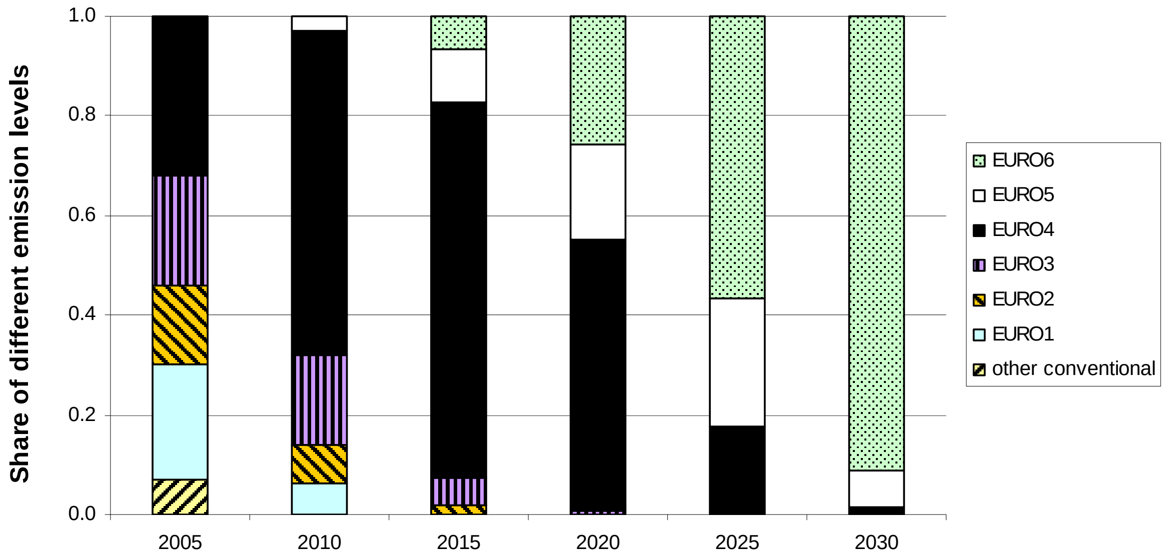


Figure 3: Present and projected share of emission regulation levels for the German passenger car fleet with spark ignition engine (updated from IFEU, 2005)

The resulting TTW energy consumption and emission factors for CO_2 and CO_{2eq} per vkm are presented in Table 4. The average fuel consumption for the spark ignition engine fleet in Germany for 2005 is calculated as 7.77 l/100vkm. Due to the efficiency increases, the fuel consumption drops about 27% to 5.66 l/100vkm in 2030. The corresponding CO_{2eq} emissions for the fleet are calculated as 184 and 133 g CO_{2eq}/vkm for 2005 and 2030 respectively. One should be careful before comparing these values with the 2012 EU target of 120 g CO_2 emission per vkm (EU, 2009) since the presented values in Table 4 are for an average fleet but the EU targets are for the new vehicles for the year 2012.

Table 4: Present and projected tank to wheel fuel consumption and emission factors of the German passenger car fleet with spark ignition engine

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100vkm	7.8	7.2	6.5	5.8	5.7	5.7
CO_2 emissions	g CO_2/vkm	182.6	169.8	152.7	135.7	133.9	133.0
CO_{2eq} emissions [a]	g CO_{2eq}/vkm	184.0	170.6	153.1	136.1	134.3	133.4

a) The CO_{2eq} emissions include CO_2, CH_4, and N_2O with corresponding CO_2 equivalent factors of 1.0, 23.0, and 296.0 respectively (IPCC, 2001).

2.1.2 Freight trucks

The freight trucks are divided into heavy duty vehicle (HDV) and light duty vehicles (LDV). Spark ignition engines play a small role only for light duty vehicles. The main reason for that is the relatively lower average mileage of light duty vehicles compared to average mileage of the heavy duty vehicles. Nevertheless, the share of spark ignition engines in light duty vehicles is only slightly higher than 10% (IFEU, 2005). The assumed development of emission level shares are taken from IFEU (2005) and updated for EURO5 and 6 and extended to 2030 (Figure 4). It is expected that more than 50% of light duty vehicles with spark ignition engines will have EURO6 regulation in 2020 and almost all vehicles will have EURO6 regulation in 2030.

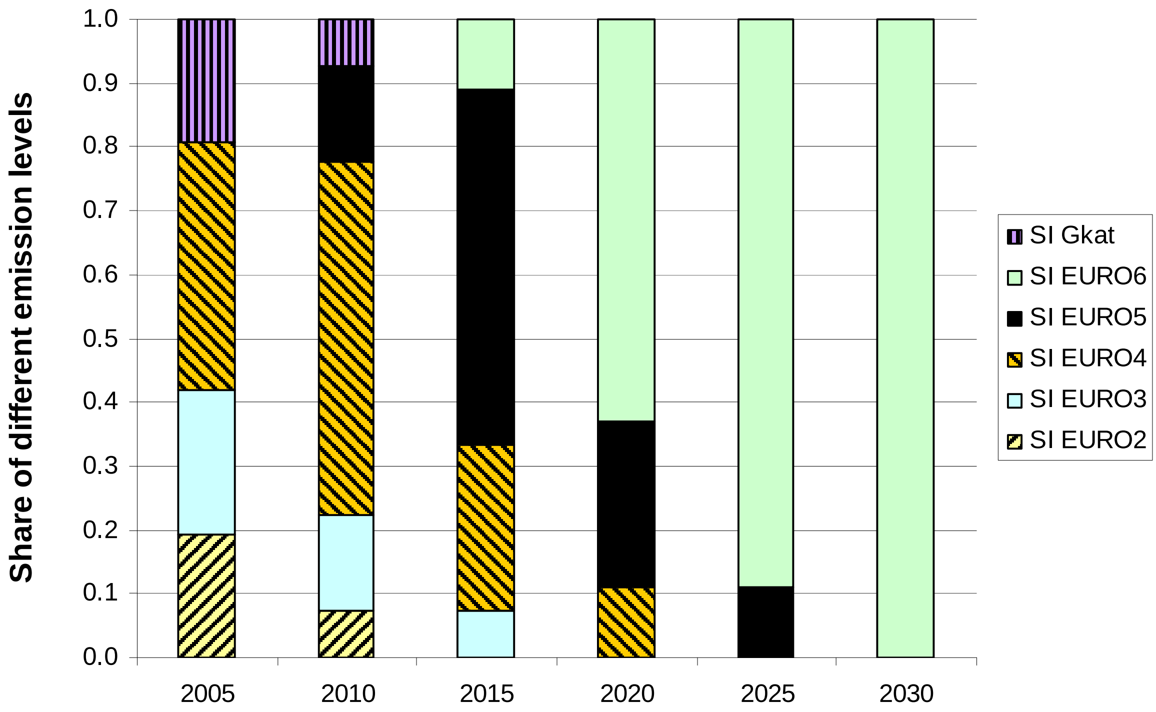


Figure 4: Present and projected share of emission regulation levels for the German light duty vehicle fleet with spark ignition engine (updated from IFEU, 2005)

The resulting fuel consumption and emission values are given in Table 5. As in the passenger cars, the fuel consumption and corresponding CO_{2eq} emissions of light duty vehicles with spark ignition engines are expected to decrease about 6% between the years 2005 and 2030. Furthermore, the occupancy level (ratio of tkm to vkm) is expected to increase in future (see chapter 2.2.3).

Table 5: Present and projected tank to wheel fuel consumption and emission factors of the German light duty vehicle fleet with spark ignition engine

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100vkm	10.2	9.9	9.7	9.6	9.6	9.6
Fuel consumption	l/100tkm	25.4	23.3	21.6	20.3	19.2	18.3
CO_2 emissions	g CO_2/vkm	239.5	233.1	228.7	226.4	225.3	225.0
CO_{2eq} emissions	g CO_{2eq}/vkm	240.5	233.8	229.2	226.9	225.8	225.5

2.1.3 Motorcycles & mopeds

The TTW energy consumption and emission factors for motorcycles (>50cc) and mopeds (<50cc) are calculated with a quite similar method as for the passenger cars. The assumed development of emission level shares are taken from IFEU (2005) and extended to 2030 (see Figure D 1 presented in the appendix). It is expected that motorcycles will have a much higher share of 2-wheelers in 2030 (>85%) than in 2005 (about 60%). Furthermore, it is expected that almost all motorcycles will have 4-stroke spark ignition engine with EURO3 emission regulation after 2020. On the other hand, all the mopeds are expected to have EURO2 regulation.

With the help of the HBEFA database, the TTW energy consumption and emission factors are calculated (see Table D 1 presented in the appendix). The fuel consumption per vkm of both motorcycles and mopeds decrease until 2030. However, the motorcycles have higher fuel consumption and as their share in 2-wheelers increase, the overall fuel consumption of 2-wheelers increases as well. Thus, the average 2-wheelers fuel consumption is expected to rise from 3.3 l/100vkm in 2025 to 3.4 l/100vkm in 2030.

2.2 Compression ignition engines

Compression ignition (CI or Diesel) engines have higher compression ratios than spark ignition engines which on one side increases the engine temperature and thereby the engine efficiency, on the other side results in higher NO_x emissions. Investment costs for compression ignition engines are higher than those for spark ignition engines. However, compression ignition engines dominate the road and ship freight transport due to its superior efficiency. Its popularity in Europe is increasing in other transport sections as well.

In this chapter, only diesel fuel is investigated. Other fuels that might be used in compression ignition engines are examined in chapter 3.

2.2.1 Passenger cars

The compression ignition engine vehicle stock share in the passenger car sector in 2005 was about 20% (DIW, 2011). This share is increased to about 25% in 2010 (DIW, 2011). Furthermore, passenger car drivers with compression ignition engine tend to drive about 60% more vkm per year than those drivers with spark ignition engines (Shell, 2009a).

The development of emission level regulation shares for passenger cars fleet for compression ignition engines is taken from IFEU (2005). This source only estimated the regulations EURO1 to EURO4 until the year 2020. This emission regulation level development is updated for EURO5 and 6 passenger cars and extended to the year 2030 (Figure 5). It is expected that the passenger cars with EURO5 and 6 compression ignition engines will have more than 50% of the vehicle fleet share from 2015 onwards. It is further expected that all vehicles will have EURO5 or 6 regulations in 2030.

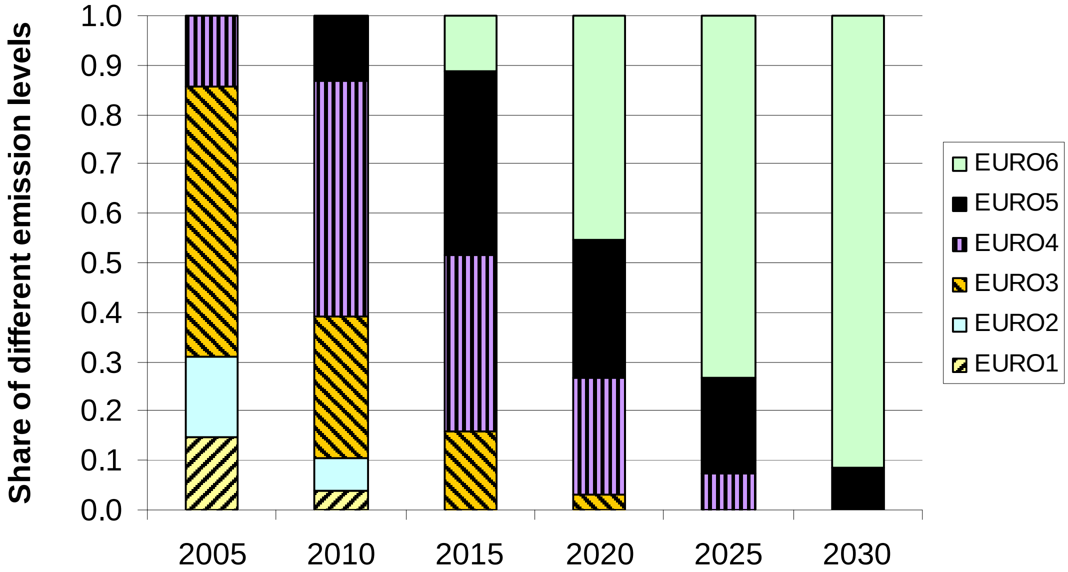


Figure 5: Present and projected share of emission regulation levels for the German passenger car fleet with compression ignition engine (updated from IFEU, 2005)

The resulting TTW energy consumption and emission factors are presented in Table 6. According to this table, the compression ignition engine passenger car fleet in 2005 consumed 6.1 l of diesel fuel per 100vkm, which is 13% less energy than the average spark ignition engine fleet fuel consumption in 2005. The fuel consumption of compression ignition engine passenger car fleet is expected to decrease to 4.5 l of diesel fuel for 100vkm in 2030. This fuel consumption corresponds to about 121 g CO_2/vkm for the fleet average.

Table 6: Present and projected tank to wheel fuel consumption and emission factors of the German passenger car fleet with compression ignition engine

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100vkm	6.1	5.8	5.2	4.6	4.5	4.5
CO_2 emissions	g CO_2/vkm	163.6	153.5	138.2	123.2	120.9	120.5
CO_{2eq} emissions	g CO_{2eq}/vkm	165.1	155.1	139.9	124.9	122.6	122.2

2.2.2 Buses

The fleet of buses for different emission levels are taken from IFEU (2005) and updated for EURO6 vehicles and extended to 2030 as done with the conventional passenger cars (Figure 6). As in the passenger cars with compression ignition engines, more than 50% of the bus vehicle fleet in the year 2015 is expected to have EURO5 and 6 regulations. Furthermore, it is expected that the whole bus fleet will be consisting of EURO5 and 6 vehicles in 2030.

The buses are divided into two as public buses[15] and coaches[16]. Although both bus types have nearly the same capacity (52 persons for public buses and 53 persons for coaches), the

[15] *Linienbus* in German
[16] *Reisebus* in German

average occupancy level per vehicle (pkm/vkm ratio) differs for public buses (14 pkm/vkm) and coaches (23 pkm/vkm) significantly (Brosthaus et al., 2003). Furthermore, their component dimensions (see Table B 2 and Table B 3 in the appendix) and driving cycle differs considerably.

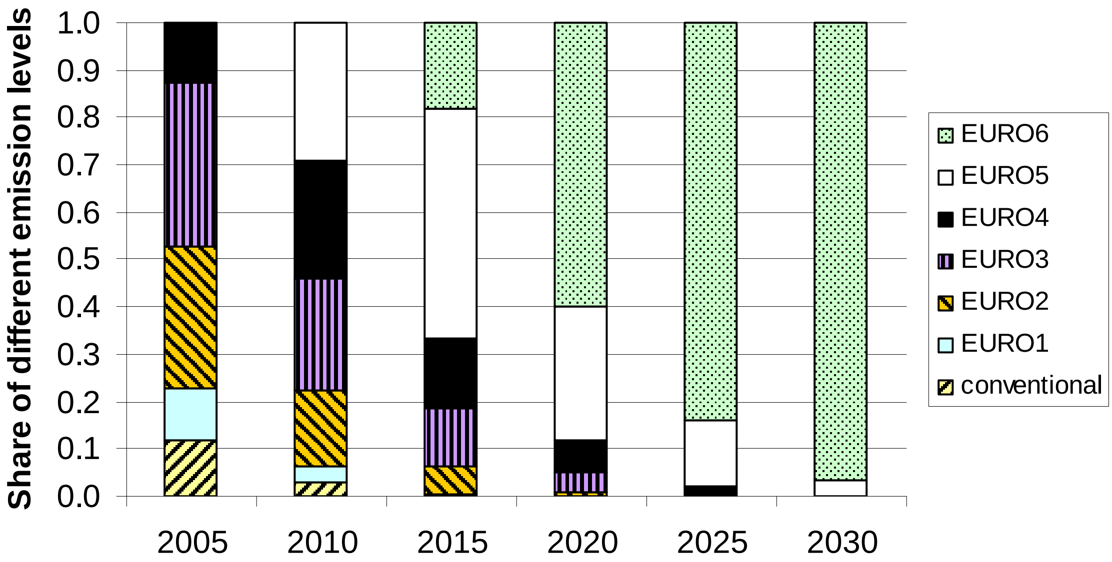


Figure 6: Present and projected share of emission regulation levels for German bus fleet (updated from IFEU, 2005)

The resulting TTW energy consumption and emission factors are presented in Table 7. The increase in fuel consumption from 2005 to 2025 is due to the strict emission regulations which would be achieved by sacrificing engine efficiency slightly (see also chapter 2.2.3).

Table 7: Present and projected tank to wheel fuel consumption and emission factors of the German bus fleet

		2005	2010	2015	2020	2025	2030
Public buses							
Fuel consumption	l/100vkm	36.2	36.5	37.0	37.2	37.3	37.3
CO_2 emissions	g CO_2/vkm	874.3	882.0	894.6	899.8	900.9	900.3
CO_{2eq} emissions	g CO_{2eq}/vkm	877.1	884.5	896.9	902.0	903.1	902.5
Coaches							
Fuel consumption	l/100vkm	32.8	34.0	35.2	35.6	35.7	35.7
CO_2 emissions	g CO_2/vkm	792.2	821.8	849.6	860.7	863.0	862.5
CO_{2eq} emissions	g CO_{2eq}/vkm	794.6	823.9	851.6	862.7	865.1	864.5

2.2.3 Freight trucks

The freight trucks are divided into heavy and light duty vehicles. The majority (96%) of the freight transport is carried out with heavy duty vehicles in Germany. The heavy duty vehicles are exclusively powered by compression ignition engines due to the higher energy requirement of the vehicle and higher efficiency of these engines. The fleet of heavy duty vehicles for different emission levels are taken from IFEU (2005) and updated for EURO6 vehicles and extended to 2030 (Figure 7). It is expected that heavy duty vehicles with EURO5 and EURO6 regulations will account for about 70% of the vehicle fleet in 2015. Furthermore, all the heavy duty vehicles in 2030 are expected to have EURO6 regulations.

Hausberger et al. (2003) discusses the experimental results of heavy duty vehicles for emission regulations of EURO1 to EURO3. Although the fuel consumption decreases from EURO1 to EURO2, the fuel consumption of EURO3 vehicles are higher than EURO2 vehicles due to the strict pollution regulations. The prediction is that EURO4 fuel consumption is slightly lower than EURO3; however, the EURO5 level is again on the level of EURO3 (Hausberger et al., 2003). Furthermore, EURO6 is assumed to be 1% more efficient than the EURO5.

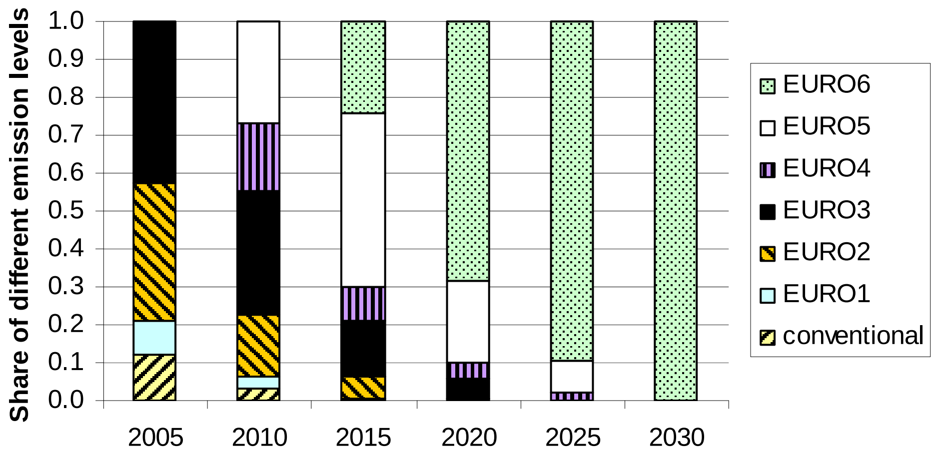


Figure 7: Present and projected share of emission regulation levels for the German heavy duty truck fleet (updated from IFEU, 2005)

On the other hand, the fuel consumption per vehicle kilometer (MJ/vkm) is not the only parameter that affects the overall efficiency of the freight transport. The average occupancy level (tkm/vkm ratio) is at least as important as the fuel consumption per vkm. The average tkm/vkm ratio for heavy duty vehicles is increased from 4.5 in 1995 to 5.6 in 2005 (DIW, 2011). It is anticipated that the average occupancy level will increase 30% until 2030 compared to 2007 (IFEU, 2005). Thus, the energy consumption per tkm will decrease not due to the efficiency increase in the engine but due to the higher occupancy level (Table 8).

Compression ignition engines play a dominant role for the light duty vehicles, besides the spark ignition engines that are mentioned in the chapter 2.1.2. Similar calculation methods are also performed for the light duty vehicle section. The expected share of different emission regulation levels are presented in Figure 8, which is taken from IFEU (2005), updated for EURO5 and 6, and extended until 2030. It is expected that the EURO6 light duty vehicles are introduced in 2015 for the first time and they will constitute more than 95% share of all light duty vehicles in 2030.

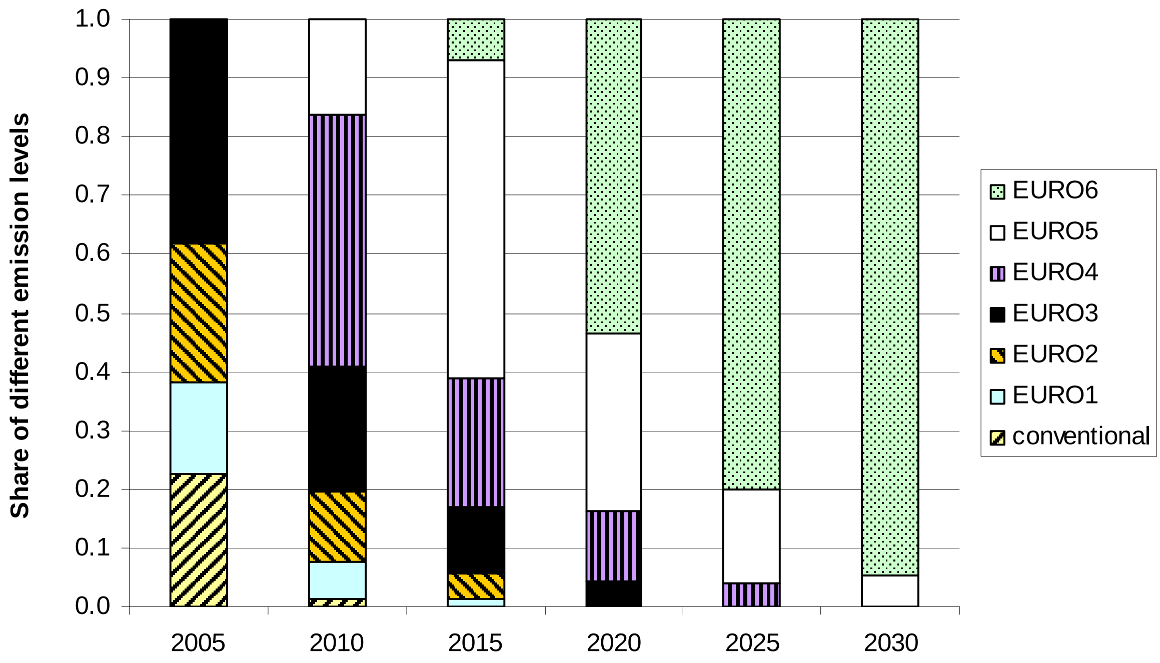


Figure 8: Present and projected share of emission regulation levels for the German light duty truck fleet (updated from IFEU, 2005)

Table 8: Present and projected tank to wheel fuel consumption and emission factors of the German freight truck fleet with compression ignition engine

		2005	2010	2015	2020	2025	2030
HDV							
Fuel consumption	l/100vkm	26.0	26.7	27.2	27.4	27.7	27.8
Fuel consumption	l/100tkm	4.7	4.5	4.4	4.2	4.0	3.9
Occupancy level	tkm/vkm	5.6	5.9	6.2	6.6	6.9	7.2
CO_2 emissions	g CO_2/vkm	692.5	713.5	724.5	730.7	739.6	741.5
CO_{2eq} emissions	g CO_{2eq}/vkm	799.9	819.3	812.2	783.1	776.2	769.4
LDV							
Fuel consumption	l/100vkm	8.9	8.8	8.7	8.6	8.6	8.5
Fuel consumption	l/100tkm	25.4	23.7	22.2	20.8	19.7	18.8
Occupancy level	tkm/vkm	0.35	0.37	0.39	0.41	0.43	0.45
CO_2 emissions	g CO_2/vkm	237.2	234.6	231.9	229.7	228.4	227.9
CO_{2eq} emissions	g CO_{2eq}/vkm	238.6	236.2	233.5	231.3	230.1	229.5

The occupancy level plays a significant role for the light duty vehicles similar to the heavy duty vehicles. The occupancy level is assumed to increase from 0.35 tkm/vkm in 2005 to 0.45 tkm/vkm in 2030. Thus, the increase in occupancy level and increase of engine efficiency together contribute to the reduction of fuel consumption per 100 tkm from 25.4 liters in 2005 to 18.8 liters in 2030 (Table 8).

2.2.4 Rail transport

The output power of compression ignition engines in rail transport is generally not transferred mechanically as in trucks. The mechanical energy that the compression ignition engine provides is transferred either hydraulically (e.g. with a hydraulic torque converter) or electrically (with generator and electromotor). Although the electrical transfer is often used globally, the hydraulic one is common in Germany (Rudolph et al., 2008).

The rail transport is divided into two as passenger and freight transport.

Passenger: The emissions and efficiencies of rail personal transport with compression ignition engine are calculated with the average fuel consumption per seat km (from IFEU, 2005) and average occupancy level differentiated for short[17] and long[18] distance transport.

$$\eta_{pkm} = \frac{100 \cdot \theta_{pkm}}{\lambda} \qquad \textbf{(1)}$$

where,

η_{pkm} is the specific energy consumption (per hundred person kilometer)

θ_{pkm} is the specific energy consumption (per offered seat kilometer)

λ is the average occupancy level (between 0 and 1)

The average fuel (diesel) consumptions (θ_{pkm}) for 2005 are taken as 5.4 and 10 g per seat km for short and long distance transport respectively (IFEU, 2005). The occupancy level (λ) for short distance transport decreased between 1995 and 2005 from 26% to 21% (IFEU, 2005). The target, however, for 2020 is 24% (IFEU, 2005). It is assumed that the target is reached in 2020 and 1% engine efficiency increase is achieved every 5 years after 2005. The occupancy level for long distance is relatively higher in 2005 with about 43% (IFEU, 2005). The target for occupancy level in the year 2020 is 50%. Again it is assumed that the target is reached in 2020 and a 1% efficiency increase is achieved every 5 years after 2005. The CH_4 emissions are taken from Knörr et al. (2003) and the N_2O emissions per consumed fuel are taken to be the same as the heavy duty road vehicles. The resulting fuel consumption per hundred pkm and emissions per pkm are presented in the appendix in Table E 1.

Freight: The emissions and efficiencies of rail freight transport with compression ignition engine are calculated with the average fuel consumption per offered tkm (from IFEU, 2005) and average occupancy level.

[17] Short distance transport is defined as less than 50 km and includes S-Bahn (fast city train) among other trains.
[18] Long distance transport is defined as more than 50 km.

$$\eta_{tkm} = \frac{100 \cdot \theta_{tkm}}{\lambda} \qquad \textbf{(2)}$$

where,

η_{tkm} is the specific energy consumption (per hundred ton kilometer)

θ_{tkm} is the specific energy consumption (per offered ton kilometer)

The average fuel (diesel) consumption (θ_{tkm}) for 2005 is taken as 4.2 g per offered tkm (IFEU, 2005). The occupancy level (λ) increased between 1995 and 2005 from 30% to 42% (IFEU, 2005). It is assumed that this level of 42% will be constant until 2030 and 1% engine efficiency increase is achieved in every 5 years after 2005. The CH_4 emissions are taken from Knörr et al. (2003) and the N_2O emissions per consumed fuel are taken to be the same as the heavy duty road vehicles. The resulting fuel consumption per hundred tkm and emissions per tkm are presented in the appendix in Table E 2.

2.2.5 Freight inland ship

The international maritime transport is beyond the scope of this work. Thus, in this study only inland freight ships are considered. Furthermore, the international maritime transport emissions are not limited by the Kyoto Protocol (UNFCCC, 2010).

The freight ship transport is exclusively powered by compression ignition engines. However, as in the rail transport the transfer of power of the compression ignition engine is not mechanically but hydraulically or electrically.

In 2005, the fuel consumption of freight ships and transported tkm are 306 kt and 64.1 Gigatkm respectively (DIW, 2011). The same occupancy level is assumed for the further years. Furthermore, the fuel efficiency is assumed to increase 5% between 2005 and 2020 (IFEU, 2005) the resulting fuel consumption and emissions are presented in the appendix in Table E 3.

2.3 Gas turbines

Gas turbines operate on the principle that the chemical energy of the fuel is converted to propulsion. For this purpose the incoming air is compressed and transferred to the combustion chamber where the fuel is added and the temperature is increased. The gases that have high temperatures and pressure drive the turbine and the expelled air propels the vehicle.

2.3.1 Aviation

There are three types of gas turbines (turbojet, turboprop and turbofan) with slightly different applications. Turbojet gas turbines, due to their inferior characteristics for noise level and fuel consumption, are not utilized commonly (La Franca, 2006 in Canali, 2009). Turboprop engines utilize a gas turbine to power the propeller. The turboprop gas turbines are appropriate only for small sized airplanes and the global fuel consumption in turboprop turbines is less than 2% of the total fuel consumption in aviation (Kim et al., 2005). Thus, turboprop turbines are not considered further in this work.

Turbofan gas turbines are widely utilized in the aviation sector due to their capacity to power commercial passenger airplanes and their relatively low fuel consumption and noise level. Today, almost all commercial aircrafts with gas turbines utilize kerosene as fuel. The specific energy consumption for aviation are taken from ITP et al. (2007) and the specific GHG emissions are taken from Canali (2009) (see Table E 4 presented in the appendix). The results show that as the air freight transport becomes more efficient per tkm, the passenger transport becomes less efficient per pkm in the future. These efficiency changes are mostly related to occupancy level rather than efficiency increase/decrease of engines or other technical equipment.

Other innovative engines like fuel cell for aviation are not considered in this work. Other considered fuel alternatives in this study for the aviation sector are biodiesel, hydrated vegetable oil and synthetic diesel (see chapter 3). Their efficiency is taken to be the same as the kerosene as they are only thought to be blended with kerosene.

2.3.2 Other gas turbine utilizations

Three are also non-aviation applications of gas turbines. The most important application is stationary electricity generation (and industrial mechanical drive applications), which is (are) outside of the scope of this study.

There are also other applications related to the transport sector. Gas turbines have the advantages of lower weight and volume per unit of power, lower need for changing gear ratios and lower emissions against internal combustion engines (Walsh et al., 2004). However, in automotive applications the main disadvantages of gas turbines are the low part load efficiency, long acceleration time and additional cost of manufacturing facilities (Soares, 2008).

There are some commercial marine applications. The marine applications differ considerably from automotive applications since the acceleration time is not critical and there is an insignificant emission regulation for marine applications (Walsh et al., 2004). However, poor fuel efficiency at the part load is the main disadvantage of marine applications of gas turbines (Saravanamuttoo et al., 2009). The role of gas turbines might change in the future if there are stricter emission regulations for the marine transport. However, gas turbine applications for other sectors than the aviation sector are not considered in this study further due to their low utilization level.

2.4 Electric motors

Electric motors (EM) are applied broadly. In the transport sector they are almost exclusively utilized in trains and trams. However, there are some efforts to introduce electric motors in automotive applications commercially.

There are no onboard emissions if the vehicle is only powered by electric motor, but the emissions due to the electricity generation are considered for a holistic approach in the following chapters.

2.4.1 Rail transport

The rail transport is divided into passenger trains, trams and freight trains.

Passenger trains: The efficiencies of electric motors for rail personal transport are calculated with the average energy consumption per seat km (from IFEU, 2005) and average occupancy level differentiated for short and long distance transport as in chapter 2.2.4. The average energy consumptions (θ_{pkm}) for 2005 are taken as 31.9 and 34.2 Wh/seat km for short and long distance transport respectively (IFEU, 2005). The occupancy level (λ) and motor efficiency increases are assumed to be the same as in rail personal transport with compression ignition engine (chapter 2.2.4). The results are presented in the appendix in Table E 5. The energy consumption difference between short and long distance occur due to the low occupancy level at short distance transport.

The results show that the energy consumptions of passenger electric trains in 2030 are about 46 and 23 MJ/100pkm for short and long distance respectively. These energy consumptions in 2030 correspond to 1.3 and 0.7 liter of diesel equivalent per 100 passenger kilometer for short and long distance trains respectively and are between 50% and 70% lower than the energy consumption of compression ignition passenger trains in 2030 (cf. chapter 2.2.4).

Trams: The average energy consumptions (θ_{pkm}) for 2005 and the occupancy level (λ) are taken as 23.0 Wh/seat km and 21% respectively (IFEU, 2008). The efficiencies of electric motors for trams are calculated with the average energy consumption per seat (from IFEU, 2005) and the occupancy level of 21% (IFEU, 2008). The motor efficiency increase is taken as 1% as with the passenger trains. The results are presented in the appendix in Table E 6.

The energy consumption results show that trams have 18% lower specific energy consumption (per 100 pkm) compared to short distance electric passenger trains in 2030. These results are mainly influenced by three aspects: electric motor efficiency, occupancy level and weight of the vehicle. The 18% difference is not due to the electric motor efficiency, which is assumed to be similar for trams and trains or occupancy level in 2030 which is comparable for trams (21%) and short distance passenger trains (24%). However, the difference is due to the trams being lighter than the trains per offered seat which lowers the specific energy consumption.

Freight: The efficiencies of electric rail freight transport are calculated with the average energy consumption per offered tkm (from IFEU, 2005) and average occupancy level as in chapter 2.2.4. The average energy consumption (θ_{tkm}) for 2005 is taken as 16.7 Wh/ offered tkm (IFEU, 2005). The occupancy level (λ) for 2005 is 41.8% and assumed to stay constant (IFEU, 2005). Furthermore, it is assumed that 1% motor efficiency increase is achieved in every 5 years after 2005. The resulting energy consumption per hundred tkm and emissions per tkm are presented in the appendix in Table E 7.

The results show that the specific energy consumptions of freight electric trains in 2030 are about 14 MJ/100tkm which corresponds to 0.4 liter of diesel equivalent per 100 tkm. This energy consumption is about 67% lower than the energy consumption of compression ignition freight trains in 2030 (cf. chapter 2.2.4).

2.4.2 Passenger cars

There are some efforts in recent years to make electric cars commercial. One of the significant barriers is the battery. Today the cost of the battery is almost half of the total investment cost of the vehicle (Bohr, 2009). Furthermore, the driving ranges of electric passenger cars (generally between 75 and 200 km) are significantly less than the internal combustion engine powered vehicles (between 450 and 1000 km), which creates acceptance problems for the consumers. Only 18% of car owners are interested in an electric car with a driving range of up to 150 km. The driving range of more than 200 km is acceptable for 64% of the drivers (Bohr, 2009). Therefore, the driving range is taken as 200 km for the battery electric passenger cars in this study (see chapter 2.8.1).

Charging may be done at the distribution grid voltage level (230 V and 16 A in Germany) or it may also be done at the 3 phase level (400 V and 16 A in Germany). The difference would be the cost of adapters and charging time. In this study, it is assumed that the cars are exclusively charged at the distribution grid voltage level.

The average energy consumption of electric cars is taken as 73 MJ/100vkm and expected to decrease to 59 MJ/100vkm in 2030 (EPRI, 2007; Engel, 2007; Hartmann and Özdemir, 2011). There are no tank to wheel emissions of battery electric vehicles (Table 9).

Table 9: Present and projected tank to wheel energy consumption and emission factors of the German electric passenger car fleet

		2005	2010	2015	2020	2025	2030
Average energy consumption	MJ/100vkm	73.0	70.2	67.4	64.6	61.8	59.0
Short distance (<50 km)	MJ/100vkm	55.0	52.8	50.6	48.4	46.2	44.0
Long distance (>50 km)	MJ/100vkm	83.0	79.6	76.2	72.8	69.4	66.0
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0	0.0

2.4.3 Buses

Electric motor powered buses consist of trolleybus and buses with batteries. The trolleybus was much more common in Germany after the Second World War period, however, almost all of them were replaced over time with compression ignition engine buses. Only three cities (Eberswade, Esslingen and Solingen) still have trolleybus lines (Groneck et al., 2007). Thus, only battery carrying buses are considered in this work. Battery electric buses are mainly relevant for public buses and not for coaches due to their driving range restriction. Therefore, the analysis below only applies to public buses.

The energy consumption of buses for the year 2005 is calculated with the assumption that the energy consumption ratio of battery electric buses to conventional buses is the same as the energy consumption ratio of battery electric passenger cars to compression ignition engine passenger cars. This assumption is reasonable since only the powertrains are changed for passenger cars and public buses under similar driving conditions.

$$\eta_{BUS}^{EM} = \frac{\eta_{PC}^{EM}}{\eta_{PC}^{CI}} \eta_{BUS}^{CI} \tag{3}$$

where,

η_{BUS}^{EM} is the specific energy consumption of an electric motor powered bus (per 100 vkm)

η_{BUS}^{CI} is the specific energy consumption of a compression ignition engine powered bus (per 100 vkm)

η_{PC}^{EM} is the specific energy consumption of an electric motor powered passenger car (per 100 vkm)

η_{PC}^{CI} is the specific energy consumption of a compression ignition engine powered passenger car (per 100 vkm).

For the upcoming years it is assumed that the energy consumption will decrease similarly to the electric passenger cars. The results are presented in Table 10.

Table 10: Present and projected tank to wheel energy consumption and emission factors of the German electric public bus fleet

		2005	2010	2015	2020	2025	2030
Energy consumption	MJ/100vkm	324.7	311.7	298.7	285.7	272.7	259.7
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0	0.0

2.5 Hybrid electric vehicles

The term hybrid means the combination of more than one. In this context, it means that more than one powertrain is combined and utilized for transportation purposes. The hybrid electric vehicle (HEV) implies the combination of powertrains, where at least one of them is capable of delivering electrical energy. Although the general definition is so broad, many people would only understand a combination of internal combustion engine with battery and electric motor under the term hybrid electric vehicle (Chau et al., 2002). Although for example fuel cell hybrid electric vehicle (see chapter 2.7) is also a hybrid electric vehicle in broad terms, it is not classified in this thesis under this group.

The hybrid electric vehicles might be classified in terms of their hybridization level (micro, mild and full) and their power management system design (series, parallel, series-parallel and complex).

For the **micro** hybrid electric vehicles the conventional starter motor is removed and the conventional generator is replaced by integrated starter generator (B-ISG) which is belt-driven (Chau at al., 2007 and Leonardi, 2008). Thus, the vehicle is capable of stopping the engine at idle times and starting again when needed. Furthermore, minimal regenerative braking and power assist is possible (Karden et al., 2007; Genc, 2008 and Chau et al., 2007).

The **mild** hybrid has a higher rated ISG than the micro hybrid, which is mounted on a crankshaft (C-ISG) due to the torque limitation of the belt (Leonardi, 2008). This enables moderate regenerative braking and power assist (Karden et al., 2007). However, mild hybrid electric vehicles cannot be purely electrically driven (Karden et al., 2007; Genc, 2008 and Chau at al., 2007).

The **full** hybrid electric vehicle is capable of driving purely on electricity in addition to all the features of mild hybrid electric vehicle (Karden et al., 2007; Genc, 2008 and Chau at al., 2007). The efficiency as well as the investment cost of vehicles increases as the hybridization level increases.

The different power system design types are shown in Figure 9 with corresponding hydraulic, electrical and mechanical links. Common energy flow directions are marked with arrow.

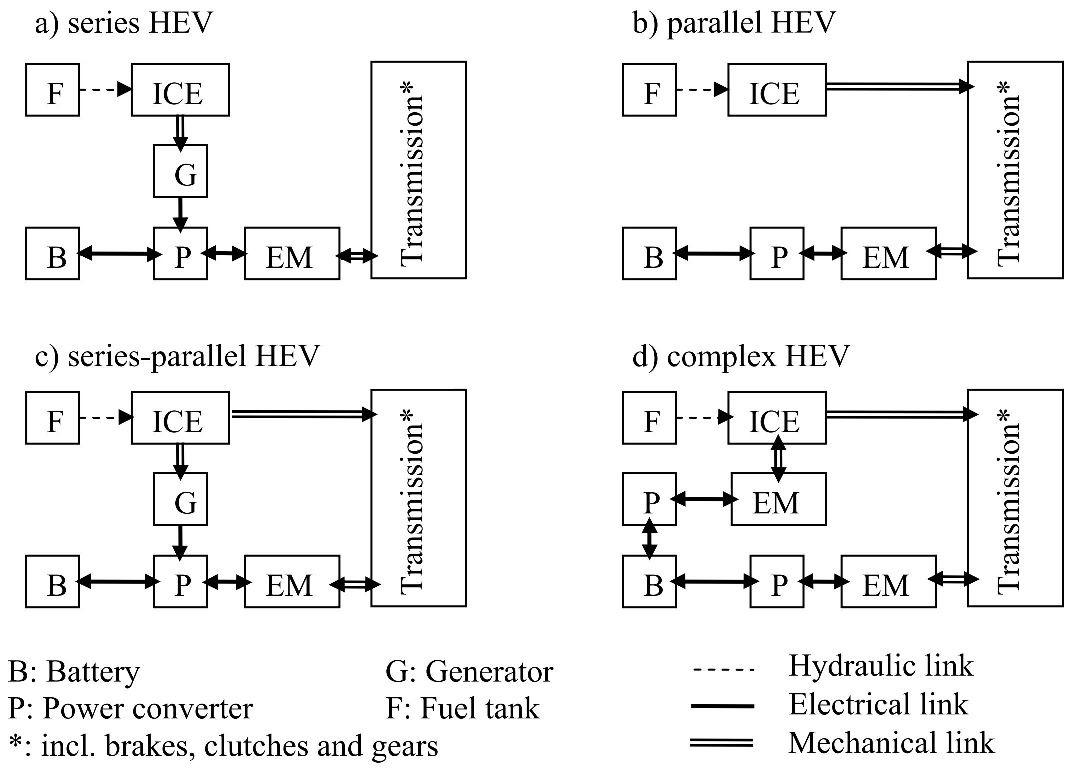


Figure 9: Different power management system designs for hybrid electric vehicles (Chau et al., 2002)

The **series** hybrid electric vehicle is actually an electric vehicle with an onboard electricity generation capability. As there is no mechanical connection between ICE and the transmission, this type is the simplest hybrid electric vehicle design. The disadvantage is that three propulsion devices (internal combustion engine, electric motor and generator) are needed and all of them should be dimensioned at maximum power output (Chau et al., 2002). The *Toyota Coaster HEV* Bus has this design (Chau et al., 2002).

On the other hand, by the **parallel** hybrid electric vehicles both internal combustion engine and electric motor might power (in parallel) the transmission. The advantage against the series hybrid electric vehicle is that generator is not needed and the charging of the battery is still possible through the transmission (with corresponding mechanical energy losses). Furthermore, the hybridization level might vary due to the application (micro, mild or full hybrids). As the hybridization level increases the size of the electric motor, the voltage level and the storage capacity of the battery and the ability for regenerative braking increases (Jené et al., 2004; Lam et al., 2006; Chau et al., 2007). The *Honda Insight HEV* utilizes mild parallel hybrid electric vehicle design.

The **series-parallel** hybrid electric vehicle has a generator in addition to the series hybrid electric vehicle and one mechanical link in addition to the parallel hybrid electric vehicle (Chau et al., 2002). Two different power flow controls are possible: engine heavy and electric heavy (Chau et al., 2002). The engine heavy flow control (which corresponds to mild hybrid) is only different from serial hybrid electric vehicle in that sense that the battery charging energy flow is through the generator not through the transmission, which increases the efficiency by eliminating mechanical energy losses. The electric heavy flow control corresponds to full hybrid. By this flow control, the generator (driven by internal combustion engine) supplies electricity for the electric motor by normal cruise and acceleration in addition to the features of engine heavy flow control. The *Toyota Prius* is a series-parallel full hybrid (Chau et al., 2002).

The **complex** hybrid electric vehicle design is for separately powering the front and the rear axle with two electric motors (Chau et al., 2002). Thus, this type has the highest complexity and costs.

The improvement of energy efficiency is between below 10% for mild and 30% for highly hybridized vehicles depending on the driving cycle and vehicle (Sciarretta et al., 2007).

2.5.1 Passenger cars (hybrid electric vehicles with spark ignition engine)

The passenger car sector is concentrated on full and mild hybrids (Genc, 2008). Thus, in this study only full and mild (parallel) hybrid electric designs are analyzed.

The fuel consumption compared to conventional spark ignition engine decreases 20% and 15% for full and mild hybrid electric vehicles respectively (Brinkman et al., 2005). The CO_2 emissions decrease in relation to the fuel consumption. The methane (CH_4) emissions of full hybrids are slightly less than conventional spark ignition engine (Brinkman et al., 2005). However, the nitrous oxide (N_2O) emissions would be 5% less for the same driven vkm with the full hybrid electric vehicle (Brinkman et al., 2005). The emissions of a mild hybrid electric vehicle are found by interpolating for the fuel consumption. The resulting emissions and fuel consumption are presented in Table 11.

Table 11: Present and projected tank to wheel fuel consumption and emission factors of the German (parallel) hybrid electric passenger car fleet with a spark ignition engine

		2005	2010	2015	2020	2025	2030
Full HEV passenger car (SI)							
Fuel consumption	l/100vkm	6.2	5.8	5.2	4.6	4.6	4.5
Fuel consumption	MJ/100vkm	202.0	187.9	168.9	150.1	148.2	147.2
CO_2 emissions	g CO_2/vkm	146.1	135.8	122.1	108.5	107.1	106.4
CO_{2eq} emissions	g CO_{2eq}/vkm	147.4	136.6	122.6	108.9	107.5	106.8
Mild HEV passenger car (SI)							
Fuel consumption	l/100vkm	6.6	6.2	5.5	4.9	4.9	4.8
Fuel consumption	MJ/100vkm	214.6	199.6	179.5	159.5	157.4	156.4
CO_2 emissions	g CO_2/vkm	155.2	144.3	129.8	115.3	113.8	113.1
CO_{2eq} emissions	g CO_{2eq}/vkm	156.6	145.1	130.2	115.7	114.2	113.4

2.5.2 Passenger cars (hybrid electric vehicles with compression ignition engine)

The first focus of the automotive industry was the hybrid electric vehicle with spark ignition engine rather than the hybrid electric vehicle with compression ignition engine. However, the hybrid electric vehicle with compression ignition engine has additional potential to reduce the fuel consumption. On the other hand, there is also the risk of combining two relative expensive technologies (compression ignition engine and hybrid electric vehicle) and come up with a too expensive end product. In this study only full hybrid electric vehicle with compression ignition engine (parallel) is considered.

