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Long-term optimization of the transport sector to address greenhouse gas reduction targets under rapid growth – Application of an energy system model for Gauteng province, South Africa

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Long-term optimization of the transport sector to address greenhouse gas reduction targets under rapid growth

Application of an energy system model for Gauteng province, South Africa

Von der Fakultät Energie-, Verfahrens- und Biotechnik der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von
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Preface

This thesis was conducted within the research project “EnerKey: Energy as a key element of an Integrated Climate Protection Concept for the City Region of Gauteng” (www.enerkey.info), which took place from 2008–2013. The project was conducted in the framework of the research programme “Research for Sustainable Development of the Megacities of Tomorrow – Energy- and climate-efficient structures in urban growth centres” of the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF, refer to www.future-megacities.org for further information). I would like to acknowledge and thank for the support of all colleagues involved in that project:

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- The Institute for Futures Studies and Technology Assessment developed the stakeholder participation process for the iterative energy planning process through their “EnerKey long-term perspective group” (ELPG). Furthermore, they were responsible for a consistent scenario umbrella, which covered plausible future developments of socio-economic drivers for Gauteng.
- The Fraunhofer Institute of Building Physics developed the “EnerKey adviser” tool, which allows analysing the energy demand patterns of various buildings types and energy conservation measures.
- TÜV Rheinland Carbon Services developed an emission inventory and specific energy consumption figures for road based transport modes in Gauteng, which are used in this thesis. Furthermore, they developed an emission-modelling tool, which allows for spatial distribution of road transport emission within the Province.
- The Energy Supply Technologies and Systems group evaluated the techno-economic and environmental performance of available and future technologies for using renewable energy, especially focussing on solar energy technologies.

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Abbreviations

Acronym	**Definition**
ACSA	Airports Company South Africa
ADAC	Allgemeiner deutscher Automobilclub, München
AFA	Annual availability factor
ANF	Annuity factor
ATZ	*Automobiltechnische Zeitschrift*
BAU	Business as usual
bbl	Barrel
BEV	Battery electric vehicle
BLS	U.S. Bureau of Labor Statistics, Washington DC
BMBF	Bundesministerium für Bildung und Forschung, Berlin
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Berlin
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung, Berlin
BRT	Bus rapid transit
BTL	Biomass to liquid
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CDM	Clean development mechanism
CEF	Central Energy Fund, Johannesburg
CGS	Council for Geoscience, Pretoria, South Africa
CI	Compressed ignition
CNG	Compressed natural gas
COJ	City of Johannesburg
CONCAWE	Conservation of Clean Air and Water in Europe
conv	Conventional
COT	City of Tshwane
CPES	Center for Power Electronics Systems, Virginia
CPI	Consumer price index
CSIR	Council for Scientific and Industrial Research, Pretoria
CSP	Concentrated solar power
CTL	Coal to liquid
DEA	Department of Environmental Affairs and Tourism, Pretoria
DIW	Deutsches Institut für Wirtschaftsforschung, Berlin
DLGH	Department of Local Government and Housing, Johannesburg
DLR	Deutsches Zentrum für Luft- und Raumfahrt, Berlin
DME	Department of Minerals and Energy Affairs, Pretoria

Acronym	**Definition**
DNT	Department National Treasury, Republic of South Africa, Pretoria
DOE	Department of Energy, Pretoria
DOT	Department of Transport, Pretoria
DST	Diesel (distillate)
DWAF	Department of Water Affairs and Forestry, Pretoria
EBTP	European Biofuels Technology Platform
ECE	Economic Commission for Europe
EFOM	Energy flow optimization
EIA	U.S. Energy Information Administration, Washington DC
EM	Electric motor
EMME	Equilibre multimodal/ multimodal equilibrium
ENERKEY	Energy as a Key Element of an Integrated Climate Protection Concept for the City Region of Gauteng
EOH	Ethanol
ERC	Energy Research Centre, Cape Town
ETAG	European Technology Assessment Group
ETH	Eidgenössische Technische Hochschule, Zürich
ETSAP	Energy Technology Systems Analysis Program
EUR	Euro
FAEE	Fatty acid ethyl ester
FAME	Fatty acid methyl ester
FAO	Food and Agriculture Organization of the United Nations, New York
FBC	Fluidized bed combustion
FC	Fuel cell
FCC	Fluid catalyst cracking
FCHEV	Fuel cell hybrid electric vehicle
FEC	Final energy consumption
FED	Federal Reserve System, Washington DC
FGD	Flue gas desulphurisation
FICFB	Fast internally circulating fluidized bed
FNR	Fachagentur Nachwachsende Rohstoffe, Gülzow
FOM	Fixed operating and maintenance costs
FT	Fischer-Tropsch
FTS	Fischer-Tropsch synthesis
GAIN	Global Agricultural Information Network, Washington DC
GAMS	General Algebraic Modelling System

Acronym	**Definition**
GATACO	Gauteng Taxi Council
GCRO	Gauteng City-Region Observatory, Johannesburg
GDP	Gross domestic product
GDPR	Gross domestic product by region
GDPTRW	Gauteng Department of Public Transport, Roads and Works
GEECO	Gauteng Energy and Emission Cost Optimisation
GEF	Global Environment Facility of the UNDP, Washington DC
GEMIS	Globales Emissions-Modell Integrierter Systeme
GHG	Greenhouse gas
GIES	*Gauteng Integrated Energy Strategy*
GIS	Geographic information system
GMM	Global Multi-regional MARKAL model
GNI	Gross national income
GNTA	Gauteng National Taxi Alliance
GPG	Gauteng Provincial Government, Johannesburg
GPS	Global Positioning System
GSL	Petrol (gasoline)
GTL	Gas to liquid
GTS	*Gauteng Transportation Study*
HBEFA	*Handbook Emission Factors for Road Transport*
HCCI	Homogeneous charge compression ignition
HDSAM	Hydrogen Delivery Scenario Model
HDV	Heavy duty vehicle
HEV	Hybrid electric vehicle
hh	Household
IAÖ	Institut für angewandte Ökologie, Darmstadt
ICE	Internal combustion engine
ICIS	Chemical Industry News & Chemical Market Intelligence
IEA	International Energy Agency, Paris
IEEE	Institute of Electrical and Electronics Engineers, Washington DC
IER	Institut für Energiewirtschaft und Rationelle Energieanwendung, Stuttgart
IEW	International Energy Workshop
IGCC	Integrated gasification combined cycle
IGU	International Gas Union, Oslo
IMF	International Monetary Fund, Washington DC
IPCC	International Plant Protection Convention

Acronym	**Definition**
IRP	Integrated Resource Plan Electricity
ISES	International Solar Energy Society, Freiburg
ITDP	Institute for Transportation and Development Policy, New York
IZT	Institute for Future Studies and Technology Assessment, Berlin
JODIDB	*Joint Oil Data Initiative Database*
LCA	Life-cycle assessment
LDV	Light duty vehicle
LEAP	Long-range Energy Alternatives Planning System
LHV	Lower heating value
LPG	Liquefied petroleum gas
LTMS	Long-term mitigation scenarios
MACC	Marginal abatement costs curve
MARKAL	Market allocation
MATSim	Multi Agent-Based Transport Simulations
MBI	MBendi Information Services, Cape Town
NATIS	National Transportation Information System
NATMAP	*South African National Transport Master Plan*
NEA	Nuclear Energy Agency, Issy-les-Moulineaux
NETL	National Energy Technology Laboratory, Washington DC
NLR	National Aerospace Laboratory, Amsterdam
NMT	Non-motorized transport
NPC	National Petroleum Council, Washington DC
NREL	National Renewable Energy Laboratory, Golden
OCGT	Open cycle gas turbine
OECD	Organization for Economic Co-operation and Development, Paris
OPEC	Organization of the Petroleum Exporting Countries, Vienna
ÖPNV	Öffentlicher Personennahverkehr
PEC	Primary energy consumption
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PHEV	Plug-in hybrid electric vehicle
pkm	Person kilometre
PTIF	Public Transport Infrastructure and System Fund
PV	Photovoltaics
PWR	Pressurized water reactor
RDP	Reconstruction and Development Programme
REC	Renewable energy consumption