The fuel consumption of full hybrid electric vehicle with compression ignition engine decreases 17% compared to conventional compression ignition engine (Brinkman et al., 2005). The carbon dioxide emissions decrease in relation to the fuel consumption. The methane (CH_4) emissions of full hybrids are twice the level of the conventional compression ignition engine (Brinkman et al., 2005). However, the nitrous oxide (N_2O) emissions would be the same for both technologies (Brinkman et al., 2005). The resulting emissions and fuel consumption are presented in Table 12.

Table 12: Present and projected tank to wheel fuel consumption and emission factors of the German (parallel) hybrid electric passenger cars fleet with a compression ignition engine

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100vkm	5.1	4.8	4.3	3.8	3.8	3.8
Fuel consumption	MJ/100vkm	182.5	171.3	154.2	137.5	134.9	134.5
CO_2 emissions	g CO_2/vkm	135.8	127.4	114.7	102.3	100.4	100.0
CO_{2eq} emissions	g CO_{2eq}/vkm	137.3	129.0	116.4	104.0	102.1	101.7

2.5.3 Buses

There is not a consensus for the optimal hybrid electric bus design in the literature. Azu (2001) argue that the series hybrids have greater fuel efficiency with interrupted driving cycle (stop and go), whereas the parallel hybrids are better rather at nearly constant high speeds. However, Williamson et al. (2007) and Suh (2008) argue that the parallel hybrid electric bus design is superior against the series hybrids in terms of fuel efficiency. In this study a parallel hybrid bus design is analyzed for public buses and coaches in order to be able to compare the results with passenger cars.

It is assumed that hybrid electric buses have the same efficiency improvement (17%) as the hybrid passenger cars with compression ignition engine. This assumption is consistent with the demonstration projects in Switzerland, where the efficiency increase of public buses was between 10 for rural regions and 20% for urban environment (Bossart, 2008).

On the other hand, due to inferior efficiency gains it is not expected that the conventional coaches will be substituted with hybrid electric buses in the near future (Hellgren, 2007). The expected driving cycle of coaches includes much less stop and go characteristics. Thus, the braking energy is not as significant as by the public buses. Hellgren (2007) argues that in 2005 the energy consumption of intercity hybrid electric buses was higher than (at the best case equal to) the conventional buses. This might be due to two reasons: the inferior efficiency gain by the coaches and the weight increase of the vehicle. The efficiency of hybrid electric buses will be improved slightly until 2020 resulting in a 1% increase in efficiency against the conventional diesel coaches. Table 13 summarizes the energy consumption and emission values for public buses and coaches.

Table 13: Present and projected tank to wheel fuel consumption and emission factors of the German (parallel) hybrid electric bus fleet

		2005	2010	2015	2020	2025	2030
Public buses							
Fuel consumption	l/100vkm	30.0	30.3	30.7	30.9	30.9	30.9
CO_2 emissions	g CO_2/vkm	801.4	808.5	820.0	824.8	825.8	825.3
CO_{2eq} emissions	g CO_{2eq}/vkm	805.0	811.4	822.6	827.2	828.2	827.7
Coaches							
Fuel consumption	l/100vkm	32.8	33.8	35.0	35.3	35.2	35.0
CO_2 emissions	g CO_2/vkm	874.9	903.0	933.5	941.0	938.8	933.5
CO_{2eq} emissions	g CO_{2eq}/vkm	878.4	906.0	936.2	943.4	941.1	935.8

2.5.4 Freight trucks

It is expected that hybrid freight trucks have similar characteristics as the hybrid electric buses. Although there are significant efficiency gains for the trucks traveling in urban conditions, the situation changes drastically (similar to hybrid electric buses) with highway driving conditions due to less utilizable regenerative braking energy (Shan, 2009; Nennelli, 2001). Thus, this technology is not considered as a viable option for the heavy duty trucks but only for light and medium duty trucks (Shan, 2009).

Therefore, similar assumptions are made for hybrid freight trucks as for hybrid electric buses. It is interesting to see that heavy duty hybrid freight trucks for interrupted (urban) driving and highway driving conditions result in similar specific energy consumption (per tkm), although the occupancy level is much lower for interrupted (urban) driving (Table 14). Interrupted and highway driving are especially relevant for short and long distance driving respectively. Similarly results for light duty hybrid freight trucks are presented in Table 15.

Table 14: Present and projected tank to wheel fuel consumption and emission factors of the German (parallel) heavy duty hybrid electric truck fleet with a compression ignition engine

		2005	2010	2015	2020	2025	2030
Short distance (<50 km) driving							
Fuel consumption	l/100vkm	19.9	20.5	20.7	20.9	21.1	21.1
Fuel consumption	l/100tkm	4.6	4.5	4.3	4.1	4.0	3.8
CO_2 emissions	g CO_2/vkm	531.4	545.8	553.1	556.9	562.2	564.1
CO_{2eq} emissions	g CO_{2eq}/vkm	534.3	548.3	555.3	559.0	564.2	566.1
Long distance (>50 km) driving							
Fuel consumption	l/100vkm	24.0	24.5	24.8	24.9	25.0	25.0
Fuel consumption	l/100tkm	4.6	4.5	4.3	4.1	3.9	3.7
CO_2 emissions	g CO_2/vkm	640.3	654.1	662.5	663.6	667.2	666.1
CO_{2eq} emissions	g CO_{2eq}/vkm	643.8	657.0	665.2	666.0	669.5	668.4

Table 15: Present and projected tank to wheel fuel consumption and emission factors of the German (parallel) light duty hybrid electric truck fleet with a compression ignition engine

		2005	2010	2015	2020	2025	2030
Short distance (<50 km) driving							
Fuel consumption	l/100vkm	7.4	7.3	7.2	7.1	7.1	7.1
Fuel consumption	l/100tkm	21.1	19.67	18.40	17.29	20.30	15.58
CO_2 emissions	g CO_2/vkm	196.9	194.7	192.5	190.6	189.6	189.2
CO_{2eq} emissions	g CO_{2eq}/vkm	198.3	196.3	194.1	192.2	191.2	190.8
Long distance (>50 km) driving							
Fuel consumption	l/100vkm	8.9	8.8	8.7	8.5	8.4	8.4
Fuel consumption	l/100tkm	21.2	20.8	20.6	20.2	20.0	15.3
CO_2 emissions	g CO_2/vkm	237.2	233.4	230.7	227.4	225.0	223.4
CO_{2eq} emissions	g CO_{2eq}/vkm	238.9	235.3	232.7	229.3	226.9	225.3

2.6 Plug-in hybrid electric vehicles

The plug-in hybrids are a special kind of hybrid electric vehicles. Besides having all the characteristics of a full hybrid electric vehicle, they have also the capability of being electrically charged, which resembles to electric cars (see chapter 2.4.2).

The most probable utilization of plug-in hybrids will be for passenger cars with spark ignition engines. A further potential utilization of plug-in hybrids is in the public bus section. It is assumed that the energy consumption of the electric motor and the internal combustion engine in the plug-in hybrid vehicles are the same as the consumption of battery electric vehicles and full hybrid electric vehicles respectively.

2.6.1 Passenger cars (plug-in hybrid electric vehicles with spark ignition engine)

One of the challenges for energy modelers is the estimation of the energy consumption share of electricity versus gasoline for plug-in hybrid electric vehicles. This information gets more important if the number of plug-in hybrid electric vehicles increase in future as expected. However, in literature there are very few studies that concentrate on this subject. Gül (2008) estimates the share of gasoline consumption for a plug-in hybrid electric vehicle in 2030 as 72%. The rest (28%) is electrical energy from the grid and not generated by the internal combustion engine onboard. However, these values are only mentioned in a table and not supported and justified elsewhere.

The daily mileage distribution for passenger cars in Germany is presented in Figure 10. The x-axis indicates the cumulative share of passenger cars and the y-axis the average daily mileage. For example, 67% of the existing passenger cars travel short distances (less than 50 km). In this study, a battery driving range of 65 km (similar to GM Volt) is taken.

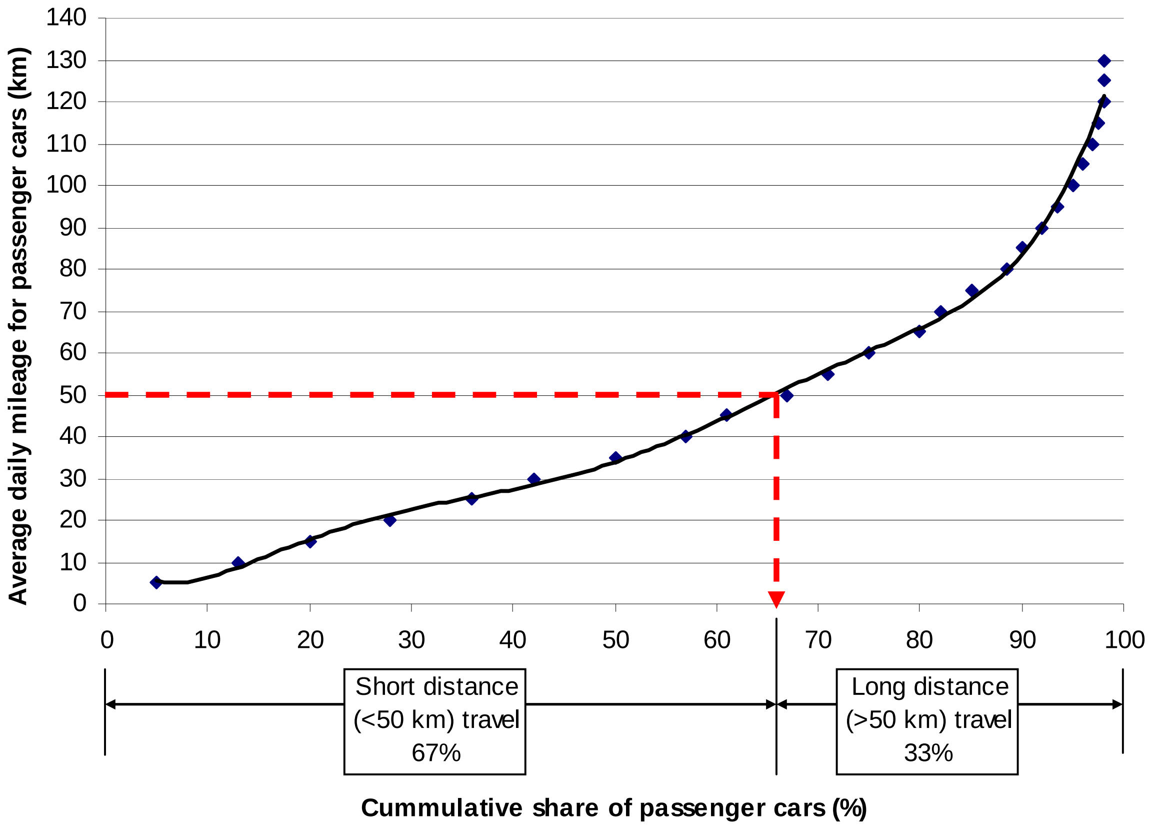


Figure 10: Distribution of average daily mileage of passenger cars in Germany (INFAS and DIW, 2004)

It is assumed that among the fuel alternatives, plug-in hybrid electric vehicle drivers will give priority to electricity from grid rather than gasoline. The assumption for priority to electricity consumption from the grid makes sense since electric driving exhibits high investment cost (especially batteries) but lower operating costs than a conventional powertrain. Therefore, the internal combustion engine is only used after the battery is depleted (i.e. after 65 km).

It is clear that for a short distance travel (less than 50 km), the plug-in hybrid electric vehicle resembles to the battery electric vehicle, where no internal combustion engine support is needed (65 km > 50 km). However, for a long distance travel (more than 50 km), the battery cannot provide enough energy for the whole trip and assistance of internal combustion engine is required. Therefore, the plug-in hybrid electric vehicle resembles to the full hybrid electric vehicle after 65 km. Figure 11 shows the share of mileages for a long distance (more than

50 km) traveling plug-in hybrid electric vehicle with 65 km electric driving range. The grey field represents the situations where plug-in hybrid electric vehicle is electrically driven ("battery electric vehicle mode"). The white field with black dots represents internal combustion engine driving ("full hybrid electric vehicle mode").

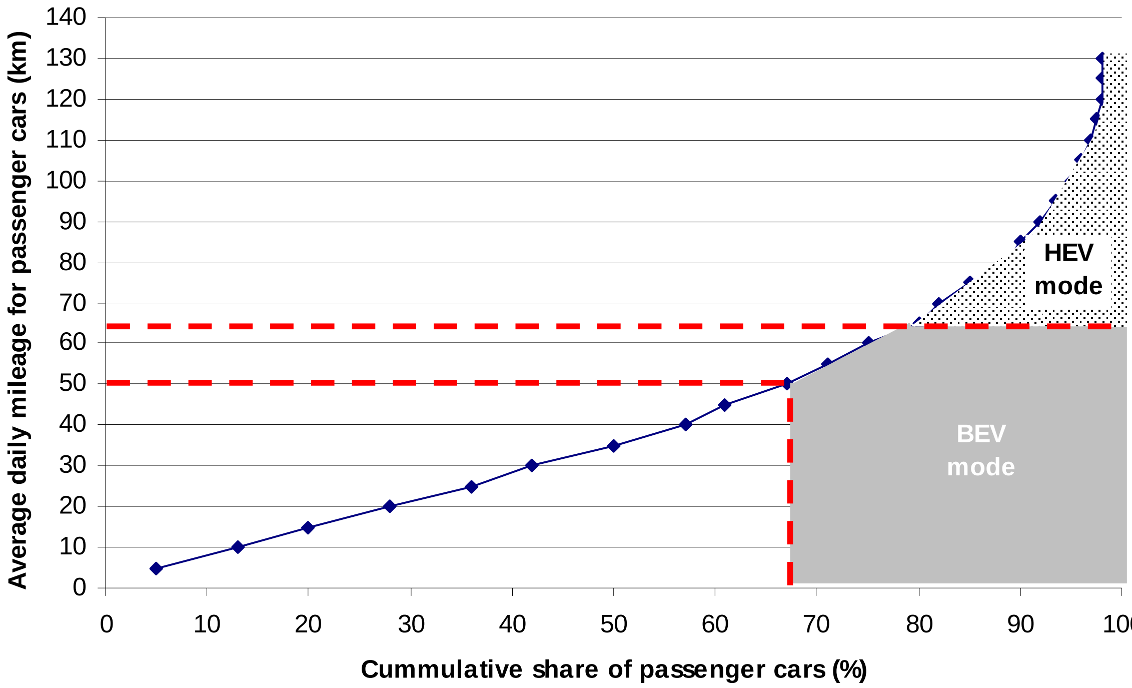


Figure 11: Share of driving distances for "full hybrid electric vehicle (HEV) mode" and "battery electric vehicle (BEV) mode" for a long distance (>50 km) travelling plug-in hybrid electric vehicle with an electric driving range of 65 km

The ratio of the areas, therewith the mileage shares of "battery electric vehicle mode" to "full hybrid electric vehicle mode" is 4.2 for a long distance (>50 km) travelling plug-in hybrid electric vehicle with 65 km electrical driving range. This means that on average 81% of the driving distance is accomplished with electricity from the grid ("battery electric vehicle mode") and only 19% with "full hybrid electric vehicle mode". The share of energy consumption (electricity from grid and gasoline) is calculated as well. 65% of the total energy consumption is coming from electricity from the grid, which is much lower than driving distance shares of "battery electric vehicle mode" (81%). This lower energy consumption share is due to higher electric motor efficiency (Table 16).

The results show that the daily mileage has an important impact on the driving mode of plug-in hybrid electric vehicle. These vehicles could be even utilized as pure electric cars if the daily mileage is lower than the assumed electric driving range of 65 km. Therefore, the short distance travelers drive purely on electric motor. Even the long distance travelers may drive on average 81% of the driving distance electrically.

Table 16: Present and projected tank to wheel fuel consumption and emission factors of the German plug-in hybrid electric passenger car fleet with an electric driving range of 65 km

		2010	2015	2020	2025	2030
Short distance (<50 km)						
Fuel (gasoline) consumption	l/100vkm	0.0	0.0	0.0	0.0	0.0
	MJ/100vkm	0.0	0.0	0.0	0.0	0.0
Electricity* consumption	MJ/100vkm	52.8	50.6	48.4	46.2	44.0
Total energy consumption	MJ/100vkm	52.8	50.6	48.4	46.2	44.0
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0
Share of electrical drive	km_e/km_{total}	1.00	1.00	1.00	1.00	1.00
Share of electricity input	MJ_e/MJ_{total}	1.00	1.00	1.00	1.00	1.00
Long distance (>50 km)						
Fuel (gasoline) consumption	l/100vkm	1.1	1.0	0.9	0.9	0.9
	MJ/100vkm	36.0	32.3	28.7	28.4	28.2
Electricity* consumption	MJ/100vkm	64.4	61.6	58.9	56.1	53.4
Total energy consumption	MJ/100vkm	100.3	93.9	87.6	84.5	81.5
CO_2 emissions	g CO_2/vkm	26.0	23.4	20.8	20.5	20.4
CO_{2eq} emissions	g CO_{2eq}/vkm	26.1	23.5	20.8	20.6	20.4
Share of electrical drive	km_e/km_{total}	0.81	0.81	0.81	0.81	0.81
Share of electricity input	MJ_e/MJ_{total}	0.64	0.66	0.67	0.66	0.65
(*) electricity is taken from the grid not generated via ICE onboard						

2.6.2 Buses (plug-in hybrid electric vehicles with compression ignition engine)

A similar method as in passenger cars (see chapter 2.6.1) is utilized to obtain the TTW values of plug-in hybrid electric buses.

The average daily mileage for public buses and coaches are calculated as 190 km and 300 km respectively (see Table 17). It is assumed that this daily driven mileage for both categories is relatively constant for all public buses and coaches. The plug-in hybrid electric bus batteries are conceptualized to drive about 125 km with electricity from the grid. Thus, this results in a share of distance driven on “battery electric vehicle mode” of 66 % and 42% for public buses and coaches respectively. These driven distances result in an electrical energy (from grid) input share of about 36 % for public buses and 20 % by coaches (see Table 18).

Table 17: Mileage per traffic day for public buses and coaches

		Public buses	Coaches	Sources
Mileage per year	vkm/bus/a	57,000	60,000	Leuthardt, 2005; own assumption
Traffic days*	d/a	300	200	Leuthardt, 2005
Mileage per traffic day	vkm/bus/d	190	300	Own calculation
*) Traffic days: Number of days in a year, where buses are employed				

The comparison of plug-in hybrid passenger cars with plug-in hybrid buses show that passenger cars might substitute a higher share of the driven distance with electric motor (more than 81%) than public buses (66%) or coaches (42%). This is due to the fact that public buses and coaches have higher mileage per day than passenger cars.

Table 18: Present and projected tank to wheel fuel consumption and emission factors of the German plug-in hybrid electric bus fleet

		2010	2015	2020	2025	2030
Public buses						
Fuel (diesel) consumption	l/100vkm	10.4	10.5	10.6	10.6	10.6
	MJ/100vkm	371.8	377.0	379.2	379.7	379.5
Electricity* consumption	MJ/100vkm	205.0	196.5	188.0	179.4	170.9
Total energy consumption	MJ/100vkm	576.8	573.5	567.2	559.1	550.3
CO_2 emissions	g CO_2/vkm	276.6	280.5	282.2	282.5	282.3
CO_{2eq} emissions	g CO_{2eq}/vkm	277.8	281.6	283.1	283.4	283.2
Share of electrical drive	km_e/km_{total}	0.66	0.66	0.66	0.66	0.66
Share of electricity input	MJ_e /MJ_{total}	0.36	0.34	0.33	0.32	0.31
Coaches						
Fuel (diesel) consumption	l/100vkm	19.7	20.4	20.6	20.5	20.4
	MJ/100vkm	708.0	731.9	737.8	736.1	731.9
Electricity* consumption	MJ/100vkm	177.4	169.8	162.2	154.7	147.1
Total energy consumption	MJ/100vkm	885.4	901.8	900.0	890.8	879.0
CO_2 emissions	g CO_2/vkm	526.8	544.6	548.9	547.7	544.5
CO_{2eq} emissions	g CO_{2eq}/vkm	528.5	546.1	550.3	549.0	545.9
Share of electrical drive	km_e/km_{total}	0.42	0.42	0.42	0.42	0.42
Share of electricity input	MJ_e /MJ_{total}	0.20	0.19	0.18	0.17	0.17

(*) electricity is taken from the grid not generated via ICE onboard

2.7 Fuel cell engines

The fuel cell (FC) applications range from stationary power to transport applications. The transport application of fuel cells is divided into fuel cell electric vehicle (FCEV), where the generated electricity from fuel cell is directly coupled with the electric motor, and fuel cell hybrid electric vehicle (FCHEV), where a battery is located between the fuel cell and electric motor so that the brake energy is recovered.

There are several fuel cell types, however, in this study only the polymer electrolyte fuel cell (PEFC) – also named proton exchange membrane (PEM) – is investigated further as this type is most suitable for automotive applications (Mench, 2008). It is also assumed that the fuel cells in this work only operate with hydrogen fuel and is stored onboard in a compressed gas tank with a pressure level of 700 bars.

The components and functioning principle of polymer electrolyte fuel cell are presented in Figure 12. The incoming hydrogen (H_2) is separated into hydrogen ions (H^+) and electrons (e^-). Hydrogen ions may pass through the polymer electrolyte whereas the electrons may not. Therefore, the electrons utilize the external circuit where the power is recuperated. The electrons, hydrogen ions and oxygen in the air react in the cathode to water vapor (see the reaction below). Later on, the residual gases and water vapor are exhausted from the fuel cell.

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \qquad \textbf{(4)}$$

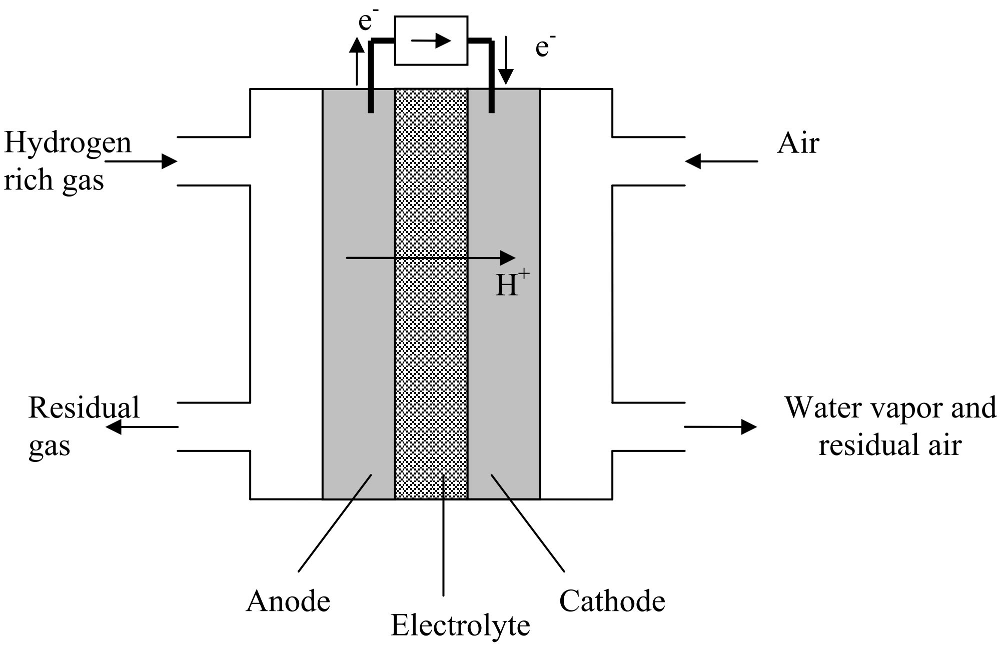


Figure 12: Components and functioning principle of polymer electrolyte fuel cells (Tanaka, 2010)

2.7.1 Passenger cars

The fuel cell (hybrid) electric passenger cars are expected to consume 58% (63%) less energy in 2010 for the same vehicle kilometer compared to the spark ignition engine passenger car of 2002 (CONCAWE, 2009). The expected efficiency increase between 2010 and 2030 is 22% for fuel cell passenger cars (Gül, 2008). The energy consumption and emission results of fuel cell (hybrid) electric passenger cars are presented in Table 19. As in battery electric vehicles, there are no onboard GHG emissions from vehicles powered by fuel cell.

The results show that the energy consumptions of fuel cell electric and fuel cell hybrid electric passenger cars in 2030 are 97.0 and 85.4 MJ/100vkm respectively. The energy consumption in 2030 correspond to 3.0 and 2.6 liters of gasoline equivalent per 100 vehicle kilometer for fuel cell electric and fuel cell hybrid electric passenger cars respectively, which is about half of the energy consumption of conventional spark ignition passenger car in 2030.

Table 19: Present and projected tank to wheel fuel consumption and emission factors of the German fuel cell passenger car fleet

		2010	2015	2020	2025	2030
FCEV						
Fuel consumption	MJ/100vkm	110.2	106.9	103.6	100.3	97.0
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0
FCHEV						
Fuel consumption	MJ/100vkm	97.1	94.2	91.3	88.4	85.4
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0

2.7.2 Buses

For buses, only the fuel cell application with the hybrid option is investigated as they are expected to be more common. Similar to the electric buses (chapter 2.4.3), the energy consumption in year 2005 is found with the following formula:

$$\eta_{BUS}^{FC} = \frac{\eta_{PC}^{FC}}{\eta_{PC}^{CI}} \eta_{BUS}^{CI} \tag{5}$$

where,

η_{BUS}^{FC} is the specific energy consumption of fuel cell hybrid electric bus (per 100 vkm)

η_{PC}^{FC} is the specific energy consumption of fuel cell hybrid electric passenger car (per 100 vkm)

For the upcoming years, it is assumed that the specific energy consumption per vkm will decrease similarly to the fuel cell hybrid electric passenger cars. The results presented in Table 20 show that the energy consumptions of public buses and coaches in 2030 are 542.1 and 505.1 MJ/100vkm respectively. These energy consumptions in 2030 correspond to 15.1 and 14.1 liter of diesel equivalent per 100 vehicle kilometer for public buses and coaches respectively. Therefore, the energy consumption of fuel cell hybrid electric buses is about 60% lower than the conventional compression ignition buses in 2030.

Table 20: Present and projected tank to wheel fuel consumption and emission factors of the German fuel cell hybrid electric bus fleet

		2010	2015	2020	2025	2030
Public buses						
Fuel consumption	MJ/100vkm	616.0	597.5	579.0	560.6	542.1
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0
Coaches						
Fuel consumption	MJ/100vkm	573.9	556.7	539.5	522.3	505.1
CO_2 emissions	g CO_2/vkm	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/vkm	0.0	0.0	0.0	0.0	0.0

2.8 Comparison of powertrains in terms of investment costs and energy consumption

In this chapter, different types of powertrains are compared for passenger cars, buses and freight trucks in terms of their investment costs and their tank to wheel energy consumption per 100 vkm.

The assumed specific costs for different vehicle components for 2010 and for 2030 are presented in the appendix (Table A 1). The costs of some components (especially batteries and fuel cells) are expected to decrease significantly until the year 2030 (Gül, 2008; IEA, 2008; OECD/IEA, 2005 and IPTS, 2005). The specific costs of batteries are assumed to decrease from 565 EUR_{2000}/kWh in 2010 to 188 EUR_{2000}/kWh in 2030. Furthermore, the costs of fuel cells decrease from 328 EUR_{2000}/kW in 2010 to its floor cost (i.e. the lowest achievable cost) of 46 EUR_{2000}/kW in 2030.

2.8.1 Passenger cars

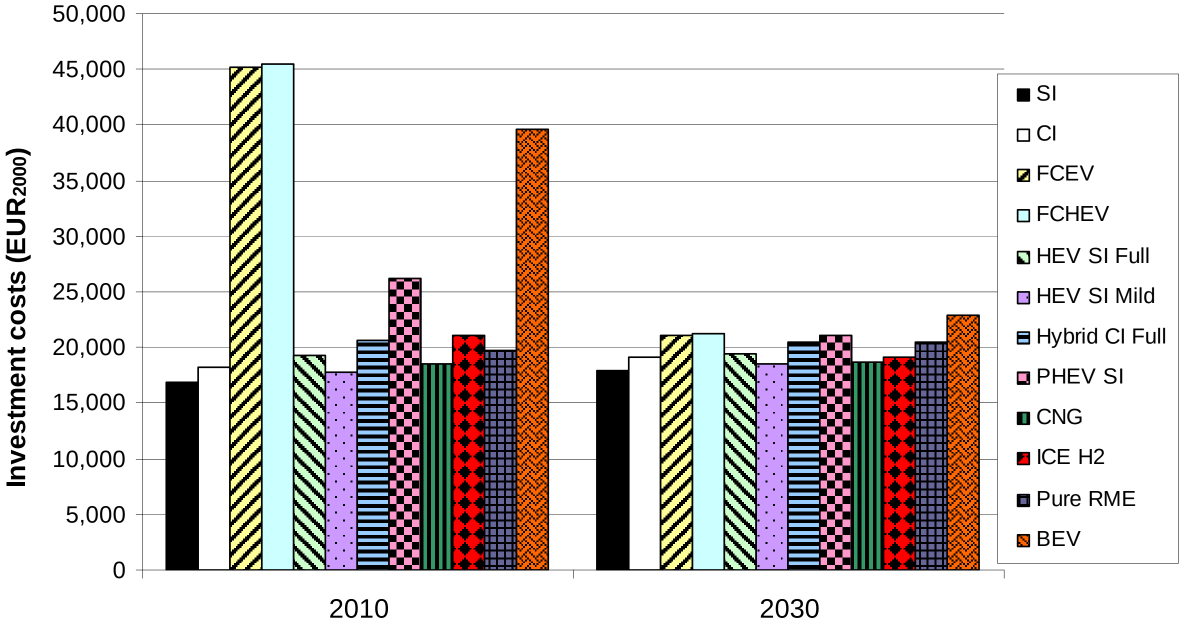
To calculate the investment cost of different powertrains for passenger cars, dimensions of the vehicle components are needed. The assumptions for passenger car dimensions are presented in the appendix (Table B 1). The size of the internal combustion engine is selected as 75 kW for conventional average passenger cars. The size of the electric motor is also taken as 75 kW for fuel cell, battery electric and plug-in hybrids since it is used as the main driver. For the other vehicles, where electric motor is only for assisting purposes (mild and full hybrids), the size of the electric motor is dimensioned smaller. The size of the battery (and also the capacity of the gas tank for hydrogen or CNG) is calculated with the driving range and energy consumption of the vehicle. The assumed driving range of the passenger cars are presented in Table 21.

The investment costs of different powertrains for middle class passenger cars are calculated with the specific cost of components (see Table A 1 in the appendix), and size of components (see Table B 1 in the appendix) and presented in Figure 13. The detailed cost calculation differentiated for each component is presented in the appendix (see Table C 1 in the appendix).

Table 21: Driving range of different passenger car powertrains

(km)	Driving range
BEV - battery electric vehicle	200
PHEV - plug-in hybrid electric vehicle (electric driving range)	65
CNG - internal combustion engine powered by compressed natural gas	500
ICE H_2 - internal combustion engine powered by hydrogen	
Other powertrains	>500

The results show that the conventional spark ignition engine passenger car costs about 16,800 EUR_{2000} in 2010. The investment costs are expected to increase to about 18,000 EUR_{2000} in 2030 due to the additions of a direct injection system, emission regulation requirements and a turbocharger. The conventional compression ignition engine passenger car is expected to follow a similar trend with its cost increasing from about 18,200 EUR_{2000} in 2010 to about 19,100 EUR_{2000} in 2030, mainly due to the emission regulation requirements.



SI: Spark ignition, **CI**: Compression ignition, **FCEV**: Fuel cell electric vehicle, **FCHEV**: Fuel cell hybrid electric vehicle, **HEV**: Hybrid electric vehicle, **PHEV**: Plug-in hybrid electric vehicle, **CNG**: ICE powered by compressed natural gas, **ICE H2**: ICE powered by hydrogen, **Pure RME**: ICE powered by pure rape oil methyl ester (biodiesel), **ICE**: Internal combustion engine, **BEV**: Battery electric vehicle

Figure 13: Investment costs of middle class passenger cars having different powertrains in 2010 and 2030

The conventional spark ignition engine passenger car is selected as the reference vehicle. The additional investment costs are determined for all other powertrains by subtracting their investment costs from investment cost of the reference vehicle. The investment costs in 2010 for battery electric and fuel cell passenger cars are more than double the investment costs of original spark ignition engine passenger car. Plug-in hybrid electric vehicle with spark ignition engine has moderate additional costs of about 9,400 EUR_{2000}. All the other powertrain alternatives have much lower additional costs varying between around 1,000 EUR_{2000} for mild hybrid electric vehicle and around 4,200 EUR_{2000} for hydrogen powered spark ignition engines.

The cost reduction until 2030 is especially remarkable for the battery and fuel cell components (see Table A 1 in the appendix). With these assumptions, the total costs of battery electric, fuel cell electric, fuel cell hybrid electric and plug-in hybrid electric passenger cars reduce significantly until 2030 (see Figure 13). The costs of all vehicle types are below 25,000 EUR_{2000} in 2030. Furthermore, the additional costs are lower than 5,000 EUR_{2000} in 2030 for all powertrains which are much lower than those in 2010.

The comparison of results for energy consumption and additional investment costs for all powertrains is presented in Figure 14. Figure 15 presents a close-up view for the powertrain technologies which are highlighted in a dashed box in Figure 14.

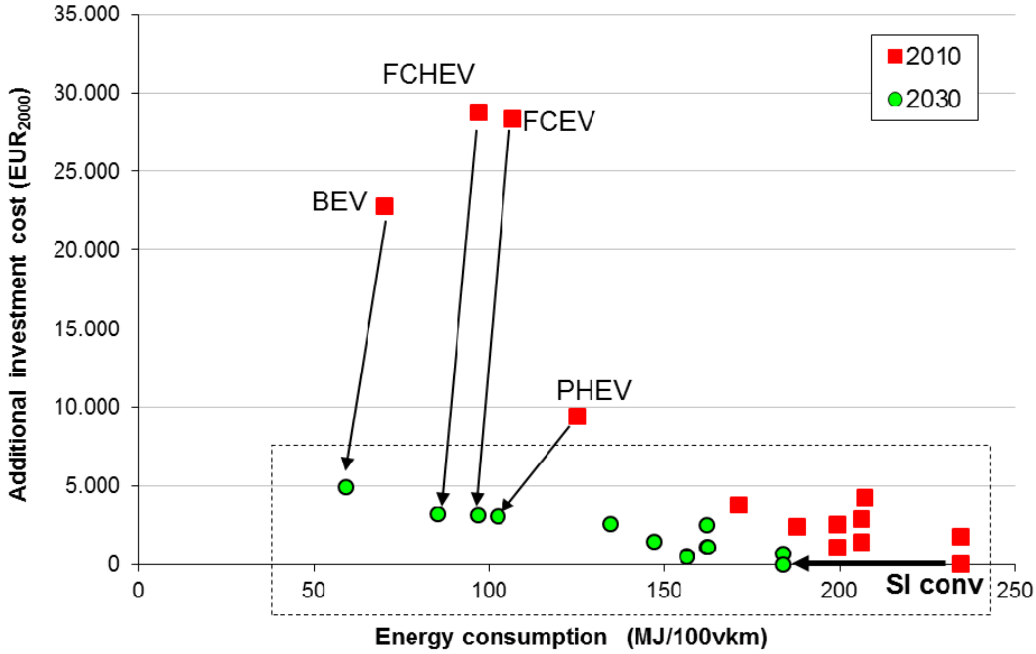


Figure 14: Development of specific energy consumption and additional investment costs (compared to the conventional spark ignition engine) for different powertrains for passenger cars between 2010 and 2030

Figure 14 and Figure 15 show that all powertrain alternatives are expected to consume less energy in 2030 on a vkm basis. The conventional average spark and compression ignition engines are expected to have 20% lower energy consumption. Similarly, the energy consumptions of most of the alternative powertrains are anticipated to decrease (about 20%) in the next 20 years. However, it is expected that the energy consumption of battery electric vehicles and fuel cell systems will be decreased only by 10 to 14% due to the fact that these systems are already highly efficient. It is expected that the battery electric vehicles will have the lowest energy consumption with 59 MJ/100vkm. Fuel cell powered vehicles and plug-in hybrid electric vehicles follow with an energy consumption of 85 to 103 MJ/100vkm. Hybrid electric vehicles, pure biodiesel engine, hydrogen internal combustion engine and conventional compression ignition engine are anticipated to have an energy consumption of between 134 and 162 MJ/100vkm. Highest energy consumption is expected by conventional spark ignition engine and CNG engine in the year 2030 with 184 MJ/100vkm. This comparison shows that the specific energy consumption (per vkm) decreases as the conventional internal combustion engine is substituted by a fuel cell and/or electrified and assisted by an electric motor. The lowest energy consumption is achievable with a battery electric car.

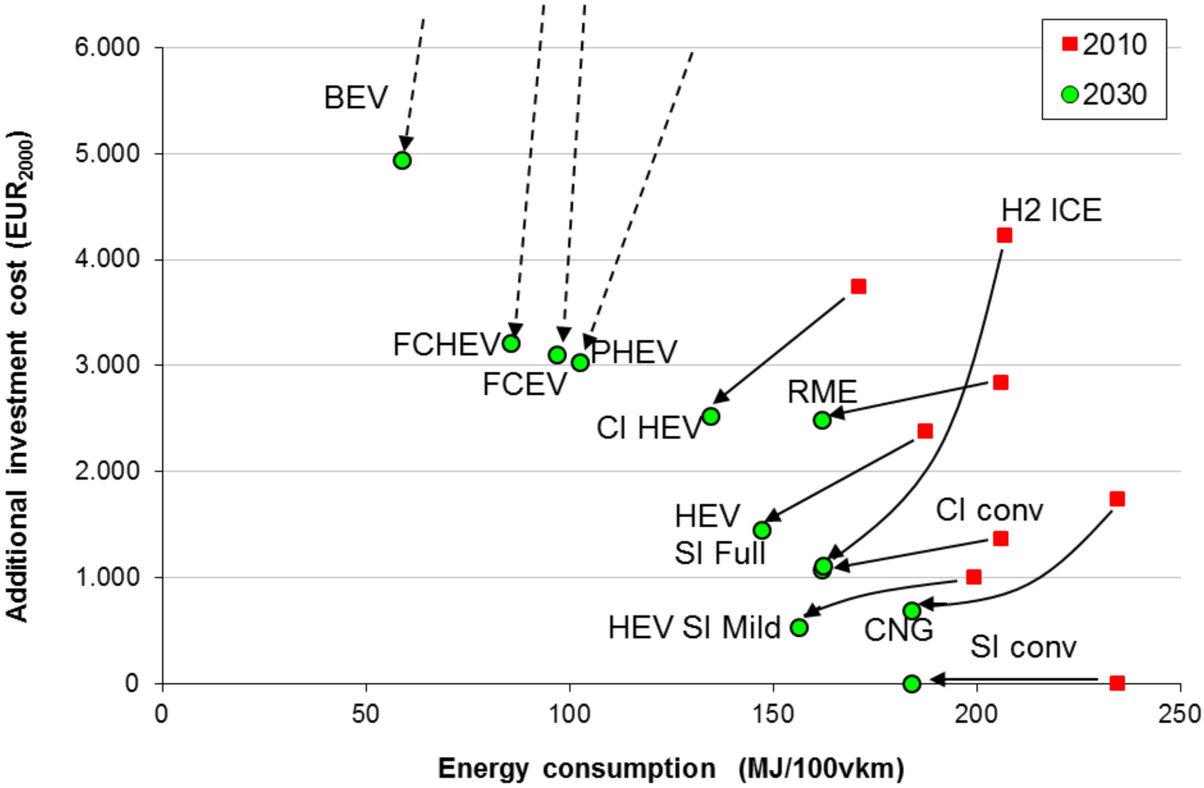


Figure 15: Development of specific energy consumption and additional investment costs (compared to the conventional spark ignition engine) for different powertrains for passenger cars between 2010 and 2030 (excerpt of Figure 14)

Furthermore, additional costs of all alternative powertrains compared to conventional spark ignition engine are expected to be less by the year 2030. The most remarkable cost reductions are expected for battery electric (about 17,800 EUR_{2000}), fuel cell electric (about 25,200 EUR_{2000}), fuel cell hybrid electric (about 25,500 EUR_{2000}) and plug-in hybrid electric (about 6,300 EUR_{2000}) vehicles.

The additional costs show a different trend as opposed to the energy consumption. Generally, as the energy consumption of powertrains decreases, the additional costs increase. Battery electric vehicle, which has the lowest energy consumption, has the highest additional costs of almost 5,000 EUR_{2000} in 2030. The fuel cell systems and plug-in hybrid electric vehicles are expected to have an additional cost of about 3,000 EUR_{2000}, which are followed by other hybrid electric systems. In order to evaluate the economic and environmental aspects of the alternative powertrains holistically, at least additional information on fuel production (see chapter 3) is needed. These questions are answered with the system analysis approach (see chapter 4 and 5).

2.8.2 Buses

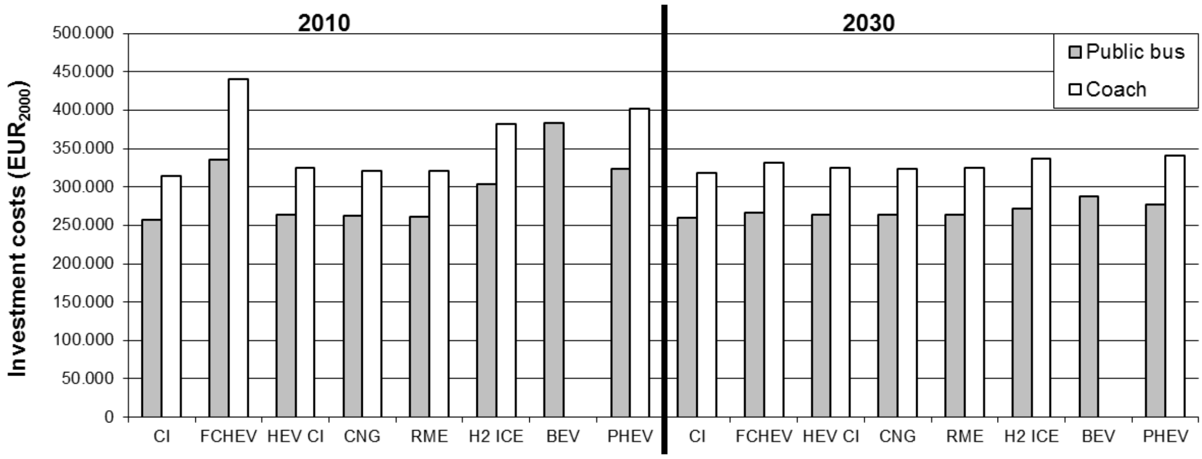
The same procedure as in passenger cars is followed to obtain the investment costs of buses. The specific costs of components (see Table A 1 in the appendix) are multiplied by the component dimensions for public buses and for coaches (see Table B 2 and Table B 3 in the appendix), which partly depend on the assumed range values (Table 22).

Table 22: Driving range of different bus powertrains

(km)	Public bus	Coach
BEV	250	-
PHEV (electric driving range)	125	125
CNG	400	650
ICE H_2	400	650
Other powertrains	>400	>650

The resulting investment costs are summarized in Figure 16 and presented in the appendix (Table C 2 and Table C 3) differentiated for components. The results show that conventional public bus with compression ignition engine costs about 257,000 EUR_{2000} in 2010 and about 260,000 EUR_{2000} in 2030. On the other hand, the conventional coach costs about 315,000 EUR_{2000} in 2010 and about 318,000 EUR_{2000} in 2030. The conventional compression ignition engine buses (for both public and coach) are selected as the reference and the additional investment costs are determined compared to these vehicles.

As in the passenger cars, the additional investment costs of alternative powertrains in 2010 are highest for fuel cell and battery electric buses among alternative powertrains. The additional costs of alternative powertrains reduce significantly in 2030 for almost all powertrains. In 2030, additional investment costs of alternative powertrains for public buses range between 3,700 EUR_{2000} for a CNG bus and 27,500 EUR_{2000} for a battery electric bus. For coaches, it varies between 5,300 EUR_{2000} (CNG bus) and 22,800 EUR_{2000} (plug-in hybrid electric bus).



CI: Compression ignition, **FCHEV**: Fuel cell hybrid electric vehicle, **HEV**: Hybrid electric vehicle, **PHEV**: Plug-in hybrid electric vehicle, **CNG**: ICE powered by compressed natural gas, **ICE H2**: ICE powered by hydrogen, **RME**: ICE powered by pure rape oil methyl ester (biodiesel), **ICE**: Internal combustion engine, **BEV**: Battery electric vehicle

Figure 16: Investment costs of public buses and coaches having different powertrains in 2010 and 2030

The comparison of additional investment costs with specific energy consumption (per 100 vkm) for public buses and coaches are presented in Figure 17 and Figure 18 respectively. The comparison of energy consumption shows that the conventional compression ignition, hybrid electric vehicle and RME engine buses (both for public and coach) have a slight increase in specific energy consumption until 2030 due to the stricter emission regulations for diesel engines. The specific energy consumption of the other powertrains (battery electric vehicle, fuel cell hybrid electric vehicle, plug-in hybrid electric vehicle, CNG and hydrogen for internal combustion engine) is expected to decrease until 2030.

The additional investment costs of public buses compared to a conventional public bus with compression ignition engine in 2010 vary significantly for different powertrains from 4,000 EUR_{2000} for pure biodiesel internal combustion engine modification to 126,000 EUR for fuel cell hybrid electric vehicle (Figure 17). The additional investment costs, however, are expected to decrease to a level that the highest additional investment cost (for battery electric vehicle) is only about 28,000 EUR_{2000} in 2030. The additional investment costs of CNG and RME powertrains change marginal, if at all.

The additional investment costs of coaches show the same characteristics as the public buses except that the additional investment costs for alternative powertrains are at a much higher level due to longer driving range requirements (Figure 18).