Acronym	**Definition**
RES	Reference energy system
RME	Rapeseed methyl ester
RTMC	Road Traffic Management Corporation, Pretoria
SANERI	South African National Research Energy Institute, Pretoria
SANRAL	South African National Roads Agency, Pretoria
SAPIA	South African Petroleum Association, Sandton
SARCC	South African Rail Commuter Corporation, Braamfontein
SAS	Sasol Advanced Synthol process
SATC	Southern Africa Transport Conference
SI	Spark ignition
SNG	Substitute natural gas
SPD	Sasol Slurry Phase Distillate process
SQL	Structured Query Language
STATSSA	Statistics South Africa, Pretoria
SUTP	Sustainable Urban Transport Project
SUV	Sports utility vehicle
SWD	Stadtwerke Düsseldorf AG
TEMT	Transport Emission Modelling Tool
TIMES	The integrated MARKAL-EFOM system
tkm	Tonne kilometre
TRP	The (minibus) taxi recapitalization programme
TTW	Tank-to-wheel
TÜV	Technischer Überwachungs-Verein, Deutschland
UCT	University of Cape Town, South Africa
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	US dollar
USDOE	US Department of Energy, Washington DC
V2G	Vehicle-to-grid
VDI	Verein Deutscher Ingenieure, Stuttgart
VEDA	Versatile Data Analyst
vkm	Vehicle kilometre
VOC	Volatile organic compound
VOM	Variable operating and maintenance costs
WBCSD	World Business Council on Sustainable Development, Geneva
WEC	World Energy Council, London
WEO	*World Energy Outlook*

Acronym	Definition
WTT	Well-to-tank
WTW	Well-to-wheel
WWF	World Wildlife Fund, Washington DC
XTL	Fischer-Tropsch fuels
ZAR	South African rand

Abstract

The transport sector is seen as one of the key factors for driving future energy consumption and greenhouse gas (GHG) emissions. Especially in developing countries, significant growth in transport demand is expected. Gauteng province, as the economic centre of South Africa and transport hub for the whole of southern Africa, is one emerging urban region that faces rapid growth. However, the province is on its way to playing a leading role for supporting ways to adapt to climate change and mitigate GHG emissions.

Conversely, there is a lack of scientific research on the promising measures for GHG mitigation in the transport sector. For the rapidly growing transport sector of the province in particular, research is focused primarily on extending and structuring the road infrastructure. Moreover, it is important that the transport sector is considered as part of the whole energy system, as significant contributions to GHG emissions and the associated costs arise from energy supply, provision and conversion.

This research is the first application of an integrated energy system model (i.e. the TIMES-GEECO model) for the optimization of the transport sector of Gauteng. Optimizing energy system models allows finding least-cost measures for various scenarios, by considering dependencies and interlinkages in the energy system as well as environmental constraints. To do so, the transport sector and the energy supply sector had to be incorporated into the model application in terms of the characteristics of a developing urban region, which includes all relevant transport modes, vehicle technologies, fuel options, vehicle-to-grid energy storage, the consideration of road types as well as explicit expansions of the public transport system and income-dependent travel demand modelling. Additionally, GHG mitigation options outside the provincial boundaries were incorporated to allow for mitigation at least cost and to consider regional resource availability. Moreover, in TIMES-GEECO, the other demand sectors (such as residential or industry) are also represented.

In this thesis, a comprehensive analysis was conducted of alternative fuels, vehicle technologies as well as transport infrastructure for the transport sector of Gauteng. As a result, there are many possibilities of reducing GHG emissions and/or of increasing energy efficiency in the transport sector by using alternative fuels or vehicle technologies. In scenario analysis, it was recognized that under current policies significant growth in both energy consumption and climate emissions can be expected in Gauteng. Marginal GHG abatement cost curves have been calculated, which permit the identification of least-cost mitigation measures for the transport sector under consideration of the whole energy system. It was shown that biofuels from waste cooking oil and cellulosic biomass as well as the substitution of fossil synthetic fuels with crude oil products could result in significant GHG emission reductions. Moreover, hybrid vehicles offer prospects for increasing energy efficiency and reducing GHG emissions at low marginal mitigation costs, where, it was identified that measures should first be applied for vehicles with high annual mileages such as buses, minibuses and heavy-duty vehicles (HDVs). However, the analysis also showed that the transport sector is not the first sector to address for GHG mitigation as significant mitigation potentials with low associated costs lie in the provision of electricity and in the supply of fuels.

Kurzfassung

Der Verkehrssektor wird als einer der zentralen Treiber der zukünftigen Entwicklung von Energieverbrauch und Treibhausgasemissionen (THG) angesehen. Vor allem in Entwicklungsländern ist von einem starken Anstieg der Transportnachfrage auszugehen. Die Provinz Gauteng, das ökonomische Zentrum Südafrikas, ist eine urbane Region, der eine Phase solch schnellen Wachstums prognostiziert wird. Die Provinzregierung sieht hierin die Möglichkeit, eine Vorbildfunktion einzunehmen und den Klimaschutz voranzutreiben.

Andererseits liegen nur wenige Forschungsergebnisse vor, welche die Effekte und Kosten von Klimaschutzmaßnahmen im Verkehrssektor für Gauteng quantifizieren. Bisherige Forschungsaktivitäten richteten ihren Fokus vor allem auf verkehrsplanerische Maßnahmen, wie etwa die Erweiterung der Verkehrsinfrastruktur. Auch die vorgelagerten Emissionen des Verkehrssektors Gautengs fanden bisher wenig Beachtung.

Die vorliegende Arbeit ist die erste Anwendung eines integrierten Energiesystemansatzes (TIMES-GEECO) zur Optimierung des Verkehrssektors von Gauteng. Mit Energiesystemmodellen ist es möglich, kostenminimale Maßnahmen zur Erreichung von szenarioabhängigen Zielen, unter Berücksichtigung von Abhängigkeiten und Verflechtungen im Energiesystem zu identifizieren und dabei Klimaschutzziele zu berücksichtigen. Um dies zu erreichen, wurde in dieser Arbeit der Verkehrssektor und die Energiebereitstellung im Modell abgebildet, unter besonderer Berücksichtigung aller relevanten Verkehrsmodi, Fahrzeugtechnologien, alternativen Kraftstoffe, „vehicle-to-grid“ Energiespeicherung, unterschiedlicher Fahrzustände als auch möglicher Erweiterungen der öffentlichen Verkehrsinfrastruktur und einkommensbasierter Verkehrsbedarfsberechnung. THG-Minderungsoptionen außerhalb der Provinzgrenzen von Gauteng auf Basis der regionalen Verfügbarkeit von Ressourcen als auch andere Nachfragesektoren (z. B. Haushalte, Industrie) sind ebenfalls in der Modellierung berücksichtigt.