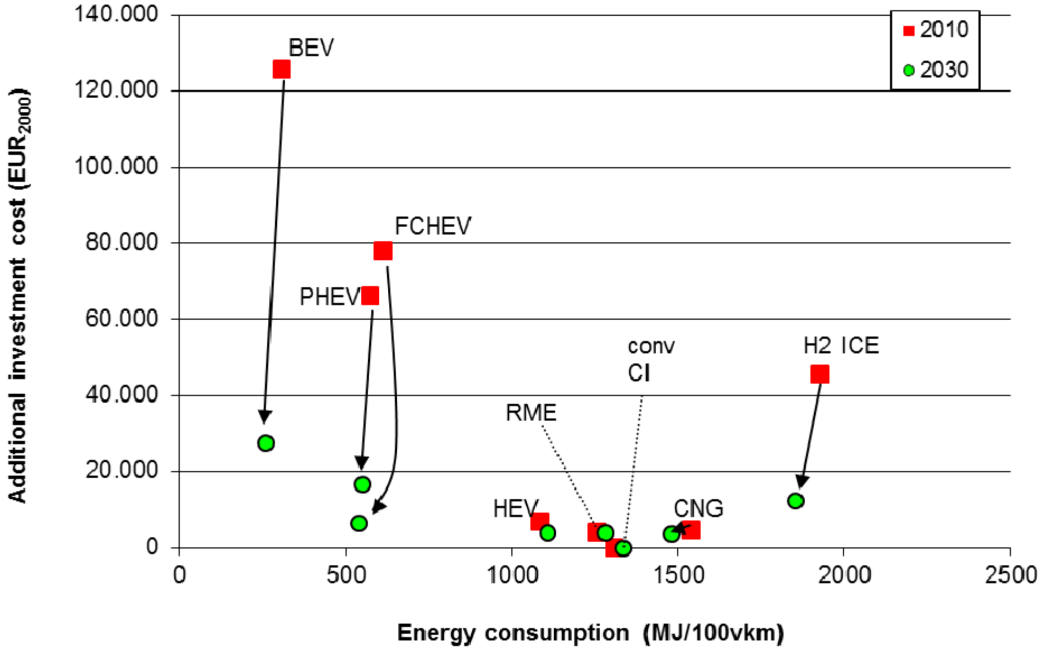


Figure 17: Development of specific energy consumption and additional investment costs (compared to the conventional compression ignition engine) for different powertrains for public buses between 2010 and 2030

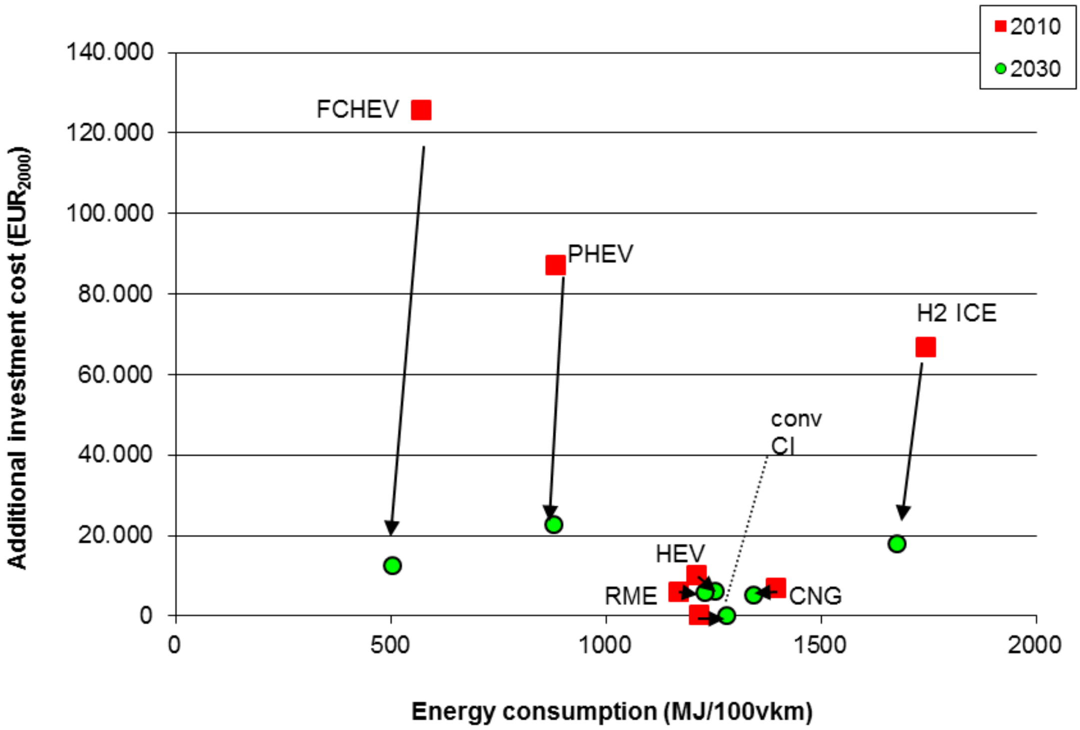


Figure 18: Development of specific energy consumption and additional investment costs (compared to the conventional compression ignition engine) for different powertrains for coaches between 2010 and 2030

As in the passenger cars, the comparison of additional costs and energy consumption show that as the energy consumption of powertrains decreases, the additional costs increase except for some powertrains (internal combustion engines powered by CNG and hydrogen). This will imply that the tank to wheel energy savings compared to conventional compression ignition engine require additional investment costs for the powertrain.

2.8.3 Freight trucks

Similar procedure as in passenger cars and buses is followed to obtain the investment costs of trucks. The specific costs of components (see Table A 1 in the appendix) are multiplied by the component dimensions for heavy and light duty vehicles (see Table B 5 and Table B 4 in the appendix). It is assumed that the heavy and light duty vehicles have 320 and 120 kW of engine power respectively. The assumed driving ranges are listed in Table 23.

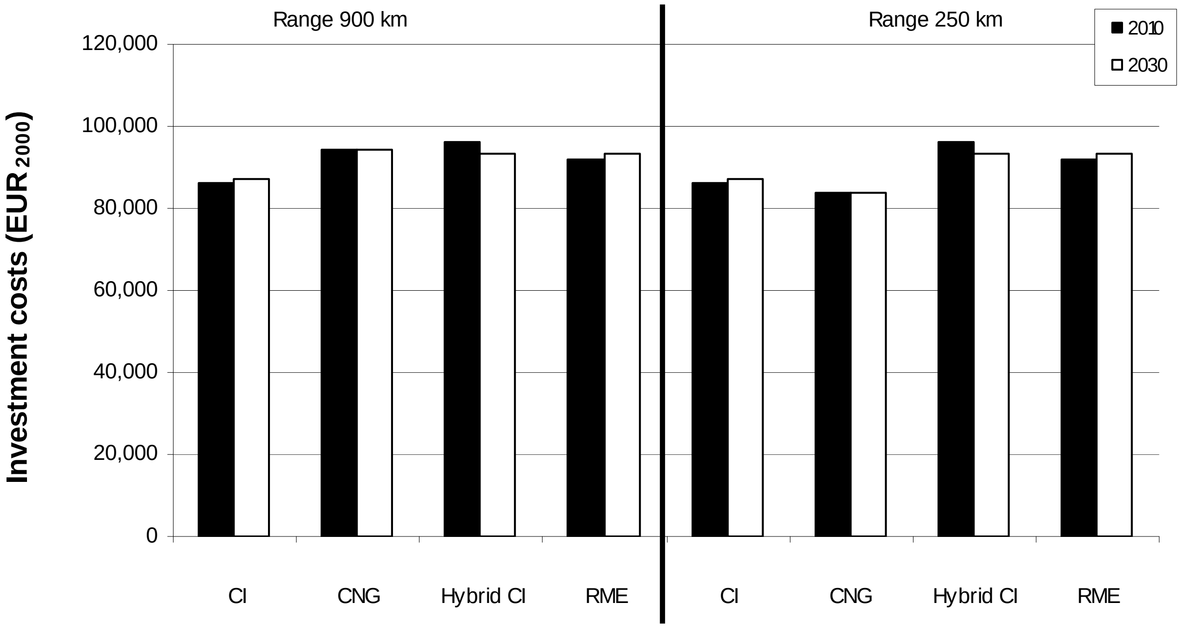
Table 23: Driving range of different truck powertrains

(km)	Long driving range	Short driving range
CNG	900	250
Other powertrains	>900	>250

The resulting investment costs of trucks are presented in Figure 19 und Figure 20 for heavy and light duty vehicles respectively and are presented in the appendix (Table C 4 and Table C 5) differentiated for components. The results show that a conventional average heavy duty truck costs about 86,000 EUR_{2000} in 2010 and about 87,100 EUR_{2000} in 2030. On the other hand, the conventional average light duty truck costs about 21,000 EUR_{2000} in 2010 and about 21,400 EUR_{2000} in 2030. The conventional trucks with compression ignition engine (for heavy and light duty vehicles) are selected as the reference and the additional investment costs are determined compared to these vehicles.

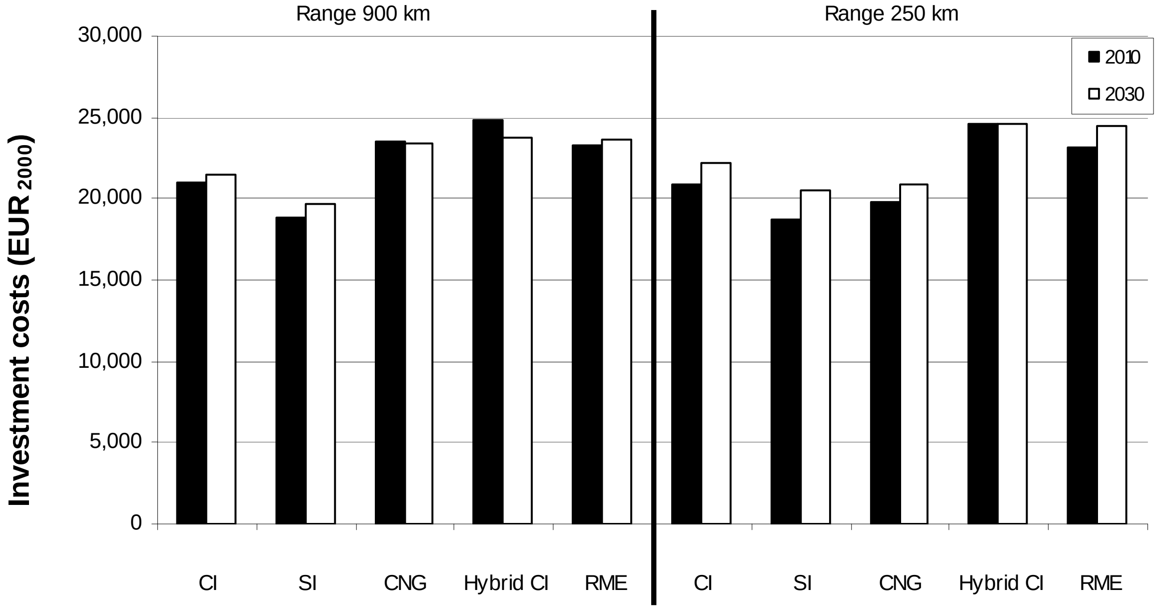
The investment costs of alternative powertrains also depend on driving range but only for the CNG powertrain. All other investment costs are the same for both short and long driving range. This change is due to the size (and the specific cost) of the CNG tank, which influences the resulting costs significantly. The cost of a heavy duty truck with a CNG powertrain in 2010 is about 8,400 EUR_{2000} higher than a conventional truck for a long driving range and about 2,200 EUR_{2000} lower for a short driving range. It can be concluded that CNG powertrains are best for shorter driving ranges.

The highest investment costs in 2010 are for the hybrid electric trucks among all alternative powertrains. The hybrid electric vehicle investment costs are about 96,200 EUR_{2000} for heavy duty and about 24,800 EUR_{2000} for light duty vehicles in 2010. However, it is expected that the total investment costs of hybrid powertrains will decrease between 3 and 4 percent until 2030 compared to the year 2010.



CI: Compression ignition, **Hybrid**: Hybrid electric vehicle, **CNG**: ICE powered by compressed natural gas, **RME**: ICE powered by pure rape oil methyl ester (biodiesel), **ICE**: Internal combustion engine

Figure 19: Investment costs of heavy duty trucks having different powertrains for driving ranges of 900 and 250 km in 2010 and 2030



SI: Spark ignition, **CI**: Compression ignition, **Hybrid**: Hybrid electric vehicle, **CNG**: ICE powered by compressed natural gas, **RME**: ICE powered by pure rape oil methyl ester (biodiesel), **ICE**: Internal combustion engine

Figure 20: Investment costs of light duty trucks having different powertrains for driving ranges of 900 and 250 km in 2010 and 2030

The comparisons of additional investment costs with specific energy consumption (per 100 vkm) for heavy duty vehicles for long driving ranges and light duty vehicles for short driving ranges are presented in Figure 21 and Figure 22 respectively.

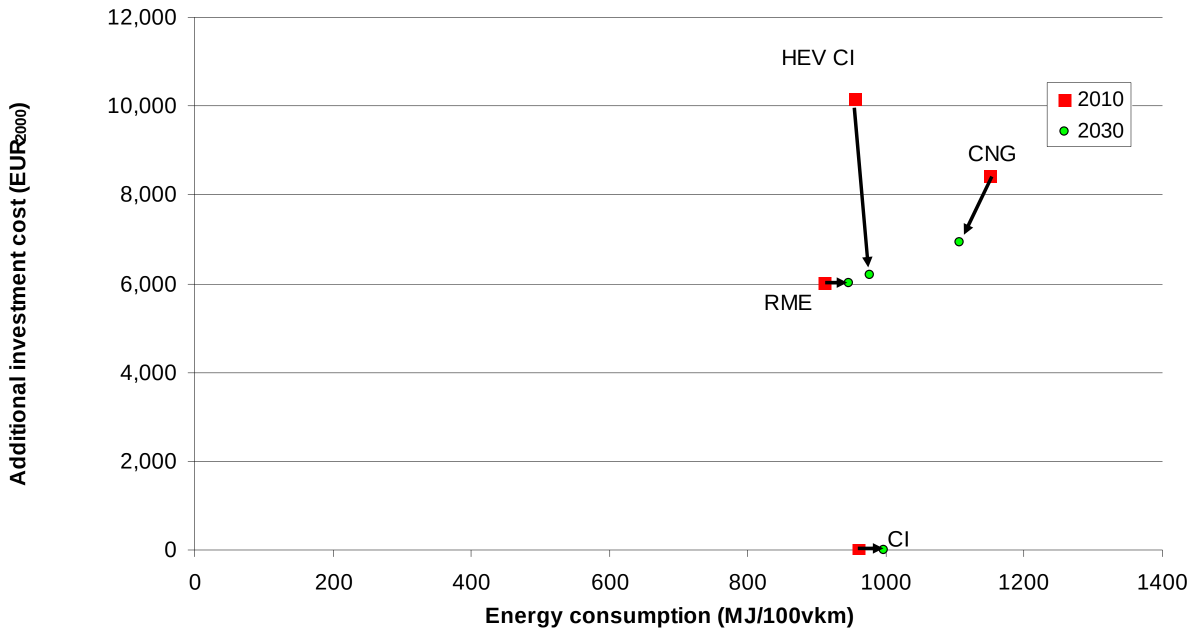


Figure 21: Development of specific energy consumption and additional investment costs (compared to the conventional compression ignition engine) for heavy duty vehicles (long driving range) for different powertrains between 2010 and 2030

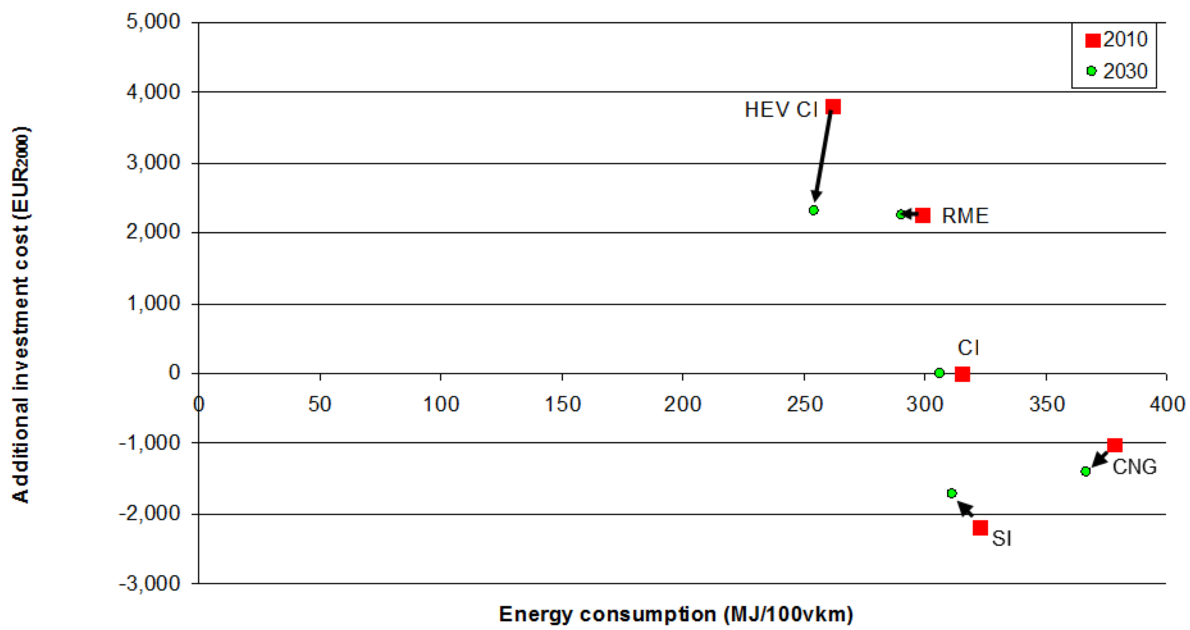


Figure 22: Development of specific energy consumption and additional investment costs (compared to the conventional compression ignition engine) for light duty vehicles (short driving range) for different powertrains 2010 and 2030

The comparison of specific energy consumption shows that all the heavy duty vehicle powertrains (except for CNG) are expected to consume more energy per 100 vkm in 2030 compared to the year 2010 due to the stricter emission regulations. However, it is also expected that the specific energy consumption (per tkm) will decrease due to the higher occupancy level as explained in chapter 2.2.3. On the other hand, the light duty vehicle powertrains are expected to consume less specific energy (per 100 vkm) in 2030 compared to 2010.

The additional investment cost changes from 2010 to 2030 are significant for hybrid electric vehicles and CNG powertrains but marginal for pure RME powertrains. Light duty vehicles might be also powered by spark ignition engines. Spark ignition engine costs about 2,200 EUR_{2000} less in 2010 compared to compression ignition engines. Furthermore, it is expected that this investment cost advantage of a spark ignition engine will be lower (about 1,700 EUR_{2000}) in 2030.

The comparison of additional costs and energy consumption for a long driving range vehicle (>50 km) show another trend then for passenger cars and buses. Although different powertrain alternatives have higher investment costs than the conventional compression ignition engine, their energy consumption is marginally lower, if at all. Therefore, there are not many possibilities to reduce the specific energy consumption (per 100 vkm) for the heavy duty vehicle section. For short driving ranges (<50 km), the specific energy consumption reduction is possible with hybrid electric vehicles at relative low additional costs.

2.9 Summary of alternative powertrains in the German transport sector

This chapter describes the characteristics of relevant powertrains for the German transport sector in terms of their energy consumption, GHG emissions and costs. The following section summarizes the main findings of chapter 2.

Conventional internal combustion engines (spark ignition as well as compression ignition engines) are expected to get more efficient in the future with the exception of heavy duty trucks (see Table 8). The reason for the slight increase of projected specific energy consumption (per 100 vkm) by heavy duty trucks is the upcoming stricter emission regulations. Energy efficiency is expected to be sacrificed in order to achieve emission regulation targets.

Furthermore, the results show that the occupancy level of vehicles is important for the energy consumption. This is particularly the case in road freight transport. On the one hand, it is expected that the specific fuel consumption per vkm increases slightly until 2030 compared to 2010 in the road freight. On the other hand, the occupancy level (ratio of tkm/vkm) is expected to be increased significantly, which result in lower specific energy consumption per tkm. This finding suggests that the occupancy level of vehicles is at least as important as the engine efficiency for the specific fuel consumption (per tkm).

The average specific CO_2 emission of the German passenger car fleet is not expected to go below 120 g/vkm level until 2030. The emissions for passenger cars are about 133 g for spark ignition engines and about 121 g for compression ignition engines in 2030. The direct comparison of these values with the 2012 EU target of 120 g CO_2 emission per vkm (EU, 2009) is not possible since the presented values are for the average fleet but the EU targets are for the new vehicles for the year 2012. However, even the new vehicles in 2030 are not expected to have significantly lower specific CO_2 emissions. This target might be only achievable with a powertrain or fuel switch.

The comparison of tank to wheel energy consumption with investment costs of different powertrains shows that as the energy consumption of powertrains (compared to conventional technology) decreases, the additional costs increase generally. Therefore, it is not possible to choose the "suitable" powertrain with only the information on powertrains. Additional information on fuel production (see chapter 3) and a system analysis approach (see chapter 4 and 5) are needed to understand the future role of different powertrains in Germany.

3 Description and analysis of alternative fuels in the German transport sector

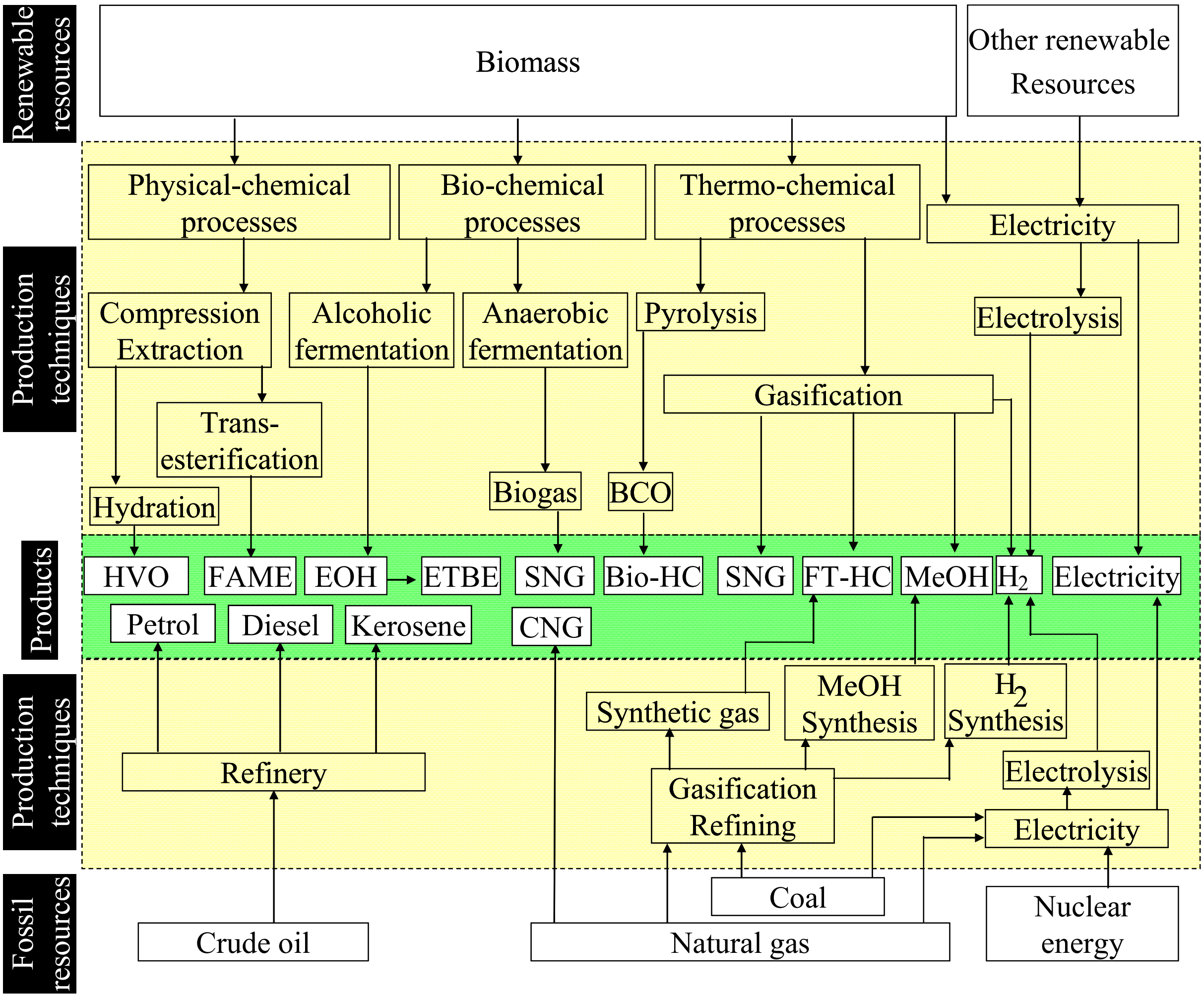
The objective of this chapter is to analyze the relevant fuel production pathways for the German transport sector beginning from feedstock until the filling station (well to tank – WTT analysis). In chapter 3.1 an overview of the fuel production pathways is given. The relevant fuel production pathways are introduced in chapters 3.2 to 0 and the status quo of fuel production is presented. Furthermore, future development of efficiency increases and cost reduction possibilities are analyzed for each pathway with the help of a literature survey. Moreover, the fuel production plants are compared and contrasted in terms of their investment costs and production capacities in chapter 3.9. In chapter 3.10, the delivery costs of different fuels is analyzed. Lastly, the chapter is summarized in 3.11.

3.1 Overall view

The fossil and renewable energy pathways that are relevant for the transport sector are illustrated in Figure 23. Transport fuels are currently mainly dependent on fossil resources particularly crude oil.

Crude oil is processed in refineries to obtain gasoline, diesel, kerosene and other products. Conventional fuels (gasoline, diesel and kerosene) in the German transport sector covered about 94% of the final transport energy demand in 2010 (BMU, 2011b). The rest is provided by renewable energy sources. In the refinery, crude oil is converted and segregated to different hydrocarbons. Most valuable products are gasoline, diesel and kerosene. However, there are also other products which are less valuable such as LPG (liquefied petroleum gas) and petroleum coke (Fahim et al., 2010). Catalytic and hydro cracking (see chapter 3.4.1 and 3.4.2) increase the product quality and process efficiency in the refineries (Fahim et al., 2010). The techno-economic specifications of the refinery pathways can be found in Krüger (2002) and Berninger (1996).

Natural gas, coal and also other fossil resources may play a role in the transport sector in the future. Natural gas might be utilized directly as compressed natural gas (see chapter 3.6.1). Furthermore, natural gas and coal may be refined/gasified to obtain further products such as synthetic diesel (chapter 3.7) or hydrogen (chapter 3.8). Moreover, electricity could also be generated from natural gas, coal or nuclear resources and utilized in the transport sector directly.



***HVO**: Hydrated vegetable oil; **FAME**: Fatty acid methyl ester (biodiesel); **EOH**: Ethanol; **ETBE**: Ethyl tert-butyl ether; **SNG**: Substitute natural gas (methane); **CNG**: Compressed natural gas (methane); **Bio-HC**: Bio-hydrocarbon; **BCO**: Bio crude oil; **FT-HC**: Fischer-Tropsch hydrocarbons or synthetic diesel (BTL, GTL and CTL); **MeOH**: Methanol and further products of methanol; H_2: Hydrogen*

Figure 23: Main production pathways for transport fuels (Specht et al., 2003; Kaltschmitt, 2009; Huber et al., 2006)

Renewable energy sources for transport fuels are divided into two categories: biomass and other renewable resources such as direct sun, wind and hydro-energy. The biomass conversion to transport fuels is divided into three main groups. These are physico-chemical, bio-chemical and thermo-chemical pathways (Kaltschmitt, 2009). The physico-chemical route requires oleaginous biomass as input and the products are either vegetable oils (chapter 3.2) or its further products such as biodiesel (chapter 3.3) and hydrated vegetable oils (chapter 3.4). The biochemical processes include bioethanol (chapter 3.5) and biogas (chapter 3.6.2) as the final product. The thermo-chemical processes are divided into pyrolysis (chapter 3.4.1) and gasification. Gasification results in substitute natural gas (chapter 3.6.3), synthetic diesel (chapter 3.7.1) or bio-hydrogen (chapter 3.8.1). Furthermore, biomass might also be converted to electricity and used in the transport sector directly or converted to hydrogen via electrolysis. The non-biomass renewable sources can only contribute to the transport sector via electricity.

There are numerous renewable and non-renewable pathways to generate electricity. However, to examine these pathways in detail will exceed the scope of this work. A list of considered electricity generation pathways is presented in the appendix (see Table G 1). The economic and environmental data for the upstream processes for these pathways are taken from Remme (2006) and König (2009).

Methanol fuel is not considered in this study as a promising fuel due to its poisonousness and its miscibility with water (GESTIS, 2009). This nature might be dangerous for public health if methanol utilization is widespread.

3.2 Vegetable oils

The idea of utilizing vegetable oils in engines goes back to Rudolf Diesel, the inventor of the diesel engine. He argued in 1912 that "*… the use of vegetable oils for engine fuels may seem insignificant today. But such oils may in the course of time become as important as petroleum and the coal tar products of present time.*"

Although utilization of vegetable oils in engines was known for a long time, it was not commercialized until the late 90s. Germany is one of the very few countries that have a relatively high share (1.3% of road transport energy in 2007; BMU, 2011b) of vegetable oil consumption in the transport sector. However, it has decreased to 0.1% in 2010 due to the change in the tax regulations (BMU, 2011b). Most of the vegetable oil (about 84%) comes from rapeseed (BMU, 2011b). Thus, the focus of this work is on rape oil. Other important vegetable oils used for energy is palm, soy and waste oil, but are not considered in this work.

3.2.1 Rape oil production

Rape (*Brassica napus L.*), which is commonly cultivated in Germany, belongs to the family of mustards (Roth et al., 2005). 2.9 million tons of rape oil was produced in Germany in 2009 corresponding to about 14% of the world production (FAOStat, 2011). Other important rape oil producers in the world are China (25%), India (11%), Canada (9%) and France (8%) (FAOStat, 2011). The average German rapeseed yield in 2009 was 4.29 t/ha/a which was the third highest yield per hectare in the world after Netherlands (4.62 t/ha/a) and Belgium (4.31 t/ha/a) in that year (FAOStat, 2011).

In this study, only industrial applications of vegetable oil production are considered. Pressing is relatively simple and well-known process. After this process the oil cake still has between 4% and 10% of oil, which cannot be extracted further mechanically. After pressing (e.g. with a screw extrusion press), the obtained oil cake is used in the extraction process with the corresponding solvent to extract more oil. The hexane is collected from distillation and hexane separation and reused (Demirbas, 2008). With this method much higher oil yields are achieved. The combination of these processes is the most common production pathway for vegetable oil.

The techno-economic parameters of rape oil production are presented in Table 24. It is assumed that the techno-economic parameters for rape oil production do not change in the future since the technology is identified as "*non-learning*"[19] due to the well-known process.

Table 24: Present (2005) and projected (2030) techno-economic specifications of a rape oil production plant

	Unit	2005	2030	Sources
Input		Rapeseed		
Output		Rape oil		
Process		Pressing and extraction		
Production capacity	PJ_{output}/a	3.82		Henniges, 2007
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.57		Ecoinvent, 2007
EFLH	h/a	8000		Own assumption
Lifetime of the plant	a	20		Own assumption
Specific investment cost [a]	$EUR_{2000}/(GJ_{output}/a)$	2.38		Henniges, 2007 and own calculation
FOM costs [b]	EUR_{2000}/GJ_{output}	0.13		Henniges, 2007 and own calculation
VOM cost [c]	EUR_{2000}/GJ_{output}	1.06		Henniges, 2007 and own calculation
By-product (oil cake)	Revenues EUR_{2000}/GJ_{output}	-3.99		Henniges, 2007 and own calculation
	Carbon credits [d] $kg\ CO_{2eq}/GJ_{output}$	-11.28		Özdemir et al., 2009; GEMIS, 2009 and own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.007		Borken et al., 1999 own calculation
	Fuel oil $GJ_{fuel\ oil}/GJ_{output}$	0.023		Borken et al., 1999 own calculation
Direct GHG emissions	$kg\ CO_{2eq}/GJ_{output}$	1.74		GEMIS, 2009 own calculation

a) Total investment cost is divided by the annual production capacity.
b) FOM: Fixed Operating and maintenance (O&M) costs.
c) VOM: Variable O&M costs without the feedstock and auxiliary energy costs.
d) Carbon credits of oil cake are calculated with the substitution method. Rapeseed oil cake is assumed to substitute soybean oilcake coming from USA (GEMIS, 2009).
LHV: Lower heating value
EFLH: Equivalent full load hours

[19] Non-learning technologies are assumed that they have been already fully developed and there will be no additional cost reduction or efficiency increase in the future.

The production capacity of the rape oil production plant is selected as 3.82 PJ rape oil per year (corresponds to 101,500 t rape oil/a) which is suitable for the rape oil requirement (111,375 t rape oil/a) of an average German biodiesel plant capacity (FNR, 2009a). As the average biodiesel plant capacity is not expected to grow significantly in the future, the capacity in 2030 is selected to be the same as in the year 2005.

The ratio of output rape oil energy content to the input rapeseed energy content based on lower heating value (LHV) is taken as 0.57 (Ecoinvent, 2007) and is not expected to alter significantly in the future. The most important by-product of rape oil production is the oil cake (meal) which has high energy content. It is mainly used for animal feed as a protein source (Özdemir et al., 2009). Selling oilcake brings revenue of 150.2 EUR_{2000}/t rape oil (Henniges, 2007). This revenue (-3.99 $EUR_{2000}/GJ_{rape\ oil}$) is considered in the calculations due to its significance compared to the production costs of rape oil. Oil cakes might also be used as energy, as an organic fertilizer or in biotechnology applications (Ramachandran et al., 2007).

The auxiliary energy requirement of the rape oil production plant is taken from Borken et al., 1999 as 52.6 kWh of electricity and 876 MJ of steam per ton rapeseed. It is assumed that the required heat for the steam production is provided by fuel oil boiler with an efficiency of 85%. As a result, the required auxiliary energy is calculated as 0.007 GJ of electricity and 0.023 GJ of fuel oil per GJ rape oil.

The direct GHG emissions result from fuel oil burning. The emission coefficients for CO_2, CH_4 and N_2O are 74.2, 0.000057 and 0.000611 kg/$GJ_{fuel\ oil}$ respectively (GEMIS, 2009). As a result, 1.74 kg of direct CO_{2eq} emissions are generated for the production of 1 GJ of rape oil from rapeseed.

3.2.2 Vegetable oil utilization in compression ignition engines

Vegetable oils are more suitable to use in compression ignition (diesel) engines rather than spark ignition engines. However, some modifications in the compression ignition engines are required if the vegetable oil is going to substitute conventional diesel fuel.

The most important differences between vegetable oil and diesel fuel are viscosity, cetane number and melting points. Vegetable oil engines need a better atomization of the fuel at the injection, higher temperatures for combustion and a larger combustion chamber than diesel engines. Furthermore, the air-fuel blend must be well mixed (Kleinfelder, 2007).

The best known dedicated vegetable oil engine is called Elsbett engine, after Ludwig Elsbett. In this type of engine, the air-fuel blend is injected so that a turbulence flow occurs in the combustion chamber. Today, however, specialized vegetable oil engines (like Elsbett engine) are no longer built. Instead, mass production diesel engines are modified (FNR, 2007). Currently in Germany, vegetable oil is primarily utilized in tractors and combined heat and power (CHP) plants. Therefore, dedicated vegetable oil engines are not considered in this work further.

3.3 Biodiesel

Biodiesel (RME – rape oil methyl ester) has much similar characteristics to conventional diesel rather than vegetable oil. The background idea here is to adjust the fuel to the engine and not vice versa. The most important characteristic change is that the methyl esters have much shorter chain lengths than vegetable oils and therewith also much lower viscosities. This reduction of viscosity enables the use of the fuel with far less modifications in the existing engines.

German biodiesel industry is established. About 67 PJ of biodiesel is produced in Germany in 2005 (BMU, 2011b). This corresponds to 55% of the world biodiesel production (REN21, 2011). The production increased to 95 PJ in 2010 (BMU, 2011b).

3.3.1 Biodiesel production

Biodiesel is obtained via transesterification of vegetable oils with an alcohol and the help of a catalyst. The utilized alcohol is typically methanol. However, the reaction is also possible with other alcohols, e.g. ethanol (Van Gerpen, 2005). The used catalyst may be alkali metals (e.g. sodium, potassium), alkali hydroxides (e.g. NaOH, KOH) or alkali alkoxides (e.g. sodium ethoxide). Although almost all commercial producers use alkali catalysts today, acid catalysis and enzymes may be a further option (Van Gerpen, 2005).

Biodiesel can be produced discontinuously or continuously. The discontinuous (batch) production is suitable for low capacities, such as 500 to 1,000 t/a (Müller-Langer and Kaltschmitt, 2009). Today, the biodiesel production capacity ranges from 2,000 to 500,000 t/a, with an average capacity of 92,000 t/a (FNR, 2008). Furthermore, the average capacity of the planned facilities is higher than 120,000 t/a (FNR, 2008). Therefore, in this study only continuous biodiesel production is considered.

The process schematic of continuous biodiesel production is presented in Figure 24. The products of the transesterification are glycerin and biodiesel, which need to be separated from each other. The separation procedure depends on the low solubility of the two raw materials in each other and on the significant density difference (Demirbas, 2008). The separation is done by gravity in the simplest case. To speed up the process, centrifugation might be used (Van Gerpen, 2005). Water (and also acids) may also be added in this process to improve the separation and to purify the biodiesel from residuals (e.g. catalyst, formed soaps, and methanol) (Van Gerpen , 2005; NREL, 2004). Consequently, a drying process is needed to remove the water content from the biodiesel (NREL, 2004). The glycerin by-product can be utilized in the nourishment, chemical and cosmetics industries. A further option is to use it as an energy source, which is not common today (Marshall and Haverkamp, 2008).

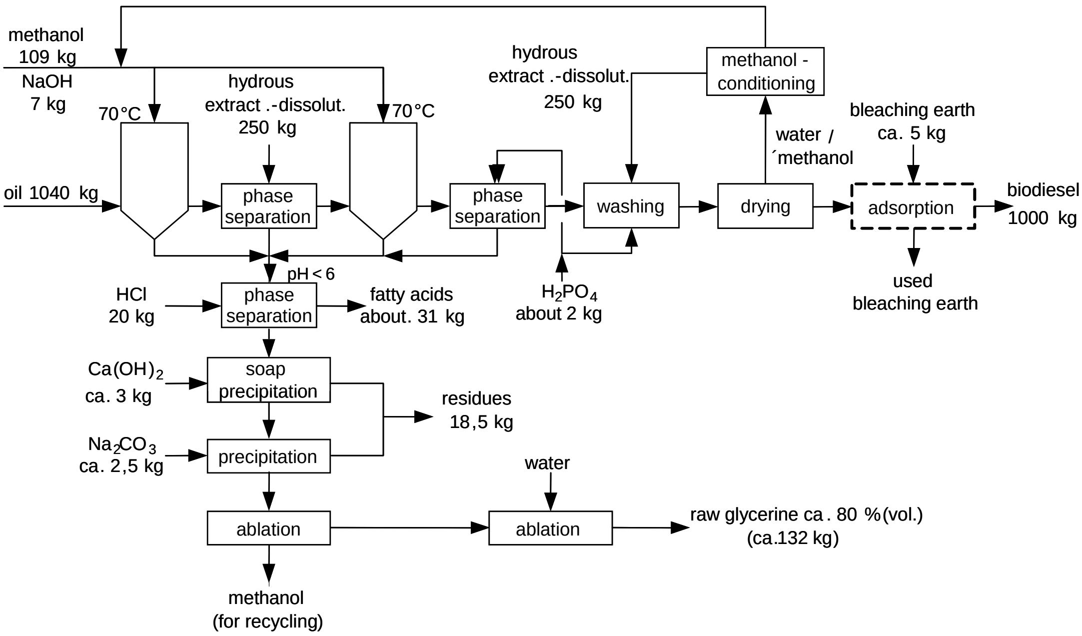


Figure 24: Scheme for a continuous biodiesel production plant[20] (Scharmer et al., 1994)

The techno-economic analysis for biodiesel production is presented in Table 25. It is assumed that the techno-economic parameters for biodiesel production do not change (as rape oil production) in the future since the technology is identified as "*non-learning*" technology.

The ratio of output biodiesel energy content to the input energy content of rape oil and methanol based on LHV is taken as 0.92 (Henniges, 2007). This value is not expected to alter significantly in the future as rape oil production efficiency.

Glycerin is the by-product of biodiesel production. It is reported that the glycerin price reduced in the recent years drastically due to the increasing biodiesel production worldwide (Oleoline, 2005). Therefore, recent glycerin prices are taken into account which leads to low revenues in the order of 0.73 EUR_{2000} per GJ biodiesel.

The auxiliary energy requirement of the biodiesel production plant is taken from Borken et al., 1999 as 45.5 kWh of electricity and 1346 MJ of steam per ton rape oil. As a result the required auxiliary energy is calculated as 0.005 GJ of electricity and 0.047 GJ of fuel oil per GJ biodiesel. The direct GHG emissions result from fuel oil burning. As a result, 3.56 kg of direct CO_{2eq} emissions are generated for the production of 1 GJ of biodiesel from rape oil.

[20] The adsorption process may be disregarded if the vegetable oil is refined (Scharmer et al., 1994)

The analysis of biodiesel production costs show that the main cost component (about 75%) is the feedstock (rapeseed) costs. Therefore, rape oil and biodiesel production plant efficiencies and rapeseed yield per hectare are the most cost influencing factors for biodiesel production.

Table 25: Present (2005) and projected (2030) techno-economic specifications of a biodiesel production plant

	Unit	2005	2030	Sources
Input		Rape oil, methanol		
Output		RME		
Process		Transesterification		
Production capacity	PJ_{output}/a	3.71		FNR, 2008
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.92		Henniges, 2007
EFLH	h/a	8015		Own assumption
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	7.34		Henniges, 2007
FOM costs	EUR_{2000}/GJ_{output}	0.42		Henniges, 2007 and own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	1.41		Henniges, 2007 and own calculation
Methanol requirement	GJ_{MeOH}/GJ_{input}	0.0537		Henniges, 2007
By-product (glycerin)	Revenues EUR_{2000}/GJ_{output}	-0.73		Henniges, 2007 and own calculation
	Carbon credits [a] $kg\ CO_{2eq}/GJ_{output}$	-9.40	-8.42	GEMIS, 2009 own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.005		Borken et al., 1999 own calculation
	Fuel oil $GJ_{fuel\ oil}/GJ_{output}$	0.047		Borken et al., 1999 own calculation
Direct GHG emissions	$kg\ CO_{2eq}/GJ_{output}$	3.56		GEMIS, 2009 own calculation

a) Carbon credits of glycerin are calculated with the substitution method. By-product glycerin is assumed to substitute glycerin produced from fossil fuels (GEMIS, 2009). As the glycerin production is expected to get slightly less carbon intensive in the future, the carbon credits of by-product glycerin decreases gently.

3.3.2 Biodiesel utilization in compression ignition engines

Today, biodiesel is utilized in the pure form[21] (B100) or as a blend with conventional diesel. B100 utilization in the transport sector requires marginal modifications. Although the engine does not need any modifications, there might be some technical difficulties for its low temperature behaviors and its reaction potential with some elements in the fuel line (DOE, 2006). There are also some properties of pure biodiesel which make it technically favorable against conventional diesel. Biodiesel utilization brings much higher lubricity than the

[21] The notification B100 refers to 100% biodiesel. On the other hand, B5 or B20 would mean that 5% or 20% of biodiesel by volume is blended with conventional diesel respectively.

conventional diesel fuel. Furthermore, the 11% oxygen content in the fuel provides a more complete combustion, which reduces the unburned carbon emissions and increases the efficiency (DOE, 2006).

Biodiesel blending may be an option to eliminate any required modifications of B100 utilization, while keeping some of the biodiesel benefits (DOE, 2006). In Germany, the biodiesel blend in the conventional diesel is limited to B5, which amounts to 4.4% energy content. However, in the short run it is expected that B7 is enabled which amounts to 6.2% of energy content (BMU et al., 2007). In this study, it is assumed that B7 is allowed in Germany after the year 2010.

The comparison of energy consumption and direct GHG emissions from engines for B100 and B5 fuels with conventional diesel is presented in Table 26. It is assumed that any biodiesel blending up to B7 will have the same efficiency and emission characteristics as the B5 blend. The results show that the biodiesel blending does not have any effect on energy efficiency, but does on GHG emissions. The pure biodiesel utilization enhances both energy efficiency and GHG emissions.

Table 26: Fuel consumption and greenhouse gas emissions from the use of pure and blended biodiesel compared to conventional diesel fuel

		B100 [c]		B5 [c]	
Passenger car	Fuel consumption [a]	1.0	Krüger, 2002	1.0	Concawe, 2009
	CH_4 [b]	0.78	Ecoinvent, 2007	2.5	Ecoinvent, 2007
	N_2O	0.87	Ecoinvent, 2007	1.0	Ecoinvent, 2007
Bus	Fuel consumption	0.96	Krüger, 2002	1.0	Concawe, 2009
	CH_4	0.85	Krüger, 2002	0.63	NREL, 1998
	N_2O	0.87	Krüger, 2002	1.0	Own assumption [d]
Truck (HDV)	Fuel consumption	0.95	Krüger, 2002	1.0	Concawe, 2009
	CH_4	0.85	Krüger, 2002	0.68	Wang et al., 2000
	N_2O	0.87	Krüger, 2002	1.0	Own assumption [d]
Truck (LDV)	Fuel consumption	0.88	Krüger, 2002	1.0	Concawe, 2009
	CH_4	0.73	Krüger, 2002	0.68	Wang et al., 2000
	N_2O	0.87	Krüger, 2002	1.0	Own assumption [d]

a) All fuel consumption factors represent the ratio of fuel consumption (in g/km) of alternative technology to the conventional technology.
b) All emission factors represent the ratio of direct emissions (in g/km) of alternative technology to the conventional technology.
c) CO_2 emissions are not shown here since they are considered biogenic and not relevant for the emission balance.
d) Assumed to be the same as passenger car

3.4 Further processing of vegetable oils

There are two further options to process vegetable oils to obtain fuels that are compatible with existing engines. These options are catalytic cracking and hydroprocessing (hydrocracking and hydrotreating), which have been used for a long time in oil refineries (Baldauf et al., 1994; UOP, 2005; Huber et al., 2006; Huber et al., 2007a). These processes have the advantage over biodiesel production process that the existing oil refineries are utilized with relatively low modification costs (UOP, 2005; Huber et al., 2007a).

3.4.1 Catalytic cracking of vegetable oils

Catalytic cracking is used in oil refineries to control the ratio of end products and to maximize the output of lighter distillates. Large crude oil molecules are divided with the help of moderate temperatures (400-500°C) and a zeolite catalyst. Thus, the catalytic cracking of vegetable oils includes pyrolysis with the help of a solid catalyst (Huber et al., 2007a). Pyrolysis is a thermal decomposing method which occurs at elevated temperatures without oxygen. Generally, the products of pyrolysis are liquid and gaseous hydrocarbons and coke. The reaction pathway for vegetable oil pyrolysis is shown in Figure 25.

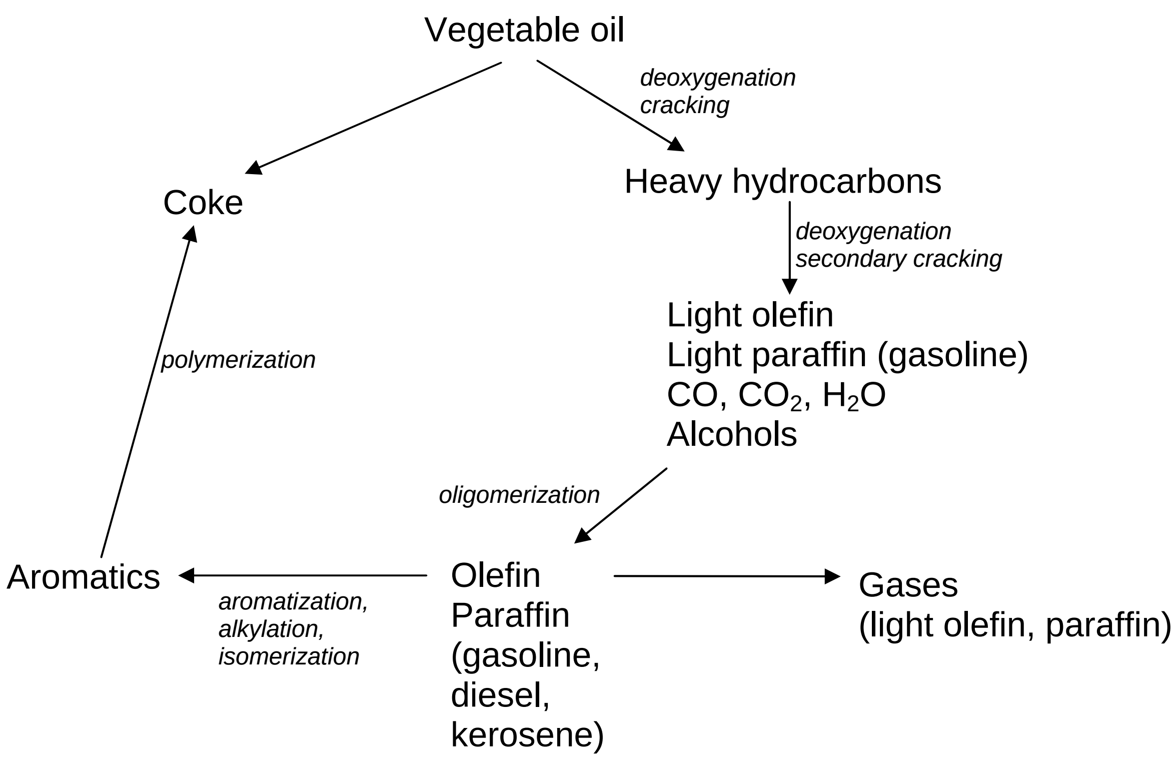


Figure 25: Reaction pathway for catalytic cracking of vegetable oil (Huber et al., 2007a)

The vegetable oil is thermally cracked and deoxygenated first to heavy hydrocarbons and following that to light olefin, paraffin, CO, CO_2, water and alcohols. The oligomerization of light olefins yields olefin and paraffin, which could be utilized as gasoline, diesel and kerosene. Meanwhile aromatic compounds could be formed as well. The aromatics may produce undesired coke via polymerization. On the other hand, the olefin and paraffin may experience further cracking reactions which lead to gaseous products of light olefin and paraffin (Huber et al., 2007a).

However, the exact reaction mechanism is very complex (Huber et al., 2006; Maher et al., 2007). The reaction mechanism and, therewith, the products of the reaction may vary considerable depending on the reaction characteristics and whether or not a catalyst was included (Maher et al., 2007).

The advantage of the catalytic cracking process is that the process does not require any additional hydrogen. Another advantage is the fact that the technology is simple and inexpensive to build (Onay et al., 2004) as the technology is known for a long time from oil refineries.

One of the disadvantages is the undesired coke production (Huber et al., 2006) which amounts to 4.5% to 6.5% of the weights of the products (UOP, 2005). Although pyrolysis of vegetable oils is a commercial technology, the bio-oils are used currently for chemical production rather than as a fuel. The development stage of catalytic cracking of vegetable oils for fuel applications is still on the laboratory scale (Huber et al., 2006), and therefore, not investigated in this work further.

3.4.2 Hydrocracking and hydrotreating of vegetable oils

By hydrocracking and hydrotreating, hydrogen is additionally fed to the reactor at elevated temperatures which reduces the coke production and enables a wider range of products. These processes are known very well for oil refineries. Hydrotreating is utilized to remove sulfur, nitrogen and metals (Huber et al., 2007b); whereas hydrocracking is used to reduce the chain length of the hydrocarbons (Fahim et al., 2010).

The reaction begins with the hydrogenation of double carbon bonds. Thereafter, the triglyceride molecule is split (Huber et al., 2007a). A possible reaction mechanism for splitting of the vegetable oils is illustrated in Figure 26.

The reaction requirements for hydrotreating are temperatures between 350°C and 450°C, pressures between 40 atm and 150 atm, and catalyst (Huber at al., 2006). Furthermore, hydrogen content about 1.5% to 3.8% of the weight of the input vegetable oil is required for the reaction (UOP, 2005).

The products of the reaction are propane, methane, water, carbon dioxide and n-paraffin as seen in Figure 26. The gaseous products of the reaction are propane and methane, which amounts to 2% to 5% of the products weights (UOP, 2005). Water and carbon dioxide make up 12% to 16% of the weights of the product (UOP, 2005). The liquid n-paraffin is utilized as diesel substitute and consists of 83% to 86% of the weight of the products (UOP, 2005).

Several companies produce hydrated vegetable oils (HVO). Neste Oil Company and Universal Oil Products (UOP) are marketing their products under the labels NExBTL and Green Diesel respectively (Arvidsson et al., 2011).

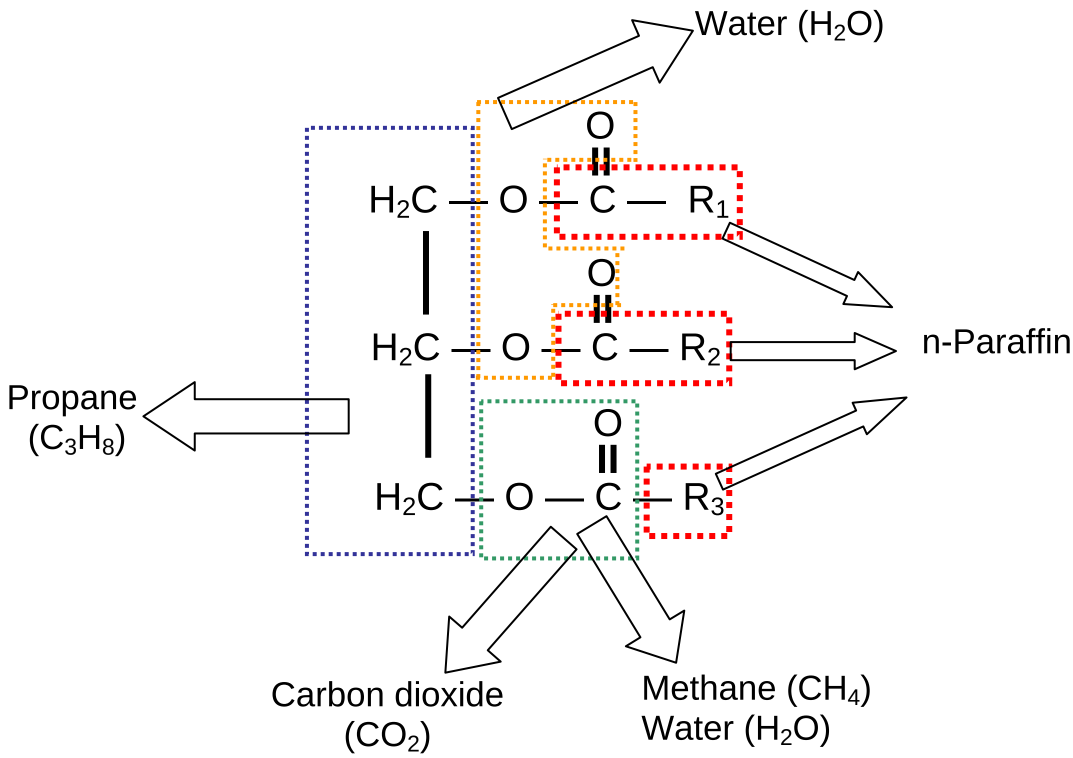


Figure 26: Conversion of vegetable oil via hydrotreating and hydrocracking (Baldauf et al., 1994)

There are two main approaches to hydrotreat vegetable oils: stand-alone systems or co-processing (Huber et al., 2007a; Holge, 2006). The advantage of stand-alone systems is the higher control on the products and higher product quality (Holge, 2006). The disadvantage is the higher investment costs compared to co-processing systems. The co-processing systems require slight changes in the existing refineries, which costs less than 1% of initial refinery costs (Oja, 2008). In this study only co-processing systems are considered. The techno-economic parameters of co-processing vegetable oils are presented in Table 27.

As the HVO production process is basically a slightly modified refinery process, almost all techno-economic specifications are taken from refineries except for the investment costs. Furthermore, as the refinery process is known for a long time any improvements of these specifications are not expected.

The feedstock costs represent the highest share in the total HVO costs due to relatively low investment and FOM costs similar to the biodiesel production. The only significant cost component beside the feedstock costs is the hydrogen production cost, which will vary depending on the production method (see chapter 3.8). However, even including the hydrogen costs, the total HVO production cost is lower than biodiesel production.

Table 27: Techno-economic specifications of vegetable oil co-processing in refineries

	Unit	2005	2030	Sources
Input		Rape oil, hydrogen		
Output		HVO, methane, propane		
Process		Hydrocracking and hydrotreating		
Production capacity	PJ_{output}/a	205		Same as refineries
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.9		Same as refineries
EFLH	h/a	8322		Same as refineries
Lifetime of the plant	a	30		Same as refineries
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	0.053		Oja, 2008
FOM costs	EUR_{2000}/GJ_{output}	0.080		Same as refineries
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.037		Same as refineries
Hydrogen requirement	$GJ_{Hydrogen}/GJ_{input}$	0.025		UOP, 2005
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	0.0		own assumption

There was no commercial vegetable oil processing in oil refineries until 2008 in Germany. However, BMU et al. (2007) foresees that 3% of the crude oil demand could be satisfied with vegetable oil (as blending) in the refineries in a short period of time.

3.4.3 Hydrated vegetable oils in compression ignition engines

The hydrated vegetable oils might be utilized in pure form or by blending with conventional diesel fuel. As only co-processing of hydrated vegetable oils is considered in this work, the utilization of hydrated vegetable oils in compression ignition engines is analyzed only in the blended form.

For hydrated vegetable oils produced by stand-alone systems, 30% volumetric (29% energy content) blendings are allowed (Schütte, 2008). It is assumed that hydrated vegetable oils produced with co-processing technologies have similar characteristics and could be blended up to the same amount. Comparison of energy consumption and direct GHG emissions from engines for hydrated vegetable oils with conventional diesel is presented in Table 28.

Table 28: Fuel consumption and greenhouse gas emissions from the use of hydrated vegetable oils compared to the conventional diesel technologies

		Hydrated vegetable oil	
Passenger car	Fuel consumption [a]	1.0	Concawe, 2009
	CH_4 [b]	0.0	Mason et al., 2008
	N_2O	1.0	Own assumption [d]
Bus	Fuel consumption	1.0	Concawe, 2009
	CH_4	0.0	Own assumption [e]
	N_2O	1.0	Own assumption [e]
Truck (HDV)	Fuel consumption	1.0	Concawe, 2009
	CH_4	0.0	Own assumption [e]
	N_2O	1.0	Own assumption [e]
Truck (LDV)	Fuel consumption	1.0	Concawe, 2009
	CH_4	0.0	Own assumption [e]
	N_2O	1.0	Own assumption [e]

a) All fuel consumption factors relate the ratio of fuel consumption (in MJ/km) of alternative technology compared to the conventional technology.
b) All emission factors relate the ratio of direct emissions (in g/km) of alternative technology compared to the conventional technology.
c) CO_2 emissions are not shown here since they are thought to be biogenic and not relevant for the emission balance.
d) Assumed to be the same as synthetic diesel (see chapter 3.7.4)
e) Assumed to be the same as passenger car

The results show that the HVO blending does not have any effect on energy efficiency, but does on GHG emissions. Besides the fact that the CO_2 emissions of HVO are biogenic and therefore not relevant for GHG emission balance, the methane (CH_4) emissions are reduced drastically. Only N_2O emissions are not altered by changing the fuel from conventional diesel to HVO. Therefore, the tailpipe GHG emissions are reduced significantly by HVO utilization compared to the conventional diesel.

3.5 Bioethanol

Although bioethanol is the World's most produced biofuel for transport purposes, it was commercialized only recently in Germany. Only 0.9% of world bioethanol production in 2008 is manufactured in Germany (F.O. Lichts, 2008), which is rather small compared to the production in USA and Brazil.

3.5.1 Bioethanol production

The raw materials for bioethanol are sugar, starch and celluloses containing materials (Henniges, 2007). The first step of bioethanol production is to convert the feedstock into glucose, where the complexity of this step varies severely with the feedstock. Principally only sugars can be fermented into alcohol. Thus, the starch and celluloses containing feedstock should first be degraded into sugars. The second step is the fermentation, which is more or less the same for all feedstock. The glucose is converted to carbon dioxide and ethanol with the help of yeast (Schmitz, 2003). The third step is the distillation and dehydrogenation which is required to have higher ethanol concentration.

The relevant **sugar containing feedstocks** are sugar beet (*Beta vulgaris* L.), sugarcane (*Saccharum*) and *sorghum bicolor* (Demirbas, 2010; Friedl et al., 2009). Among the sugar containing feedstocks, only sugar beet is cultivated in Germany to a significant degree (Schmitz, 2003). Germany is third in the sugar beet production quantity with 25.9 million tons of production in 2009 after France and USA (FAOStat, 2011).

It requires relatively less effort to convert sugar containing feedstock to glucose, which only includes washing and milling to extract the sugar juice (Friedl et al., 2009). The sugar juice (molasses) from sugar beet consists of disaccharide which is decomposed into monosaccharide (Schmitz, 2003). The techno-economic parameters for bioethanol production from sugar beet are presented in Table 29.

The average ethanol production plant capacity in Germany is about 1.9 PJ of ethanol per year. The plants that are in construction have the average production capacity of 3.8 PJ/a (FNR, 2008). Thus, the plant sizes 2.1 PJ/a and 4.2 PJ/a are selected for the years 2005 and 2030 respectively.

The ratio of output bioethanol energy content to the input sugar beet energy content based on LHV is taken as 0.58 (Ingelspacher, 2003) and expected to increase slightly until 2030 to 0.59 (König, 2009).

The decrease of specific investment costs in 2030 are a direct result of the capacity increase from 2.1 to 4.2 PJ/a. It is assumed that the investment costs are increased only by 60% if the plant capacity is doubled (Henniges, 2007). Therefore, the specific investment costs are expected to decrease from 24.26 in 2005 to 19.43 $EUR_{2000}/(GJ_{output}/a)$ in 2030. Similarly, the FOM and VOM costs are expected to decrease.

By-product of bioethanol production from sugar beet is the pressed beet slices which are mainly used for animal feed (Özdemir et al., 2009). Selling pressed beet slices bring revenue of 103.5 EUR_{2000}/t slice (Henniges, 2007). The resulting revenue is about 2.37 EUR_{2000} per GJ produced bioethanol which is almost equal to the VOM costs.

The auxiliary energy requirement of the bioethanol production from sugar beet is significantly high. The electricity consumption is 0.04 GJ per GJ produced bioethanol. Furthermore, the heat requirement is much higher than the electricity requirement. For the processes of biomass conditioning, milling and extraction, 0.19 GJ of fuel oil is required per GJ produced bioethanol (Ingelspacher, 2003). Furthermore, 0.22 GJ of fuel oil per GJ bioethanol is required for fermentation, distillation and dehydrogenation processes (Ingelspacher, 2003). As a result, more than 40% of the energy content of the bioethanol is required to be supplied by fuel oil, which has a negative effect on the GHG emission balance. The direct CO_{2eq} emissions per GJ of bioethanol are calculated as 31.06 kg, which are coming from burning of fuel oil for the heat requirements.

Table 29: Present (2005) and projected (2030) techno-economic specifications of a bioethanol production plant using sugar beet

	Unit	2005	2030	Sources
Input	Sugar beet			
Output	Bioethanol			
Process	Milling, fermenting, distillation and dehydrogenation			
Production capacity	PJ_{output}/a	2.1	4.2	Henniges, 2007; Vetter, 2006 and own assumptions
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.58	0.59	Ingelspacher, 2003; König, 2009
EFLH	h/a	8000		BSE, 2008
Lifetime of the plant	a	15	20	Henniges, 2007 and own assumptions
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	24.26	19.43	Henniges, 2007 and own calculations
FOM costs	EUR_{2000}/GJ_{output}	1.36	1.17	Henniges, 2007 and own calculations
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	2.66	2.48	Henniges, 2007; CONCAWE, 2007 and own calculation
By-product (pressed beet slices [a])	Revenues EUR_{2000}/GJ_{output}	-2.37		Henniges, 2007 and own calculations
	Carbon credits [b] kg CO_{2eq}/GJ_{output}	-7.12		Özdemir et al., 2009; GEMIS, 2009 and own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.04		Ingelspacher, 2003 and own calculation
	Fuel oil $GJ_{fuel\ oil}/GJ_{output}$	0.41		Ingelspacher, 2003 and own calculation
Direct GHG emissions [c]	kg CO_{2eq}/GJ_{output}	31.06		GEMIS, 2009 own calculation

a) Pressed beet slices are utilized as animal feed
b) Carbon credits of pressed beet slices are calculated with the substitution method. Beet slices are assumed to substitute maize, which is used as animal feed (Özdemir et al., 2009). Emissions to produce maize for animal feed are taken from GEMIS (2009).
c) Direct GHG emissions are calculated with respect to auxiliary fuel oil consumption per GJ_{output}. Therefore, the direct GHG emissions in 2030 are estimated the same as in 2005, although the efficiency of the plant increases slightly between these years.

The **starch containing feedstocks** which are cultivated for fuel production in Germany are potato (Solanum tuberosum L.), Jerusalem artichoke (Helianthus, tuberosus), maize (Zea mays L.) and cereals (Demirbas, 2010; Lewandowski and Böhmel, 2009). Wheat (Triticum aestivum L.) has the highest starch content in the cereal family but the highest requirements for warmth and water as well. In this work, only wheat is considered.

Extracting glucose from starch containing feedstock is known and has been used for a long time to produce alcoholic beverages. After cleaning and grinding, the starch, which is a polymer of glucose, will decompose into sugars (glucose) via hydrolysis (Schmitz, 2003). This reaction needs two different enzymes first α-amylase to liquefy the starch and then glucoamylase to convert the liquefied starch to glucose (Senn and Friedl, 2009). This conversion is microbiologically and technically more complex than decomposition of disaccharide (Schmitz, 2003).

The wheat yield in Germany in 2006 was 7.2 t/ha/a (FAOStat, 2011). One hundred kg of wheat brings about 40 liters of ethanol (Senn, 2001). Thus, the ethanol yield is about 2,880 l/ha/a. FNR gives an average ethanol yield for cereals in Germany which is 2,550 l/ha/a for 2005 and 3,212 l/ha/a for 2015 (FNR, 2006a). For ethanol production from wheat, the same plant capacities as sugar beet plants are selected (Table 30).

The ratio of output bioethanol energy content to the input wheat energy content based on LHV is taken as 0.53 and not expected to increase in the future (Ingelspacher, 2003 and König, 2009).

The bioethanol production plant from wheat has the same specific investment and FOM costs as the bioethanol production plant from sugar beet due to very similar processes (Henniges, 2007). However, the VOM costs and especially the auxiliary energy requirement of the wheat bioethanol plant differ considerably from the sugar beet bioethanol plant. To produce one GJ of bioethanol, 0.15 GJ of fuel oil is required, which is almost one third of the requirements in the sugar beet bioethanol plant. This lower fuel oil requirement influences the direct GHG emissions from the bioethanol production in a positive way.

By-product of bioethanol production from wheat is the Distiller's Dried Grain and Solubles (DDGS) which are mainly used for animal feed (Özdemir et al., 2009). Selling DDGS brings revenue of 84.7 EUR_{2000}/t (Henniges, 2007). The resulting revenue is about 3.1 EUR_{2000} per GJ produced bioethanol. This revenue is slightly higher than the sugar beet bioethanol plant by-product revenue from pressed beet slices (2.37 $EUR_{2000}/GJ_{bioethanol}$).

The considered **celluloses containing** feedstocks for ethanol production in this study are agricultural wastes (mainly straw), cellulose energy crops (miscanthus, and short rotation coppice -SRC) and residual wood.

Cellulose containing feedstocks are the most difficult feedstock to convert to ethanol. Cellulose is also a polymer of glucose like starch. The difference lies in the type of linkages in the glucose molecules, which makes the break down of cellulose difficult (Gray, 2007). The pretreatment of the feedstock includes removal of lignin and hemicelluloses, reduction of celluloses crystallinity and increase of the porosity of the materials (Sun and Cheng, 2002). There are physical, physico-chemical, chemical and biological pretreatment methods that are explained in detail by Sun and Cheng (2002). Pretreatment by cellulosic ethanol production is the single unit operation with highest costs (Wyman, 2007). After the pretreatment the celluloses are degraded to glucose either by a physico-chemical process (via acid hydrolysis) or by a biochemical process (via enzymatic hydrolysis). Other hydrolysis methods (e.g. gamma-ray irradiation) are not significant for commercial applications (Demirbas, 2005).

Table 30: Present (2005) and projected (2030) techno-economic specifications of a bioethanol production plant using wheat

		Unit	2005	2030	Sources
Input		Wheat			
Output		Bioethanol			
Process		Milling, hydrolysis, fermenting, distillation and dehydrogenation			
Production capacity		PJ_{output}/a	2.1	4.2	Henniges, 2007; Vetter, 2006 and own assumptions
Efficiency (LHV)		GJ_{output}/GJ_{input}	0.53		Ingelspacher, 2003; König, 2009
EFLH		h/a	8000		BSE, 2008
Lifetime of the plant		a	15	20	Henniges, 2007 and own assumptions
Specific investment cost		$EUR_{2000}/(GJ_{output}/a)$	24.26	19.43	Henniges, 2007 and own calculations
FOM costs		EUR_{2000}/GJ_{output}	1.36	1.17	Henniges, 2007 and own calculations
VOM cost w/o feedstock, auxiliary energy and revenues		EUR_{2000}/GJ_{output}	5.56	5.33	Henniges, 2007; CONCAWE, 2007 and own calculation
By-product (DDGS [a])	Revenues	EUR_{2000}/GJ_{output}	-3.10		Henniges, 2007 and own calculations
By-product (DDGS [a])	Carbon credits [b]	kg CO_{2eq}/GJ_{output}	-6.35		Özdemir et al., 2009; GEMIS, 2009 and own calculation
Auxiliary energy requirement	Electricity	$GJ_{electricity}/GJ_{output}$	0.059		Ingelspacher, 2003 and own calculation
Auxiliary energy requirement	Fuel oil	$GJ_{fuel\ oil}/GJ_{output}$	0.154		Ingelspacher, 2003 and own calculation
Direct GHG emissions		kg CO_{2eq}/GJ_{output}	11.67		GEMIS, 2009 own calculation

a) DDGS is distiller's dried grain and solubles and used mainly for animal feed
b) Carbon credits of DDGS are calculated with the substitution method. DDGS is assumed to substitute maize, which is used as animal feed (Özdemir et al., 2009). Emissions to produce maize for animal feed are taken from GEMIS (2009).

The techno-economic parameters for bioethanol production from cellulosic feedstock are presented in Table 31. The average capacity of cellulosic bioethanol plant in 2010 is selected similar to the capacity (110,000 m^3/a) of existing commercial plant in the city of Shelley in USA owned by the company Iogen (Solomon et al., 2007). The average capacity is assumed to be doubled until the year 2030.

The plant efficiency is taken as 0.35 for 2010 (IEA, 2008) and 0.45 for 2030 (Solomon et al., 2007). The efficiency of 0.45 is rather optimistic but achievable. Therefore, a significant research and development effort is required for efficiency improvement until 2030. Similar to the plant efficiency, equivalent full load hours is also assumed to be improved from 7,000 h/a in 2010 to 8,400 h/a in 2030 (IEA, 2008 and NREL, 2002).

Table 31: Present (2010) and projected (2030) techno-economic specifications of a bioethanol production plant using cellulosic feedstock

	Unit	2010	2030	Sources
Input		Cellulosic biomass		
Output		Bioethanol		
Process		Milling, hydrolysis, fermenting, distillation and dehydrogenation		
Production capacity	PJ_{output}/a	2.3	4.6	Solomon et al., 2007; own assumptions
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.35	0.45	IEA, 2008 and Solomon et al., 2007
EFLH	h/a	7000	8400	IEA, 2008; NREL, 2002
Lifetime of the plant	a	15		GEMIS, 2009
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	53.33	38.79	Solomon et al., 2007; own assumptions
FOM costs	EUR_{2000}/GJ_{output}	4.77	3.47	Solomon et al., 2007; own assumptions
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	3.07	2.79	Solomon et al., 2007; own assumptions
Additional electricity generation	$GJ_{elec}/GJ_{feedstock}$	0.045		NREL, 2002
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	0.0		own assumptions

The specific investment costs are calculated for the year 2030 as 38.79 EUR_{2000}/(GJ/a) for a plant capacity of 4.6 PJ per year (Solomon et al., 2007). The investment costs of the year 2010 are calculated with two effects. On the one hand, the capacity change is considered (see Table F 1 in the appendix). On the other hand, the technology learning is taken into account. It is assumed that the specific investment cost decrease will be in the same order as the efficiency improvement. As a result, the specific costs of the bioethanol production plant from cellulosic feedstock is calculated as 53.33 EUR_{2000}/(GJ/a). The FOM costs are calculated similarly to the investment costs. However, the VOM costs decrease only 10% similar to the technology learning and not with the increase in the capacity.

The auxiliary energy requirement of the bioethanol production from cellulosic feedstock is relatively low compared to the sugar beet and wheat bioethanol plants. The electricity consumption is 0.045 GJ per GJ produced bioethanol. Furthermore, there is no significant auxiliary heat requirement (NREL, 2002). Consequently, no direct GHG emissions are generated in the bioethanol production from cellulosic feedstock.

3.5.2 ETBE and further processing of ethanol

ETBE (Ethyl *tert*-butyl ether) is one of the oxygenates that can be obtained by further processing of ethanol and isobutene, a refinery product (Ancillotti et al., 1998). Blending oxygenates with gasoline has the advantage of getting higher octane numbers as ethanol blending. Historically, MTBE (Methyl *tert*-butyl ether), a product derived from methanol and isobutene, is used in the transport sector as an octane booster. However, in recent years MTBE has been restricted in certain countries due to its potential for groundwater contamination (de Menezes et al., 2006). In Germany, all the MTBE plants, which had a total production capacity of 2.2 million t/a (corresponds to 77.2 PJ/a) in 2003 have been converted to ETBE plants after 2005 due to certain tax regulations of the government (IAWR, 2008). On the other hand, some scholars argue that ETBE will only bring slight environmental advantages against MTBE (Koenen et al., 2005).

The techno-economic properties of ETBE production are presented in Table 32. One MJ (27.78 g) ETBE production requires 0.33 MJ (12.53 g) of ethanol and 0.69 MJ (15.25 g) of isobutene. The required isobutene is not commercially available as it is a by-product of the refinery process (SenterNovem, 2008). Therefore, it is difficult to calculate the cost of ETBE.

Table 32: Present (2005) and projected (2030) techno-economic specifications of an ETBE production plant

	Unit	2005	2030	Sources
Input		Bioethanol Isobuthene		
Output		ETBE		
Process		ETBE synthesis		
Production capacity	PJ_{output}/a	4.7		
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.978		SenterNovem, 2008
Additional output	LPG GJ_{LPG}/GJ_{input}	0.022		Own assumption
EFLH	h/a	8322		Same as refineries
Lifetime of the plant	a	30		Same as refineries
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	*	3.48	Krüger, 2002
FOM costs	EUR_{2000}/GJ_{output}	*	0.31	Krüger, 2002
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	*	0.09	Krüger, 2002
Auxiliary energy requirement	Natural gas $GJ_{natural\ gas}/GJ_{output}$	0.13		SenterNovem, 2008
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	7.31		GEMIS, 2009 own calculation

*) After 2005 all MTBE plants have been converted to ETBE plants in Germany with relatively low expenditures (IAWR, 2008 and Koenen et al., 2005)

3.5.3 Ethanol and ETBE for spark ignition engines

Today, ethanol is utilized in the pure form (E100) or as a blend with conventional gasoline. To use E100 and E85, which are very common in Brazil and Sweden respectively, the engine requires some modifications. In Germany, E5 is allowed without any engine modifications (BMU et al., 2007). Furthermore, it is allowed to sell E10 after December 2010 in Germany (BMU, 2011a). E10 is an appropriate fuel for 90% of the existing passenger car fleet in 2010 and almost all of the new purchased cars in Germany (BMU, 2011a). Therefore, it is expected that all vehicles with the spark ignition engine are suitable to use E10 fuel after 2020. In this study only ethanol blends up to E10 are considered as this is considered to be the only important ethanol use in the German transport sector.

ETBE is only utilized as an additive for gasoline. In Germany, blending up to 15% volumetric (12.8% energy content) ETBE is allowed (BMU et al., 2007).

Comparison of energy consumption and direct GHG emissions from spark ignition engines for blended ethanol and ETBE with conventional gasoline is presented in Table 33.

The results show that the blending of bioethanol or ETBE does not have any effect on energy efficiency. However, the tailpipe GHG emissions are reduced with the bioethanol and ETBE blending significantly, especially for bioethanol. The CO_2 emissions of ETBE are accounted due to its fossil fuel content coming from isobutene.

Table 33: Fuel consumption and greenhouse gas emissions from the use of blended bioethanol and ETBE compared to the conventional gasoline technologies

		Bioethanol blending [c]		ETBE blending	
Passenger car	Fuel consumption [a]	1.0	Concawe, 2009	1.0	Concawe, 2009
	CO_2	-	-	0.68	Ecoinvent, 2007
	CH_4 [b]	0.0	Ecoinvent, 2007	1.0	Ecoinvent, 2007
	N_2O	0.77	Ecoinvent, 2007	1.0	Ecoinvent, 2007
Truck (LDV)	Fuel consumption	1.0	Concawe, 2009	1.0	Concawe, 2009
	CO_2	-	Own assumption [d]	0.68	Own assumption [d]
	CH_4	0.0	Own assumption [d]	1.0	Own assumption [d]
	N_2O	0.77	Own assumption [d]	1.0	Own assumption [d]

a) All fuel consumption factors are presenting the ratio of fuel consumption (in MJ/km) of alternative technology to the conventional technology.
b) All emission factors are presenting the ratio of direct emissions (in g/km) of alternative technology to the conventional technology.
c) CO_2 emissions are not shown here since they are thought to be biogenic and not relevant for the emission balance.
d) Assumed to be the same as passenger car

3.6 Methane

Methane has the chemical formula (CH_4) and is the simplest hydrocarbon. It is the main component of natural gas and could be utilized in the transport sector as CNG - compressed natural gas (chapter 3.6.1). Methane might also be obtained from biomass, which is called substitute natural gas (SNG). There are two different ways to obtain SNG, namely biogas (chapter 3.6.2) and synthesis gas (chapter 3.6.3). Utilized feedstock and the production steps are totally different, but both of the products require an upgrading before one can utilize it in the transport sector. The utilization of CNG in the spark ignition engine (see chapter 3.6.4) is identical to the SNG, as both of them are compressed methane.

3.6.1 Compressed natural gas (CNG)

Natural gas provision is dependent mainly on imports into Germany and the share of natural gas imports is expected to increase to 90% by 2020 (GEMIS, 2009). Main natural gas suppliers are Russia and Norway. To utilize natural gas in the transport sector, it is transported via high pressure natural gas pipelines and then distributed to filling stations (see chapter 3.10).

3.6.2 Biogas production and upgrading to substitute natural gas

Biogas is obtained by the anaerobic fermentation of energy crops (maize, wheat and grass in Germany) and/or manure. Maize is the mostly utilized feedstock for biogas plants with a fresh mass share of 47%. Wheat and manure have the fresh mass utilization shares of 5% and 33% respectively (Weiland, 2006 and own calculation). It is assumed that the rest of the feedstock (15%) is provided by grass in Germany. These fresh mass shares correspond to 67%, 6%, 5% and 22% shares of energy production from maize, wheat, manure and grass respectively (own calculation based on KTBL, 2007).

The techno-economic parameters for biogas production from energy crops and from manure are presented in Table 34 and Table 35 respectively. Biogas process is identified as "*non-learning*" as the sector is well established in Germany (FNR, 2009b).

The average capacity of biogas plants is selected as 250 Nm^3 (volume under normal conditions) of raw biogas production per hour (FNR, 2006b), which is slightly higher than the average biogas plant capacity in Germany.

The biogas plant efficiencies (from biomass to raw biogas) are taken as 0.70 for energy crops and 0.67 for manure, which are not expected to improve significantly in the future (König, 2009). The comparison of specific investment costs show that they are slightly lower with manure compared to the energy crops. FOM and VOM costs for energy crops and manure biogas plant do not differ significantly. Most of the other techno-economic data are identical for both systems.

The obtained raw biogas contains between 51% and 65% methane, between 25% and 45% carbon dioxide, between 2% and 7% water vapor and other substances with small amounts such as hydrogen sulfide (KTBL, 2007; Edelmann, 2001). After the fermentation the raw biogas is cleaned from contaminants such as hydrogen sulfide, and dried. The output biogas can be either utilized in CHP (combined heat and power) plants to generate electricity and heat, or upgraded to natural gas quality (SNG) by separating carbon dioxide. The automotive biogas applications require mostly upgraded biogas due to driving range requirements (IER et al., 2007).

Table 34: Present (2005) and projected (2030) techno-economic specifications of a biogas production plant using energy crops

	Unit	2005	2030	Sources
Input	Maize, wheat or grass			
Output	Raw biogas			
Process	Anaerobic digestion			
Production capacity	PJ_{output}/a	0.04		Own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.70		König, 2009
EFLH	h/a	8000		FNR, 2006b
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	29.10		FNR, 2006b; own calculation
FOM costs	EUR_{2000}/GJ_{output}	0.80		FNR, 2006b; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	1.16		FNR, 2006b; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.03		FNR, 2004
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	4.6		IFEU et al., 2008; own calculation

Direct GHG emission includes diffuse emissions from the biogas plant due to leakages, which are about 1% (IFEU et al., 2008). The energy content of 1 kg methane is 50 MJ, which results in 0.2 kg of methane emissions (or 4.6 kg of CO_{2eq}) per one GJ energy production. These emissions are relevant for both biogas feedstock (energy crops and manure). However, the manure has a special case due to the fact that there are (at least) more methane emissions if the manure is not utilized in a biogas plant and instead left on the field. Thus, it is assumed that manure biogas plants do not have methane leakages.

On the other hand, the GHG emissions regarding the digested residue are not considered for both biogas pathways due to the fact that they are mostly utilized as fertilizer and substitute mineral fertilizer.

Installed capacity and number of biogas plants boomed recently in Germany due to the EEG (renewable energy law) regulation, which guarantees higher revenues for electricity from biogas. The EEG was first introduced in 2000 and then revised in 2004 and again in 2009

(BMU, 2009a). As the regulation mainly includes electricity generation, almost all the biogas plants generate electricity as the output. Nevertheless, in Germany, there are 65 biogas upgrading plants in operation in 2011. Furthermore, 80 plants are in planned or in the constructing phase (Biogaspartner, 2011).

Table 35: Present (2005) and projected (2030) techno-economic specifications of a biogas production plant using manure

	Unit	2005	2030	Sources
Input		Manure		
Output		Raw biogas		
Process		Anaerobic digestion		
Production capacity	PJ_{output}/a	0.04		Own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.67		König, 2009
EFLH	h/a	8000		FNR, 2006b
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	27.93		FNR, 2006b; own calculation
FOM costs	EUR_{2000}/GJ_{output}	0.90		FNR, 2006b; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	1.03		FNR, 2006b; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.03		FNR, 2004
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	- [a]		Own assumption

a) There is 1% methane leakage from the biogas plant as in the energy crops case (IFEU et al., 2008). However, these emissions are not considered since there are (at least) more methane emissions if the manure is not utilized in biogas plant and left on the field.

There are different techniques for biogas upgrading (FNR, 2006b; Bauer, 2008). The most commonly utilized process among the operating biogas upgrading plants is the pressure swing adsorption (PSA) which is used by 17 projects (Biogaspartner, 2011). This process has four steps: compression of raw biogas, removal of hydrogen sulfide, conditioning (drying and cooling) and removal of carbon dioxide via pressure swing adsorption (Bauer, 2008). The operating principle of a PSA plant is based on the fact that some gas molecules (in this case carbon dioxide) tend to make Van-der-Waals bonds with a solid material at elevated pressures and are released if pressure sinks again. Thus, the carbon dioxide and methane can be separated. The output gas is called SNG and is 97% methane (Bauer, 2008).

The techno-economic parameters for biogas upgrading are presented in Table 36. Although the biogas upgrading is a newly establishing process, it is conservatively assumed that the techno-economic parameters will not be improved in the future significantly. The production capacity is selected according to the biogas production capacity of 0.04 PJ/a.

There is a methane loss of 2.5% in the process (Bauer, 2008), which lowers on one hand the efficiency of the system and on the other hand, emits 0.5 kg of methane per one GJ of produced SNG.

Table 36: Present (2005) and projected (2030) techno-economic specifications of a biogas upgrading plant with pressure swing adsorption

	Unit	2005	2030	Sources
Input		Raw biogas		
Output		Upgraded biogas		
Process		PSA		
Production capacity	PJ_{output}/a	0.04		Own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.975		Bauer, 2008
EFLH	h/a	8000		Own assumption
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	20.96		FNR, 2006b; own calculation
FOM costs	EUR_{2000}/GJ_{output}	0.23		FNR, 2006b
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.23		FNR, 2006b; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.052		Bauer, 2008; own calculation
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	11.5		Bauer, 2008; own calculation

3.6.3 Synthesis gas production and upgrading to SNG

Synthesis gas production includes gasification process, which is a thermo-chemical conversion pathway. The aim of gasification is to convert cellulosic biomass to a gaseous product. Most of the research for gasification is concentrated on the lignocelluloses containing biomass as the substrate. In this work, straw, miscanthus, residual wood and short rotation coppice (SRC) are investigated as biomass feedstock for gasification.

There are various gasification techniques and concepts that might be of interest. However, Ramesohl et al. (2005) argues that fast internal circulating fluidized bed gasification (FICFBG) is the gasification pathway of the future. This technology is proven by the Güssing demonstration plant, which has a furnace heating capacity of 8 MW_{th}. Furthermore, FICFBG is the SNG production pathway with the least costs (Stahlschmidt et al., 2010). Thus, this work concentrates on the FICFBG process (Table 37).

The production capacity in 2005 is taken as 0.66 PJ/a based on the thermal capacity of 25 MW. However, it is projected that the average capacity of gasification and gas cleaning plants will increase in the future. It is assumed that the average future plant capacity will be about 3-fold of today's capacity, which is similar to the capacity of existing biomass gasification plant (84 MW_{th}) in Netherlands owned by the EPZ Company (NETL, 2004).

The plant efficiency (based on LHV) and specific investment cost are estimated for 2005 as 0.735 and 16.15 EUR_{2000}/(GJ/a) based on Ramesohl et al., 2005 respectively. It is assumed that the efficiency will be improved to 0.800 based on the best case analysis of existing gasification demonstration plants (IER et al., 2007).

Table 37: Present (2005) and projected (2030) techno-economic specifications of a gasification and gas cleaning plant

	Unit	2005	2030	Sources
Input		Cellulosic biomass		
Output		Synthesis gas		
Process		FICFBG		
Production capacity	PJ_{output}/a	0.66	1.98	Ramesohl et al., 2005; Own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.735	0.800	Ramesohl et al., 2005; IER et al., 2007 ; own assumption
EFLH	h/a	8000		Ramesohl et al., 2005
Lifetime of the plant	a	15	20	Ramesohl et al., 2005; Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	16.15	10.65	Ramesohl et al., 2005; own calculation
FOM costs	EUR_{2000}/GJ_{output}	0.80	0.53	Ramesohl et al., 2005; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.56	0.53	Ramesohl et al., 2005; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.016		Ramesohl et al., 2005; own calculation
	Fuel oil $GJ_{fuel\ oil}/GJ_{output}$	0.002		GEMIS, 2009
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	0.20	0.19	GEMIS, 2009; own calculation

The specific investment costs are expected to reduce due to technology learning and capacity increase. The specific investment costs are expected to reduce about 30% with the triple capacity (see Table F 1 in the appendix). Furthermore, the technology learning effect is assumed to be coupled to the efficiency improvement (6.5%). The resulting specific investment costs for 2030 are 10.65 EUR_{2000}/(GJ/a). The FOM costs are calculated similarly to the investment costs. However, the VOM costs decrease only 6.5% similar to the technology learning and not with the increase in the capacity.

The improvement of direct GHG emissions is based on the efficiency improvement as the emissions are expressed per output bioethanol energy content.

Although the initial focus of the gasification was electricity generation, it is also possible to utilize synthesis gas (with corresponding conversions) in the transport sector. To utilize the produced synthesis gas in the liquid form, a Fischer-Tropsch synthesis is required. The output of this process is biomass to liquid (see chapter 3.7.1). However, the obtained synthesis gas can be upgraded to gaseous products like hydrogen (see chapter 3.8.1) or even to SNG. The SNG production from the synthesis gas requires methanization process, where carbon monoxide molecules react with hydrogen and result in methane and water vapor. The techno-economic parameters for methanization of synthesis gas are presented in Table 38.

Table 38: Present (2005) and projected (2030) techno-economic specifications of a plant for upgrading synthesis gas to SNG

	Unit	2005	2030	Sources
Input	Synthesis gas			
Output	SNG			
Process	Methanization			
Production capacity	PJ_{output}/a	0.56	1.78	Own calculation
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.85	0.90	Ramesohl et al., 2005; own assumption
EFLH	h/a	8000		Ramesohl et al., 2005
Lifetime of the plant	a	15	20	Ramesohl et al., 2005; Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	14.21	9.36	Ramesohl et al., 2005; own calculation
FOM costs	EUR_{2000}/GJ_{output}	0.36	0.24	Ramesohl et al., 2005; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	2.05	1.96	Ramesohl et al., 2005; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.051		Ramesohl et al., 2005; own calculation
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	9.2		Bauer, 2009; own calculation

It is assumed that the capacity increase of upgrading plant for synthesis gas to SNG will be corresponding to the gasification and gas cleaning plant. Therefore, it is expected that the initial capacity of 0.56 PJ/a will be increased to 1.78 PJ/a in the year 2030. Furthermore, the efficiency is assumed to increase to 90% in 2030.

The specific investment costs for the year 2005 are taken from Ramesohl et al. (2005) as 14.21 $EUR_{2000}/(GJ_{output}/a)$, which is expected to reduce to 9.36 $EUR_{2000}/(GJ_{output}/a)$ due to capacity increase and technology learning. The FOM costs are calculated similarly to the investment costs. However, the VOM costs decrease only 5% similar to the technology learning and not with the increase in the capacity.

3.6.4 Methane for spark ignition engines

SNG has essentially the same fuel quality as natural gas. Therefore, it can be used in conventional natural gas engines without any modification. CNG and SNG are utilized in spark ignition engines due to its favorable characteristics, especially, the high octane number of about 130 (FNR, 2005).

The characteristics of spark ignition engines for SNG are presented in Table 39. The fuel consumption of SNG is the same as the gasoline powered spark ignition engine passenger car and trucks (Krüger, 2002). However, the fuel consumption increases about 20% for the HDVs due to changing the compression ignition engine to the spark ignition engine.

The CNG utilization has the only difference compared to SNG utilization that the resulting CO_2 emissions are not biogenic and therewith relevant for the emission balance (56 g CO_2/MJ_{CNG}).

Table 39: Fuel consumption and greenhouse gas emissions from the use of SNG compared to the conventional technologies

compared to		SNG [c]	
Passenger car SI engine	Fuel consumption [a]	1.0	Krüger, 2002
	CO_2	-	-
	CH_4 [b]	26.5	Krüger, 2002
	N_2O	0.2	Krüger, 2002
Truck (LDV – SI engine)	Fuel consumption	1.0	Krüger, 2002
	CO_2	-	-
	CH_4	7.0	Krüger, 2002
	N_2O	1.0	Krüger, 2002
Truck (HDV – CI engine)	Fuel consumption	1.2	Krüger, 2002
	CO_2	-	-
	CH_4	0.2	Krüger, 2002
	N_2O	1.67	Krüger, 2002

a) All fuel consumption factors are presenting the ratio of fuel consumption (in MJ/km) of alternative technology to the conventional technology.
b) All emission factors are presenting the ratio of direct emissions (in g/km) of alternative technology to the conventional technology.
c) CO_2 emissions are not shown here since they are thought to be biogenic and not relevant for the emission balance.

3.7 Synthetic diesel

Synthetic diesel (also called designer fuel) might be obtained from different feedstock. The renewable synthetic diesel is called biomass to liquid (BTL), which is presented in chapter 3.7.1. CTL (coal to liquid) and GTL (gas to liquid) are fossil synthetic diesel options presented in chapters 3.7.2 and 3.7.3 respectively.

CTL was first developed in 1920s in Germany to provide alternative fuels not originating from crude oil (Höök, 2009). After the war period the interest was lost due to the low oil prices. The only exception was the SASOL in South Africa. From 1960s onwards, they produced significant amount of CTL for the transport energy demand of the country with their relatively low cost coal (Höök, 2009). The interest in synthetic diesel has been raised again recently. There are several existing demonstration plants for BTL and GTL.

3.7.1 Biomass to liquid (BTL) production

The BTL production includes gasification of the cellulosic biomass as presented in chapter 3.6.3. The gasification is followed by Fischer-Tropsch synthesis where the synthesis gas is converted to high quality diesel-like fuel.

There are several developed BTL concepts, CHOREN, Bioliq, CUTEC etc. (HMULV, 2006). However, a commercial BTL production was not realized until end of 2010 (Beiermann, 2010). Among these concepts, the CHOREN process is taken as the focus in this study as it is closest to commercialization. Furthermore, CHOREN process is identified as the least cost BTL pathway (Stahlschmidt et al., 2010; Beiermann, 2010). The first commercial BTL plant is currently under construction (CHOREN, 2009). The techno-economic parameters for BTL production are presented in Table 40.