Es wurde eine umfassende Analyse der alternativen Kraftstoffe, Fahrzeugtechnologien und Infrastrukturerweiterungen für den Verkehrssektor Gauteng durchgeführt und viele Möglichkeiten zur Reduzierung der THG-Emissionen und / oder zur Erhöhung der Energieeffizienz im Verkehrssektor durch alternative Treibstoffe oder Antriebssysteme identifiziert. Die Szenarioanalyse hat gezeigt, dass mit der gegenwärtigen Politik ein deutliches Wachstum sowohl im Energieverbrauch als auch der THG-Emissionen in Gauteng verbunden wäre. Um die kostenoptimalen Klimaschutzmaßnahmen im Verkehrssektor unter Berücksichtigung des Energiesystems zu bestimmen, wurden THG-Minderungskurven berechnet. Biokraftstoffe aus Altspeiseöl und solche aus zweiter Generation, sowie die Substitution von synthetischen Kraftstoffen fossilen Ursprungs durch Erdölprodukte könnten demnach zur Verringerung der THG-Emissionen beitragen. Darüber hinaus bieten Hybridfahrzeuge Möglichkeiten zur Steigerung der Energieeffizienz und zur Verringerung von THG-Emissionen. Hier sollten zunächst Fahrzeuge mit höheren jährlichen Laufleistungen wie Busse und schwere Nutzfahrzeuge (HDV) betrachtet werden. Allerdings zeigte die Analyse auch, dass der Verkehrssektor nicht der primäre Sektor ist der zur THG-Minderung zu adressieren ist. Die kostengünstigsten Möglichkeiten liegen in der Strombereitstellung und Kraftstoffversorgung.

1 Introduction and scope of the analysis

While transport-related emissions of air pollutants, e.g. NO_x, VOC, CO and particulates, have been reduced significantly in industrialised countries in the last 20 years due to strict emission legislation, global transport GHG emissions grew by 45% between 1990 and 2007 /IEA 2010k/, /WBCSD 2004/. These are the fastest growth rates of GHG emissions among all energy-consuming sectors worldwide /Bertaud et al. 2009/. In 2010 the transport sector accounted for about 23% of global CO_2 emissions from fuel combustion, which is also a consequence of the high fossil fuel dependency (about 98%) of the sector /IEA 2010k/, /Bertaud et al. 2009/.

Climate change and the need for intervention and adaption have been identified as needing serious attention in many countries worldwide (see e.g. /BMU 2011/ or /DEA 2004/). In order to stop or limit global GHG emissions, strategies have been developed in many countries around the world. South Africa, for example, developed its so called Long-term Mitigation Scenarios (LTMS) in the framework of the United Nations Framework Convention on Climate Change (UNFCCC) to show the interventions needed to reduce GHG emissions to reach a global warming target of 2 degrees Celsius /Winkler 2007/. One of the proposed measures for reducing greenhouse gas emissions in South Africa is the implementation of carbon taxes based on CO_2 equivalents for all energy consuming sectors /Winkler 2007/, /DNT 2010/. However, the rate at which such a tax should be applied (an amount of 120 ZAR/t CO_2eq has been proposed) is still under discussion as well as possible exemptions for energy-intensive industries /DNT 2013/.

Gauteng province is the economic and socio-economic centre of South Africa, in which about one fifth of the country's population lives, and generates about one third of the national GDP (gross domestic product) /StatsSA 2010a/, /StatsSA 2011/. The province sees its dominance for the country as a duty and as a chance to provide innovative leadership for the whole nation in terms of the future structure of energy supply and use /Madumo 2010/. It has developed its own Gauteng Integrated Energy Strategy (GIES) to demonstrate the sustainable use of energy /DLGH 2010/.

In the field of transport as well, Gauteng sees an opportunity to be a national leader and to investigate several options for GHG mitigation including LPG and CNG vehicles as well as options for biofuel production and utilization /Madumo 2010/, /GDPTRW 2010/, /Smit 2011/. Although those strategies recognize the urgency and importance of taking options in the transport sector, they do not give a clear analysis of cost-optimal measures for transport energy supply and use /Winkler 2007/, /DLGH 2010/. Moreover, they do not imply specific options for Gauteng as part of the national energy system and do not provide a clear strategy for how Gauteng's transport sector could and should develop in the future /Winkler 2007/, /DLGH 2010/.

Consequently, this study aims to quantify the opportunities for alternative technologies, alternative fuels and the expansion of public transport system for Gauteng and to deduce least-cost options for the province for different future scenarios. The marginal abatement-cost curves derived in this thesis provide a basis for formulating action plans for policy recommendations.

Marginal abatement-cost curves (MACC) – sometimes also referred to as cost potential curves or technology costs curves – allow the quantification of cost-optimal measures for GHG emission reductions (see e.g. /McKinsey 2009/, /Kesicki 2010/, /Schroten et al. 2012/, /Bockel et al. 2012/). Using MACCs it is possible to show the necessary measures for any given mitigation target and the associated marginal abatement costs. In general, there are two different approaches for creating MACCs: static (or expert based) MACCs, which address single measures at a given point in time, and (energy) model-based MACCs that take into account the interactions, dynamics and dependencies between measures /Kesicki 2011/. Both concepts are applied in this research.

In this chapter, the study area of Gauteng is introduced and placed in the South African context. First, the general socio-economic framework of South Africa is given and the conditions of energy provision, conversion and use in South Africa are outlined. Subsequently, the relevance of Gauteng in South Africa is shown by demonstrating the contribution of the province to both economic activity and population but also Gauteng's reliance on the rest of the country in terms of energy supply. The next section of the chapter presents studies available for the energy system analysis of South Africa and particularly for the transport sector of Gauteng. It demonstrates the need for further research on GHG mitigation in the province, especially in the transport sector. The studies available in the context of energy system analysis and transport are listed, evaluated and briefly summarized in terms of their aims, methodology, fields analysed and limitations. Based on the research needs identified, the aims and scope of the analysis are postulated in the fourth section of this chapter, which ends with an overview of the further structure of this thesis.

1.1 South Africa's socio-economic status quo and energy system

South Africa's population has grown rapidly in the past, and almost doubled in the last 30 years, to about 50 million people in 2010 /StatsSA 2010a/. However, growth rates are not expected to remain at such high levels in the future so that the population is forecast to grow slowly in future /UN-Habitat 2008/, /Van Aardt 2007/. South Africa generated a GDP of about $8.5 \cdot 10^{12}$ ZAR_{2007} ($1.2 \cdot 10^{12}$ USD_{2009}) in 2009 /World Bank 2009/. In the same year its gross national income (GNI) per capita (i.e. the GDP plus net receipts for primary income such as employee compensation and property income, divided by midyear population) was 40,260 ZAR_{2007} (5,720 USD_{2009}) /World Bank 2009/. This was about 6 times the average GNI per capita of all southern African countries. However, compared to Germany (274,460 ZAR_{2007} or 38,990 USD_{2009}), the South African GNI is low. The world average GNI in 2009 was about 56,280 ZAR_{2007} (7,995 USD_{2009}) /World Bank 2009/.