Table 40: Present (2010) and projected (2030) techno-economic specifications of a biomass to liquid (BTL) production plant

	Unit	2010	2030	Sources
Input		Cellulosic biomass		
Output		BTL		
Process		Gasification and FT synthesis (CHOREN process)		
Production capacity	PJ_{output}/a	8.8	13.0	Blades, 2006; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.48	0.50	HMULV, 2006; own assumption
EFLH	h/a	8000		Own assumption
Lifetime of the plant	a	15	20	Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	42.04	36.27	HMULV, 2006; own calculation
FOM costs	EUR_{2000}/GJ_{output}	1.79	1.55	HMULV, 2006; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	4.36	4.27	HMULV, 2006; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.077		Arnold et al., 2006
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	0.02		Gemis, 2009

The production capacity, efficiency, specific investment, FOM and VOM costs for 2010 are based on the so called Sigma plant of the CHOREN Company (HMULV, 2006). It is expected that the capacity would be higher in the future. However, the capacity of the sigma plant is already very large with about 1 million ton biomass requirement per year. Therefore, the capacity is assumed to increase about 50% to the maximum level of 13 PJ/a in 2030. Furthermore, the efficiency is expected to reach 50% with an assumed efficiency increase of 2 percent points.

The specific investment costs are expected to reduce due to capacity increase (12%) and technology learning (2%). The resulting specific investment costs are 36.27 $EUR_{2000}/(GJ_{output}/a)$. The FOM and VOM costs are calculated accordingly.

3.7.2 Coal to liquid (CTL) production

CTL production includes gasification of the solid raw material and FT synthesis as in the BTL process. The techno-economic parameters of CTL are presented in Table 41. The overall efficiency of the process is taken as 50% for 2005 and 52% for 2030 which is slightly higher than the BTL process (Concawe, 2009). Similar specific investment cost reductions (in percentage) are obtained for CTL and BTL plants due to similar efficiency improvements and capacity increases. FOM costs are calculated correspondingly.

Table 41: Present (2010) and projected (2030) techno-economic specifications of a coal to liquid (CTL) production plant

	Unit	2010	2030	Sources
Input		Coal		
Output		CTL		
Process		Gasification and FT synthesis		
Production capacity	PJ_{output}/a	64.3	95.0	Concawe, 2009; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.50	0.52	Concawe, 2009; own assumption
EFLH	h/a	8000		Concawe, 2009
Lifetime of the plant	a	30		DOE-NETL, 2007
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	48.09	41.50	Concawe, 2009; own calculation
FOM costs	EUR_{2000}/GJ_{output}	2.16	1.86	Concawe, 2009; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.00		Concawe, 2009
Direct GHG emissions	kg CO_{2eq}/GJ_{input}	60.65	59.24	Own calculation

One of the hash critiques of the CTL process is the excessive amount of GHG emissions of the whole pathway. The direct GHG emissions, excluding coal extraction, amount to ca. 60 kg CO_{2eq}/GJ_{input} which in turn makes this pathway emit even higher emissions than the conventional fuels.

3.7.3 Gas to liquid (GTL) production

Another synthetic fossil fuel is the GTL. The initial motivation to consider GTL was the oil crisis in the early 1970s. The technology matured in 1983 to build the first pilot plant. The first commercial GTL plant followed 10 years later by the Shell Company (Shell, 2009b).

In the GTL process, natural gas (methane) is reformed to synthesis gas so that the H_2/CO ratio is suitable for a Fischer-Tropsch synthesis.

GTL pathway is simpler than CTL pathway, as the resource is already in gaseous form. This is the reason of relatively lower specific investment costs and higher efficiencies of GTL compared to CTL and BTL (Table 42). The investment costs of GTL plant are estimated by Boerrigter (2006) based on 3 ongoing GTL projects. With this data the cost reduction potential is estimated for the future. The efficiency is taken as 63% for 2005 (Concawe, 2009) and it is expected that there will be a 2 percent point efficiency improvement until 2030.

Table 42: Present (2010) and projected (2030) techno-economic specifications of a gas to liquid (GTL) production plant

	Unit	2010	2030	Sources
Input		Natural gas		
Output		GTL		
Process		Reforming and FT synthesis		
Production capacity	PJ_{output}/a	71.6	100.0	Boerrigter, 2006; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.63	0.65	Concawe, 2009; own assumption
EFLH	h/a	8000		Same as CTL
Lifetime of the plant	a	25		EIA, 2006
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	11.91	10.55	Boerrigter, 2006; own assumption
FOM costs	EUR_{2000}/GJ_{output}	0.61	0.54	EIA, 2006; own assumption
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.00		Own assumption
Direct GHG emissions	kg CO_{2eq}/GJ_{input}	10.46	9.05	Own calculation

3.7.4 Synthetic diesel utilization in compression ignition engines

Synthetic diesel (BTL, CTL and GTL) is a high quality liquid diesel-like fuel, which can be utilized at any share in conventional diesel engines without any modification. The cetane number that indicates the quality of diesel fuel is more than 70 by synthetic diesel whereas conventional diesel fuel has 50 (FNR, 2005). The characteristics of synthetic diesel fuel compared to conventional diesel fuel are presented in Table 43. As the synthetic diesel is expected to be blended to the conventional diesel, it is assumed that the fuel consumption will not change. CO_2 emissions are not shown in Table 43 since they are thought to be biogenic for BTL and not relevant for the emission balance. For CTL and GTL, the CO_2 emissions are 70.7 g CO_2/MJ (GM, 2002).

Table 43: Fuel consumption and greenhouse gas emissions (CH_4, N_2O) from the use of synthetic diesel in internal combustion engines compared to the conventional diesel technologies

		Synthetic diesel	
Passenger car	Fuel consumption [a]	1.0	Concawe, 2009
	CH_4 [b]	0.23	Andorf, 2008
	N_2O	1.0	IFEU, 2006
Bus	Fuel consumption	1.0	Own assumption [c]
	CH_4	0.23	Own assumption [c]
	N_2O	1.0	Own assumption [c]
Truck (HDV)	Fuel consumption	1.0	Own assumption [c]
	CH_4	0.23	Own assumption [c]
	N_2O	1.0	Own assumption [c]
Truck (LDV)	Fuel consumption	1.0	Own assumption [c]
	CH_4	0.23	Own assumption [c]
	N_2O	1.0	Own assumption [c]

a) All fuel consumption factors present the ratio of fuel consumption (in MJ/km) of alternative technology to the conventional technology.
b) All emission factors present the ratio of direct emissions (in g/km) of alternative technology to the conventional technology.
c) Assumed to be the same as passenger car

3.8 Hydrogen

Hydrogen can be obtained from various pathways. Natural gas provided 48% of the hydrogen demand worldwide in 2003. 30% of the hydrogen was obtained from refinery by-products, 18% from coal and 4% from electricity via electrolysis (OECD/IEA, 2005). Gasification for hydrogen production can use different feedstocks such as renewable sources like biomass (chapter 3.8.1) or fossil sources like coal or natural gas (chapter 3.8.2). Electrolysis process is presented in chapter 3.8.3. Lastly the utilization of hydrogen in the transport sector is presented in chapter 3.8.4.

3.8.1 Hydrogen from biomass gasification

Hydrogen from biomass might be obtained through various biological and thermo-chemical pathways. As biological pathways are slower and much more costly, this study only investigated thermo-chemical pathways. Furthermore, the focus in this study among thermo-chemical pathways is on the gasification process rather than pyrolysis, since this receives the most focus in current research (OECD/IEA, 2005).

The resources (straw, miscanthus, residual wood and SRC) and gasification process (FICFB) for biomass to hydrogen are similar to the gasification and SNG production pathway (chapter

3.6.3). The difference lies mainly in the upgrading. In biomass to hydrogen, a CO-shift reaction is utilized so that the CO gas can be converted to hydrogen and carbon dioxide with the help of water vapor. Furthermore, hydrogen is separated from the rest via a PSA process (Specht et al., 2003). The techno-economic parameters for biomass gasification and reforming are presented in Table 44.

Table 44: Present (2005) and projected (2030) techno-economic specifications of a biomass gasification plant with reforming to hydrogen

	Unit	2005	2030	Sources
Input		Cellulosic biomass		
Output		Hydrogen		
Process		Gasification and reforming		
Production capacity	PJ_{output}/a	3.3	6.0	Concawe, 2009; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.45	0.55	Gül, 2008
EFLH	h/a	7884		Gül, 2008
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	12.01	9.00	Gül, 2008; own calculation
FOM costs	EUR_{2000}/GJ_{output}	1.08	0.81	Gül, 2008; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	1.18	1.07	Gül, 2008; own calculation
Auxiliary energy requirement	Electricity $GJ_{electricity}/GJ_{output}$	0.047	0.028	Gül, 2008; own calculation
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	0.00		Own assumption

The production capacity in 2005 is taken as 3.3 PJ/a production (Concawe, 2009) and expected to grow in 2030 to 6.0 PJ/a. The efficiency of the biomass to hydrogen plant is also expected to increase from 0.45 in 2005 to 0.55 in 2030 (Gül, 2008).

The economic parameters like specific investment, FOM and VOM costs for the year 2005 are taken as 12.01 $EUR_{2000}/(GJ_{output}/a)$, 1.08 EUR_{2000}/GJ_{output} and 1.18 EUR_{2000}/GJ_{output} respectively (Gül, 2008). The capacity and the efficiency increases are expected to affect the economic parameters of the plant in the future. As a result, cost parameters are expected to reduce between 10 and 25% in the future.

There are CO_2 emissions from the biomass gasification and reforming plant as the input raw material has carbon content. However, these emissions are considered biogenic and, therefore, not relevant for the emission balance.

3.8.2 Hydrogen from coal and natural gas

As with synthetic fuels, this process also includes a synthesis gas production. The difference is that the synthesis gas is converted to hydrogen and carbon dioxide and separated from each other as in the hydrogen production from biomass (chapter 3.8.1). The techno-economic characteristics of hydrogen production from coal and natural gas are shown in Table 45 and Table 46 respectively.

Table 45: Present (2005) and projected (2030) techno-economic specifications of a hydrogen production plant using coal

	Unit	2005	2030	Sources
Input		Coal		
Output		Hydrogen		
Process		Gasification and reforming		
Production capacity	PJ_{output}/a	5.8	10.5	Concawe, 2009; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.53	0.59	Gül, 2008; own calculation
EFLH	h/a	7884		Gül, 2008
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	19.17	14.89	Gül, 2008; own calculation
FOM costs	EUR_{2000}/GJ_{output}	1.33	1.03	Gül, 2008; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.20	0.19	Gül, 2008; own calculation
Additional output	$GJ_{electricity}/GJ_{output}$	0.09		Gül, 2008
Direct GHG emissions	$kg\ CO_{2eq}/GJ_{output}$	181.1	162.2	Own calculation

The investment costs are significantly lower in hydrogen production from natural gas compared to hydrogen from coal. This feature is similar to the synthetic fuel production and explained with the fact that natural gas requires only reforming to convert to synthesis gas whereas coal should first be gasified. This effect is also reflected in the efficiencies. The process to convert natural gas to hydrogen has considerably higher efficiencies than coal to hydrogen.

The future costs are calculated with two effects (capacity increase and technology learning). The resulting cost reduction percentages are similar for both of the technologies, although it is slightly more for the hydrogen production from coal. This difference is due to less commercial experience of industry for hydrogen production from coal compared to production from natural gas.

The direct GHG emissions from hydrogen production from fossil fuels (especially for hydrogen from coal) are significantly high. The switch from conventional powertrain to hydrogen powered car will increase the total GHG emissions if the hydrogen is produced from coal. On the other hand, hydrogen from natural gas would reduce the overall GHG emission balance although the largest emission reductions are possible with biomass gasification and reforming to hydrogen (see chapter 3.8.1). The direct GHG emissions are expected to lower in the future for hydrogen production from fossil fuels due to the increase in the plant efficiencies. Therefore, the reductions in the direct GHG emissions are directly coupled to the increase of efficiency.

Table 46: Present (2005) and projected (2030) techno-economic specifications of a hydrogen production plant using natural gas

	Unit	2005	2030	Sources
Input		Natural gas		
Output		Hydrogen		
Process		Refining and steam reforming		
Production capacity	PJ_{output}/a	5.8	10.5	Gül, 2008; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.74	0.78	Gül, 2008; own calculation
EFLH	h/a	7884		Gül, 2008
Lifetime of the plant	a	20		Pehnt, 2002
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	5.91	4.69	Gül, 2008; own calculation
FOM costs	EUR_{2000}/GJ_{output}	0.30	0.28	Gül, 2008; own calculation
VOM cost w/o feedstock, auxiliary energy and revenues	EUR_{2000}/GJ_{output}	0.22	0.21	Gül, 2008; own calculation
Additional output	$GJ_{electricity}/GJ_{output}$	0.02		Gül, 2008
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	74.3	71.0	Own calculation

3.8.3 Hydrogen from electrolysis

Electrolysis is the process where water is split into hydrogen and oxygen using electricity. This process enables hydrogen production from any primary energy source which can be utilized for electricity generation (OECD/IEA, 2005; Gül, 2008). One of the ideas to use electrolysis is to couple it with the renewable energy sources that have fluctuating character (such as wind energy) so that the hydrogen production can act as “storage” for the electricity generation (Gutiérrez-Martín et al., 2010).

There are two options for electrolysis: polymer electrolyte membrane (PEM) and alkaline electrolysis (OECD/IEA, 2005). PEM is basically a reverse fuel cell process (see chapter 2.7) and is still in the research and development phase (OECD/IEA, 2005; Gül, 2008). Therefore, PEM is not considered further in this study. Alkaline electrolysis is a well-known process and its techno-economic parameters for central production are presented in Table 47.

Table 47: Present (2005) and projected (2010) techno-economic specifications of a water electrolysis plant

	Unit	2005	2030	Sources
Input		Electricity		
Output		Hydrogen		
Process		Electrolysis (alkaline)		
Production capacity	PJ_{output}/a	3.3	6.0	Concawe, 2009; own assumption
Efficiency (LHV)	GJ_{output}/GJ_{input}	0.63	0.75	Gül, 2008; own assumption
EFLH	h/a	7885		Gül, 2008
Lifetime of the plant	a	20		Own assumption
Specific investment cost	$EUR_{2000}/(GJ_{output}/a)$	24.35	17.89	Gül, 2008; own calculation
FOM costs	EUR_{2000}/GJ_{output}	1.61	1.18	Gül, 2008; own calculation
VOM cost w/o feedstock	EUR_{2000}/GJ_{output}	0.18	0.16	Gül, 2008; own calculation
Direct GHG emissions	kg CO_{2eq}/GJ_{output}	0.00		

The production capacity of the electrolysis plant is taken as 3.3 PJ/a (Concawe, 2009) and assumed to increase to 6.0 PJ/a similar to the biomass gasification and reforming plant. The increase of the production capacity lowers the investment costs. The future cost reductions are derived from the production capacity and technology learning, similar to the other technologies. The resulting investment costs in 2030 are about 25% lower than the current costs. This cost reduction share is rather conservative compared to the assumptions of Gül, which is about 60% (Gül, 2008).

However, as the main cost component of the electrolysis is the electricity costs, the efficiency increases are more important than the investment costs. The theoretical maximum efficiency is given as about 0.85 (IEA, 2005). The current efficiency is taken as 0.63 (Gül, 2008). It is assumed that the future efficiency will be 0.75, which is almost the average of the current and theoretical maximum efficiency.

As the electrolysis process only requires electricity, there are no direct GHG emissions. However, depending on the electricity generation technology the total GHG emissions in the whole pathway might be significant.

3.8.4 Hydrogen in spark ignition engines

The produced hydrogen can be utilized in two different powertrains (spark ignition or fuel cell engine). Utilization of hydrogen in fuel cells is explained in chapter 2.7. The characteristics of hydrogen in spark ignition engines are presented in Table 48.

Table 48: Fuel consumption and greenhouse gas emissions from the use of hydrogen in internal combustion engines compared to the conventional technologies

		Hydrogen ICE	
	Fuel consumption [a]	0.882	Concawe, 2009
Passenger car	CO_2	0.0	Krüger, 2002
(SI engine)	CH_4 [b]	0.0	Krüger, 2002
	N_2O	0.5	Krüger, 2002
	Fuel consumption	1.5	Krüger, 2002
Bus	CO_2	0.0	Krüger, 2002
(CI engine)	CH_4	0.0	Krüger, 2002
	N_2O	0.1	Krüger, 2002

a) All fuel consumption factors show the ratio of fuel consumption (in MJ/km) of alternative technology to the conventional technology.
b) All emission factors show the ratio of direct emissions (in g/km) of alternative technology to the conventional technology.

It is shown in this table that the energy consumption of hydrogen powered passenger car with internal combustion engine is less (about 12%) than the conventional vehicle (spark ignition engine). On the other hand, the energy consumption of hydrogen powered bus with internal combustion engine is higher (about 50%) than the conventional vehicle (compression ignition engine). This difference is due to the fact that the passenger car and buses have different reference technologies (the spark ignition engine and the compression ignition engine).

3.9 Future development of fuel production plants in terms of investment costs and production capacities

The comparison of results for production capacity and specific investment costs are presented in Figure 27. The comparison shows that most of the specific investment costs of the fuel production plants are expected to decrease and average production capacities are projected to increase until 2030 except for the vegetable oil, biodiesel and biogas plants, which are considered as *non-learning* technologies.

The specific investment costs of ethanol production from sugar and starch are expected to decrease about 20% merely due to the increase of production capacity between 2010 and 2030. The reduction of specific investment costs for ethanol production from cellulosic feedstock is expected to be higher (about 27%). This result is sound as the first commercial cellulosic ethanol production plant started operation in 2007 (Soloman et al., 2007) and this process has a higher potential to reduce specific investment costs in the future.

The highest reduction of specific investment cost till 2030 with 34% is seen with synthesis gas production and synthesis gas upgrading processes. This reduction is mainly due to the capacity increase but also due to technology learning.

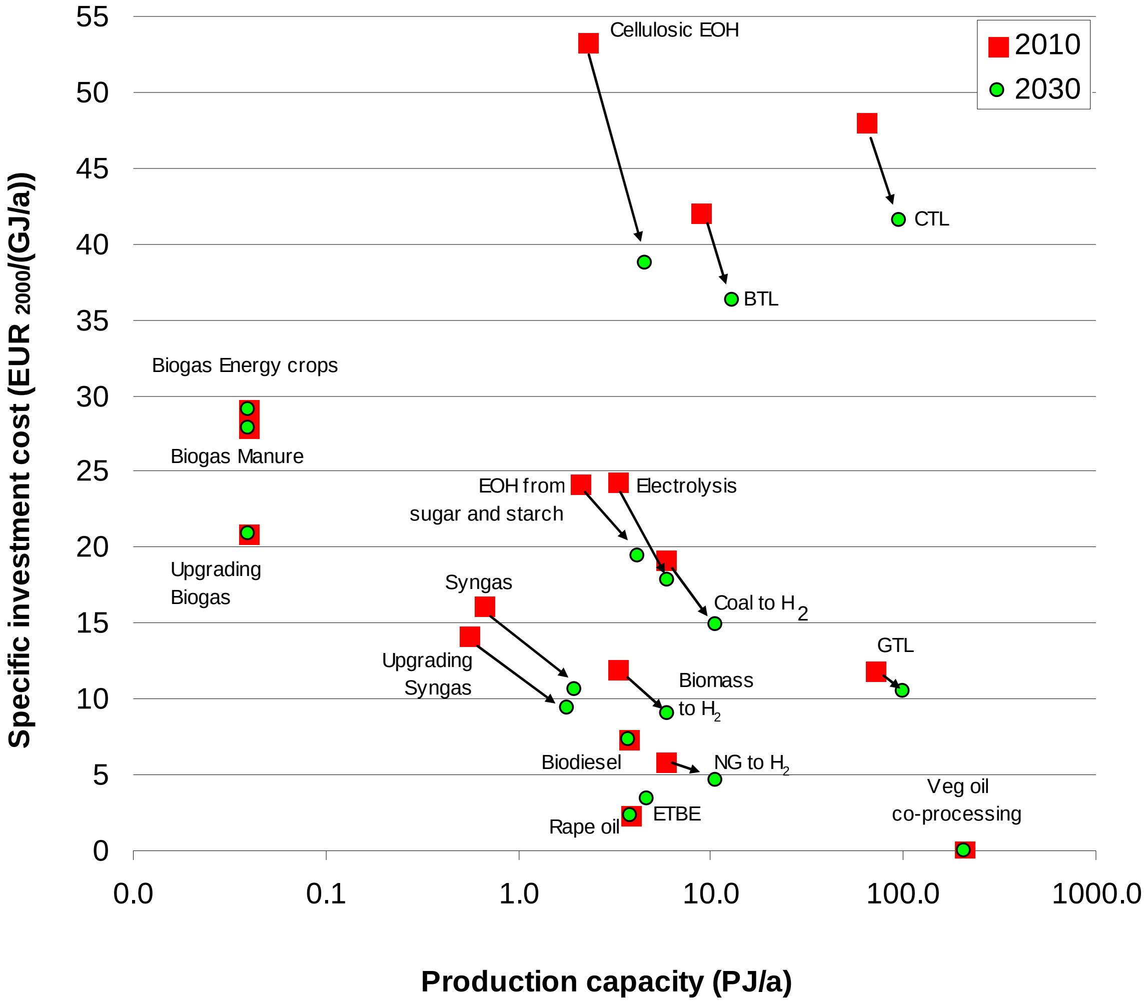


Figure 27: Development of average production capacity and specific investment costs for different fuel production plants from 2010 to 2030

The synthetic diesel production pathways via Fischer-Tropsch synthesis from biomass, coal or natural gas are expected to have similar reductions (between 11 and 14%) of specific investment costs in the future. These percentages are significantly lower than the reduction percentages of synthesis gas production and synthesis gas upgrading (about 34%). This difference, however, conforms to the fact that synthetic diesel production from coal and natural gas is already commercial worldwide. Furthermore, BTL production is expected to be commercial in the near future (CHOREN, 2009). Therefore, it is reasonable to foresee lower investment cost reduction percentages for the synthetic diesel production than synthesis gas production and synthesis gas upgrading.

The hydrogen production pathways display different reductions of specific investment costs for different processes. Hydrogen from natural gas is expected to have the lowest reduction among the hydrogen production pathways with about 21% until 2030. This low reduction compared to the other hydrogen production pathways makes sense since almost 50% of the current hydrogen production, which is mainly used in the industry not in the transport sector, is provided by natural gas (IEA, 2005). The specific investment costs of hydrogen production from coal, biomass and electrolysis are expected to decrease by about 22%, 25% and 27% respectively.

3.10 Distribution costs of fuels

The distribution costs of fuels consist of storage, land transport and filling station costs, assuming that the fuel is produced in Germany (Ekbom et al., 2003). Among these, storage and land transport, depend on volumetric energy density (IEA, 1999). With decreasing volumetric energy density, these costs will increase. The filling station costs depend on the physical state of the fuel (gas/liquid). The distribution costs are presented in Table 49.

Table 49: Costs and electricity consumption for the distribution of fuels including fuel stations

Fuel	Distribution costs without cost of electricity consumption for compression (EUR_{2000}/GJ_{fuel})	Electricity consumption for compression (GJ_{elec}/GJ_{fuel})	Source
Gasoline	1.00	-	Ekbom et al., 2003
Diesel	0.91	-	Own calculation [a]
BTL/CTL/GTL	0.97	-	Own calculation [a]
Biodiesel	1.00	-	Own calculation [a]
Hydrated vegetable oil	1.00	-	Own calculation [b]
Ethanol for blending	1.36	-	Own calculation [a]
ETBE	1.21	-	Own calculation [a]
SNG/CNG [c]	4.63	0.03	Krüger, 2002; Kavalov, 2004; Pölz et al., 2005
Hydrogen (truck) [d]	42.14	0.10	Gül, 2008
Hydrogen (pipeline) [e]	9.67	0.08	Gül, 2008
Electricity [f]	0.00	-	Own assumption

a) Calculations based on volumetric energy density
b) Taken to be the same as biodiesel
c) The high pressure pipeline (0.31 EUR_{2000}/GJ) and distribution costs (0.18 EUR_{2000}/GJ) are taken from Krüger (2002). The fueling station costs are 5 to 10 times higher than gasoline stations (Kavalov, 2004). Thus, SNG/CNG fueling station costs (4.13 EUR_{2000}/GJ) are taken 7 times higher than gasoline stations (0.59 EUR_{2000}/GJ). The electricity consumption for compressing the gas is estimated as 0.03 GJ_{elec}/GJ_{fuel} (Pölz et al., 2005).
d) It is assumed, conservatively, that hydrogen delivery could only be realized with a gaseous truck and small fueling station until 2020.
e) It is assumed that the hydrogen pipeline and large fuel station is only available after the year 2020.
f) Electricity is assumed to be filled at the household (or at the work) without any additional distribution costs.

The distribution and filling station costs for gaseous fuels are significantly higher than for liquid fuels. The delivery of SNG/CNG requires a gas pipeline and the gas will be pressurized to 200 bar at the filling station. As in this study only centrally produced hydrogen pathways are considered, there is a need to transport and distribute the hydrogen. Gül (2008) states that the delivery infrastructure is a significant cost factor as it at least doubles the hydrogen production costs. There are several possibilities to distribute the hydrogen (Gül, 2008). The physical state of hydrogen (gas or liquid), mean of transport (via truck or pipeline) and the size of the filling station should be decided. Although gaseous hydrogen transport via pipeline and large filling station result in the lowest delivery costs of 9.86 US$_{2000}$/GJ, it requires a significant amount of hydrogen in the energy system (Gül, 2008). These delivery costs might be as high as 45 US$_{2000}$/GJ depending on the infrastructure type (Gül, 2008). In this study, it is assumed that gaseous hydrogen will be distributed via trucks until 2020. The pipeline option is only considered to be available after 2020.

3.11 Summary of alternative fuels in the German transport sector

This chapter describes the characteristics of relevant fuels for the German transport sector. The fundamental principles of alternative fuel production pathways are briefly mentioned and the fuel production plants are investigated in terms of their average production capacity, economic characteristics, auxiliary energy requirement and direct GHG emissions. Furthermore, the investigated aspects are projected until the year 2030 with corresponding assumptions.

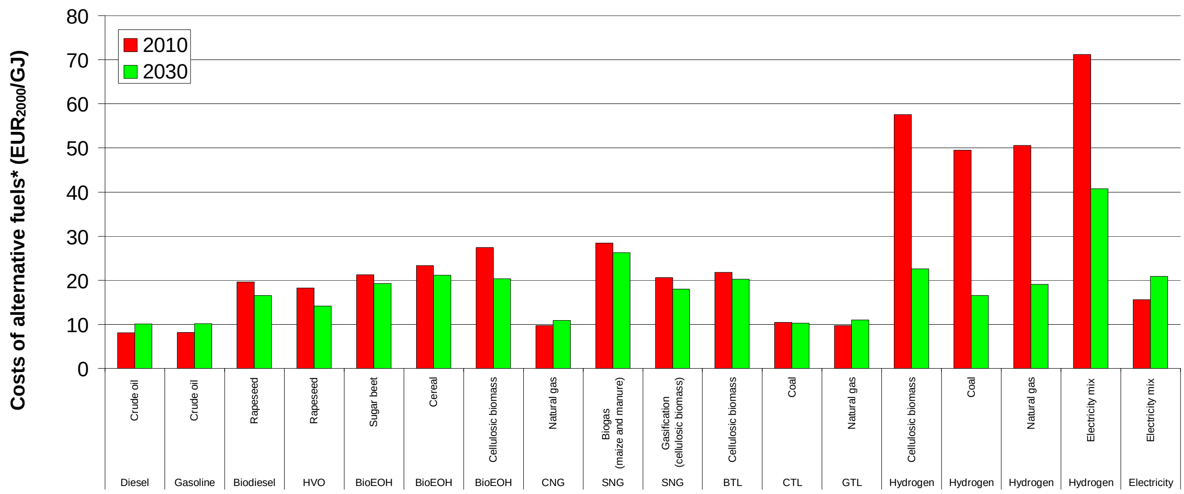
The well to tank (WTT) costs of alternative fuels (which include feedstock, production and distribution costs including fuel station) are presented in Figure 28. The results in this figure are supposed to give an overview of the costs of alternative fuels. The assumed feedstock costs for this calculation are presented in Table 50, which might differ from the endogenously calculated feedstock costs in the model (cf. chapter 5.1). Therefore, the costs presented in Figure 28 should be considered as indicative rather than definite. The results include revenues from by-products (e.g. oil cake for rapeseed oil production, additional electricity output for hydrogen production from coal).

The comparison of costs of alternative fuels shows that the costs of conventional and non-conventional fuels are expected to increase and decrease in the future respectively. Although costs of CTL (and partly GTL) are very close to the conventional fuels in 2030, crude oil products (diesel and gasoline) have lowest costs both in 2010 (about 8 EUR$_{2000}$/GJ) and 2030 (about 10 EUR$_{2000}$/GJ). However, CTL might be competitive against crude oil products for elevated fossil fuel prices.

Biofuels have costs between 18 and 28 EUR$_{2000}$/GJ in 2010 and these costs are expected to decrease about 3 EUR$_{2000}$/GJ on average between 2010 and 2030.

Resulting costs of biodiesel from rapeseed (about 20 EUR_{2000}/GJ in 2010 and about 17 EUR_{2000}/GJ in 2030) in this study are comparable with the results of Specht et al. (2003), which are between 17 and 20 EUR_{2000}/GJ, and FNR (2009b), which are between 20 and 21 EUR_{2000}/GJ.

FNR (2009b) argues that the cost of HVO with a stand-alone production system is similar to biodiesel cost. However, the investment costs of HVO for co-processing systems are significantly lower than stand-alone production (Oja, 2008). Furthermore, in this study only hydrated vegetable oils (HVO) with co-processing in refineries is considered as mentioned before (cf. chapter 3.4.2). Therefore, it makes sense that results of HVO costs are slightly (about 1.5 EUR_{2000}/GJ) lower than biodiesel costs.



*) These values do not necessarily reflect modeling results (in later sections) as especially feedstock costs (e.g. lingo-cellulosic biomass or electricity mix) are endogenously calculated within the model.
All calculations are based on a real interest rate of 4%.

Figure 28: Well to tank (feedstock, production and distribution including fuel station) costs of alternative fuels in 2010 and 2030

Bioethanol production costs in 2010 are about 21, 23 and 27 EUR_{2000}/GJ for feedstocks of sugar beet, wheat and lingo-cellulosic biomass respectively. These results are in line with Specht et al., (2003) and FNR (2009b). Specht et al., (2003) calculated bioethanol production costs as between 20 and 22 EUR_{2000}/GJ for feedstocks of sugar beet and wheat. Furthermore, FNR (2009b) mentions bioethanol production costs in 2007 as about 22, 23 and 26 EUR_{2000}/GJ for feedstocks of sugar beet, wheat and lingo-cellulosic biomass respectively.

Substitute natural gas (SNG) from biogas is assumed to be produced from 35% manure and 65% maize (fresh mass). SNG produced from these shares of fresh mass contains 5% manure biogas and 95% maize biogas in energy terms. Obviously, increasing the manure share will reduce the costs considerably. However, it is not expected that the share of manure in biogas production will increase in the future significantly due to the restrictions of its potential and transportability. The costs of SNG from biogas in 2010 are calculated as 28 EUR_{2000}/GJ, where the distribution costs including fuel station amounts to 5 EUR_{2000}/GJ. On the other hand, SNG fuel from gasification pathway has lower costs of about 21 EUR_{2000}/GJ depending on the assumed cellulosic biomass cost of 4.5 EUR_{2000}/GJ, which might change in the modeling results (see Figure 32).

Table 50: Assumed feedstock costs in 2010 and 2030 (EUR_{2000}/GJ)

Feedstock [a,b]	2010	2030
Crude oil	5.8	7.5
Natural gas	4.6	5.7
Coal	2.2	2.5
Rapeseed	9.8	8.1
Sugar beet	6.9	5.7
Wheat (whole plant)	11.1	9.2
Wheat (corn)	7.2	6.0
Cellulosic biomass	4.5	4.5
Maize	9.6	7.9
Manure	0.0	0.0
Electricity mix	15.0	20.0
Methanol	12.8	12.3

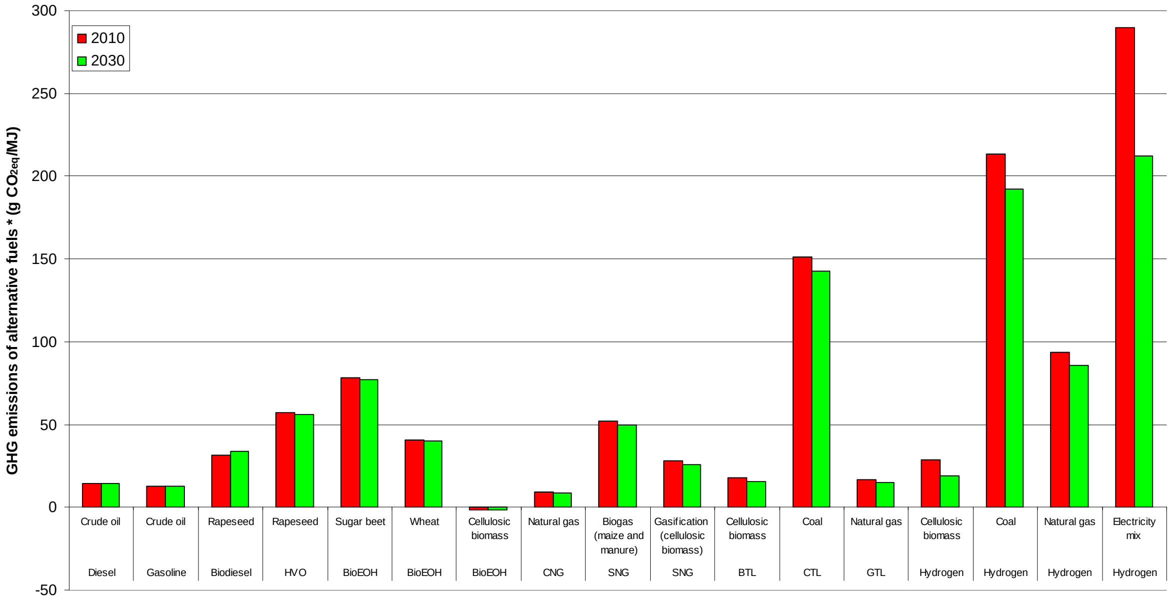
a) These costs are only used for Figure 28 and might differ in the modeling results.
b) The fossil fuel prices correspond to moderate price level (see Table 53). The crude oil price level in 2030 corresponds to $75\$_{2007}$/bbl.

The WTT costs of hydrogen are between 50 and 70 EUR_{2000}/GJ in 2010. The determining factor for the cost of hydrogen is the distribution costs including fuel station, which comprises up to 89% of the WTT costs in 2010. With the introduction of hydrogen pipeline after 2020 (see Table 49), the WTT costs of hydrogen reduce significantly to a range between 16 and 41 EUR_{2000}/GJ.

The well to tank (WTT) GHG emissions costs of alternative fuels (which include feedstock, production and distribution costs including fuel station) are presented in Figure 28.

The results in this figure are supposed to give an overview of the GHG emissions of alternative fuels. The GHG emissions of feedstocks for this calculation might differ from the endogenously calculated feedstock emissions in the model. Therefore, the GHG emissions presented in Figure 29 should be considered as indicative rather than definite. The results include carbon credits from by-products (e.g. oil cake for rapeseed oil production, additional electricity output for hydrogen production from coal).

The results imply that the conventional fuels have lower GHG emissions (about 13 g CO_{2eq}/MJ) than most of the alternative fuels. However, the tank to wheel (TTW) GHG emissions (i.e. onboard emissions) are not shown in this figure. Adding TTW emissions would change this figure considerably since carbon dioxide emissions from fossil fuels should be considered but these emissions from biofuels are disregarded. This is due to the characteristic of biofuels that the carbon content in the fuel does not increase the carbon dioxide amount in the atmosphere but just recycles them.



*) These values do not necessarily reflect modeling results (in later sections) as especially feedstock GHG emissions (e.g. lingo-cellulosic biomass or electricity mix) are endogenously calculated within the model.

Figure 29: Well to tank (feedstock, production and distribution including fuel station) GHG emissions of alternative fuels in 2010 and 2030

The biofuels (except for bioethanol from lingo-cellulosic feedstock) have well to tank GHG emissions between 18 and 79 g CO_{2eq}/MJ. Generally second generation biofuels (e.g. SNG from gasification and BTL) have lower GHG emissions than first generation biofuels (e.g. bioethanol from sugar beet and biodiesel from rapeseed) as repeatedly mentioned in the literature.

Bioethanol production from lingo-cellulosic feedstock has slightly negative emissions due to two reasons. The first reason is the autarkic production process where the required heat and electricity are supplied by biomass feedstock rather than by fossil fuels. The second reason is the additional electricity production regarded as a by-product. The carbon credits of substituting German electricity mix make the GHG emission balance of the whole pathway negative.

Alternative fuel production pathways that utilize coal as a feedstock have generally quite high (between 150 and 200 g CO_{2eq}/MJ) GHG emission balance. Furthermore, hydrogen producing pathways are generally having high GHG emission balance except for hydrogen from biomass. It should be noted that, the hydrogen might also be produced from low carbon intensive electricity (e.g. wind or nuclear) rather than electricity mix as shown in the figure.

The following section summarizes the **main findings** of chapter 3.

The reductions of specific investment costs in the future are determined with two effects. The first effect is the "*economics of scale*" or the increase of the average production capacity. It is assumed that the investment costs increase 60% when the capacity doubles (Henniges, 2007), which brings a reduction of 20% for the specific investment costs (cf. Table F 1 in the appendix). It is expected that the production capacities of almost all alternative fuel production pathways will be increased until 2030. Only the already commercial processes such as vegetable oil, biodiesel and biogas production and refineries are considered so that the average production capacity of these technologies will not increase in the future significantly.

The second effect is the "*technology learning*". The technology learning effect is coupled in this work to the efficiency increases. As the efficiency increases, the specific investment costs decreases proportionally. Similar to the production capacities, most of the fuel production plant efficiencies are expected to increase until 2030. Refineries and vegetable oil, biodiesel and biogas plants are considered as *non-learning* technologies due to their maturity level so that significant improvements are not likely to be expected. The highest plant efficiency increases are seen in the electrolysis, biomass to hydrogen and cellulosic bioethanol production process with an efficiency increase of 12, 10 and 10 percent points in the next 20 years respectively. Other efficiency increases are expected, amongst others, in synthesis gas production, synthesis gas upgrading and hydrogen production plants from coal and natural gas.

The comparison of the investment cost reduction among all fuel production pathways shows that the highest reductions of specific investment costs are seen with synthetic gas production and upgrading (34%), cellulosic ethanol (27%), electrolysis (27%), and hydrogen production from coal and biomass (between 25 and 23%). Reasonably, the results in this chapter show that the production processes with high maturity level have lower reduction percentages of specific investment costs until 2030.

The delivery costs for gaseous fuels are distinctly higher than for liquid fuels. The methane costs are about 4 times higher than the conventional fuels, whereas hydrogen delivery might be between 10 and even 40 times depending on the transportation pathway. These results are in line with the findings of Gül (2008) that the delivery costs may be a significant factor especially for gaseous fuels.

The comparison of costs of alternative fuels shows that the conventional fuels (diesel and gasoline) have lowest costs both in 2010 and 2030. These costs are followed by the costs of CTL, GTL and biofuels. The costs of hydrogen are quite high in 2010 due to the distribution costs, which are expected to decrease significantly until 2030.

The WTT GHG emissions from fuel production processes are significantly higher for coal pathways (hydrogen and synthetic diesel from coal) than for the conventional diesel and gasoline production. Therefore, switching to these technologies will make a negative effect on the overall GHG emission balance.

The comparison of fuel production pathways with production capacity, economic characteristics, auxiliary energy requirement and direct GHG emissions shows that the analysis is relatively complex. It is only possible to analyze the future role of different fuels in Germany with the information on powertrains (see chapter 2) and a system analysis approach (see chapter 4 and 5).

4 Modeling of the German transport system using a linear optimization model – TIMES

4.1 Energy models and their classification

There are several energy models with different methodologies and approaches which are utilized to answer diverse research questions. The differentiation between top-down and bottom-up approaches is one of the most significant classifications for these models (Remme, 2006).

Top-down models investigate the overall economic system and then disaggregate into smaller sectors. Game theory, econometric models and computational general equilibrium models are utilizing top-down approach (Kemfert, 2004). However, bottom-up models (energy system models) intend to describe each process (from primary energy to final energy) in the system from a technological point of view. Energy system models are regarded as partial equilibrium models as the scope of these models is restricted only to consider the equilibrium of a particular sector of the economy, such as the energy sector in this case. (Remme, 2006). The direct result of this restriction is the negligence of the interrelationships between the energy sector and the rest of the economy. Furthermore, the economic growth, energy carrier import prices and energy demand values need to be given to the model exogenously.

There are two main energy system model approaches: simulation and optimization. Whereas simulation models require a share of each utilized technology as exogenous factors, the optimization models can give the least-cost solution for the system under certain set of assumptions and restrictions. Additional restrictions might be, for example, about environmental effects or government regulations.

Among different existing models, the linear optimization (bottom-up) energy system model TIMES (The Integrated MARKAL EFOM System) is selected. This model is utilizing the advantages of two different model families: MARKAL (MARKet ALlocation) and EFOM (Energy Flow Optimization Model). In the TIMES model, the costs of the energy system are minimized with the help of a linear equation system (Remme, 2006).

$$\min \sum_{j=1}^{n} c_j x_j \qquad \textbf{(6)}$$

where,

x_j is the variable for energy flows

j is the index for variable x between 1 and n,

c_j is the costs (e.g. investment, operating and maintenance) of variable x_j

Additional equations are required to characterize the relationship between input and output flows and to define the additional restrictions such as GHG reduction targets (Remme, 2006).

$$\sum_{j=1}^{n} a_{ij} x_j \geq b_i \tag{7}$$

where

a_{ij} is the coefficient of variable x_j in the equation i

b_i is the right hand side of the equation i

i is the index for equations between 1 and m,

The TIMES model has the implicit assumptions of perfect competition and perfect foresight. The perfect competition refers to an ideal liberal capitalist market, where market power cannot be exercised by any stakeholder. The perfect foresight assumption is related to the theoretical condition that the market stakeholders are able to perfectly predict the future energy demand and characteristics of technologies (e.g. costs, efficiencies etc.) and energy carrier prices.

The spatial and temporal resolution of the TIMES models can be chosen according to the requirements. The TIMES is a poly-point model, where each region is represented as points. Interactions (e.g. trade) between different regions (points) and between modeled region and external regions are allowed. The TIMES model can handle any desired number of time segments, whereby increased temporal resolution means increased computational time. Generally typical days of year (e.g. summer-weekday-day, winter-Sunday-night) are identified and modeled.

To sum up, the TIMES model is found to be a suitable tool to answer the research questions mentioned in the chapter 1.4. It allows modeling promising fuel and powertrain options of the transport sector for today and for the future. Furthermore, the model is an appropriate tool to answer the question of which of these promising alternatives would be economically feasible under which set of assumptions regarding political framework and various environmental restrictions.

4.2 Structure of TIMES-D model

The TIMES model family has been developed within the Energy Technology Systems Analysis Program (ETSAP) of IEA since 1999. Among others, the TIMES-D model is developed for the energy sector of Germany on a highly detailed level (Remme, 2006). The analysis is done for the years between 1995 and 2050 in 12 time periods with 5 years interval each. Each year is divided into 2 seasons (winter & summer) and 2 time of the day (day & night) for heating and electricity sectors. The transport sector is modeled yearly.

The pre-existing TIMES-D model has very detailed technological description especially for the conventional technologies in the sectors of heating systems, electricity generation and refineries.

The updated reference energy system of the TIMES model is shown in Figure 30. The pre-existing TIMES-D model from Remme (2006) is extended, updated and improved in this work by the following points:

- Energy conversion technologies (among others biogas, gasification, gas upgrading/reforming, ethanol, ETBE, hydrated vegetable oil and synthetic fuels) and bioenergy resources (among others sugar beet, manure, algae oil, maize, wheat, grass and firewood) are included into the analysis.
- Other existing fuel conversion technologies are updated entirely for their efficiencies, emissions and costs.
- The fuel utilization in the transport sector has been reviewed thoroughly for their efficiencies, emissions and costs. New powertrain technologies (mild, full and plug-in hybrid) and sections (road freight is separated as light and heavy duty vehicles) are added.
- Fuel blending options are added into the model for the following fuels with corresponding maximum blending restrictions:
    - Ethanol and ETBE for gasoline spark ignition engines
    - Biodiesel, hydrated vegetable oil, BTL, CTL and GTL for compression ignition engines
    - SNG for natural gas spark ignition engines
- Transport demand (as person kilometer and ton kilometer) is updated.
- All energy crops (rapeseed, sugar beet, wheat, maize, miscanthus, grass and short rotation coppice) are associated with land area requirement. The land area requirement for bioenergy in Germany is restricted at 4.3 million hectares in 2030 (Nitsch et al., 2004) rather than restricting the amount of yearly produced bioenergy.
- The potential for residual biomass (residual wood, straw etc.) are updated (König, 2009).

- The analysis is restricted to the years between 2010 and 2030. Previous years (1995-2005) are utilized as calibration purposes.

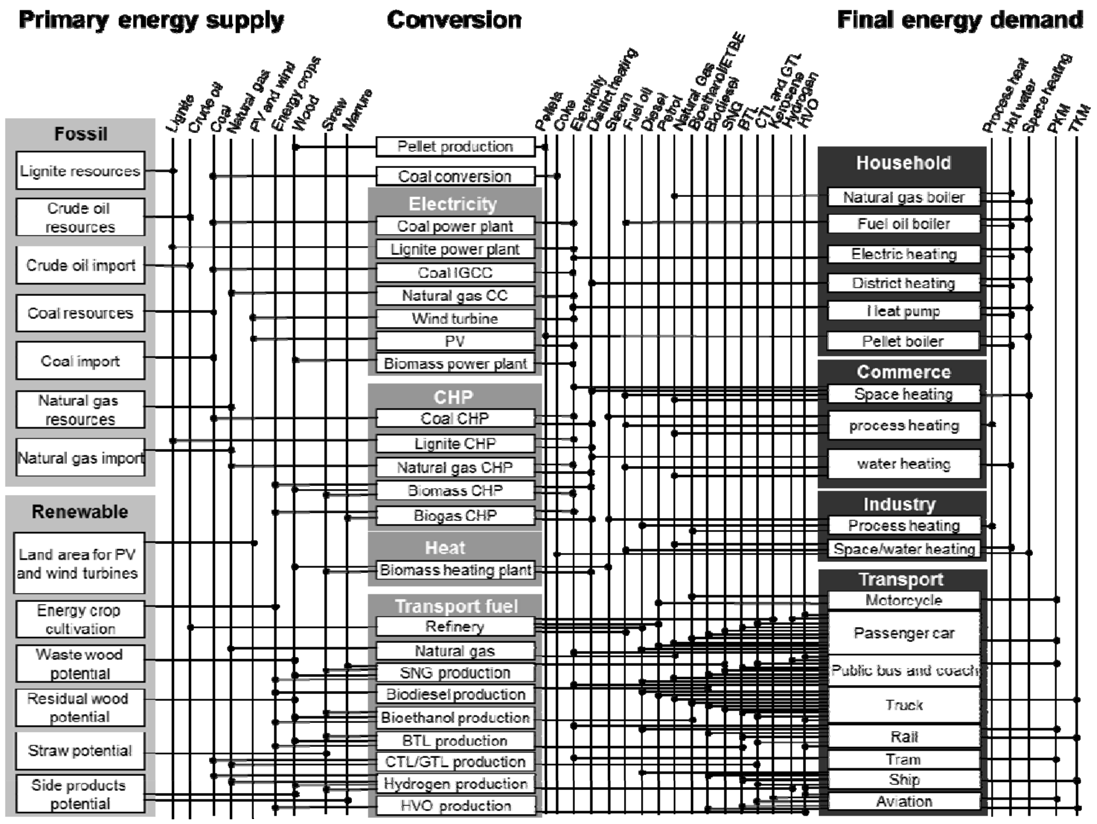


Figure 30: Simplified scheme of the updated reference energy system of TIMES model (updated from König, 2009)

To sum up, the extensions, updates and improvements in this work are mainly in the transport sector (specifically in the road transport) and related processes for this sector. Almost all of the energy supply and utilization pathways in the transport sector are improved and updated. Furthermore, the model is extended with new fuels and powertrain options and with the land area requirement association of energy crops. Investigated powertrain and fuel combinations in the TIMES model are presented in Table 51.

The new TIMES-D model is utilized to show the effect of different assumptions on the energy system and particularly on the transport sector with the help of scenario analysis method. Therefore, several scenarios are developed with different assumptions for political, economic, environmental and technical conditions to see their effect on the linear cost optimization model (see chapter 5).

Table 51: Investigated powertrain and fuel combinations in the TIMES model

Transport mode	Powertrain	Fuel
Motorcycle	SI gasoline mix	Gasoline, bioethanol, ETBE
Passenger car	SI gasoline mix	Gasoline, bioethanol, ETBE
	SI hybrid mild	Gasoline, bioethanol, ETBE
	SI hybrid full	Gasoline, bioethanol, ETBE
	SI PHEV	Gasoline, bioethanol, ETBE, electricity
	SI gas engine	CNG/SNG
	SI gas engine	Hydrogen
	FCEV	Hydrogen
	FCHEV	Hydrogen
	EM	Electricity
	CI diesel mix	Diesel, biodiesel, BTL, CTL, GTL, HVO
	CI biodiesel	Biodiesel
	CI hybrid full	Diesel, biodiesel, BTL, CTL, GTL, HVO
Public bus and coach	CI diesel mix	Diesel, biodiesel, BTL, CTL, GTL, HVO
	CI biodiesel	Biodiesel
	CI hybrid full	Diesel, biodiesel, BTL, CTL, GTL, HVO
	SI gas engine	CNG/SNG
	SI gas engine	Hydrogen
	CI PHEV	Diesel, biodiesel, BTL, CTL, GTL, HVO, electricity
	EM	Electricity
	FCHEV	Hydrogen
Truck	CI diesel mix	Diesel, biodiesel, BTL, CTL, GTL, HVO
	CI biodiesel	Biodiesel
	CI hybrid full	Diesel, biodiesel, BTL, CTL, GTL, HVO
	SI gas engine	CNG/SNG
	SI gasoline mix (*)	Gasoline, bioethanol, ETBE
Rail	EM	Electricity
	CI diesel mix	Diesel, biodiesel, BTL, CTL, GTL, HVO
	CI biodiesel	Biodiesel
Tram	EM	Electricity
Ship	CI diesel mix	Diesel, biodiesel, BTL, CTL, GTL, HVO
	CI biodiesel	Biodiesel
Aviation	Gas turbine	Kerosene, biodiesel, BTL, CTL, GTL, HVO

*) SI engines are only available for light duty trucks.

5 Scenario analysis

The scenario analysis method is employed in this study in order to assess the effect of different technological, economic, environmental and political conditions on the overall system. The developed scenarios are summarized in Table 52.

Table 52: Overview of the key parameters in the analyzed scenarios

Scenarios		Blending quota	GHG emission restrictions	Technology cost variations	Fossil fuel prices		
					moderate	high	very high
Base		X	Max as in 2007		X		
FM	FMM		No restriction		X		
	FMH					X	
	FMV						X
GHG			Self-commitment [a]		X		X
TCR			Self-commitment [a]	X	X		X

a) Self-commitment of the German government

- Base scenario:

The base scenario (chapter 5.2) aims to present the future possible developments in the German transport sector under the current policy and market framework, with the assumptions mentioned in chapter 5.2.1. The results of this scenario analysis are presented in chapter 5.2.2.

- [FM] Free market scenarios:

The free market scenarios (chapter 5.3) aim to present the future possible developments in the German transport sector without any government regulation. The fossil fuel price level is varied in these scenarios for moderate [FMM], high [FMH] and very high [FMV] price levels to see its effect on the German transport sector under the free market conditions. The specific assumptions and results of the free market scenarios are presented in chapter 5.3.1 and 5.3.2 respectively.

- [GHG] Greenhouse gas emission restriction scenario

The greenhouse gas emission restriction scenario aims to present the future possible developments in the German transport sector under GHG reduction targets. Moreover, the fossil fuel price level is elevated in this scenario to see its effect on the results. The specific assumptions for the GHG scenario are presented in chapter 5.4.1. The results are shown in chapter 5.4.2.

- [TCR] Technology based cost reduction scenario:

The technology based cost reduction scenario aims to present the effect of investment costs of alternative fuel production and alternative powertrain technologies on the German transport sector with GHG reduction targets. Batteries, fuel cell engines and gasifier/steam reformers are selected as critical components for the transport sector and their investment costs are varied. The specific assumptions for the TCR scenario are presented in chapter 5.5.1. The results are shown in chapters 5.5.2, 5.5.3 and 5.5.4.

5.1 Key modeling assumptions for all scenarios

Overall framework assumptions that are applied to all of the above mentioned scenarios are grouped under four headings as general socio-economic (chapter 5.1.1), transport sector related (chapter 5.1.2), biomass related (chapter 5.1.3) and other technology specific (chapter 5.1.4) assumptions.

5.1.1 General socio-economic assumptions

The general socio-economic assumptions that are valid for all scenarios are:

- The population in Germany will drop from 82.2 million in 2005 to 77.9 million in 2030 (Enquete, 2002 in Remme, 2006).
- The gross domestic product (GDP) development continues with an average increase of 1.3%/a (Remme, 2006).
- The real interest rate is assumed to be constant for the whole modeling period at 4%/a.
- It is not attempted in this study to model the daily market volatility of energy carrier prices. The real energy carrier import prices for the time period 2010 to 2030 are based on IER et al., (2009). The moderate energy carrier price level is taken as basis (Table 53) for all scenarios except for the FM and GHG scenario, where the energy carrier prices are varied. The moderate crude oil price in 2030 is assumed to be 52 EUR_{2007}/bbl which corresponds to 75$\$_{2007}$/bbl.

Table 53: Average "moderate" import prices for energy carriers in Germany (IER et al., 2009)

Energy carrier	Unit	2007	2010*	2020*	2030*
Crude oil	EUR_{2007}/bbl	52	40	48	52
Natural gas	EUR_{2007}/MWh	22	17	19	21
Hard coal for power plant	EUR_{2007}/t	68	60	70	72

*) estimated by IER et al., (2009)

5.1.2 Assumptions for the transport sector

The transport sector related assumptions that are valid for all scenarios are:

- The transport demand raises considerably both for passenger and freight transport (Table 54). The main increase in transport demand is expected to take place in the road transport sector.

  The aviation sector is divided into domestic and international aviation. According to the UNFCCC (2010) the international flight emissions are not included in the Kyoto protocol. However, the supply of kerosene for international flights must be provided by the German industry. Thus, the energy consumption will be calculated for the "outgoing" aircrafts, which consists of all flights that take off from German airports. However, for the emissions, only those are considered that results from domestic aviation. The share of domestic flight energy consumption in aviation is presented in Table 55. It is assumed that the share of domestic flights will stay constant between 2007 and 2030.

Table 54: Present (2005) and projected (2030) transport demand in Germany (ITP et al., 2007; DIW, 2011; IFEU, 2005; Canali, 2009)

Transport demand	Unit	2005	2030	Percentage increase between 2005 and 2030
Passenger transport	10^9 pkm	1200.9	1574.8	31
thereof road		947.1	1108.6	17
thereof rail		91.4	102.8	12
thereof aviation*		162.5	363.4	124
Freight transport	10^9 tkm	569.1	1026.0	80
thereof road		402.6	749.4	86
thereof rail		95.4	161.5	69
thereof inland ship		64.1	85.1	33
thereof aviation*		6.9	30.0	335

*) All of the transport demand modes are based on "territorial" principle, where the activities on Germany are investigated. However, for aviation the "outgoing" principle is selected which considers all airplanes that take off from Germany. This approach is suitable since the kerosene requirement for international flights is to be provided by the German industry.

Table 55: Share of energy consumption of domestic aviation in total aviation (BMU, 2009c)

Year	1990	1995	2000	2005	2007
(%)	20.0	15.0	11.2	8.3	8.3

- In Germany, the share of compression ignition engines in passenger cars is increasing. Current share of compression ignition engines in passenger car fleet and new registrations are 20% (KBA, 2009) and 42% (VDA, 2006) in 2005 respectively. This shows that the share of compression ignition engine will increase in future even more. It is assumed that the share of compression ignition cars in passenger car fleet will reach 42% in 2030. With the traveled vehicle kilometer expectations differentiated for spark and compression ignition engine passenger cars (Shell, 2009a), the share of traveled vehicle kilometer by diesel passenger cars are calculated (Figure 31).

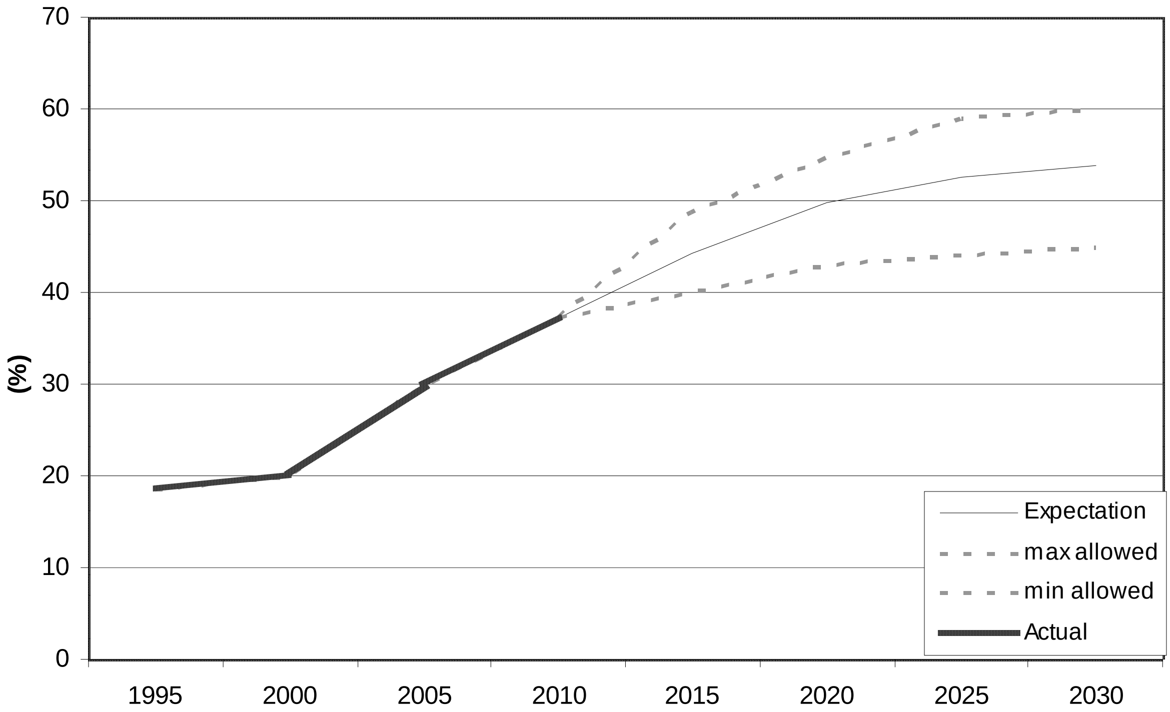


Figure 31: Share of vehicle kilometers of compression ignition engine passenger cars in all passenger cars

- Assumed mileage and lifetime of vehicles are presented in Table 56.

Table 56: Assumptions of mileage and lifetime for different vehicles in Germany

	Mileage vkm/a	Lifetime a	Source
Passenger car	12,626	12	ADAC, 2009 and own calculation
Bus (public)	60,000	12	GEMIS, 2009
Coach	67,200	12	Berg, 2010 and GEMIS, 2009
Truck (LDV)	20,000	10	GEMIS, 2009 and own calculation
Truck (HDV)	55,165	10	GEMIS, 2009 and own calculation

- The lifetime of the battery is assumed to be 250,000 vkm (Lave et al., 2002). This assumption is slightly higher than the battery life time of 190,000 vkm calculated with the battery life time of 4,500 cycles (VDE, 2008; Zhang and Wang, 2009; Hartmann and Özdemir, 2011) with an average daily driven kilometer of 42 vkm (Hartmann and Özdemir, 2011). Both of the battery life time values are enough to enable a lifetime operation for passenger cars and light duty trucks without any battery replacements (Lave et al., 2002). However, heavy duty trucks, public buses and coaches require battery replacement about every four years. The costs of battery replacement are considered in the model.
- The annual maintenance costs of all vehicles are calculated as 2% of the investment cost of vehicle.

5.1.3 Assumptions for the biomass provision

Assumptions for the biomass provision that are valid for all scenarios are:

- Land area requirement for bioenergy production is limited according to Table 57.

Table 57: Maximum land area requirement (in million ha) for bioenergy production in Germany (FNR, 2009a; Nitsch et al., 2004)

	2008	2010	2015	2020	2025	2030
Maximum land area requirement for bioenergy	1.60*	2.50	2.95	3.40	3.85	4.30

*) 1.60 million ha is the actual land area requirement for bioenergy in 2008 (FNR, 2009a)

- The yield and production costs of energy crops are given in Table 58. The costs and diesel consumption per hectare are derived from KTBL (2006). The yields are assumed to increase 5% in each 5 years until 2030, which will in turn reduce the biomass costs per GJ slightly from 2010 to 2030.

Table 58: Economics and yield of agricultural biomass production (König, 2009; KTBL, 2006; own calculation)

Biomass	FOM cost (EUR_{2000}/ha/a)	VOM cost without diesel consumption (EUR_{2000}/ha/a)	Diesel consumption (l/ha/a)	Yield[1] in 2005 (GJ/ha/a)
Rapeseed	400.0	389.1	71.53	79.0
Maize (whole plant silage)[2]	751.3	762.8	104.2	337.8
Wheat (whole plant silage)[3]	623.5	543.9	98.3	239.6
Wheat (corn for ethanol)	437.1	421.3	94.2	116.7
Sugar beet	620.3	848.5	139.3	207.5
Grass	780.0	525.1	156.1	188.3
SRC[4]	631.5	51.6	38.6	147.2
Miscanthus[4]	669.3	473.1	45.5	264.7

1) Yields are assumed to increase 5% each 5 years until 2030.
2) Maize yield is given as input to silo. Biomass losses in silo are about 12%.
3) Wheat yield is given as input to silo. Biomass losses in silo are about 12%.
4) SRC and miscanthus cultivation are only done for a long time period. To indicate this to the model the lifetime of the cultivation process for SRC and miscanthus are selected as 20 and 15 years respectively. If the model decides to switch to another energy crop before the lifetime ends, the FOM costs should still be paid until the end of the lifetime.

- There is limited land area in Germany suitable for miscanthus cultivation. It is assumed that the maximum available land area for miscanthus is 100,000 ha (SFV, 2007).
- The technical potential and corresponding costs of residual biomass assumptions for wood and straw are shown in Figure 32.
  - The wood resources are divided into different categories according to their origin (e.g. used wood, industry waste, forest residue) and they are associated with corresponding costs (König, 2009). A very restricted amount (12.5 PJ) of residual wood can be obtained with negative costs, which means that utilizing

this type of wood brings additional revenues. All other types have positive costs as shown in Figure 32.

- o The total straw potential is taken as 268 PJ (Leible et al., 2007). This potential is divided into three segments and matched with the straw costs from FNR, 2003.

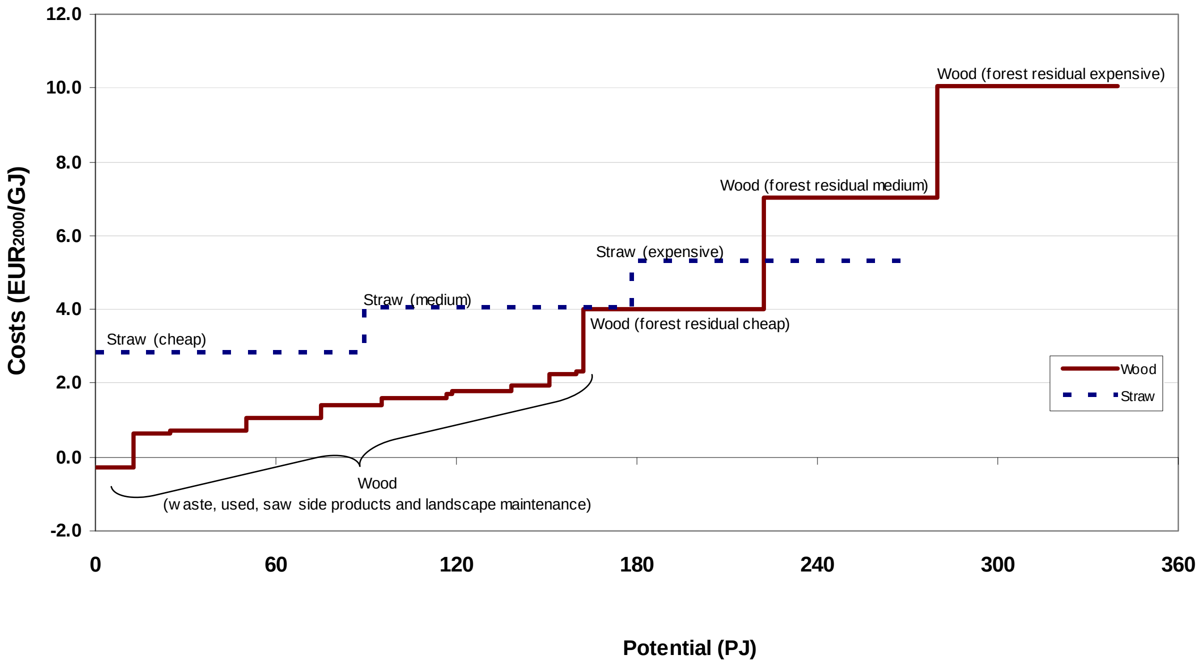


Figure 32: Cost-potential curve for wood and straw in Germany (König, 2009; Leible et al., 2007; FNR, 2003; own calculation)

- Manure is regarded as waste of livestock industry and assumed that it is available without any costs. The manure potential in Germany is estimated as 98 PJ/a (Staiß, 2007).
- Some biomass resources are traded internationally. In this work, only import of bioethanol from Brazil and rapeseed, rape oil and biodiesel from Eastern Europe are considered. The biomass import is restricted with 10% of the biomass demand in the country (König, 2009).

5.1.4 Other technology specific assumptions

- It is assumed that energy supply and powertrain systems will be experiencing technological development (e.g. improved efficiencies, reduced costs etc.) until 2030. The assumptions for these developments are presented in chapters 2 and 3 for each technology. These assumptions are the same for all scenarios except for the technology based cost reduction scenario (see chapter 5.5).

- The model is calibrated with the historical development of renewable energy for the time period 1995 to 2005. The following assumptions and parameters apply:
  - In 2005, 33% of the biodiesel consumption was added to the conventional diesel. The rest is used as a pure fuel in trucks (53%) or automobiles (14%) in Germany (Staiß, 2007).
  - Bioethanol is only used as blending fuel in Germany until 2010.
  - Electricity generation from hydropower, landfill gas, waste and geothermal energy are constrained for the upcoming years according to Table 59.

Table 59: Assumptions of electricity generation constraints in 2030 for various technologies in all scenarios based on the present electricity generation in 2005 (König, 2009; Remme, 2006)

Technology	2005 (PJ/a)	2030 (PJ/a)	
		lowest	highest
Hydropower	76.6	88.1	92.9
Landfill gas	7.9	0.0	3.0
Waste incineration	14.0	25.0	25.0
Geothermal	0.4	0.0	15.3

- Synthetic fuels (BTL, GTL and CTL) and lignocellulosic ethanol will be commercially available by 2015.
- It is assumed that the energy share of biogas produced from manure and energy crops (maize, wheat and grass) remain 5% and 95% also in the future respectively, which correspond to a fresh mass share of about 35% for manure and 65% for energy crops (see chapter 3.6.2).
- Hybrid electric passenger cars will be available by 2010, whereas hybrid electric trucks and buses will be available not earlier than 2015.
- The political decision for nuclear phase out is considered. The German government agreed on nuclear power phase out in 2002 (Bundesgesetzblatt, 2002). The law abolishes new nuclear power plants and determines operation time of each existing plant in Germany. According to that the last power plant should be shut down in 2022. This law is updated in summer 2010 and the life time of nuclear power plants are elongated 12 years on average (BMWi and BMU, 2011). The government changed the law after the accident in Fukushima so that the last nuclear power plant will be shut down in 2022 (BMWi and BMU, 2011). In this study, last nuclear power plant will be shut down in 2022 as stated by the updated law.

5.2 Base scenario

The specific assumptions for the base scenario are presented in chapter 5.2.1. The results of this scenario are presented in chapter 5.2.2.

5.2.1 Specific assumptions for the base scenario

The base scenario aims to analyze the future developments under the current policy and market framework (see chapter 1.2). Additional to the key modeling assumptions that correspond to all scenarios, the base scenario has the following specific assumptions:

- The German government introduced the biofuel quotas law in 2006 (BioKraftQuG). Through this law, oil companies are obliged to blend a certain amount of biofuels in their products starting from 2007 (Bundesgesetzblatt, 2006). The defined quotas until the year 2015 are presented in Table 2 in chapter 1.2. For the years between 2020 and 2030, the EU biofuel targets of 10% are taken conservatively, although it might be expected that Germany would overfulfill the EU targets.
    - Considered biofuels for gasoline blends are bioethanol and ETBE. For ETBE only the renewable share is considered as biofuel.
    - Considered biofuels for diesel blends are hydrated vegetable oil, biodiesel and BTL. Furthermore, GTL and CTL may also be blended to diesel fuel, but they are not biofuels and not included in the BioKraftQuG law.
    - Total fuel quota: The oil companies are free to choose if the additional biofuel blending requirements of total fuel quota are to be fulfilled by gasoline or diesel substitutes. Similar to the real world, the model decides between additional gasoline or diesel substitutes to fulfill the total fuel quota according to minimal costs.
    - The German law defines the quotas only until 2015. However, EU defined a biofuel target for 2020 with 10% of total fuels. Thus, for the further years 10% total fuel quota are set according to the EU targets. Gasoline and diesel quotas are kept at the same level as in 2015.
- As it is unlikely that the annual GHG emissions in Germany will rise in the future, the GHG emissions in the base scenario are limited to the latest available year's (2007) emission level.
- Electricity generation from wind, photovoltaic and biomass are limited for the upcoming years according to Table 60.

Table 60: Assumptions of electricity generation constraints in 2030 for various technologies in the base scenario based on the present electricity generation in 2005 (König, 2009; Remme, 2006)

Technology	2005 (PJ/a)	2030 (PJ/a)	
		lowest	highest
Wind (total)	93.6	181.3	351.3
thereof offshore	0.0	69.7	219.8
Photovoltaic	3.1	21.4	30.4
Biogas “on-site”	9.0	31.0	42.0
Gasification CHP “on-site”	0.2	2.4	11.1
Biogas and gasification “off-site” via SNG	0.0	3.5	7.0
Wood CHP	17.1	23.6	76.6
Wood organic rankine cycle (ORC)	1.0	2.4	17.0
Wood steam turbine	0.8	2.4	21.3
Wood combined cycle	0.0	0.0	4.3
Wood co-firing	0.0	0.0	1.7
Vegetable oil CHP	1.6	10.0	20.0
Sewage gas	3.1	3.1	5.0

- Biogas is considered to be produced from today’s substrates mix also in the future (see chapter 3.6.2). Furthermore, it is assumed that 5% of the produced biogas will be upgraded to SNG in 2030.
- Heat production from biomass is limited for the upcoming years according to Table 61.

Table 61: Assumptions of heat generation constraints in 2030 for biomass technologies in the base scenario based on the present heat generation in 2005 (König, 2009)

Technology	2005 (PJ/a)	2030 (PJ/a)	
		lowest	highest
Wood pellets	5.9	27.0	38.0
Wood central heating plant	7.0	22.0	32.0
Straw central heating plant	0.8	4.0	20.0

5.2.2 Base scenario results

a) Primary and final energy consumption

The primary energy consumption in Germany in the base scenario is presented in Figure 33 for the years between 1995 and 2030. The results show that the total primary energy consumption is reduced about 5% between 2005 and 2030. Under the base scenario assumptions, it is expected that the primary fossil energy consumption is reduced by about 15% and the primary renewable energy consumption is increased by more than 100% in the same time period. The main increase of renewable energy is expected to come from biomass and wind sources.

Figure 34 presents the final energy consumption in Germany differentiated for sectors. It is expected that the final energy utilization of household sector will be reduced until 2030, whereas the transport sector will experience an increase in final energy consumption due to the growing demand. Only marginal final energy utilization changes are expected in industry and commerce sectors. Thus, the share of transport final energy consumption in total final energy consumption is anticipated to increase from 30.6% in 2005 to 34.4% in 2030.

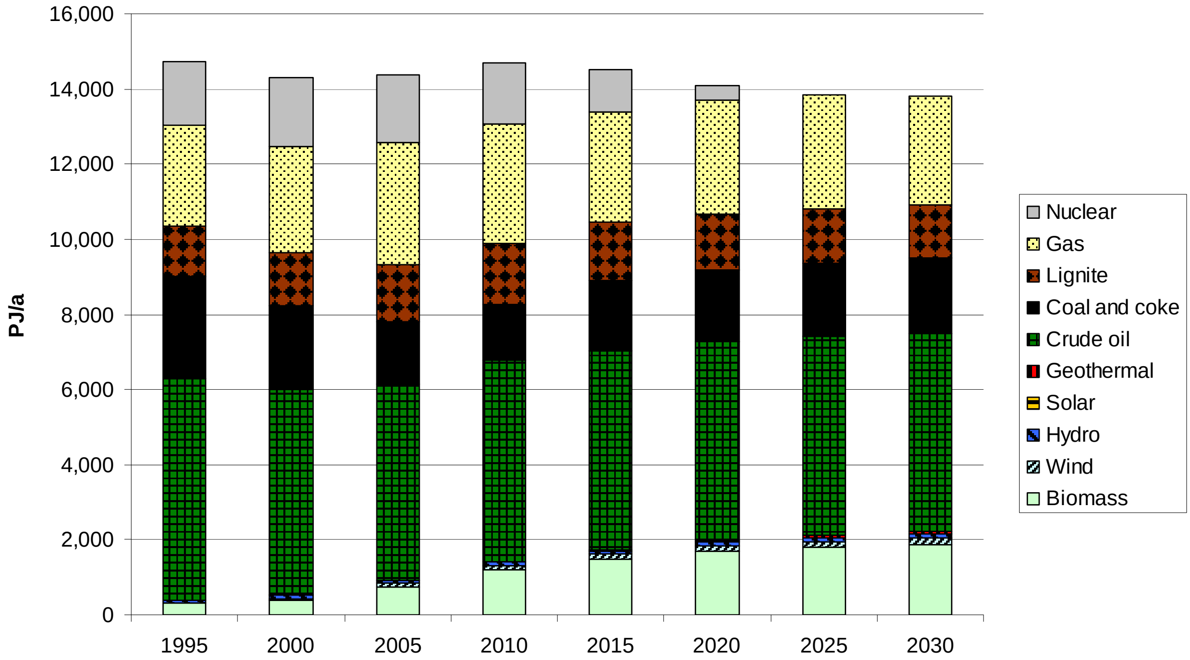


Figure 33: Primary energy consumption in Germany in the base scenario

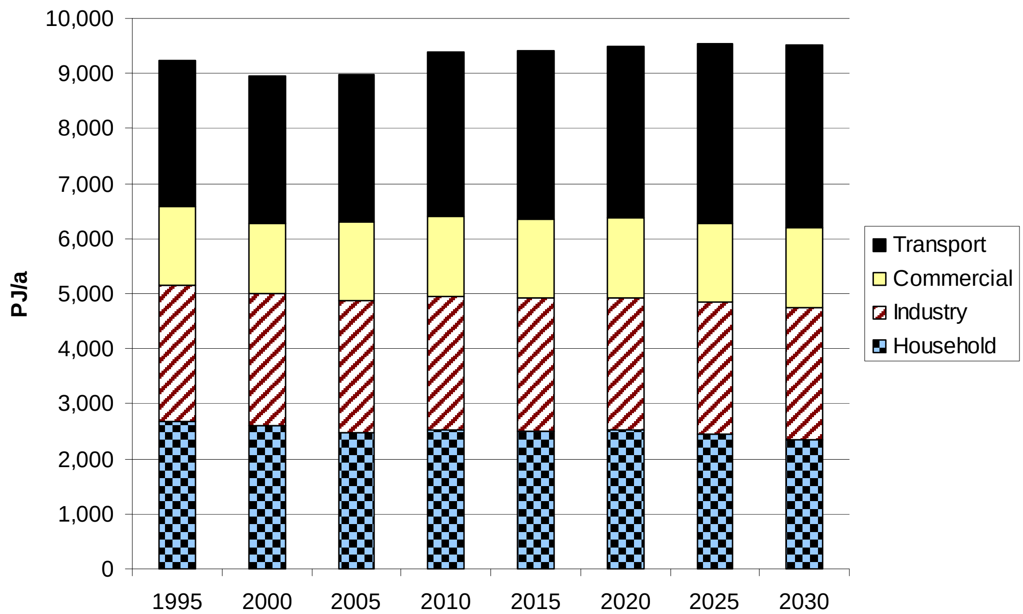


Figure 34: Final energy consumption (differentiated for sectors) in Germany in the base scenario

Furthermore, the ratio of final energy consumption to primary energy consumption is expected to increase slightly until 2030, which indicates overall energy efficiency increase in the German energy system.

b) Different powertrain utilizations

It is expected under the base scenario assumptions that the main passenger car demand is satisfied with conventional vehicles (spark and compression ignition powertrains) until 2030 (Figure 35). The market penetration of innovative powertrains such as electric vehicles, fuel cells or hybrid electric vehicles is not anticipated under the base scenario assumptions.

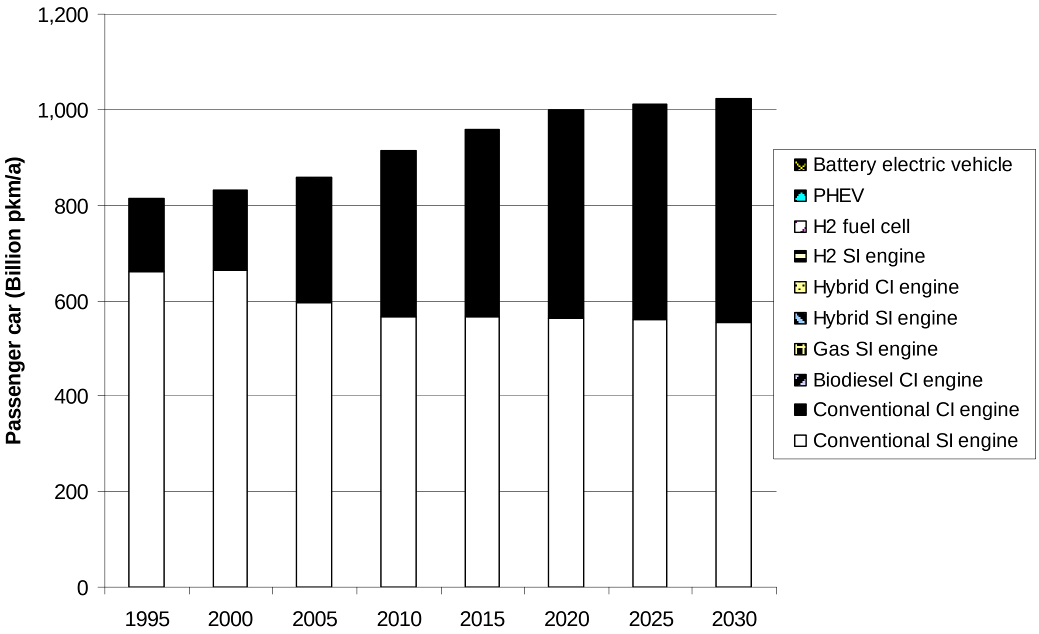


Figure 35: Utilization of powertrains for passenger cars in Germany in the base scenario

The results for buses show a different trend than for passenger cars (Figure 36). All conventional public buses will be substituted by hybrid electric powertrains as soon as the hybrid technology is available (2015). This result is in line with the findings of Clark and Zen (2009). They argue that the hybrid electric buses are proved to be economical for low speed applications (e.g. for public buses). On the other hand, conventional coaches are not substituted by hybrid powertrains in the base scenario. This result is reasonable since the efficiency gains of hybrid buses in the public bus sector are much higher than in coaches (see chapter 2.5.3). After 2025, it is expected that fuel cell hybrid electric vehicles will substitute almost half of the hybrid electric buses in the public bus sector. Other powertrain options (e.g. battery electric and plug-in hybrid buses) are utilized neither for public buses nor for coaches under the base scenario assumptions.

The utilization of powertrains for heavy and light duty trucks is presented in Figure 37. The results show a similar trend for trucks and for passenger cars. The conventional compression ignition engine will be the main powertrain until 2030. The only exception is pure biodiesel consumption which is not used after 2005. This result is rational since the new legislation cancelled the tax reductions of pure biodiesel fuel utilization and therewith it is projected that the attractiveness of pure biodiesel utilization will be reduced drastically. Furthermore, there is marginal utilization of light duty vehicles, which are powered by conventional spark ignition engines.

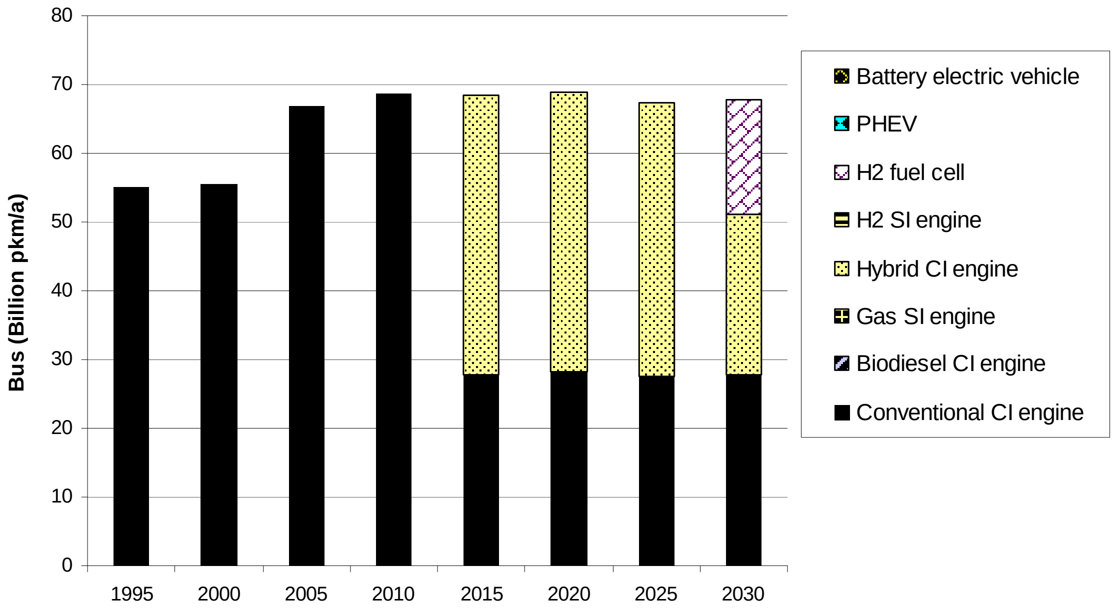


Figure 36: Utilization of powertrains for buses (public buses and coaches) in Germany in the base scenario

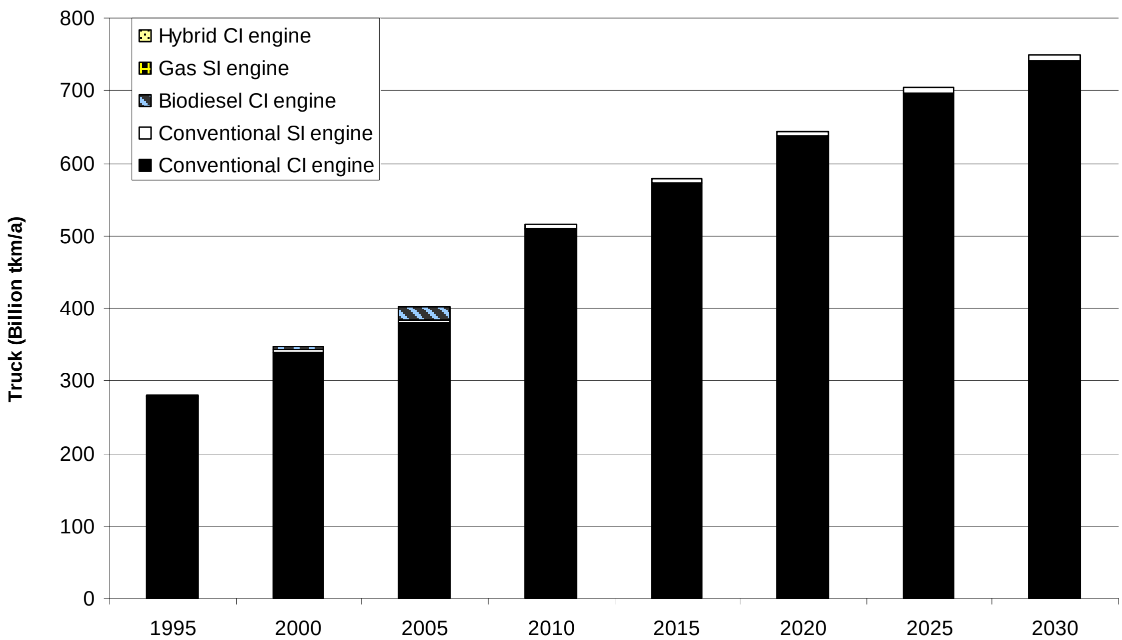


Figure 37: Utilization of powertrains for trucks in Germany in the base scenario

The results show that market penetration of alternative powertrains takes place for public buses rather than for coaches, passenger cars or trucks under the base scenario assumptions.

The reasons for this result are the relative high annual mileages of public buses and the high potential of efficiency increase for their typical driving cycle, which is mainly composed of "stop and go".

c) Final energy consumption in the transport sector

The final energy consumption in the German transport sector is presented in Figure 38. The overall final energy use in the transport sector will increase from about 2,700 PJ/a in 2005 to about 3,300 PJ/a in 2030. This increase is mainly due to the increase of kerosene consumption of about 465 PJ/a between 2005 and 2030. This increase of kerosene consumption is attributed to the increase of aviation demand for passengers as well as for freights.

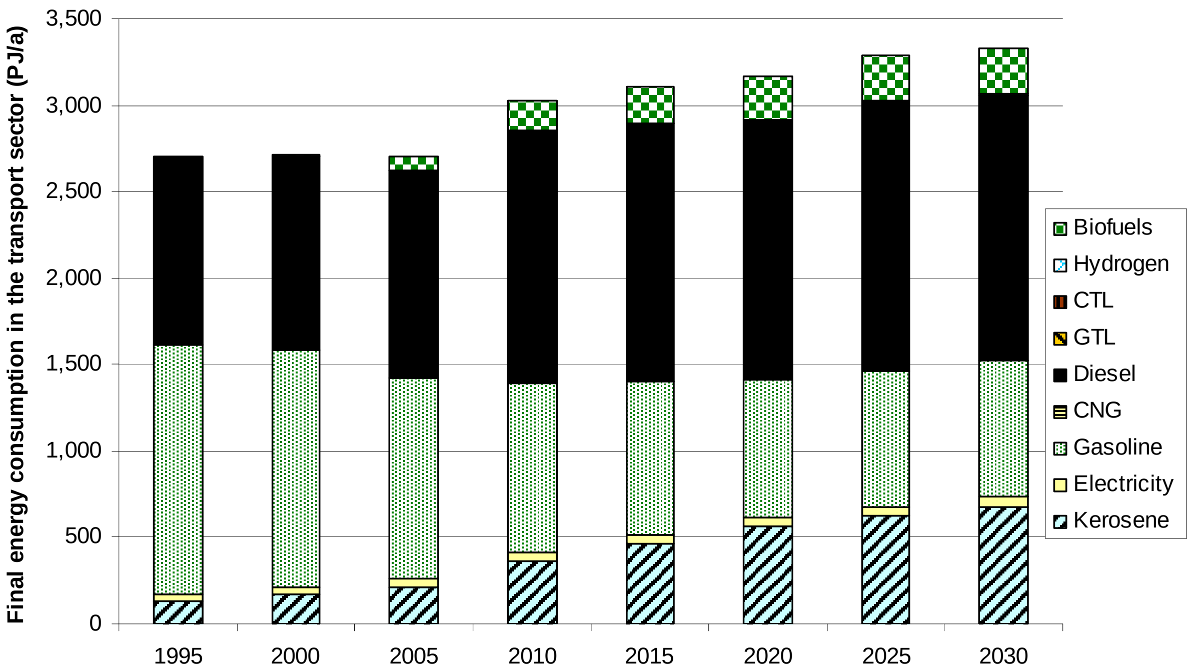


Figure 38: Final energy consumption in the German transport sector in the base scenario

It is further expected that diesel and biofuel consumption will increase in the future, whereas gasoline consumption decreases. The main reason for the increase in diesel consumption is the growth of road freight demand. Another reason is the increased share of compression ignition passenger cars in the future (see Figure 31). Biofuels are utilized due to the legislation which ensures the consumption of a certain share of biofuels as blending quota. Details of biofuel use are mentioned in the next section.

The utilized electricity in the transport sector is merely for the railway including trams. Electricity is not used as an energy source in the base scenario for the road transport because of its higher total costs compared to the conventional powertrains. The main obstacle for the use of electricity as an energy source for the road transport is the investment costs of batteries (see Table C 1 in the appendix).

Hydrogen as a fuel is only marginally utilized in the transport sector under the base scenario assumptions. It is expected that there will be a hydrogen demand of 6 PJ/a for the public bus sector after 2030. Other alternative fuels such as CTL and GTL are not utilized under the base scenario assumptions.

d) Biofuel utilization in the transport sector

The biofuel utilization in the German transport sector is presented in Figure 39 differentiated for various biofuels. Under the base scenario assumptions, it is expected that the biofuel utilization structure will change significantly after 2005. With the legislation of blending quota, pure biofuel utilization is projected to diminish and biofuels are expected to be used only as blending. The recent developments in the biodiesel market verify the findings of the present study. The use of pure biodiesel reduced from 67.7 PJ in 2007 to 8.9 PJ in 2009. On the other hand, the use of biodiesel as blend increased from 52.8 PJ in 2007 to 84.6 PJ in 2009 (UFOP, 2010).

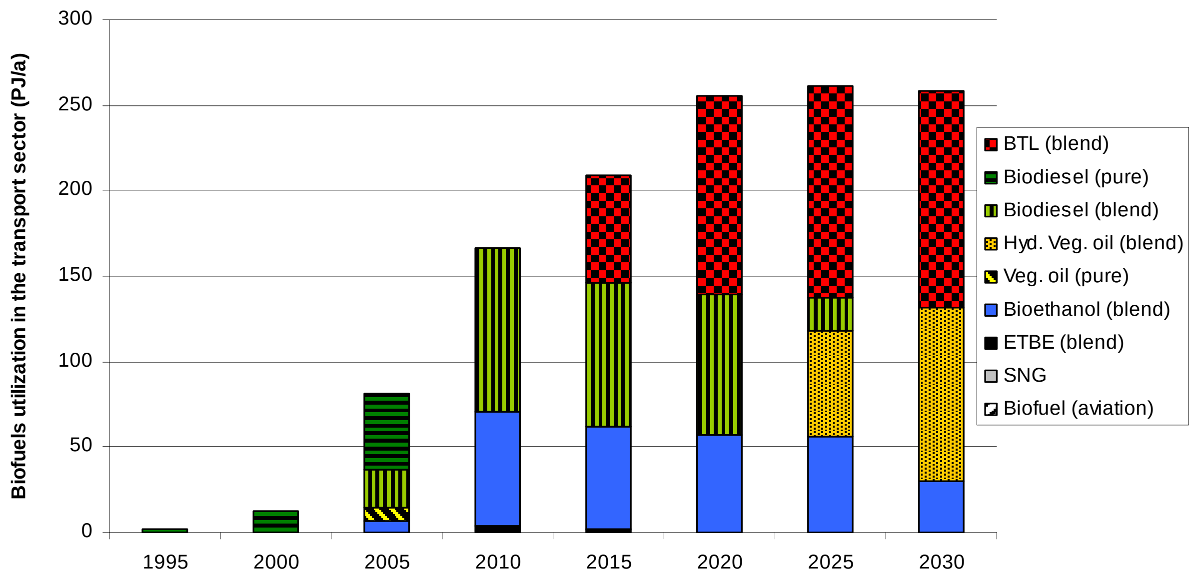


Figure 39: Final biofuel consumption in the German transport sector in the base scenario

After 2015, as diesel consumption increases significantly, demand for biofuels that may substitute conventional diesel is expected to increase as well. BTL is expected to fill this increased demand after 2015, when the BTL production is projected to be commercialized. Together with BTL, hydrated vegetable oil is also expected to play an important role in compression ignition powertrains as a blending fuel after 2025. After the existing biodiesel production facilities reach end of their life time (in 2025), they are expected to be replaced by hydrated vegetable oil production.

For spark ignition powertrains insignificant amount of ETBE is utilized until 2010 but the main biofuel contribution is expected to come from bioethanol. The use of bioethanol is expected to decrease slightly as the overall gasoline consumption decreases. Total biofuel utilization is anticipated to increase from 67 PJ/a in 2005 to about 260 PJ/a in 2030.

e) Land area requirement for bioenergy

As mentioned before, biofuels are severely criticized for their land area requirement which may imply a competition with food production. The land area requirement in Germany for energy crops in the base scenario is presented in Figure 40. In this scenario, the entire available land area is utilized for energy crop cultivation after 2005. Thus, the total land area requirement is equal to the maximum available land area for energy crops which are presented in Table 57.