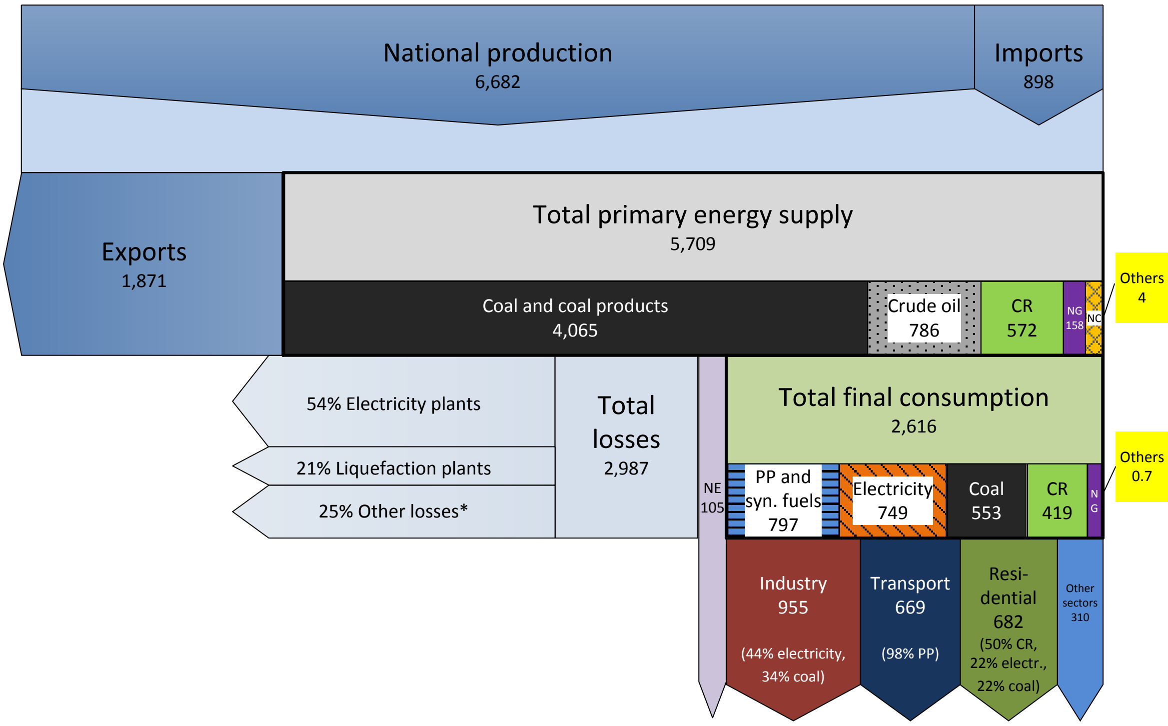
While playing a leading role in southern Africa, South Africa's economic production is very unequally distributed over the population, resulting in about 15% (in 2007) of the population living in informal dwellings with non-existent or insufficient fresh water and sanitation systems, and lacking access to various other essential services /StatsSA 2009/, /UN-Habitat 2008/. South Africa's government is committed to reducing the number of informal settlements through its Reconstruction and Development Programme (RDP), which focuses on increasing living conditions for the poor by providing access to clean water and improving the quality of housing. Consequently, in 2009, about 13.4% of the county's population lived in RDP or state-subsidised houses /StatsSA 2009/. Nevertheless, the proportion of households living in informal dwellings has declined only slightly (about 12.8% in 2009) /StatsSA 2009/.

The national unemployment rate is high and there is inconsistency between available statistics. While governmental figures state an unemployment rate of about 25%, critics argue that the real number of unemployed people could be as high as double this figure /StatsSA 2010b/, /Prozzi et al. 2002/. However, a significant part of the population also is informally employed /UN-Habitat 2008/, /GPG 2009b/.

Like other regions in the world – especially in developing countries – South Africa is rapidly becoming urbanized, particularly in Gauteng province. While in 1996 about half the population was living in urban areas, the urban population in 2006 was more than 55% and the trend is expected to continue /StatsSA 2006/, /Prozzi et al. 2002/.

Figure 1 summarizes energy supply and final energy consumption in South Africa by energy carrier, sector and end use. The country's total final energy consumption (FEC) in 2007 was 2,616 PJ (excluding non-energy use) /IEA 2007a/. This figure splits into 21.1% coal and coal products, 30.5% petroleum products, 3.7% natural gas and 16.0% combustible renewables. The share of other renewables such as solar and wind energy in the final energy consumption is small (< 1%). Electricity accounted for 28.6% of the final energy demand in 2007 /IEA 2007a/. Sectoral final energy consumption breaks down into 36.5% for the industrial sector, the transport sector consumed about 25.6% of final energy and the corresponding figure for the residential sector was 26.1%. The commerce and public services sector accounted for 7.8% of the total final energy consumption, while the balance corresponded to other sectors, such as agriculture /IEA 2007a/.

Primary energy use per capita was about 144 GJ/cap in 2007, far above the southern African average of about 28 GJ/cap /IEA 2008a/, /World Bank 2009/. However, compared to industrialised countries (e.g. Germany's energy use per capita was about 176 GJ/cap in 2009) these figures are moderate /IEA 2008a/, /World Bank 2009/. The energy-intensive mining industries and related activities (e.g. aluminium smelting) make South Africa's energy intensity (in terms of energy used per unit of GDP) one of the highest in the world, which is also a consequence of low energy prices in the country /EIA 2011/, /DME 2002/, /World Bank 2009/.



*other losses include 5% own use, 5% statistical differences, 4% non-specified, 3% oil refineries, 3% gas works, 3% distribution and 2% coal transformation.
Abbreviations: CR = combustible renewables and waste, NG = natural gas, NC = nuclear, PP = petroleum products, NE= non-energy use.

Figure 1: Energy balance (in PJ) in South Africa by energy carrier, sector and end use for the year 2007. Source: own figure based on /IEA 2008a/.

South Africa has huge recoverable coal reserves (about 30 Gt in 2008), which are the ninth largest in the world /EIA 2011/. The reserves are near the surface and, therefore, relatively easy and cheap to extract by open-cast mining. About 27% of annual coal production in 2010 (about 250 Mt, or 6 EJ) was exported /EIA 2011/. On the other hand, the country's reserves of natural gas and crude oil are small. In consequence, today South Africa mostly uses coal as an energy carrier to fulfil its energy demand (in 2008 about 71% of the primary energy supply was from coal and about 92% of gross electricity production was based on coal) /IEA 2008a/, /Eskom 2009/ and /EIA 2011/. The coal-fired power plants are usually placed close to the coalmines /EIA 2011/. These facts, in conjunction with generally low costs of labour, make South Africa's electricity among the cheapest in the world /EIA 2011/. Overall, the energy sector is of great importance to the country, by virtue of contributing about 15% of the national GDP /Eskom 2009/, /EIA 2011/.

The country has developed an advanced sector in producing synthetic fuels based mainly on coal-to-liquid technology (CTL) /EIA 2011/. In 2008, about 28% of the nation's total refinery capacity (about 692,000 bbl/d) was based on liquefying coal or gas /SAPIA 2009/. However, even though the country has the second largest refining capacity on the

African continent (after Egypt), its utilities cannot cope with the demand, meaning that in 2008 the balance of imports and exports of petroleum products showed a deficit of about 16.5 PJ /EIA 2011/, /IEA 2008a/. However, this figure is less than 2% of the total final energy consumption of oil products in that year (about 849 PJ including non-energy use) /IEA 2008a/.

The reliance on fossil energy carriers is responsible for high GHG emissions. For example, CO_2 emissions per capita in South Africa in 2007 were 7.2 t/cap compared to an African average of 0.9 t/cap. The figure for Germany by comparison was about 9.7 t/cap in 2009 /IEA 2010b/. Consequently, the CO_2 emissions per unit of GDP using purchasing power parities are comparably high. In 2007, about 0.7 kg CO_2/USD_{2000} was emitted, which is about twice the average figures for Africa and Germany (0.34 and 0.36 kg CO_2/USD_{2000}, respectively) /IEA 2010b/.

1.2 Gauteng province: The economic hub of South Africa

South Africa is subdivided into nine provinces, of which Gauteng is the smallest with only 1.4% of the country's land area. Although the province is geographically small, it plays a dominant role nationally in terms of economic output, population and in respect of energy use and environmental footprint /GPG 2009b/. Gauteng consists of the three metropolitan municipalities of the City of Johannesburg, Ekurhuleni (Germiston) and the City of Tshwane – commonly known as the JET cities – and two smaller, district municipalities (Sedibeng and West Rand). Johannesburg is the provincial capital.