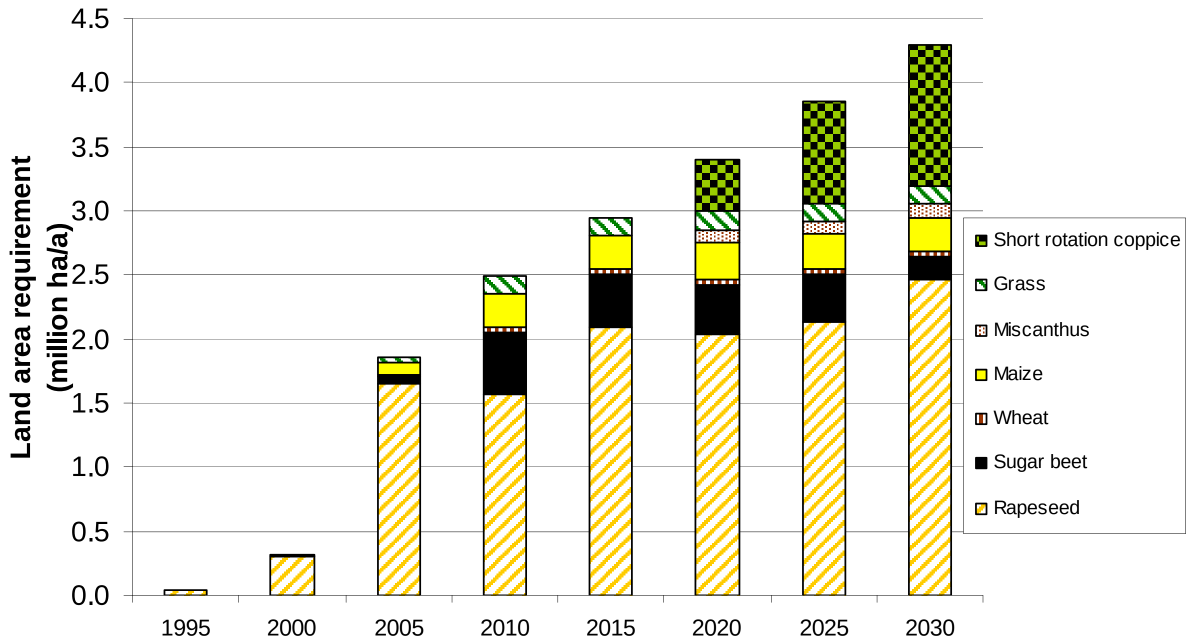


Figure 40: Land area requirement for energy crop production in Germany in the base scenario

The main energy crop that requires land area in the base scenario is rapeseed, which covers more than 70% of the available land for energy crops. Therefore, the historical dominance of rapeseed by energy crops is expected to continue until 2030 under the base scenario assumptions. Although the biodiesel consumption is expected to decrease, increased demand for the hydrated vegetable oil requires increased rapeseed land area in the future (2.8 million ha in 2030).

Short rotation coppice is expected to be utilized after 2020 and its land area requirement reaches about 1 million ha in 2030. The energy content of short rotation coppice consumption in 2030 corresponds to 192 PJ/a, which is significantly high compared to the utilization of straw (179 PJ/a) or wood (274 PJ/a) for energy purposes in the same year. However, short rotation coppice is not only utilized for the transport sector but also for heat and electricity generation. Only 36% of the short rotation coppice in 2030 is expected to be used as a raw material for BTL (29%) and lignocellulosic bioethanol (7%) production.

Other significant energy crops under the base scenario assumptions are maize (0.27 million ha), grass (0.14 million ha), miscanthus (0.10 million ha) and wheat (0.04 million ha).

f) Energy related GHG emissions

Energy related GHG emission results of the base scenario are presented in Figure 41. The GHG emissions are equal to the maximum limit (GHG emission level of the year 2007) for the years between 2010 and 2025. Only for the year 2030 the emissions are slightly lower than this bound of about 774 million tons of CO_{2eq}. CO_2 remains to be the main GHG compound as in the previous years.

This result shows that the GHG emissions will not decrease under the base scenario assumptions. It implies that explicit GHG reduction targets and appropriate legislations are required to decrease the GHG emissions in the future.

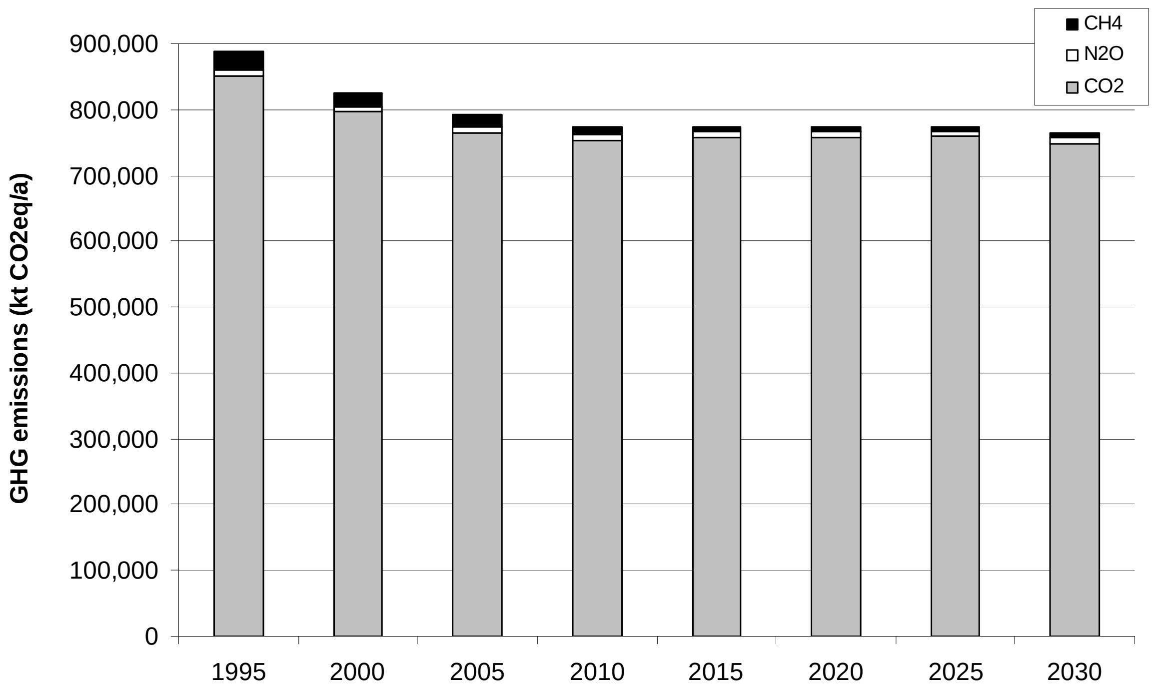


Figure 41: Energy related greenhouse gas emissions in Germany in the base scenario

5.3 Free market scenarios (FM)

The specific assumptions for the free market scenarios are presented in chapter 5.3.1. The results of these scenarios are presented in chapter 5.3.2.

5.3.1 Specific assumptions for the FM scenarios

The main assumption for the FM scenarios is that there is a government deregulation for renewable energy in general and for the transport sector in particular. The FM scenarios are only restricted by the assumptions mentioned in chapter 5.1. Therefore, there is no target for reduction of GHG emissions in the FM scenarios. These scenarios are supposed to show the cost optimal energy system without any governmental intervention after 2005.

In these scenarios, the effects of different energy carrier import price levels on the results are investigated (Table 62). The moderate price level for crude oil is at 52 EUR_{2007}/bbl (corresponds to 75$\$_{2007}$/bbl) in 2030 (see chapter 5.1). This price level is elevated to high and very high price levels of 67 EUR_{2007}/bbl (corresponds to 100$\$_{2007}$/bbl) and 97 EUR_{2007}/bbl (corresponds to 150$\$_{2007}$/bbl) in 2030 respectively. The assumed price increases for other energy carriers like natural gas and coal are presented in Table 62. However, the price increases (especially for coal) are not as strong as for crude oil. A doubling of the crude oil price from 75 to 150 $\$_{2007}$/bbl in 2030 is expected to increase natural gas and hard coal import prices in 2030 71% and 42% respectively.

Table 62: Assumptions of import prices for fossil energy carriers in three price levels (IER et al., 2009, own assumptions)

Price level	Energy carrier	Unit	2007	2010	2020	2030
Moderate (FMM)	Crude oil	EUR_{2007}/bbl	52	40	48	52
	Natural gas	EUR_{2007}/MWh	22	17	19	21
	Hard coal for power plant	EUR_{2007}/t	68	60	70	72
High (FMH)	Crude oil	EUR_{2007}/bbl	52	43	59	67
	Natural gas	EUR_{2007}/MWh	22	18	23	26
	Hard coal for power plant	EUR_{2007}/t	68	65	75	82
Very high (FMV)	Crude oil	EUR_{2007}/bbl	52	49	81	97
	Natural gas	EUR_{2007}/MWh	22	20	31	36
	Hard coal for power plant	EUR_{2007}/t	68	75	85	102

5.3.2 Results of FM scenarios

In this chapter the results of the free market scenarios are compared with the base scenario for the year 2030. Thus, rather than to present the absolute values, only the differences between the free market and the base scenarios are shown for the three different fossil fuel price levels.

a) Primary energy consumption compared to the base scenario

The differences between three different free market scenarios and the base scenario are presented in Figure 42. The presented positive (or negative) values represent a higher (or lower) utilization of a primary energy carrier compared to the base scenario. The results for the free market scenario (FMM) with moderate fossil fuel price assumption (same fossil fuel price assumption as the base scenario) show that the total primary energy consumption is only slightly lower than for the base scenario. The major difference between the free market scenario with moderate fossil fuel price assumption and the base scenario is the reduction of biomass utilization of about 800 PJ in 2030. The reduction of biomass utilization is mainly affiliated with the transport sector and this energy source is mainly substituted by crude oil. Furthermore, the coal use is increased about 700 PJ in 2030 in the FMM scenario compared to the base scenario, which is utilized in coal power plants.

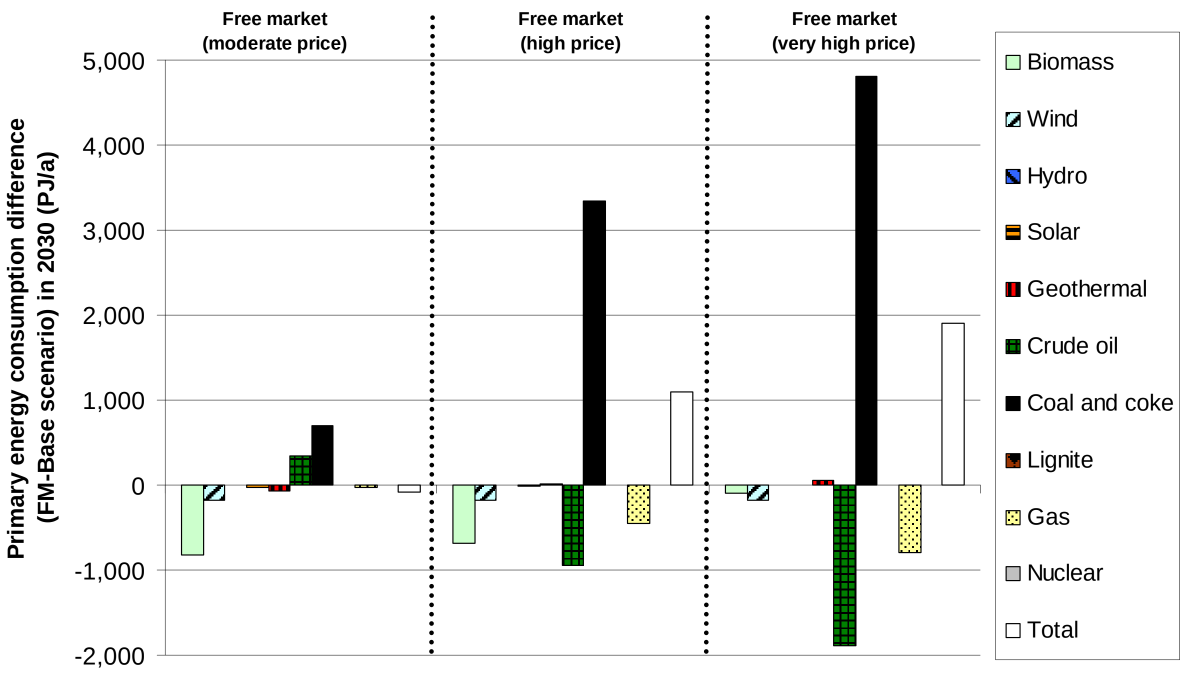


Figure 42: Differences between three free market scenarios and the base scenario for primary energy consumption in 2030

The results of the free market scenario (FMH) with high fossil fuel price assumption show that the primary energy consumption of biomass, crude oil and natural gas are decreased and consumption of coal is increased about 3400 PJ in 2030 compared to the base scenario, which is utilized in coal power plants (about 1000 PJ) and CTL production (about 2400 PJ). With the elevated fossil fuel prices, the CTL pathway gets attractive against conventional diesel and biofuels. This result makes sense since the price increases of coal are not as strong as the price increases of crude oil for the elevated fossil fuel price levels. As the conversion of coal into liquid fuels is less efficient than crude oil conversion, the total primary energy consumption in this scenario increases compared to the base scenario.

The free market scenario (FMV) with very high fossil fuel price assumption shows another trend. For the scenario with very high fossil fuel price, the CTL cost is lower than the conventional diesel similar to the high price scenario. However, biomass utilization amount is almost the same for the base scenario and the free market scenario with very high fossil fuel prices. Thus, it might be concluded that the elevated fossil fuel prices makes biomass utilization feasible. Nevertheless, biomass is expected to be utilized marginally in the transport sector (see section d). The results show that biomass is mainly used for electricity and heat generation. This is due to the fact that the utilization of biomass in electricity and heat sectors has lower costs than utilization in the transport sector.

b) Different powertrain utilizations compared to the base scenario

The results of powertrain utilizations for three free market scenarios (FMM, FMH and FMV) and the base scenario differ only marginally. This result shows that the fuel switch is preferred (cost optimally) rather than the powertrain switch. Results of utilized fuels in the transport sector for three free market scenarios are presented in the next section.

c) Final energy consumption in the transport sector compared to the base scenario

The differences between three free market scenarios and the base scenario are presented in Figure 43. The presented positive (or negative) values represent a higher (or lower) utilization of a final energy carrier in the transport sector compared to the base scenario. It is clear from this figure that the utilization of CTL fuel is increased as the price level of fossil fuels are elevated.

There is no biofuel utilization in the free market scenario with moderate price level due to the abolishment of biofuel blending quota. As the fossil fuel price is elevated, marginally more biofuels are utilized by the system (see next section). However, the increase in the biofuel utilization is at a much lower rate than the increase in the CTL utilization.

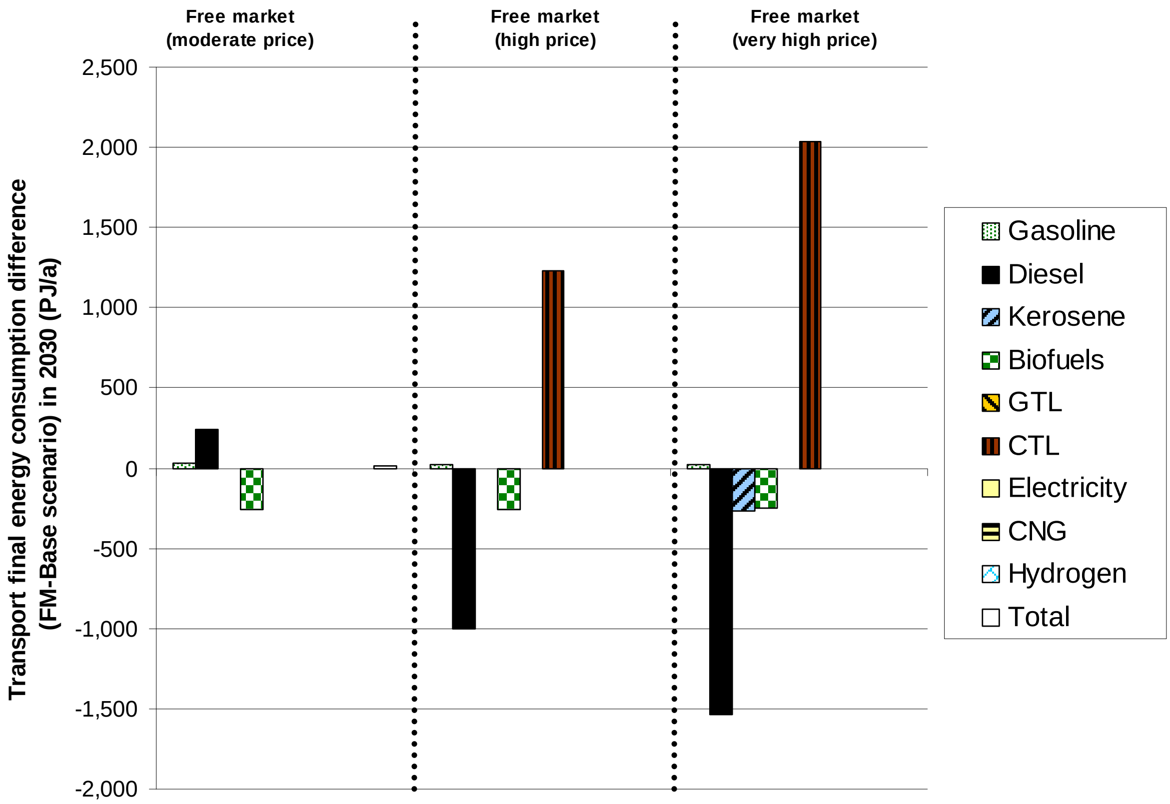


Figure 43: Differences between three free market scenarios and the base scenario for the final energy consumption of the transport sector in 2030

d) Biofuel utilization in the transport sector compared to the base scenario

There is no biofuel utilization in the transport sector in 2030 in the free market scenario with moderate fuel price assumption. As the fuel prices are elevated, a small amount of biofuels penetrate into the system. In the high price scenario, 5 PJ of ETBE is utilized only. In the very high price scenario 9 PJ of ETBE and 1 PJ of bioethanol are consumed. The required ethanol is produced from lignocellulosic material after 2025.

e) Land area requirement for energy crops compared to the base scenario

The land area requirement for energy crops for the base and three different free market scenarios are presented in Figure 44. The moderate and high price scenarios have (almost) no land requirement for energy crop purposes at all. Only the scenario with very high fossil fuel price assumption has land area requirement as a result. In this scenario, short rotation coppice and miscanthus are required and their total land area requirement is about 1.5 million ha. This lignocellulosic biomass is expected to be utilized mainly as feedstock for electricity and heat production and only 2% is anticipated to be used for bioethanol production.

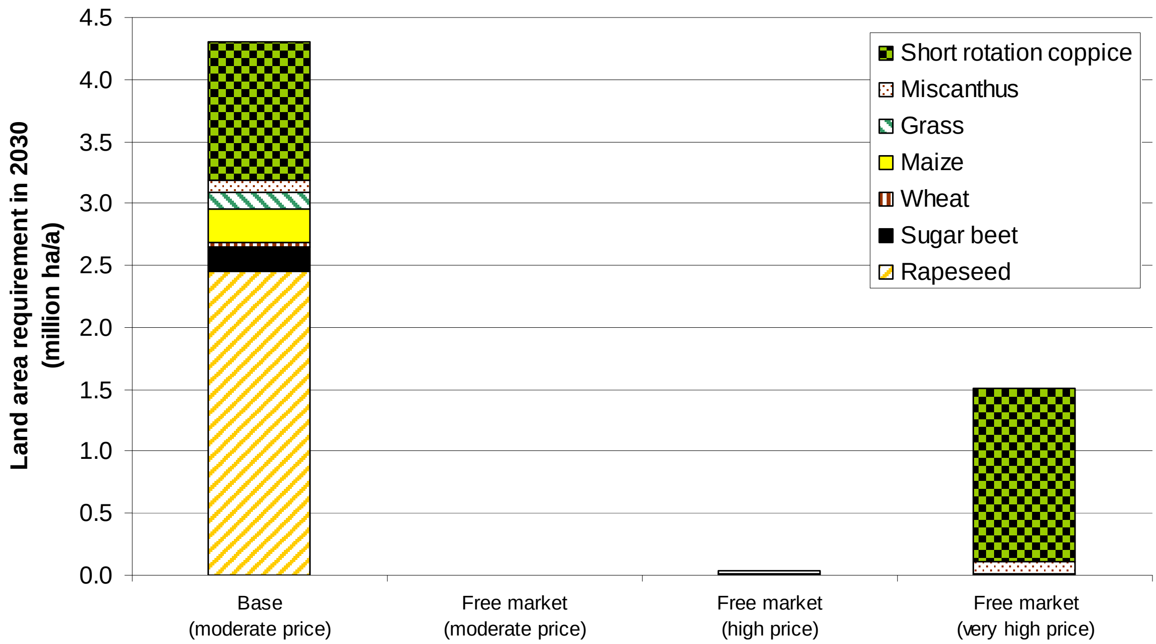


Figure 44: Comparison of land area requirement of energy crop production in Germany in 2030 for the base and three free market scenarios

f) Energy related GHG emissions compared to the base scenario

The total energy related GHG emissions in 2030 for three free market scenarios and the base scenario are presented in Figure 45. The total energy related GHG emissions are higher by the free market scenario with moderate price assumption compared to the base scenario mainly due to the abolishment of renewable energy targets including biofuel blending quota restriction. The total GHG emissions increase further as the fossil fuel price level elevates. This increase of emissions is mainly due to the utilization of CTL fuel, which has even higher GHG emissions than conventional diesel for the whole life cycle (especially at the conversion plant, see Table 41). The total GHG emission for the free market scenario with high fossil price assumption is similar to the GHG emission level in 1990 (about 1 million kt/a). The emissions are even higher than 1990 level for the free market scenario with very high fossil price assumption.

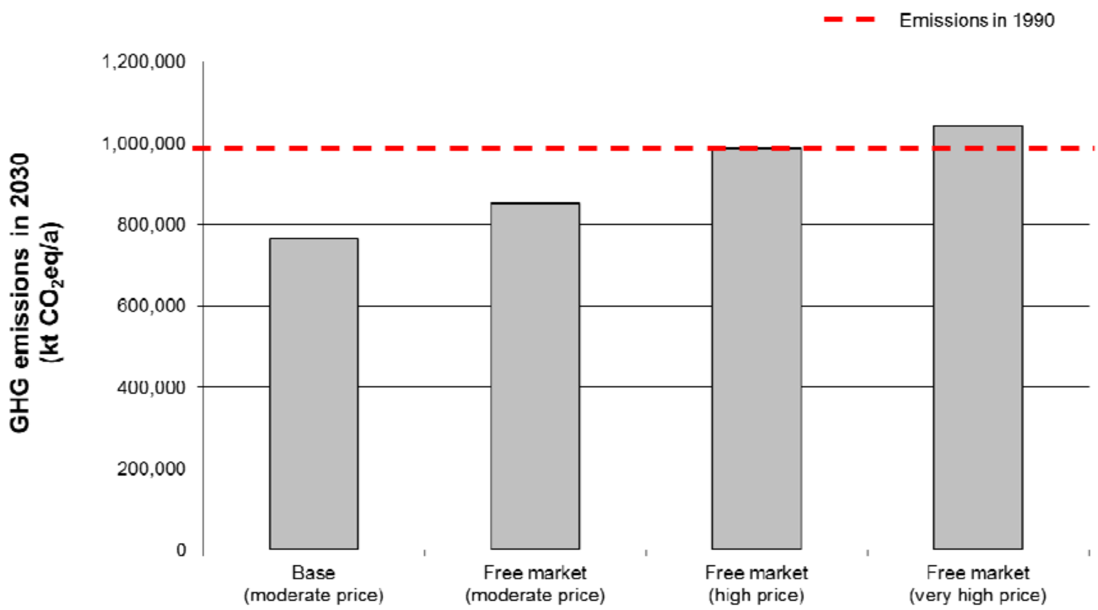


Figure 45: Comparison of total energy related greenhouse gas emissions in 2030 for the base and three free market scenarios

g) Comparison of energy system costs with the base scenario

The difference of energy system costs between the free market and the base scenario (which is based on moderate fossil price level assumption) are presented in Figure 46. Negative (and positive) values refer to lower (and higher) energy system costs for the free market scenarios compared to the base scenario.

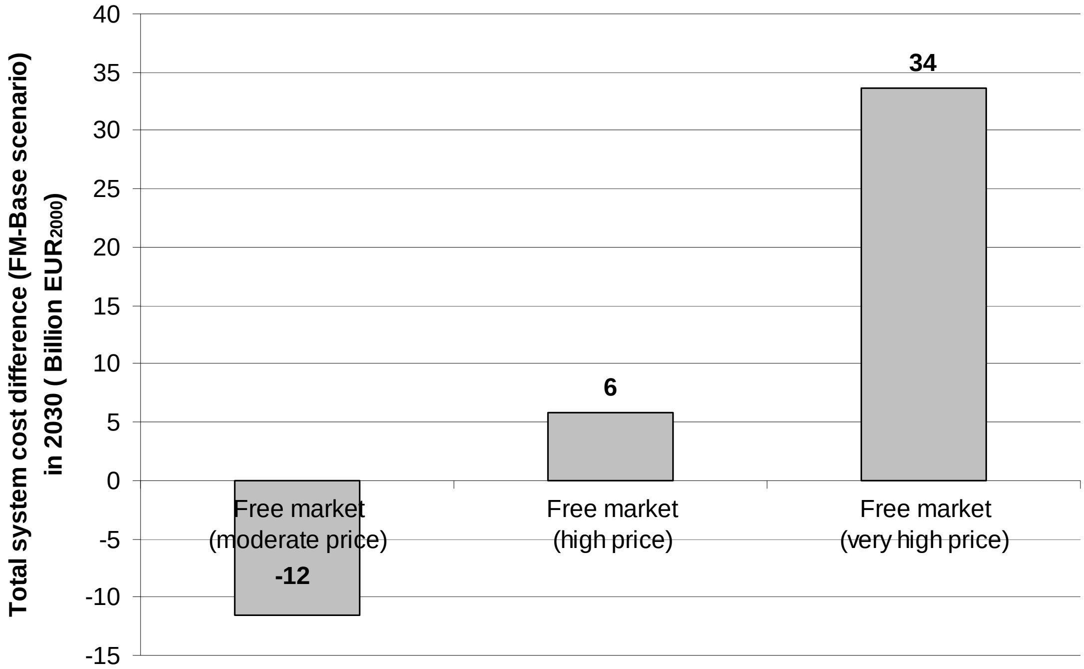


Figure 46: Differences between three free market scenarios and the base scenario for total energy system costs in 2030

The free market scenario with moderate price assumptions (same assumption as the base scenario) is expected to save 12 billion EUR_{2000}/a in 2030. These savings are mainly due to the abolishment of renewable energy targets including biofuel blending quota restriction. However, the elevated fossil fuel prices would require higher system costs compared to the base scenario. The differences would be 6 and 34 billion EUR_{2000}/a for high and very high price scenarios respectively. These additional energy system costs are due to the increase in the import price level of fossil fuels.

5.4 GHG emission restriction scenario (GHG)

The specific assumptions for the greenhouse gas emission restriction scenario are presented in chapter 5.4.1. The results including the effect of elevated fossil fuel prices under the GHG scenario assumptions are shown in chapter 5.4.2.

5.4.1 Specific assumptions for GHG scenario

The GHG scenario builds up on the FM scenario (chapter 5.3) so that there is a government deregulation for renewable energy in general and for the transport sector in particular as in the FM scenario. Furthermore, the maximum allowed GHG emissions are restricted as shown in Figure 47. The GHG reduction targets are deduced from the German government self-commitment, which aims to reach 40% GHG emission reduction until 2020 compared to 1990. This aim is extrapolated until 2030 which results in 53% GHG emission reduction compared to 1990 status.

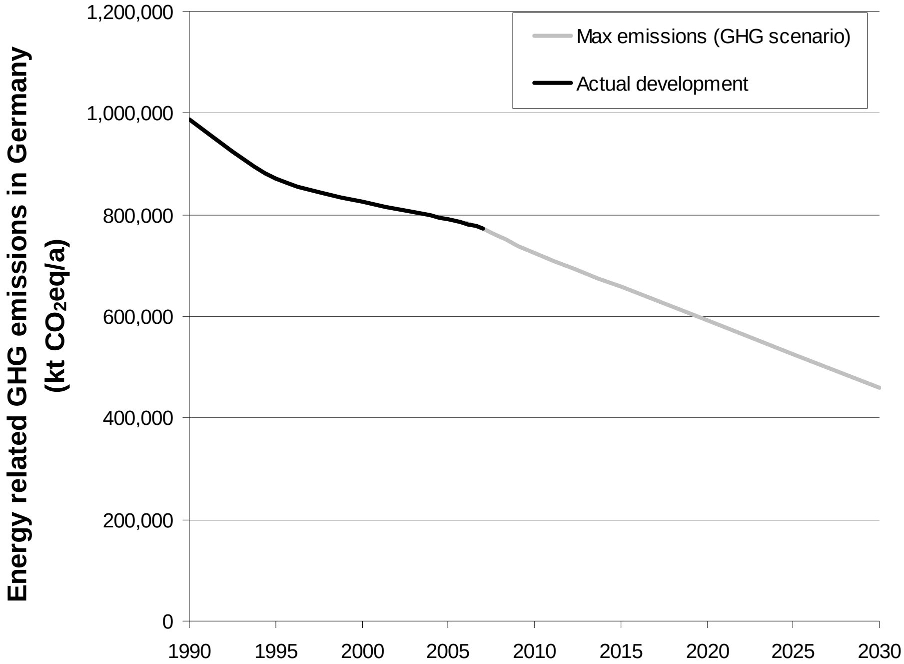


Figure 47: Energy related greenhouse gas emissions - Historical and for the GHG scenario

The fossil fuel price level is taken as moderate (same as the base and FMM scenarios). At the end of chapter 5.4.2 (see section 5.4.2h), fossil fuel prices are elevated for the GHG scenario to see its effect on the energy system.

5.4.2 GHG scenario results

In this chapter the results of the GHG emission constraint scenario are compared with the free market scenario (chapter 5.3) for the year 2030 to see the effect of the GHG emission restrictions. Thus, rather than to present the absolute values, only the differences between these scenarios are shown.

a) Primary energy consumption compared to the free market scenario

The primary energy consumption difference of the GHG restriction scenario and the FMM scenario for moderate fossil fuel price assumption is presented in Figure 48.

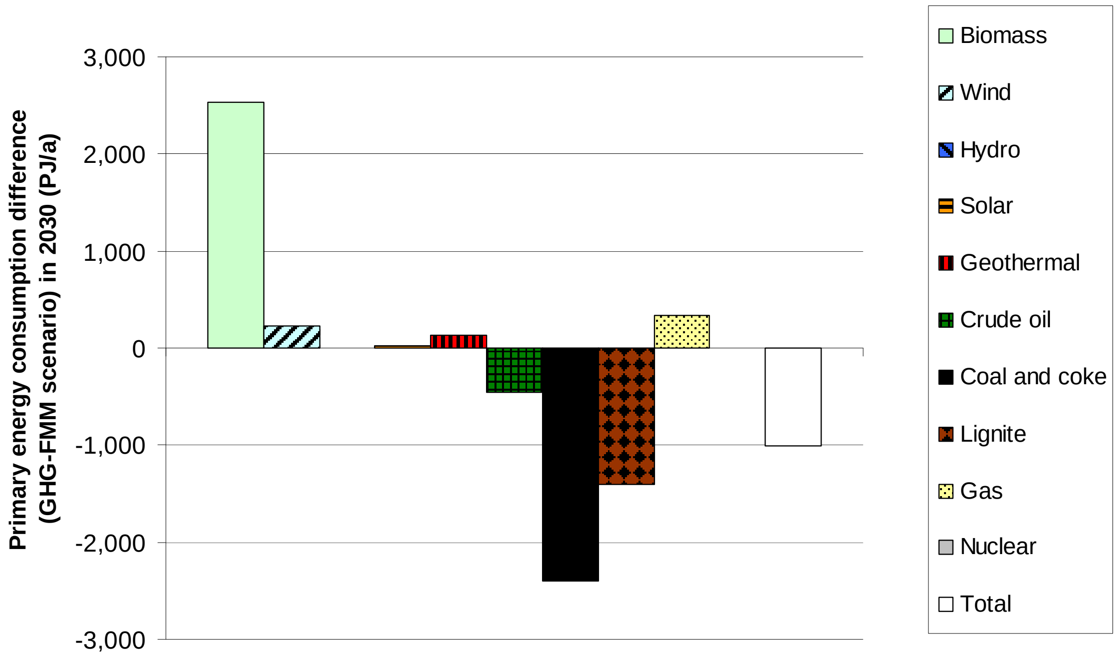


Figure 48: Difference between the GHG scenario and the FMM scenario for primary energy consumption in 2030

The GHG scenario results show that coal, lignite and crude oil utilization as primary energy carriers reduces compared to the FMM scenario. Instead of these energy carriers with high GHG emission balance, natural gas and renewable energy sources such as biomass, wind and geothermal are utilized. Especially biomass utilization difference between the GHG and the FMM scenario results is significant. The GHG scenario results show higher biomass consumption as primary energy carrier of about 2,600 PJ/a compared to the FMM scenario results. Furthermore, the overall primary energy utilization reduces about 1,000 PJ/a, which implies that the overall energy efficiency of the system increases.

The effect of the primary energy carrier utilization shift on the transport sector is investigated in the following sections.

b) Different powertrain utilizations compared to the free market scenario

The results of the two scenarios show that passenger cars are powered with similar powertrains in both of the scenarios. The main powertrain utilization difference between the free market and the GHG emission restriction scenario is noticed by the road freight and bus section.

It is expected that the conventional compression ignition engine trucks are substituted by the hybrid powertrain trucks for short distance driving in 2030 under GHG reduction assumptions. This substitution makes sense since the efficiency gains of hybrid powertrains for the short distance driving are much higher than for the long distance driving (see chapter 2.5.4). Furthermore, about 3% of the long distance conventional trucks will be substituted by gas spark ignition engine trucks, which help to lower the overall GHG emissions.

Moreover, under the GHG scenario assumptions it is expected that all the public buses and coaches are powered by fuel cell hybrid electric vehicles instead of compression ignition engines or hybrid compression ignition powertrains. This switch of powertrain is only possible with the assumption that hydrogen is delivered with a pipeline to the fuel stations after the year 2020 (see chapter 3.10). This result shows that utilization of hydrogen by fuel cell hybrid electric powertrains in public buses and coaches may contribute to the cost optimal GHG reduction.

c) Final energy consumption in the transport sector compared to the base and free market scenarios

Figure 49 presents differences between the GHG and the FMM scenarios for final energy consumption in the transport sector for the year 2030. Main differences between the results of the GHG scenario compared to the FMM scenario are the increase of biofuel (about 54 PJ/a) and CNG (about 64 PJ/a), and the decrease of crude oil consumption. Furthermore, it is expected that hydrogen from lignocellulosic biomass (22 PJ/a) are utilized to a small degree in the transport sector for public buses and coaches.

These results show that conventional fuels such as diesel and gasoline might be cost optimally substituted in the transport sector with biofuels, hydrogen and CNG in order to reduce the GHG emissions. However, the total amount of alternative fuels in the GHG scenario (ca. 140 PJ/a) is lower than in the base scenario (265 PJ/a). This indicates that the blending quota policy considered in the base scenario forced the transport sector to save more GHG emissions than it is required to save cost effectively.

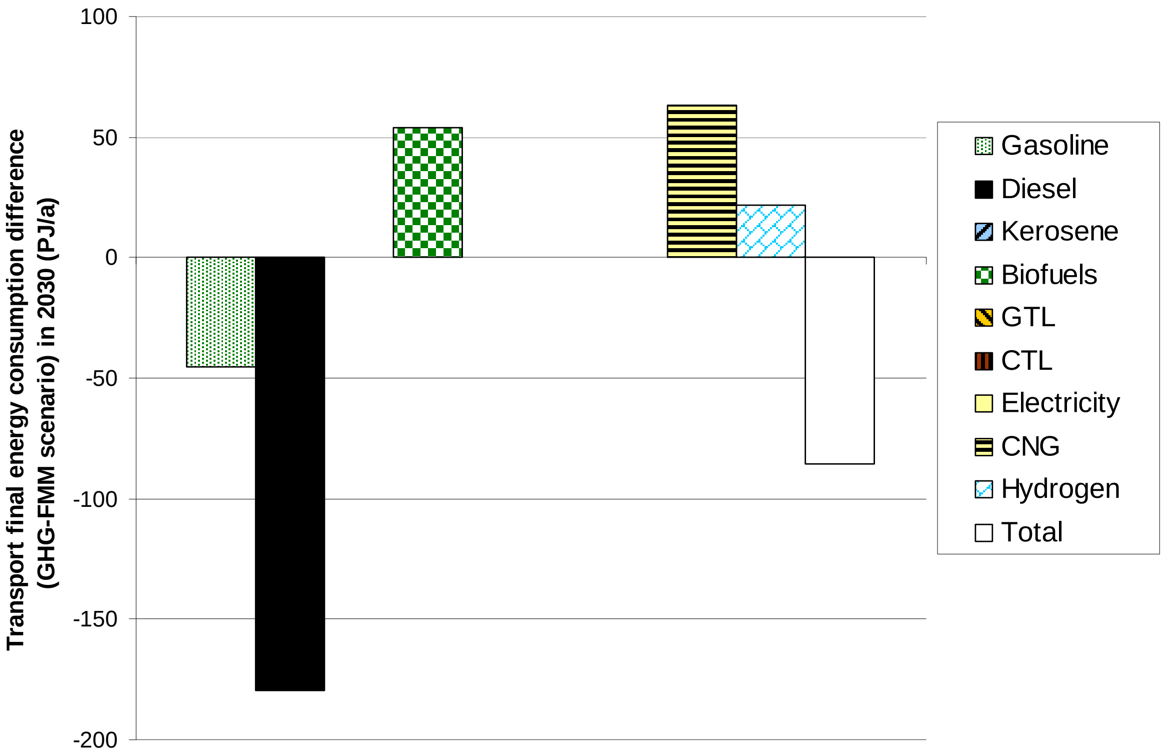


Figure 49: Difference between the GHG scenario and the FMM scenario for the final energy consumption in the transport sector in 2030

d) Biofuel utilization in the transport sector compared to the base and free market scenarios

The free market scenario with moderate fossil fuel price level showed no biofuel utilization in the transport sector in 2030 (see chapter 5.3.2). In the GHG scenario, however, the biofuel utilization in the transport sector in 2030 amounts to about 54 PJ/a. Utilized biofuels in the GHG scenario are SNG from biogas (9 PJ/a), ETBE (39 PJ/a) and bioethanol (7 PJ/a) from ligno-cellulosic raw material.

Besides the total amount of alternative fuels (see section c), also utilized biofuel energy carriers in the GHG scenario are considerably different than the biofuels utilized in the base scenario. For example, BTL fuel is not utilized in the GHG scenarios in 2030, whereas about 100 PJ is utilized in the base scenario in 2030. This result verifies the findings of Beiermann (2010) that the GHG abatement cost of BTL is quite high (more than 400 EUR/t CO_2). These results show that the blending quota policy considered in the base scenario is not necessarily supporting the alternative energy carriers for the transport sector with the lowest GHG emission reduction cost.

e) Land area requirement for bioenergy compared to the free market scenario

The land area requirement for energy crops shows a significant difference between the FMM and the GHG scenarios. The free market scenario with moderate price requires no land utilization for energy crop purposes at all. On the other hand, the GHG scenario results show that all the available land area (4.3 million ha) in 2030 is required for bioenergy production. The required crops are mainly miscanthus and short rotation coppice. These crops differ significantly from today's energy crop mix, where no significant miscanthus or short rotation coppice cultivation for energy purposes is present.

Most (about 1,100 PJ/a) of the obtained lignocellulosic biomass (miscanthus, short rotation coppice, straw and residual wood) in the GHG scenario is expected to be gasified and combusted in combined heat and power plants and only a small fraction (about 40 PJ/a of lignocellulosic biomass for hydrogen and bioethanol production each) is anticipated to be utilized in the transport sector in 2030. This result verifies that the transport sector is not the first sector to use biomass for reducing GHG emissions cost effectively. However, for ambitious GHG reduction targets, contributions from biofuels are required.

f) Energy related GHG emissions compared to the free market scenario

The energy related GHG emissions of the GHG scenario are given as restriction to the model (see Figure 47 in chapter 5.4.1). Thus, the GHG emissions are not a result but an assumption required as an input.

g) Comparison of energy system costs compared to the base and the free market scenario

Total energy system cost of the GHG scenario is 18 billion EUR_{2000} higher than the FMM scenario (6 billion EUR_{2000} higher than the base scenario) in 2030. This increase of system costs enables to save about 391 million tons of CO_{2eq}/a in 2030 compared to the free market scenario (304 million tons of CO_{2eq}/a compared to the base scenario). Thus, the average GHG abatement costs in 2030 are calculated as 45.5 EUR_{2000}/t CO_{2eq} compared to the free market scenario and 19.7 EUR_{2000}/t CO_{2eq} compared to the base scenario, which are significantly higher than the recent CO_2 market price of about 15 EUR/t CO_2 (CO_2-Handel, 2010). However, it is expected that the CO_2 market prices will be increased in the future especially as the GHG emissions are reduced. WBGU predicts slightly higher GHG abatement costs than 50 EUR/t for the year 2030 (WBGU, 2003). Therefore, it can be argued that the calculated average GHG abatement costs are reasonable for the year 2030.

h) Effect of higher fossil fuel prices on the GHG scenario results

The main influence of elevated fossil fuel prices on the energy system under the GHG scenario assumptions is the introduction of mild hybrid passenger cars into the market. For example, one fifth of all passenger cars are mild hybrids in 2030 if the fossil fuel prices are at the very high level (e.g. 150 $\$_{2007}$/bbl or 97 EUR_{2007}/bbl for crude oil).

On the other hand, as the fossil fuel prices are increased, utilization of SNG from biogas and bioethanol from lingo-cellulosic feedstock are increased slightly (about 14 and 24 PJ/a respectively) and utilization of ETBE is decreased (about 31 PJ/a).

Other transport sections are not influenced significantly from the elevated fossil fuel prices. This result shows that utilization of mild hybrid cars may contribute significantly to the cost optimal GHG emission reduction in 2030 if the fossil fuel prices are increased to a higher level.

5.5 Technology based cost reduction scenario with GHG emission restrictions (TCR)

The specific assumptions for the technology based cost reduction scenario are presented in chapter 5.5.1. The results are shown in chapters 5.5.2, 5.5.3 and 5.5.4.

5.5.1 Specific assumptions for the TCR scenario

The technology based cost reduction scenario builds up on the assumptions of the GHG scenario with moderate fossil fuel price level (chapter 5.4). To show the effect of investment costs, some critical components from vehicle powertrains and fuel production (Table 63) are selected and their investment costs in 2030 are decreased 25% and 50% successively.

Table 63: Critical components of fuel-powertrain technologies for the variation of the future investment costs

Component	Vehicle powertrain/ fuel production	Affected powertrains or fuels
Battery	Vehicle powertrain	FCHEV, HEV (mild and full), PHEV, BEV
Fuel cell	Vehicle powertrain	FCEV, FCHEV
Gasifier/steam reformer	Fuel production	BTL, CTL, GTL, Biomass to H_2, Coal to H_2, Biomass to SNG

Firstly, the battery is probably the key component for the commercialization of electric and hybrid vehicles. Considering the uncertainty of the future battery prices in the literature, it makes sense that these costs are varied. This variation will influence the investment costs of battery electric, hybrid electric, plug-in hybrid electric and fuel cell hybrid electric vehicles for all road transport modes where applicable. The battery cost in 2030, which was assumed as 188.3 EUR_{2000}/kWh (see Table A 1 in the appendix), is lowered 25% to 141.2 EUR_{2000}/kWh and 50% to 94.2 EUR_{2000}/kWh to see its effect on the energy system.

Secondly, there are also deviating future cost assumptions for fuel cell engines in the literature (i.a. Gül, 2008). Therefore, the fuel cell costs in the year 2030 are varied in this study. This will influence the future investment costs of fuel cell electric and fuel cell hybrid electric vehicles. The fuel cell cost in 2030, which was assumed as 46.1 EUR_{2000}/kW (see Table A 1 in the appendix), is lowered 25% to 34.6 EUR_{2000}/kW and 50% to 23.1 EUR_{2000}/kW to see its effect on the system.

Lastly, gasifier/steam reformer is selected to vary the future investment costs since it is a relatively new technology and their costs affect various fuel production pathways. The technologies that require gasifier or steam reformer and their share of investment cost in total investment costs are given in Table 64. Only the investment cost which is responsible for the gasifier/steam reformer is varied (lowered) 25% and 50% in this study.

Table 64: Share of investment cost of gasifier/steam reformer in the total investment cost of the fuel production plant

Technology	Component	Share of gasifier/steam reformer cost in the total investment (%)	Sources
BTL	Gasifier	14.4	Boerrigter, 2006
CTL	Gasifier	14.4	Boerrigter, 2006
GTL	Steam reformer	19.7	Boerrigter, 2006
Biomass to H_2	Gasifier	21.5	Own assumption
Coal to H_2	Gasifier	21.5	OECD/IEA, 2005
Natural gas to H_2	Steam reformer	25.0	Own assumption
Biomass to SNG	Gasifier	21.5	Own assumption

5.5.2 Results for cost reduction of battery

Reducing the specific battery costs per kWh in the year 2030 has a significant effect on the road transport. With the 25% lower battery costs, 44% of the conventional spark ignition engine passenger cars are substituted with mild hybrids in 2030. There is no other significant change in the transport sector. A further cost reduction (50% lower battery costs) do not have a considerable impact on the results.

The results show that the mild hybrid passenger cars are very close to commercialization under the GHG reduction assumptions. Yet, still the battery costs are required to be at least as low as 140 EUR_{2000}/kWh level so that the mild hybrid passenger cars would be economically feasible.

There is no significant change in the road freight, public bus and coach section results compared to the GHG scenario.

5.5.3 Results for cost reduction of fuel cell

Reducing the fuel cell costs in the year 2030 from 46.1 EUR_{2000}/kW to 34.6 EUR_{2000}/kW and even to 23.1 EUR_{2000}/kW has no significant effect on the road transport system. Expectation of further fuel cell vehicle penetration into the market is not fulfilled under the given assumption framework.

Even elevated fossil fuel prices are not sufficient for the market penetration of fuel cells. The combination of very high crude oil price level assumption of 150 $\$_{2007}$/bbl (or 97 EUR_{2007}/bbl) and 50% fuel cell cost reduction assumption, which result in fuel cell cost of 23.1 EUR_{2000}/kW in 2030 do not result economic feasibility of fuel cells and are not utilized by the system under the mentioned conditions.

5.5.4 Results for cost reduction of gasifier/steam reformer

The only utilized process that has gasifier or steam reformer in the GHG scenario is the wood gasification to synthesis gas which is not necessarily utilized for the transport sector. Reducing the gasifier and steam reformer costs in the year 2030 about 25% or 50% has no significant effect on the utilized fuel production technologies. All the processes which are not utilized by the GHG scenario (synthetic diesel and hydrogen pathways) are still not utilized in this scenario results. The changes by the wood gasification to synthesis gas process utilization are less than 0.3% compared to the GHG scenario.

5.6 Summary and discussion of scenario analysis

The aim of this section is to summarize and discuss the results of the scenario analysis (see Table 65). In this table the scenarios are compared in terms of utilization of powertrains and fuels, GHG emissions, land area requirement and energy system costs in 2030.

Utilizations of powertrains: Different scenarios shows that the alternative powertrains play a secondary role until 2030 except for some scenarios such as the GHG scenario with very high fossil fuel price level or technology based cost reduction scenarios for batteries with GHG emission restrictions. In both of these scenarios, it is projected that a significant share of mild hybrid passenger cars will be utilized in 2030.

Utilization of fuels: Different scenarios shows that the conventional fuels are expected to dominate the transport sector at least until 2030. Biofuels are used in the base scenario due to the blending quota and in the GHG scenario due to the GHG emission reduction targets.

However, the amount of consumed biofuels in the base scenario is about five times the amount in the GHG scenario. Furthermore, the biofuels used are quite different in these scenarios. BTL and hydrated vegetable oils are mainly utilized in the base scenario, whereas SNG from biogas and ETBE/bioethanol are preferred to reduce the GHG emissions cost effectively. These results show that the blending quota policy considered in the base scenario does not necessarily support alternative energy carriers for the transport sector with the lowest GHG emission reduction cost. Furthermore, CTL fuel is utilized significantly under the FM scenario assumptions (where no GHG emission restriction is applied) with high and very high fossil fuel price levels with considerable environmental effects.

Table 65: Summary of scenario results

Scenario	Fossil fuel price level	Utilization of powertrains	Utilization of fuels	GHG emissions in 2030 [a]	Land area requirement in 2030 [b]	System costs in 2030 [c]
Base [d]	Moderate	Conventional except for bus section [j]	Biofuel use due to blending quota [k]	Same as 2007 level	100% of available land, mainly rapeseed	reference
FM [e]	Moderate	Similar to the base scenario	Only conventional fuels	11% increase compared to base	No cultivation of energy crops	12 billion EUR less
FM [e]	High	Similar to the base scenario	Significant CTL utilization after 2025	29% increase compared to base	No cultivation of energy crops	6 billion EUR more
FM [e]	Very high	Similar to the base scenario	Significant CTL utilization after 2015	36% increase compared to base	35% of available land, mainly SRC for the heat sector	34 billion EUR more
GHG [f]	Moderate	Conventional except for truck and bus section [l]	Biofuel use for GHG emission reduction [m]	40% reduction compared to base [n]	100% of available land, mainly SRC	6 billion EUR more
GHG [f]	Very high	Mild hybrid passenger cars [o]	Slight increase in biofuel use [p]	Similar to the GHG moderate scenario		60 billion EUR more
TCR [g] (Battery)	Moderate	Mild hybrid passenger cars [q]	Similar to the GHG moderate scenario			6 billion EUR more
TCR [h] (FC)	Moderate	All aspects are similar to the GHG moderate scenario				
TCR [i] (Gas.)	Moderate	All aspects are similar to the GHG moderate scenario				

a) Energy related GHG emissions
b) Land area requirement for energy crops
c) Energy system costs in EUR_{2000} compared to the base scenario
d) Base scenario (see chapter 5.2)
e) Free market scenario (see chapter 5.3)
f) Greenhouse gas restriction scenario (see chapter 5.4)
g) Technology based cost reduction scenarios (25%) for batteries (see chapter 5.5)
h) Technology based cost reduction scenarios (25%) for fuel cell (see chapter 5.5)
i) Technology based cost reduction scenarios (25%) for gasifier/steam reformer (see chapter 5.5)
j) Hybrid and fuel cell powertrain public buses are projected to be utilized after 2015 and 2030 respectively.
k) BTL and hydrated vegetable oil fuels (258 PJ/a) are projected to be utilized mainly in 2030.
l) Short distance compression ignition powertrain trucks are expected to be substituted with hybrid powertrain trucks after 2020. Furthermore, about 3% of the long distance conventional trucks are projected to be substituted by spark ignition engines for CNG/SNG fuel. All of the conventional buses are expected to be substituted by fuel cell hybrid powertrains after 2030.
m) SNG from biogas (9 PJ/a), ETBE (39 PJ/a) and bioethanol blending (7 PJ/a) are expected to be utilized in 2030.
n) Correspond to 53% reduction compared to the GHG emission level of the year 1990.
o) 20% of conventional passenger cars are expected to be substituted with mild hybrid powertrain passenger cars in 2030. Other sectors are similar to the GHG scenario with moderate fossil fuel price.
p) Increased utilization of SNG from biogas (14 PJ/a) and bioethanol from lingo-cellulosic feedstock (24 PJ/a) and decreased utilization of ETBE (about 31 PJ/a).
q) 23% of conventional passenger cars are expected to be substituted with mild hybrid powertrain passenger cars in 2030 if the battery costs are reduced 25%. Other sectors are similar to the GHG moderate scenario.

GHG emissions in 2030: The results imply that the GHG emissions will only be reduced if an explicit target is present. For the scenarios without a reduction target (such as the FM scenario) the GHG emissions tend to increase. Here, it should be repeated that all the scenarios are restricted with the nuclear phase out (see chapter 5.1.4), which has a considerable impact on the GHG emission results in the future (Remme, 2006).

Land area requirements in 2030: Different scenarios show that 100% of the available land is required for the base and the GHG scenarios for energy crops. However, the required crops in these scenarios differ considerably. The main energy crop requirement in the base scenario is rapeseed, which is used in the transport sector. However, the main energy crop requirement in the GHG scenario is short rotation coppice which is mainly used for the heat and electricity sectors.

The energy system costs in 2030: Different scenarios show that the lowest costs are achieved in the FM scenario with a moderate fossil price level (12 billion EUR_{2000} less compared to the base scenario). The GHG scenario with very high fossil fuel prices has the highest energy system costs at 60 billion EUR_{2000} higher costs compared to the base scenario. The calculated average GHG emission abatement costs in 2030 are comparable with the findings of WBGU (2003).

The results of this study are interpreted in comparison with the results of König (2009) and Gül (2008) among the studies presented in Table 3 (at page 6), since only these studies explicitly examined the transport sector in detail with several scenarios (Table 66).

Table 66: Comparison of the scenarios in the present study with the scenarios of König (2009) and Gül (2008)

Scenarios of the present study	König (2009)			Gül (2008)		
	BAU [a]	BIC [b]	BIC-GHG [c]	baseline [d]	50% CO_2 [e]	FC [f]
Base	X			X		
FM		X				
GHG			X		X	
TCR						X

a) "Business as usual scenario" in König (2009)
b) "Biomass in competition scenario" in König (2009)
c) "Biomass in competition scenario with GHG reduction targets" in König (2009)
d) "Baseline scenario" in Gül (2008)
e) "50% CO_2 reduction target scenario" in Gül (2008)
f) "Role of fuel cell cost under 50% CO_2 reduction target scenario" in Gül (2008)

The results of the **base scenario** are compared with the "business as usual (BAU)" scenario of König (2009) and "baseline" scenario of Gül (2008). The total biofuel utilization in the German transport sector in 2030 is expected to be about 310 PJ/a for the BAU scenario in König (2009), which is about 50 PJ/a higher than in this study. The difference is mainly due to the vegetable oil consumption of about 30 PJ/a in König (2009). The use of vegetable oils in the transport sector is only cost competitive with conventional fuels with the support of government subsidies, which was practiced in Germany for vegetable oils with a tax exemption until 2006. In this study, the results show that the vegetable oil utilization will diminish in the future as the taxes on vegetable oil will be almost on the same level as on the conventional diesel after 2015 (see Table 1 at page 3). Therefore, pure vegetable oil will not likely be a significant energy source in the future for the German transport sector. The decrease of vegetable oil consumption from about 41 PJ in 2006 to about 4 PJ in 2009 (Neumann, 2010) verifies the findings of this study.

The shares of blended biofuels in König (2009) and in the present study are shown in Table 67. The comparison shows that hydrated vegetable oils, which are not considered in König (2009) are cost competitive against biodiesel due to their low investment costs (see chapter 3.11). Results for other biofuels are similar for both studies.

Furthermore, the land area requirement results for biofuel production in the present study are similar with the results in König (2009). For both studies, the land area requirement is dominated by rapeseed production, which is followed by short rotation coppice and maize.

The results in Gül (2008) for the baseline scenario in EU-29 show that conventional engines dominate the market till 2030. This result is consistent with the present study. However, differences in results for the present study and Gül (2008) are summarized as the utilization of biofuels and hybrid powertrains. In Gül (2008), biofuels are not utilized at all until 2030 and about 1.5% of the passenger cars are powered with hybrid powertrains in 2030. These differences are due to the lack of consideration of three important aspects in Gül (2008):

- the determined country politics such as the blending quota in Germany,
- the EU biofuel targets of 10% in 2020
- the developments in the biofuel sector (e.g. already installed production capacity of bioethanol and biodiesel in Germany).

Table 67: Comparison of shares of biofuel blends in 2030 in König (2009) with the present study

	König (2009) "business as usual scenario"	Present study "base scenario"
BTL	43%	49%
Biodiesel	43%	0%
Bioethanol	14%	11%
Hydrated vegetable oils	*	40%
Other biofuels	0%	0%

*) This fuel is not considered in König (2009)

The results for the base scenario in the present study are consistent with König (2009) and Gül (2008). However, the present study is considered to improve the existing knowledge in the literature by analyzing additional technologies (e.g. hydrated vegetable oils) and aspects (e.g. blending quota) that influences the results to some extent.

The **free market (FM) scenario** results are compared with the results of König (2009) for the "biomass in competition" scenario where the effects of abolishing the subsidies and governmental regulations in the whole system are investigated.

In both studies, the utilization of biomass in the energy system (particularly in the transport sector) is reduced significantly compared to the base scenario. However, resulting biofuel portfolio is different in these studies. In König (2009), only SNG from manure biogas is utilized and the share of biogas increases with the increasing oil prices (from 24 PJ/a in the moderate price scenario to 62 PJ/a in the high price scenario in 2030). In the present study, on the other hand, ETBE/bioethanol from lignocellulosic feedstock is the only utilized biofuel pathway with a much lower amount between 5 and 10 PJ/a in 2030. Furthermore, a significant share of CTL utilization is expected for the elevated fossil fuel prices.

The main reasons for these differences are the following points that are not considered in König (2009):

- The distribution costs of fuels and
- the CTL fuel pathway

The distribution costs of fuels are presented in Table 49. It is clear that the gaseous fuels have significantly higher costs than liquid fuels. This is one of the reasons that the model results in König (2009) include the use of SNG from manure biogas, as the distribution cost of fuels are not considered in this study. Including these costs, the cost optimizing model might switch to other fuels as in the present study.

CTL fuel is expected to be cost competitive with conventional diesel if the oil prices are higher than 100 $\$_{2007}$/bbl (or 67 EUR_{2007}/bbl) in 2030. This fuel is also not considered by König (2009) as a fuel alternative.

The **GHG emission restriction (GHG) scenario** results are compared with the results of König (2009) for the "biomass in competition with GHG reduction targets" scenario and with the results of Gül (2008) for the "50% CO_2 reduction target" scenario.

König (2009) mentions the utilized biofuels in the transport sector mainly as SNG from manure biogas. In this study, biogas is considered to be produced from a mix of manure and energy crops (cf. chapters 3.6.2 and 5.1.4). Restriction of share of biogas production from manure to 5% (energy content of biogas) increases the costs of SNG from biogas as the costs of biogas production from energy crops are significantly higher. This restriction makes sense since it is not expected that the share of manure in biogas production will increase in the future significantly due to the restrictions of its potential and transportability. Therefore, the resulting use of SNG from biogas in this study is about 9 PJ/a, which is much lower than the result in König (2009). Furthermore, ETBE and bioethanol from lingo-cellulosic feedstock are utilized in this study to some extent. Both of these fuels are not utilized in König (2009).

The biofuel market share in 2030 in Gül (2008) is about 3%, which is consistent with the results (2%) of the present study. One of the main differences between the present study and Gül (2008) is the utilization of natural gas in the transport sector. In Gül (2008), there is a significant share (7%) of natural gas powered passenger cars in the market in 2030. In the present study, natural gas is not utilized in the passenger cars, but rather it is only marginally utilized in light duty trucks in 2030.

The **technology based cost reduction (TCR) scenario** might be compared only for the variation of fuel cell costs with the "role of fuel cell cost under 50% CO_2 reduction target" scenario by Gül (2008) since no further cost variations of other components (e.g. batteries) were investigated to compare.

The results of Gül (2008) show that the change of fuel cell floor costs (i.e. the lowest achievable costs) do not change the market share of fuel cell cars in 2030. However, the market share of fuel cell vehicles in 2100 is significantly high. Consistent with Gül (2008), the results of this study show that the reduction of the investment costs of fuel cell do not have a significant effect on the energy system until 2030.

In summary, the comparison of the results with König (2009) and Gül (2008) shows that the results of the present study are mainly consistent with the literature. The differences occur due to

- different underlying assumptions for the political developments (e.g. considering biofuel targets for EU or country specific regulations such as blending quota)
- different technological scope (e.g. considering CTL as an alternative)
- different economic scope (e.g. considering the distribution and fuel station costs of transport fuels)
- different transport sections (e.g. considering freight and public transport)
- different temporal (e.g. until 2030) and spatial scopes (e.g. Germany) of the studies.

6 Conclusions

The objective of this study was to evaluate the future role of alternative powertrains and fuels for the German transport sector in terms of costs, efficiencies and GHG emissions. Furthermore, the land area requirements for the production of energy crops were investigated. Parameter variations for future costs of powertrains and fuel production pathways were performed in order to show their effect on the overall energy system.

To fulfill these aims, a scenario analysis was undertaken using a linear cost optimizing model (TIMES). The modeling results were interpreted in the light of existing literature.

6.1 The future role of alternative powertrains and fuels in the German transport sector

This study concluded that **the transport sector** should not be the first sector to reduce GHG emissions within an overall GHG emission mitigation strategy. This is due to the higher abatement costs of GHG emissions in the transport sector compared to the electricity and heat sectors. However, with the ambitious GHG emission reduction targets (such as self-commitment by the German government) some contributions also have to come from the transport sector. This study also showed that the GHG emissions could be reduced more cost effectively in other sectors (e.g. heat generation) rather than the transport sector with the measures implemented by the German legislation (e.g. biofuel quota). This current legislation forces the transport sector to save more GHG emissions than is cost effectively necessary.

The results of the scenario analysis on the future role of **alternative powertrains** in the German transport sector indicated that the transport system will still be dominated by conventional powertrains in the future. Alternative powertrains are projected to play a secondary role at least until 2030. It is not expected that the fuel cell or battery electric passenger cars will be introduced into the market until 2030 in Germany. This result is in line with the findings of WWF (2009). Nevertheless, hybrid electric powertrains might play an important role in the passenger car sector given the GHG emission reduction targets and high oil prices. It has been shown that the utilization of hybrid electric powertrains is only restricted to the mild hybrids under various scenario conditions, as they have lower GHG abatement costs than full hybrids. These results verify the findings of Karden et al. (2007) and Genc (2008).

Alternative powertrains are expected to play only a minor role in the road freight section. The conventional compression ignition engines remained the principal powertrain in the German road freight section. Under strict GHG reduction targets, however, a small share of hybrid electric powertrains and spark ignition engines with CNG/SNG fuels were required to enter the market.

The results of this study showed that the introduction of alternative powertrains (such as hybrid electric and fuel cell powertrain) was much more likely in the bus sector (especially for public buses) than in passenger cars or the road freight sector. Conventional public bus powertrains are expected to be substituted with hybrid electric powertrains for almost all of the scenarios after 2015. This substitution shows the superior economic characteristics of hybrid electric public buses against conventional ones, which verifies the findings of Clark and Zen (2009). Furthermore, the fuel cell powertrain might be an option for public buses as well as for coaches after 2025.

The results for the future role of **alternative fuels** in the German transport sector showed that conventional fuels remained an important part of the German transport system until 2030. However, different scenarios resulted in not only utilization of conventional fuels but also biofuels, hydrogen and fossil synthetic diesel utilization. Among the biofuels, BTL and hydrated vegetable oils were required under the base scenario conditions, whereas SNG from biogas, ETBE and bioethanol from lignocellulosic materials had to be utilized to achieve cost optimal and ambitious GHG reduction targets. Hydrogen is expected to be utilized exclusively in the bus sector and not in the passenger car sector. CTL was cost competitive for higher oil prices than 100$$_{2007}$/bbl (or 67 EUR_{2007}/bbl) and increased overall GHG emissions (under FM scenario without GHG emission restriction). Therefore, CTL use should be avoided to comply with the ambitious GHG reduction targets of Germany. Lastly, it is not expected that electricity will be employed in the road transport sector as a fuel until 2030.

The future uptake of alternative powertrains and fuels in the German transport sector was considerably affected by the **investment costs** of batteries. The reduction of battery costs to about 140 EUR_{2000}/kWh in 2030 resulted in an accelerated introduction of mild hybrid electric passenger cars into the system. However, neither the reduction of investment costs of fuel cells nor the gasifiers/steam reformers had a significant effect on the results.

The results showed that the **land area requirement** for energy crop production was very much dependent on the considered scenario and could be significantly high (e.g. 4.3 million ha, which is 36% of the cultivated area in Germany). Furthermore, the required crops differed considerably among the different scenarios. Mainly, oil crops were required in the base scenario, whereas today's uncommon biomass raw materials (such as miscanthus and short rotation coppice) were required in the GHG scenario. Thus, the utilization of miscanthus and short rotation coppice showed potential to reduce GHG emission costs optimally.

6.2 Policy implications

From the conclusions summarized in chapter 6.1, the following policy implications can be deduced.

Energy related GHG emissions might not decrease but even increase in the future if there are no specific GHG reduction targets. Therefore, the government is required to intervene in the market with appropriate support mechanisms if the GHG emissions are to be reduced.

Policymakers should give the electricity and heat sector priority to reduce the GHG emissions cost effectively, while keeping the transport sector in mind for significant reduction potential. As the results indicated, the existing law with the biofuel quota is not an appropriate tool to reduce GHG emissions cost effectively. However, the principles of the newly introduced federal immission control law (see chapter 1.2) are based on the decarbonisation of transport rather than biofuel blending quotas. This change demonstrates an appropriate tool to support the decrease of GHG emissions in the transport sector cost effectively.

Furthermore, policymakers should encourage companies and the scientific community to perform target oriented research and development on batteries to enable further cost reductions, as the costs of batteries have a significant effect on the market penetration of hybrid electric vehicles.

Since the results of this study showed that the bus sector has priority to introduce alternative powertrains, the policymakers should encourage vehicle manufacturers to develop hybrid electric and fuel cell buses further. At the same time, the policymakers should provide tax exemptions and/or obligations for the municipalities so that these innovative technologies are deployed effectively.

To foster the development of alternative fuels with the cost effective GHG emission reduction feature, the policymakers should enhance economic incentives for upgrading biogas to SNG and bioethanol from lingo-cellulosic feedstock to use in the transport sector.

This study showed that the land area requirement of energy crops might be significantly high depending on the relevant scenario. Furthermore, the energy crops mix might be changed significantly in the future. Policymakers are required to encourage the use of miscanthus and short rotation coppice to reduce the GHG emissions cost optimally, but on the other hand, it should be ensured that a mass cultivation of these plants do not have significant environmental effects, for example on the biodiversity. As today the miscanthus and short rotation coppice cultivation is only at an experimental stage in Germany, it is difficult to foresee the relevant problems linked with its mass cultivation. Therefore, policymakers might encourage the scientific community to contribute with appropriate research.

6.3 Outlook on future research

This study aimed to analyze the future role of alternative powertrains and fuels in the German transport sector with respect to costs, GHG emissions and land area requirement. This study has gone beyond the studies of Remme (2006) and König (2009) by analyzing additional technologies (e.g. hydrated vegetable oils, hybrid electric vehicles) for the transport sector and by applying specific scenarios for the transport sector. However, not all the aspects could be considered in this work.

In this thesis, the production costs rather than the market prices were considered. This approach inevitably disregards the taxes and the implication of the taxation policy of the government. This policy might change the behavior of the customers if different fuels are taxed differently. Disregard of taxes seemed to be reasonable for this study, as the research question is to determine the cost effective powertrain and fuel options considering GHG emissions and land area requirement rather than to forecast the utilization of fuels in the future. However, to model the consumer behavior under the influence of taxes, further studies should consider the government taxation policy.

This study focuses on GHG emissions in terms of environmental aspects. Further studies might consider air pollutants (particularly NO_x, SO_x and particulates) and their negative effects on environment and human beings as well. This analysis would require external costs of different air pollutants and the optimization of social costs (sum of internal and external costs) which would comprise the considerations of local air quality in the analysis.

As this study based on cost optimization, some aspects such as consumer acceptance could not be considered thoroughly. One of the examples is the driving range of the battery electric vehicle. Lower driving ranges would enable easier introduction of this vehicle into the system due to lower vehicle investment costs. However, the acceptance of the customers decreases with lower driving range. A further study might concentrate on the customer acceptance issues particularly for electric vehicles.

An interdisciplinary scientific research is required to evaluate the implications of a mass cultivation of miscanthus and short rotation coppice in Germany. The main focus should be on the environmental effects, such as on biodiversity.

Finally, further studies might take the new federal immission control law (see chapter 1.2) into account after the law is operationalized by the government in the near future.

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Appendix A (Specific costs of vehicle components)

Table A 1: Specific costs of vehicle components

		unit	2010	2030	Source
Powertrains	ICE SI conventional	EUR_{2000}/kW	27.2	42.7	Concawe, 2009
	ICE SI CNG	EUR_{2000}/kW	27.2	36.0	Concawe, 2009
	ICE CI conventional	EUR_{2000}/kW	45.4	57.0	Concawe, 2009
	ICE CI biodiesel	EUR_{2000}/kW	64.2	75.9	IPTS, 2005
	FC	EUR_{2000}/kW	328.3	46.1	Own assumptions based on OECD/IEA, 2005 and Gül, 2008
	EM	EUR_{2000}/kW	16.5	13.2	Graham et al., 2001
Energy storage	Conventional tank (passenger car)	EUR_{2000}/unit	113	113	Concawe, 2009
	Conventional tank (Truck HDV)	EUR_{2000}/unit	474	474	Own assumption based on Concawe, 2009
	Conventional tank (Truck LDV)	EUR_{2000}/unit	178	178	Own assumption based on Concawe, 2009
	Conventional tank (Bus coach)	EUR_{2000}/unit	466	466	Own assumption based on Concawe, 2009
	Conventional tank (Bus public)	EUR_{2000}/unit	311	311	Own assumption based on Concawe, 2009
	Battery	EUR_{2000}/kWh	564.8	188.3	IEA, 2008 and IPTS, 2005
	CNG tank	EUR_{2000}/kWh	5.1	5.1	Concawe, 2009
	Hydrogen tank	EUR_{2000}/kWh	22.6	8.5	OECD/IEA, 2005
Controllers and converters	with AC DC converter	EUR_{2000}/kWel	22.0	14.7	Graham et al., 2001
	without AC DC converter	EUR_{2000}/kWel	16.5	11.0	Graham et al., 2001
Rest of the vehicle	Passenger car	EUR_{2000}/unit	14,670	14,670	Concawe, 2009
	Bus public	EUR_{2000}/unit	247,385	247,385	IEA, 2001
	Bus coach	EUR_{2000}/unit	300,000	300,000	Own assumption based on IEA, 2001
	Truck HDV	EUR_{2000}/unit	70,595	70,595	Own assumptions
	Truck LDV	EUR_{2000}/unit	15,223	15,223	Own assumptions

Appendix B (Dimensions of vehicle components)

Table B 1: Dimensions of passenger car components for different powertrains

	Year	ICE peak power (kW)	Battery size (kWh)	FC peak power (kW)	EM peak power (kW)	Size of H_2/CNG tank (kWh)
SI	2010	75	0	0	0	0
	2030	75	0	0	0	0
CI	2010	75	0	0	0	0
	2030	75	0	0	0	0
FCEV	2010	0	0	75	75	148
	2030	0	0	75	75	135
FCHEV	2010	0	1.3	75	75	135
	2030	0	1.3	75	75	119
HEV SI Mild	2010	75	0.9	0	15	0
	2030	75	0.9	0	15	0
HEV SI full	2010	75	1.3	0	50	0
	2030	75	1.3	0	50	0
Hybrid CI full	2010	75	1.3	0	50	0
	2030	75	1.3	0	50	0
PHEV SI	2010	50	12.7	0	75	0
	2030	50	10.7	0	75	0
BEV	2010	0	39.0	0	75	0
	2030	0	32.8	0	75	0
ICE H2	2010	75	0	0	0	288
	2030	75	0	0	0	225
CNG	2010	75	0	0	0	326
	2030	75	0	0	0	256
RME	2010	75	0	0	0	0
	2030	75	0	0	0	0

Table B 2: Dimensions of public bus components for different powertrains

	Year	ICE peak power (kW)	Battery size (kWh)	FC peak power (kW)	EM peak power (kW)	Size of H_2/CNG tank (kWh)
CI	2010	210	0	0	0	0
	2030	210	0	0	0	0
BEV	2010	0	225	0	210	0
	2030	0	180	0	210	0
CNG	2010	210	0	0	0	1,713
	2030	210	0	0	0	1,646
FCHEV	2010	0	4	210	210	428
	2030	0	4	210	210	376
Hybrid CI full	2010	210	4	0	140	0
	2030	210	4	0	140	0
ICE H2	2010	210	0	0	0	2,163
	2030	210	0	0	0	2,058
PHEV CI	2010	140	113	0	210	0
	2030	140	90	0	210	0
RME	2010	210	0	0	0	0
	2030	210	0	0	0	0

Table B 3: Dimensions of coach components for different powertrains

	Year	ICE peak power (kW)	Battery size (kWh)	FC peak power (kW)	EM peak power (kW)	Size of H_2/CNG tank (kWh)
CI	2010	315	0	0	0	0
	2030	315	0	0	0	0
BEV	2010	0	769	0	315	0
	2030	0	637	0	315	0
CNG	2010	315	0	0	0	2,523
	2030	315	0	0	0	2,424
FCHEV	2010	0	5	315	315	1,036
	2030	0	5	315	315	912
Hybrid CI full	2010	315	5	0	210	0
	2030	315	5	0	210	0
ICE H2	2010	315	0	0	0	3,153
	2030	315	0	0	0	3,030
PHEV CI	2010	210	148	0	315	0
	2030	210	123	0	315	0
RME	2010	315	0	0	0	0
	2030	315	0	0	0	0

Table B 4: Dimensions of heavy duty truck components for different powertrains

	Year	ICE peak power (kW)	Battery size (kWh)	FC peak power (kW)	EM peak power (kW)	Size of H_2/CNG tank for 900 km driving range (kWh)	Size of H_2/CNG tank for 250 km driving range (kWh)
CI	2010	320	0	0	0	0	0
	2030	320	0	0	0	0	0
CNG	2010	320	0	0	0	2,877	799
	2030	320	0	0	0	2,990	830
Hybrid CI full	2010	320	6	0	213	0	0
	2030	320	6	0	213	0	0
RME	2010	320	0	0	0	0	0
	2030	320	0	0	0	0	0

Table B 5: Dimensions of light duty truck components for different powertrains

	Year	ICE peak power (kW)	Battery size (kWh)	FC peak power (kW)	EM peak power (kW)	Size of H_2/CNG tank for 900 km driving range (kWh)	Size of H_2/CNG tank for 250 km driving range (kWh)
CI	2010	120	0	0	0	0	0
	2030	120	0	0	0	0	0
CNG	2010	120	0	0	0	944	262
	2030	120	0	0	0	917	255
Hybrid CI full	2010	120	2	0	80	0	0
	2030	120	2	0	80	0	0
RME	2010	120	0	0	0	0	0
	2030	120	0	0	0	0	0
SI	2010	120	0	0	0	0	0
	2030	120	0	0	0	0	0

Appendix C (Investment costs of vehicle components)

The additional investment costs presented in this chapter do not include the battery replacement costs. However, they are considered separately in this study. See chapter 5.1 for battery replacement costs.

Table C 1: Investment costs of passenger cars differentiated for components (own calculation)

EUR_{2000}		Powertrain			Energy storage		Controller & converters	Rest of the car	SUM	Additional cost
	Year	ICE	FC	EM	Fuel tank	Battery				
SI	2010	2,042	0	0	113	0	0	14,670	**16,825**	**0**
	2030	3,203	0	0	113	0	0	14,670	**17,987**	**0**
CI	2010	3,403	0	0	113	0	0	14,670	**18,186**	**1,361**
	2030	4,278	0	0	113	0	0	14,670	**19,061**	**1,074**
FCEV	2010	0	24,623	1,234	3,362	0	1,234	14,670	**45,122**	**28,297**
	2030	0	3,460	987	1,144	0	823	14,670	**21,084**	**3,097**
FCHEV	2010	0	24,623	1,234	3,053	734	1,234	14,670	**45,548**	**28,723**
	2030	0	3,460	987	1,007	245	823	14,670	**21,192**	**3,205**
HEV SI Mild	2010	2,042	0	247	113	508	247	14,670	**17,827**	**1,002**
	2030	3,203	0	197	113	169	165	14,670	**18,518**	**531**
HEV SI full	2010	2,042	0	823	113	734	823	14,670	**19,205**	**2,380**
	2030	3,203	0	658	113	245	548	14,670	**19,438**	**1,451**
Hybrid CI full	2010	3,403	0	823	113	734	823	14,670	**20,566**	**3,741**
	2030	4,278	0	658	113	245	548	14,670	**20,512**	**2,525**
PHEV SI	2010	1,361	0	1,234	113	7,173	1,651	14,670	**26,202**	**9,377**
	2030	2,136	0	987	113	2,014	1,100	14,670	**21,021**	**3,034**
BEV	2010	0	0	1,234	0	22,026	1,651	14,670	**39,581**	**22,756**
	2030	0	0	987	0	6,171	1,100	14,670	**22,928**	**4,941**
ICE H2	2010	2,350	0	0	6,513	0	0	14,670	**23,533**	**6,708**
	2030	2,514	0	0	1,913	0	0	14,670	**19,097**	**1,110**
CNG	2010	2,042	0	0	1,668	0	0	14,670	**18,380**	**1,555**
	2030	2,702	0	0	1,307	0	0	14,670	**18,678**	**691**
RME	2010	4,815	0	0	113	0	0	14,670	**19,598**	**2,773**
	2030	5,689	0	0	113	0	0	14,670	**20,473**	**2,486**

Table C 2: Investment costs of public buses differentiated for cost components (own calculation)

EUR$_{2000}$	Year	Powertrain			Energy storage		Controller & converters	Rest of the bus	**SUM**	**Additional cost**
		ICE	FC	EM	Fuel tank	Battery				
CI	2010	9,529	0	0	311	0	0	247,385	**257,224**	**0**
	2030	11,977	0	0	311	0	0	247,385	**259,673**	**0**
BEV	2010	0	0	3,455	0	127,331	4,622	247,385	**382,793**	**125,568**
	2030	0	0	2,764	0	33,955	3,081	247,385	**287,184**	**27,512**
CNG	2010	5,717	0	0	8,761	0	0	247,385	**261,864**	**4,639**
	2030	7,565	0	0	8,420	0	0	247,385	**263,369**	**3,696**
FCHEV	2010	0	68,943	3,455	9,685	2,056	3,455	247,385	**334,979**	**77,755**
	2030	0	9,689	2,764	3,196	685	2,304	247,385	**266,023**	**6,350**
Hybrid CI full	2010	9,529	0	2,304	311	2,056	2,304	247,385	**263,887**	**6,663**
	2030	11,977	0	1,842	311	685	1,536	247,385	**263,736**	**4,063**
ICE H2	2010	6,581	0	0	48,967	0	0	247,385	**302,933**	**45,709**
	2030	7,039	0	0	17,471	0	0	247,385	**271,895**	**12,222**
PHEV CI	2010	3,812	0	3,455	311	63,665	4,622	247,385	**323,250**	**66,025**
	2030	5,980	0	2,764	311	16,977	3,081	247,385	**276,498**	**16,825**
RME	2010	13,482	0	0	311	0	0	247,385	**261,178**	**3,953**
	2030	15,930	0	0	311	0	0	247,385	**263,626**	**3,953**

Table C 3: Investment costs of coaches differentiated for cost components (own calculation)

EUR$_{2000}$	Year	Powertrain			Energy storage		Controller & converters	Rest of the bus	**SUM**	**Additional cost**
		ICE	FC	EM	Fuel tank	Battery				
CI	2010	14,293	0	0	466	0	0	300,000	**314,759**	**0**
	2030	17,966	0	0	466	0	0	300,000	**318,432**	**0**
BEV	2010	0	0	5,183	0	434,158	6,933	300,000	**746,274**	**431,514**
	2030	0	0	4,145	0	119,993	4,622	300,000	**428,761**	**110,329**
CNG	2010	8,576	0	0	12,901	0	0	300,000	**321,477**	**6,717**
	2030	11,347	0	0	12,398	0	0	300,000	**323,745**	**5,313**
FCHEV	2010	0	103,415	5,183	23,460	3,084	5,183	300,000	**440,325**	**125,566**
	2030	0	14,534	4,145	7,742	1,028	3,455	300,000	**330,905**	**12,473**
Hybrid CI full	2010	14,293	0	3,455	466	3,084	3,455	300,000	**324,754**	**9,995**
	2030	17,966	0	2,764	466	1,028	2,304	300,000	**324,527**	**6,095**
ICE H2	2010	9,872	0	0	71,388	0	0	300,000	**381,260**	**66,501**
	2030	10,558	0	0	25,726	0	0	300,000	**336,284**	**17,852**
PHEV CI	2010	5,717	0	5,183	466	83,492	6,933	300,000	**401,791**	**87,032**
	2030	8,970	0	4,145	466	23,076	4,622	300,000	**341,279**	**22,847**
RME	2010	20,223	0	0	466	0	0	300,000	**320,690**	**5,930**
	2030	23,896	0	0	466	0	0	300,000	**324,362**	**5,930**

Table C 4: Investment costs of heavy duty trucks differentiated for cost components (own calculation)

EUR$_{2000}$	Year	Powertrain ICE	Powertrain FC	Powertrain EM	Energy storage Fuel tank	Energy storage Battery	Controller & converters	Rest of the truck	**SUM**	**Additional cost**
CI	2010	14,520	0	0	474	0	0	70,595	**85,589**	**0**
	2030	18,251	0	0	474	0	0	70,595	**89,319**	**0**
CNG (long driving range)	2010	8,712	0	0	14,713	0	0	70,595	**94,020**	**8,432**
	2030	11,527	0	0	14,139	0	0	70,595	**96,261**	**6,942**
CNG (short driving range)	2010	8,712	0	0	4,087	0	0	70,595	**83,394**	**-2,195**
	2030	11,527	0	0	3,928	0	0	70,595	**86,050**	**-3,270**
Hybrid CI full	2010	14,520	0	3,510	474	3,133	3,510	70,595	**95,742**	**10,153**
	2030	18,251	0	2,808	474	1,044	2,340	70,595	**95,511**	**6,192**
RME	2010	20,544	0	0	474	0	0	70,595	**91,613**	**6,024**
	2030	24,275	0	0	474	0	0	70,595	**95,344**	**6,024**

Table C 5: Investment costs of light duty trucks differentiated for cost components (own calculation)

EUR$_{2000}$	Year	Powertrain ICE	Powertrain FC	Powertrain EM	Energy storage Fuel tank	Energy storage Battery	Controller & converters	Rest of the truck	**SUM**	**Additional cost**
CI	2010	5,445	0	0	178	0	0	15,223	**20,846**	**0**
	2030	6,844	0	0	178	0	0	15,223	**22,245**	**0**
CNG (long driving range)	2010	3,267	0	0	4,829	0	0	15,223	**23,319**	**2,473**
	2030	4,323	0	0	4,691	0	0	15,223	**24,237**	**1,992**
CNG (short driving range)	2010	3,267	0	0	1,341	0	0	15,223	**19,831**	**-1,014**
	2030	4,323	0	0	1,303	0	0	15,223	**20,849**	**-1,396**
Hybrid CI full	2010	5,445	0	1,316	178	1,175	1,316	15,223	**24,653**	**3,807**
	2030	6,844	0	1,053	178	392	878	15,223	**24,567**	**2,322**
MeOH	2010	4,067	0	0	178	0	0	15,223	**19,468**	**-1,378**
	2030	5,926	0	0	178	0	0	15,223	**21,326**	**-918**
RME	2010	7,704	0	0	178	0	0	15,223	**23,105**	**2,259**
	2030	9,103	0	0	178	0	0	15,223	**24,504**	**2,259**
SI	2010	3,267	0	0	178	0	0	15,223	**18,668**	**-2,178**
	2030	5,126	0	0	178	0	0	15,223	**20,526**	**-1,718**

Appendix D (Fuel consumption and emission factors of motorcycles and mopeds)

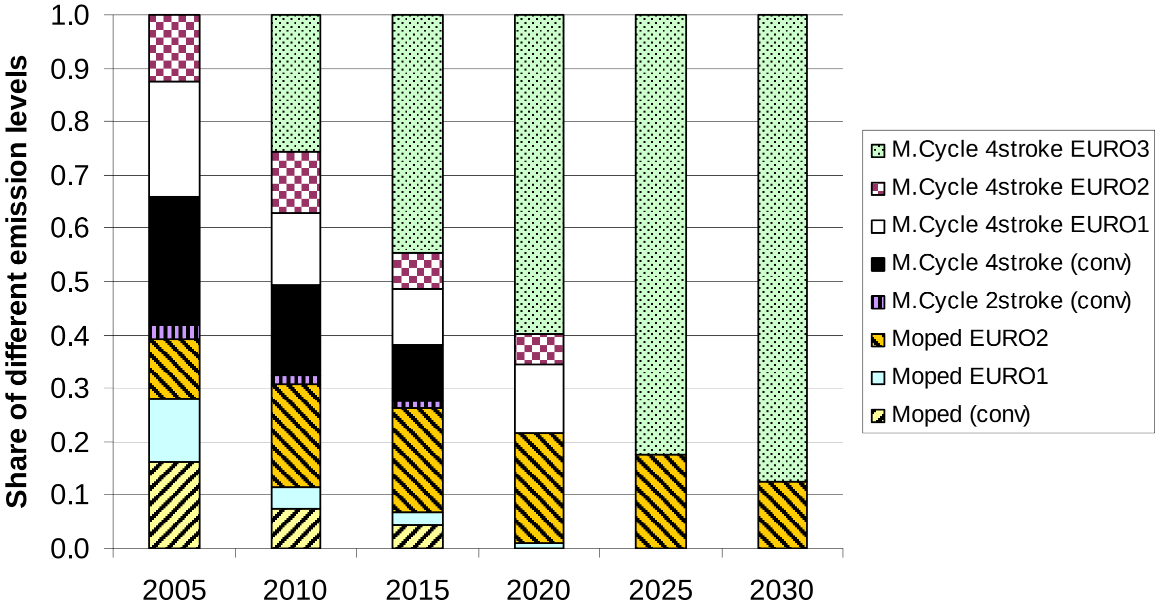

Figure D 1: Projected share of emission regulation levels for the German motorcycle and moped fleet (updated from IFEU, 2005)

Table D 1: Present and projected tank to wheel fuel consumption and emission factors of the German motorcycle and moped fleet

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100vkm	4.2	3.9	3.8	3.6	3.3	3.4
CO_2 emissions	g CO_2/vkm	97.7	91.3	88.4	83.8	77.2	79.1
CO_{2eq} emissions	g CO_{2eq}/vkm	100.5	93.5	90.2	85.0	78.6	80.2

Appendix E (Fuel consumption and emission factors of non-road transport modes)

Table E 1: Present and projected tank to wheel fuel consumption and emission factors of the German passenger rail transport with compression ignition engine

		2005	2010	2015	2020	2025	2030
Short distance (<50 km)							
Fuel consumption	l/100pkm	3.2	3.0	2.8	2.6	2.6	2.6
	MJ/pkm	1.1	1.1	1.0	0.9	0.9	0.9
CO_2 emissions	g CO_2/pkm	84.1	78.9	74.3	70.1	69.3	68.6
CO_{2eq} emissions	g CO_{2eq}/pkm	84.4	79.2	74.5	70.3	69.6	68.8
Long distance (>50 km)							
Fuel consumption	l/100pkm	2.8	2.6	2.5	2.3	2.3	2.3
	MJ/pkm	1.0	0.9	0.9	0.8	0.8	0.8
CO_2 emissions	g CO_2/pkm	74.5	69.9	65.8	62.2	61.6	61.0
CO_{2eq} emissions	g CO_{2eq}/pkm	74.9	70.2	66.1	62.4	61.8	61.2

Table E 2: Present and projected tank to wheel fuel consumption and emission factors of the German freight rail transport with compression ignition engine

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100tkm	1.2	1.2	1.2	1.2	1.2	1.2
	MJ/tkm	0.4	0.4	0.4	0.4	0.4	0.4
CO_2 emissions	g CO_2/tkm	32.2	31.9	31.6	31.3	31.0	30.7
CO_{2eq} emissions	g CO_{2eq}/tkm	32.4	32.0	31.7	31.4	31.1	30.7

Table E 3: Present and projected onboard fuel consumption and emission factors of the German freight inland ship transport with compression ignition engine

		2005	2010	2015	2020	2025	2030
Fuel consumption	l/100tkm	0.6	0.6	0.6	0.5	0.5	0.5
	MJ/tkm	0.2	0.2	0.2	0.2	0.2	0.2
CO_2 emissions	g CO_2/tkm	15.3	15.0	14.8	14.5	14.5	14.5
CO_{2eq} emissions	g CO_{2eq}/tkm	15.4	15.1	14.8	14.6	14.6	14.6

Table E 4: Present and projected onboard fuel consumption and emission factors of the German aviation

		2005	2010	2015	2020	2025	2030
Passenger							
Fuel consumption	MJ/pkm	0.67	0.98	1.07	1.15	1.17	1.16
CO_2 emissions	g CO_2/pkm	49.1	72.1	78.5	84.2	85.7	85.2
CO_{2eq} emissions	g CO_{2eq}/pkm	49.2	72.2	78.7	84.4	85.8	85.3
Freight							
Fuel consumption	MJ/tkm	14.92	10.16	9.33	8.70	8.55	8.60
CO_2 emissions	g CO_2/tkm	1,092.9	744.4	683.2	637.0	626.1	629.7
CO_{2eq} emissions	g CO_{2eq}/tkm	1,094.7	745.5	684.2	637.9	627.0	630.6

Table E 5: Present and projected tank to wheel energy consumption and emission factors of the German passenger electric rail transport

		2005	2010	2015	2020	2025	2030
Short distance (<50 km)							
Energy consumption	MJ/100pkm	55.7	52.3	49.2	46.4	46.0	45.5
CO_2 emissions	g CO_2/pkm	0.0	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/pkm	0.0	0.0	0.0	0.0	0.0	0.0
Long distance (>50 km)							
Energy consumption	MJ/100pkm	28.6	26.9	25.3	23.9	23.7	23.4
CO_2 emissions	g CO_2/pkm	0.0	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/pkm	0.0	0.0	0.0	0.0	0.0	0.0

Table E 6: Present and projected tank to wheel energy consumption and emission factors of trams in Germany

		2005	2010	2015	2020	2025	2030
Energy consumption	MJ/100pkm	39.4	39.0	38.7	38.3	37.9	37.5
CO_2 emissions	g CO_2/pkm	0.0	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/pkm	0.0	0.0	0.0	0.0	0.0	0.0

Table E 7: Present and projected tank to wheel energy consumption and emission factors of the German freight electric rail transport

		2005	2010	2015	2020	2025	2030
Energy consumption	MJ/100tkm	14.38	14.24	14.10	13.96	13.82	13.68
CO_2 emissions	g CO_2/tkm	0.0	0.0	0.0	0.0	0.0	0.0
CO_{2eq} emissions	g CO_{2eq}/tkm	0.0	0.0	0.0	0.0	0.0	0.0

Appendix F (Specific investment costs of plants depending on the plant capacity)

Table F 1: Specific investment costs of plants depending on the plant capacity

Capacity	Total investment costs [a]	Specific investment costs [b]
1	100.0	100.0
2	160.0	80.0
4	256.0	64.0
8	409.6	51.2
16	655.4	41.0

a) it is assumed that the investment costs increase 60% when the capacity doubles (Henniges, 2007)
b) The specific investment costs (y) are represented with the equation (y=100 $x^{-0.3219}$), where x is the ratio of the latter and former capacity.

Appendix G (Electricity generation pathways)

Table G 1: Electricity generation pathways considered in this work

Technology
Hydropower
Landfill gas
Waste incineration
Geothermal
Wind (offshore)
Wind (onshore)
Photovoltaic
Biogas “onsite”
Wood/straw gasification CHP “onsite”
Biogas and gasification “offsite” via SNG
Wood/straw CHP
Wood/straw ORC
Wood/straw steam turbine
Wood/straw combined cycle
Wood co-firing with coal
Vegetable oil CHP
Sewage gas
Coal power plant
Coal CHP
Coal combined cycle
Coal integrated gasification combined cycle (IGCC)
Lignite power plant
Lignite IGCC
Natural gas – gas turbine
Natural gas combined cycle
Nuclear power plants
Diesel/fuel oil generators
Hydrogen powered solid oxide fuel cell (SOFC)
Hydrogen powered molten carbonate fuel cell (MCFC)
Hydrogen powered polymer electrolyte fuel cell (PEFC)

Appendix H (Conversion of monetary values into EUR_{2000})

Table H 1: Conversion of 100 EUR in different years into EUR_{2000}

Year	Inflation rate* %	EUR	Corresponding EUR_{2000} value
1995	1.80		106.46
1996	1.40		104.99
1997	1.90		103.03
1998	1.00		102.01
1999	0.60		101.40
2000	1.40		100.00
2001	1.90		98.13
2002	1.36	100.00	96.82
2003	1.03		95.83
2004	1.79		94.15
2005	1.92		94.13
2006	1.78		90.75
2007	2.28		88.73
2008	2.75		86.36
2009	0.14		86.24

*) IMF, 2009

Table H 2: Conversion of 100 US dollar in different years into EUR_{2000}

Year	Conversion rate* EUR/$	$	EUR	Corresponding EUR_{2000} value
1995	0.76		76.41	81.35
1996	0.80		79.88	83.86
1997	0.89		88.54	91.22
1998	0.82		81.63	83.27
1999	0.94		93.88	95.19
2000	1.09		108.62	108.62
2001	1.12		111.77	109.69
2002	0.97	100.00	96.72	93.64
2003	0.89		89.29	85.57
2004	0.80		80.49	75.77
2005	0.80		80.17	75.47
2006	0.80		79.63	72.27
2007	0.73		73.05	64.82
2008	0.67		66.57	57.49
2009	0.72		72.05	62.14

*) Monthly average conversion rates are taken from (Gocurrency, 2010)

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