The role of Gauteng in South Africa in terms of share of population and contribution to the GDP is represented in Figure 2. In contrast, the share of land area is also presented in the figure. About one fifth of South Africa's population lives in Gauteng (an estimated 11.2 million people in 2010) /StatsSA 2010a/. The province contributes more than one third of the national GDP, i.e. about 34% in 2010 (720 $bZAR_{2007}$) /StatsSA 2011/.

The socio-economic activity is concentrated in the three JET cities. They represent more than 85% of the province's population (about 4.4 million in Johannesburg, 3.2 million in Ekurhuleni and 2.9 million in the City of Tshwane in 2011) and contribute more than 90% of the province's gross domestic output by region (GDPR) /StatsSA 2013/, /GPG 2009b/, /UN-Habitat 2008/.

Gauteng's unemployment rate is high at about 27% in 2010 /StatsSA 2010b/. The official employment figures vary – which is a result of the large informal sector, difficulty of census-taking and the uncertain definition of the sector – so that the differentiation between unemployment and informal employment is not always clear from the statistical records due to the. In 2001, 13% of the potential labour force was estimated to be employed in the informal sector /UN-Habitat 2008/, /GPG 2009b/. In addition to the high unemployment rates, about 2.3 million people (about 20% of the total population) are living in poverty, which has been on the increase in absolute numbers since the year 2000 /GPG 2009b/.

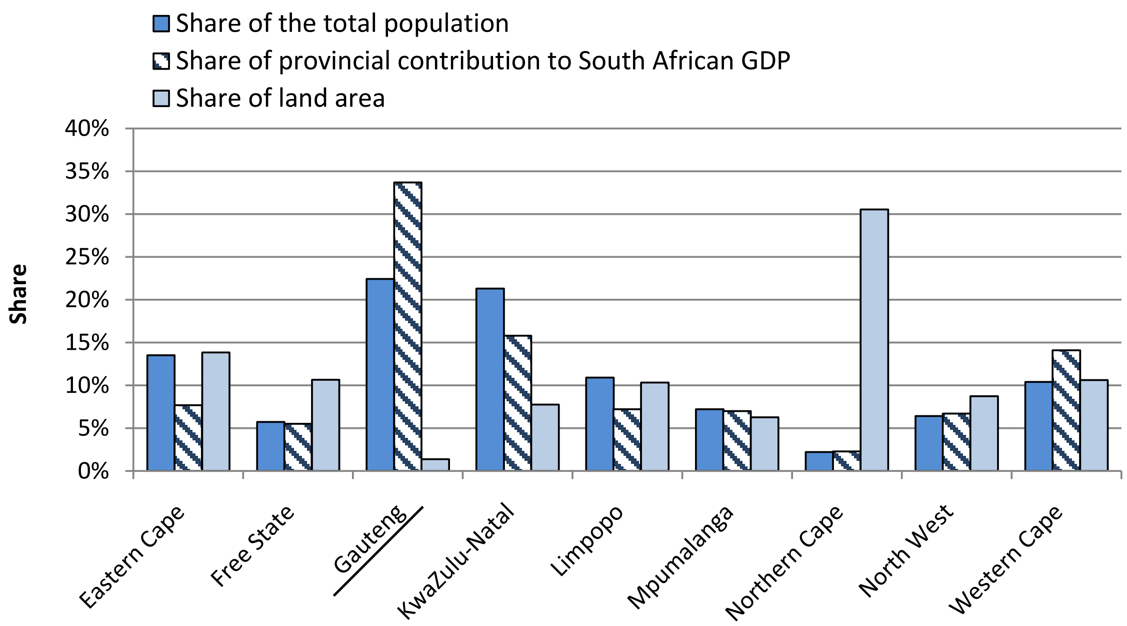
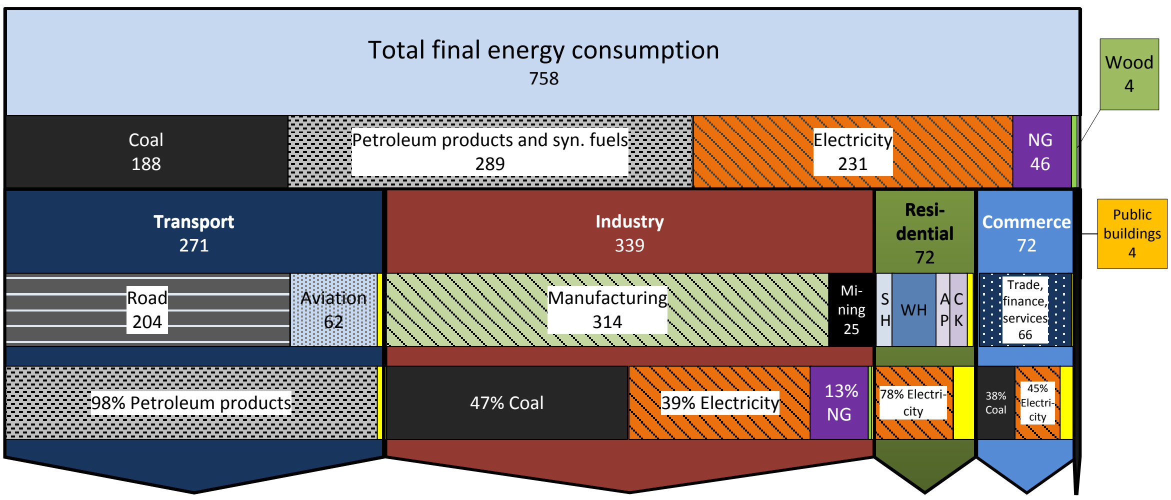


Figure 2: Contribution of the different provinces to the total population, GDP and land area of South Africa for the year 2010. Source: own figure based on /StatsSA 2010a/ and /StatsSA 2011/.

The large number of people living below the poverty line, in conjunction with the high economic output, leads to marked social inequalities, which are characteristic of the whole country /GPG 2009b/. Income inequality can be addressed by characterizing the province's population in terms of annual household (hh) income groups. The differentiation into income groups used in this thesis is based on the analysis of the Institute for Future Studies and Technology Assessment (IZT), Berlin /Hector et al. 2009/, /Wehnert et al. 2011/. They defined four income groups for South Africa: high (annual household income more than 307,200 ZAR_{2007}), medium (76,801–307,200 ZAR_{2007}), low (9,601–76,800 ZAR_{2007}) and poor (annual household income less than 9,601 ZAR_{2007}). The income groups were defined based on international and national definitions of "poor" and "poverty", such as the national poverty line, the cost of groceries that satisfy daily nutritional requirements as well as on UN and OECD definitions. The other income groups are delineated based on statistics defining the availability of household goods and luxury goods, such as the availability of passenger cars, refrigerators and TVs, which express the financial circumstances of the household /Hector et al. 2009/, /Wehnert et al. 2011/. Research shows that it is essential to consider income groups when analysing future energy consumption and GHG emissions, especially in developing counties or nations in transition (see e.g. /Tomaschek et al. 2012a/, /DLGH 2010/, /Tomaschek et al. 2009/).

Given Gauteng's role in South Africa, it is notable that almost no detailed energy statistics exist for the province. For that reason, within the EnerKey project, a detailed energy balance was derived for Gauteng for the base year 2007 /Tomaschek et al. 2012b/. The reason for choosing 2007 as base year was that most of the statistics used – such as national energy balance, population and sectoral GDP, and fuel sales figures – were not available for later years.

Figure 3 illustrates the total final energy consumption for Gauteng in terms of sectoral energy use and energy carriers used in each sector in 2007. In total, a final energy consumption of 774 PJ was calculated for Gauteng excluding non-energy use (29.6% of national final energy consumption). The final energy carrier split shows that most of the final energy consumed is based on petroleum products (38%), electricity (29%) and coal (27%). The remainder of the final energy consumption splits among natural gas (6%) and renewable energy (less than 1%), including solar energy use, wood and other combustibles /Tomaschek et al. 2012b/. In Gauteng, the sectoral final energy consumption shows that – as in the whole of South Africa – most of the energy is consumed in the industrial sector (i.e. 46%, nationally 37%). However, the second largest energy consumer is the transport sector at 35% of the total final energy consumption (nationally 26%). The remainder of the final energy consumed in 2007 is used by commerce (9%, nationally 8%), the residential (9%, nationally 26%) and government sectors (less than 1%) /Tomaschek et al. 2012b/.



Abbreviations: SH = Space heating, WH = Water heating, AP = Appliances, CK= Cooking; "others" are indicated in yellow.

Figure 3: Total final energy consumption of Gauteng in 2007 by sector and energy carrier. Source: own figure based on /Tomaschek et al. 2012b/, /Tomaschek et al. 2012d/ and own calculations.

1.3 Studies focusing on the energy system and the transport sector of South Africa

In 2006, the South African government agreed to develop scenarios for climate mitigation within the framework of the United Nations Framework Convention on Climate Change (UNFCCC). The process was named Long-term Mitigation Scenarios (LTMS). All sectors of the South African energy system have been included. However, the technological details included in the analysis were not made clear in the documentation available /Winkler 2007/. Furthermore, Winkler explains that the transport sector especially was “tightly constrained” and that it “does not optimise in the way that it does in the rest of the energy system” /Winkler 2007/. Different scenarios have been applied ranging from “business as usual” to the reductions in climate relevant emissions required to reach a global warming target of 2 degrees Celsius. The time horizon for the analysis was 2003 to 2050 /Winkler 2007/.

The basis for the analysis was a MARKAL model for South Africa, adopted by the Energy Research Centre of the University of Cape Town, which has also been used as the basis for several other studies, e.g. /ERC 2004/, /Winkler 2006/ or /Haw & Hughes 2007/. The model application is a single region representation of South Africa including all relevant supply options and demand sectors. Fuel costs as well as technology learning curves were taken from international sources such as the IEA and OECD /Winkler 2006/. Default emission factors from IPCC 1996 were used to quantify energy-related emissions. It seems that low emphasis was placed on the transport sector because it was not analysed explicitly in a scenario. Transport demand was forecast as intensity of kilometres travelled per unit of GDP based on historical figures available /Winkler 2006/. Other inputs for the transport sector were not stated and it is not evident which technological detail was modelled.

A recent study including energy figures specific to the province is the Gauteng Integrated Energy Strategy (GIES), published in 2010. In the GIES the Gauteng Department of Local Government and Housing pointed out the importance of the province for South Africa in respect of not only its large contribution to economic output and population, but also in determining the future patterns of energy consumption and environmental footprint for the country /DLGH 2010/. For that reason the GIES was established to promote sustainable energy use within the region and sees Gauteng as the leading province for South Africa’s climate protection efforts /DLGH 2010/. In this study, the LEAP (Long-range Energy Alternatives Planning System) model was applied for a time horizon until 2055 to show the effects of changes in energy supply or demand patterns in explorative scenarios (what-if scenarios). The transport sector was analysed for four passenger modes, namely bus, rail, taxi and motorized individual transport, and for freight transport in terms of the categories road and rail. However, the emphasis of the GIES clearly lies on the electricity supply and residential demand side interventions /DLGH 2010/.

Besides energy system modelling, some transport-specific research done previously in South Africa is available. Giving a detailed view on the transport sector in terms of peak-hour travel is the Gauteng Transport Study (GTS 2000), which was carried out between the years 2000 and 2005 /GDPTRW 2006/. The study focused on generating trip data for the morning peak period (06:00 to 09:00) and using this for modelling needs for infrastructure planning in the future of Gauteng /GDPTRW 2006/. For this purpose, the

Emme/2 model was applied. Emme/2 stands for Equilibre multimodal/multimodal equilibrium and is a traditional four-step model based on the principles of trip generation, trip distribution, mode split and trip assignment /Ortuzar & Willumsen 2001/. Four-step models such as Emme have been discussed as not representing the traveller's behaviour but more accurately simulating known traffic conditions, especially if historical land-use or transport patterns may change in future. However, modern applications of four-step models can also handle spatial information /Button et al. 1982/, /Timmermans 2003/, /Litman 2005/. The base year for GTS 2000 modelling is the year 2000 with forecast milestones for the years 2010 and 2025. The model claims the incorporation of minibus taxis as a single mode and also the addition of the Gautrain railway as major improvements in comparison to previous model applications /GDPTRW 2006/. On the other hand, the model does not include any freight transportation and only main roads have been modelled. Aspects of transport energy consumption or emissions were not discussed at all. Scenario analyses were kept brief and only include variations of population and economic growth /GDPTRW 2006/. As mentioned before, only the peak-hour has been considered, which does not give a picture of the total traffic volume in Gauteng.

Based on the diversification of current transport strategies in South Africa, the Department of Transport created the South African National Transport Master Plan (NATMAP) as a national strategy for further transport planning /DOT 2008a/. The model follows the traditional four-step approach of modelling the transport demand (trip generation, trip distribution, mode split and trip assignment). In this study, the time horizon is long term and extends to 2050. The study includes the major transport networks and the transport between all South African provinces and among major cities within provinces, where the emphasis lies on passenger transport. Therefore, the Gauteng GTS 2000 model framework was integrated into the NATMAP modelling efforts. Scenarios developed for NATMAP are similar to the scenarios of GTS 2000 /DOT 2008a/.

The South African Council for Scientific and Industrial Research (CSIR) is developing an agent-based travel demand model in conjunction with a spatial land-use simulation model (UrbanSim) /Fourie 2010/. The model is based on the Multi-Agent Transport Simulation Toolkit (MATSim), which is an open source software tool for agent-based transport simulations /MATSim 2012/. The model uses the data of the GTS 2000 study as in the Emme/2 travel demand application. The MATSim application for Gauteng is limited to private vehicle demand at peak hours and excludes public and freight transport /Fourie 2010/.

In addition, several models of the development of vehicle fleets in Gauteng and South Africa have been adopted. While some consider the income-dependency of car ownership /Mokonyama & Venter 2005/, /Mokonyama & Venter 2007/ others use mathematical regression models to quantify the future vehicle fleet /Letshwiti et al. 2003/, /Kelly 2007/. Extensions to those approaches were made by the Department of Transport (DoT) of South Africa, in which spatial structure was also considered /DOT 2009/.

However, it was found that spatial aspects influence car ownership much less than income /DOT 2009/. Although estimates of total vehicle numbers differ, all models come to the same result that the number of vehicles in Gauteng will grow significantly in the future. All applications of car ownership models in South Africa focus only on a short time horizon (i.e. 10 to 15 years); technology-related aspects that determine future fuel consumption or emissions have not been included in those models.

Goyns analysed in his PhD thesis, entitled “Modelling real-world driving, fuel consumption and emissions of passenger vehicles: a case study in Johannesburg”, the emission inventory for passenger cars in Johannesburg /Goyns 2006/. The emission simulation was based on GPS data and engine monitoring. The results were extrapolated to the Johannesburg vehicle fleet and integrated into a software tool /Goyns 2006/.

Table 1 summarizes the available studies and model applications in the South African and transport contexts.

Table 1: Available studies focusing on energy or transport in the South African context and for Gauteng.

	Model	**Sectors covered**	**Time horizon**	**Mathematical approach**	**Geographical coverage**	**Analysis of alternative fuels**	**Analysis of alternative powertrains**
LTMS /Winkler 2007/	MARKAL	Energy System	2003-2050	Optimisation	South Africa	not stated	not stated
MARKAL South Africa /Winkler 2006/	MARKAL	Energy System	2001-2030	Optimisation	South Africa	not stated	not stated
GIES	LEAP	Energy System	2007-2055	Simulation	Gauteng	no	no
GTS 2000 /GDPTRW 2006/	Emme/2	Transport	2000-2025	Simulation	Gauteng	no	no
NATMAP /DOT 2008a/	Emme/2	Transport	2005-2050	Simulation	South Africa & Gauteng	no	no
MATSim Gauteng /Fourie 2010/	MATSim	Transport	not stated	Simulation	Gauteng	no	no
/Goyns 2006/	MS Access / SQL	Transport	2004-2006	Simulation	Johannes-burg	no	no
Car ownership models	Regression	Transport	various (short term)	Simulation	South Africa & Gauteng	no	no

In conclusion, there are several studies available that handle the South African energy system in general, as well as particular aspects, such as the transport sector, in detail. It is evident that in all analyses of the energy system the transport sector was not modelled in detail and the possibilities of alternative powertrains and/or fuel chains were not examined explicitly. Transport plans and studies are mostly short term and focus on demand planning issues such as peak (congestion) transport modelling, especially for private vehicles. The following statements can be made regarding the state of research in transport and energy system analysis in Gauteng and in South Africa:

- Studies exist which look explicitly at the transport sector of Gauteng, or parts of it (e.g. GTS 2000, car ownership models).
- Furthermore, some studies for the whole country exist which are transport orientated (NATMAP 2050).
- However, there is only one study available that investigated the whole energy system of Gauteng (i.e. GIES). This study was based on a simulation approach but does not emphasize the transport sector.
- Optimizations for the energy system have only been done for the whole country (e.g. /ERC 2004/, /Winkler 2006/, /Haw & Hughes 2007/).
- Detailed energy data on the Gauteng transport sector are lacking. Moreover, there are no detailed analyses of options for the transport sector in terms of alternative fuels and technologies, nor are there strategies in place on how these can be used to reach the province’s climate targets.

Finally, it can be concluded that there are no studies available that have examined alternative transport technologies and fuels for Gauteng in detail. In general, there is little information on fuel use in South Africa and there is no analysis available that has addressed GHG abatement costs of alternative fuels and powertrains for Gauteng.

1.4 Aims and objectives of the analysis

In the previous sections (see sections 1.1 and 1.2), the proposed study area, Gauteng province, was identified as of major importance for South Africa, not only in terms of its economy, but also in respect of its energy consumption and climate-related emissions. It is obvious that interlinkages and interdependencies exist between Gauteng and the rest of South Africa as most of the energy supply for Gauteng is located outside the provincial boundaries. The reliance on coal and other fossil energy carriers, the high energy intensities and the high growth expectations for the province indicate that there are major threats to the environment. On the other hand, opportunities can be clearly seen to present themselves in the growing energy system.

In general there is a lack of consistent transport data and few energy data are available for South Africa /Goyns 2006/. Reasons for this include (unnecessary) confidentiality of data, bad (or non-existent) data management and non-standardised data evaluation and processing /Van Beeck 1999/.

The transport sector can be improved through different interventions (Figure 4). At the demand side GHG mitigation can for example be achieved by reducing the total demand for transportation – either the demand for passenger or for freight transport – which will obviously decrease the transport energy demand if other factors – e.g. load factor, occupancy levels or specific fuel consumption – are not changed. Additionally, shifting transport usage from less efficient to more efficient modes (in terms of energy consumption per kilometre travelled) – e.g. in the freight sector from road to rail, or in the passenger sector away from private transport – will reduce the impact of transportation.

However, total well-to-wheel (WTW) emissions of the transport sectors are dependent also on vehicle technology and fuel provision. Emissions from fuel combustion in a vehicle are generally expressed as tank-to-wheel (TTW) emissions. They can, for example, be reduced by selecting vehicles with lower specific energy consumption (e.g. hybrids) or through alternative fuels (such as natural gas or LPG) that offer reductions in TTW emissions. Biofuels can even reduce TTW emissions to zero, as the carbon is accounted for in the growth of the plants. On the supply side, options such as carbon capture and storage (CCS) can reduce the emissions even for fossil energy sources. On the other hand, those well-to-tank (WTT) emissions might be even higher for alternative fuels (e.g. biofuels) compared with fossil fuels (e.g. derived from refining crude oil) and thus partly shift the total GHG emissions to the supply side. These points make it obvious that, in integrated analysis of the whole energy provision chain and thus the overall energy system, it is necessary to include the effects of possible interventions.

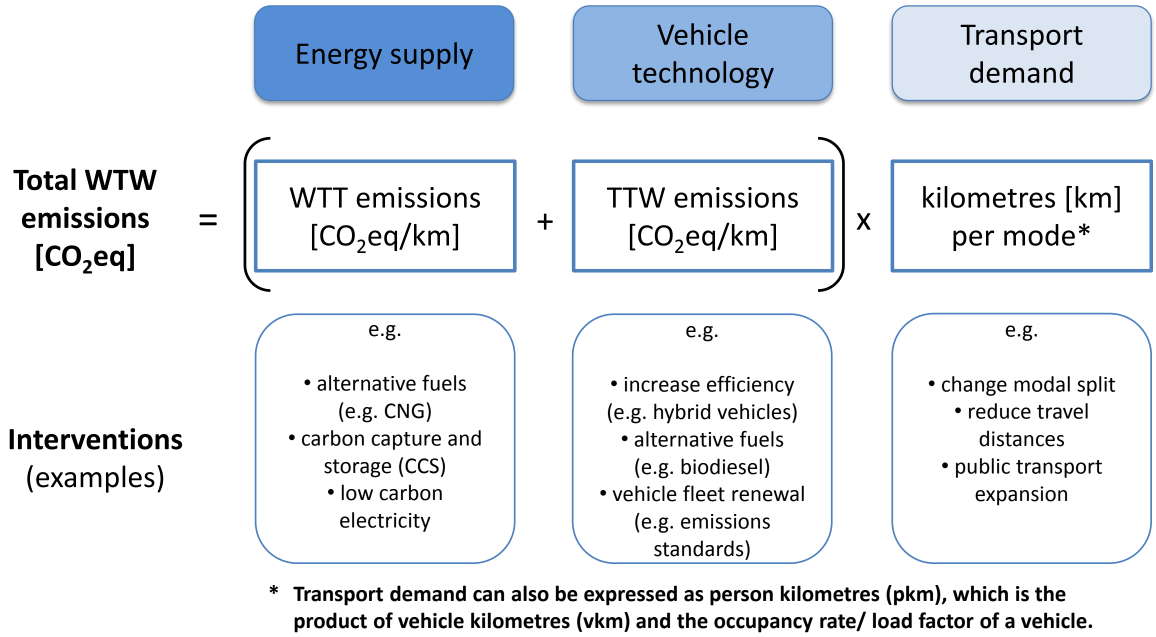


Figure 4: Transport interventions to reduce GHG emissions. Source: own figure based on /Creutzig et al. 2011/, /Becker 2010/, and /WEC 2007/.

This study analyses the three intervention components of fuel supply, vehicle powertrain technology and changes in transport demand for the Gauteng transport sector to reduce GHG emissions. It therefore provides background data on the transport sector and derives energy usage to show possible developments in relation to the socio-economic framework, to allow the application of an integrated approach for the province involving the interlinkages between the transport sector and the energy system, by including fuel supply, electricity generation, vehicle-to-grid energy storage and CCS. Using such an approach and model-based marginal abatement cost curves (MACC), this study aims:

- to investigate the opportunities provided by alternative technologies, fuels and expansions of the public transport system (including changes in modal shift) based on local conditions in terms of technical, economic and environmental evaluation characteristics; and
- to identify quantitatively cost-optimal measures for transport-related GHG emission reductions for Gauteng.

1.5 Structure of thesis and methods

The methods used in this study include statistical and econometric methods, travel demand modelling built on behaviour-based groups as well as scenario analysis and least-cost energy system optimization using the TIMES model generator combined with extensive literature research. The structure of the thesis is summarized in Figure 5.

The thesis starts by giving background on the transport sector of Gauteng (chapter 2) based on a literature review. The historical development is explained as well as the current state of the transport system. Moreover, recent initiatives and policies affecting the transport sector are analysed.

In the third chapter, the transport demand and transport energy balance of Gauteng are analysed. Thus, demand drivers are identified and quantified. A transport model is developed to forecast person kilometres (pkm) with respect to scenario parameters (economic growth and income inequality as well as population growth) using the technique of homogeneous groups of behaviour based on an analysis of various transport databases as well as available statistics on transport in Gauteng. Regression analysis is performed to calculate the development of tonne kilometres (tkm) and aviation energy demand.

Chapter 4 presents the method of an integrative analysis of the energy system. This includes a general picture of energy system analysis as well as a description of the model as applied to Gauteng. An optimization modelling approach was used to develop the TIMES-GEECO model (which stands for Gauteng Energy and Emission Cost Optimization Model) using the energy system model generator TIMES, to put all transport-relevant options into perspective with the whole energy system and to find least-cost options.

Chapter 5 presents the analysis of vehicle technologies and fuel chains in a South African context that are possible options for a future system and are integrated into the energy system model applied (i.e. the TIMES-GEECO model). The basis for the techno-economic description of all these processes is a thorough review of the literature as well as data available from existing international transport-orientated energy models (e.g. /Özdemir 2012/, /Bruchof 2013/) and information generated within the EnerKey Project (e.g. Gauteng-specific emission factors for transport /TÜV 2012a/).

In chapter 6, scenarios are defined for a comparative analysis of plausible futures for Gauteng. Subsequently, scenario results are presented and promising measures for the province are deduced by finding robust measures that are independent of any future development. To do so, marginal abatement costs curves are developed, which show the role of the transport sector in reducing GHG emissions. Various scenarios are presented in terms of the effects of different sensitive parameters, such as changes in crude oil price as well as variations of technology parameters and political issues.

Chapter 7 summarizes the thesis and provides a conclusion.

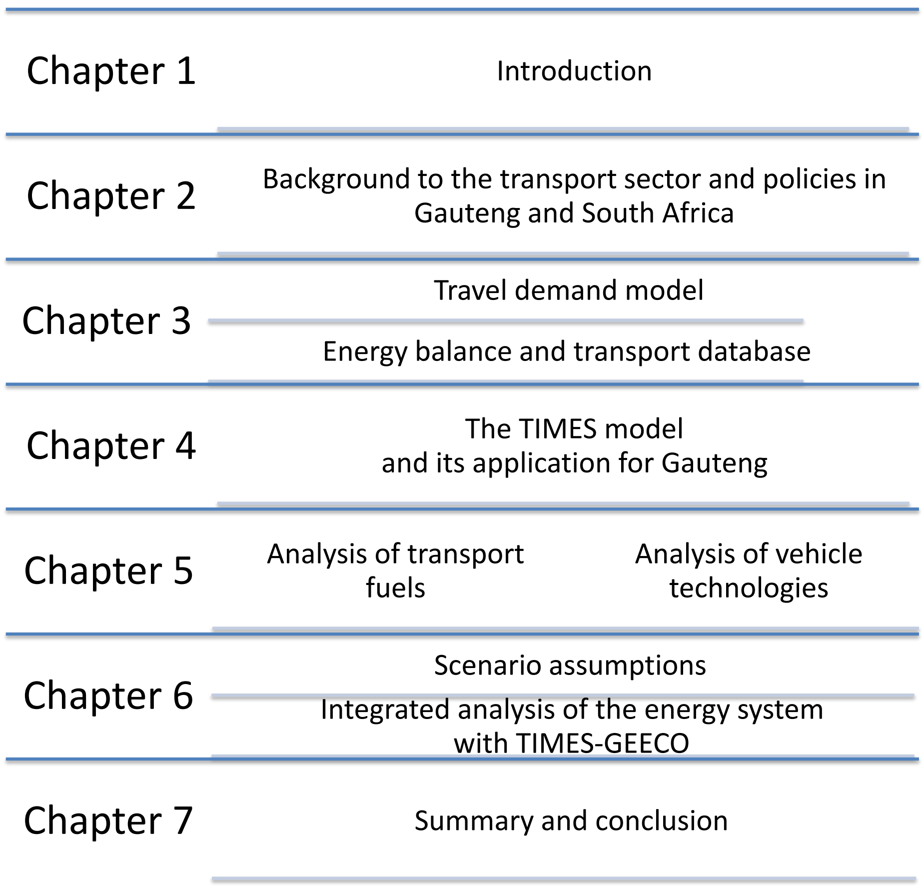


Figure 5: Structure of the thesis.

2 Background to the transport sector in Gauteng province

This chapter reviews how Gauteng’s transport system has developed in the recent past and how it currently looks. Finally yet importantly, the chapter describes recent policies and indicates which might significantly influence the future development of transport in the province and which therefore have to be taken into account in scenario development.

2.1 Historical background and state of transport in Gauteng

Historically, transport planning was not integrated into a complete planning concept in South Africa. The social dislocation of the population under apartheid led to spatially unproductive land-use patterns. This process was even accelerated due to the availability of cheap land /UN-Habitat 2008/. The government designed a public transport system as a means of low quality travel for long-distance commuters. Thus, buses and trains were mainly used to serve commuters from the outlying areas of the cities to the city centres. The government’s focus was on private transport needs and aimed mainly at building more road infrastructure. Therefore, unlike most developing countries, South Africa has an excellent road infrastructure, especially in the richer urban areas, because of apartheid politics /Jennings & Covary 2007b/. Consequently, the gap between transport needs and inadequate transport opportunities for those who cannot afford private motorized transport is filled by (partly informal) transport systems.

Even after the end of the apartheid regime, the government did not develop an integrated transport strategy /UN-Habitat 2008/. The urban and peri-urban populations are still scattered since the practice of constructing low-income housing away from the city centres has continued even after the abolition of apartheid. Consequently, for many people average travel times and distances are long, with an average travel time to work of more than 40 minutes (one way) in Johannesburg and even longer in the case of Pretoria /Van der Merwe & Vorster 2009/, /UNDP 2007/, /Cervero 2000/. Compared to other countries, commuting distances in South Africa are among the longest in the world /De Saint-Laurent 1998/.

Nowadays, Gauteng is the primary node for air and road transport in sub-Saharan Africa, with the majority of travellers, such as tourists and business passengers, arriving in or passing through the province /Landau & Gindrey 2008/. However, Gauteng’s transport system is stressed. Congestion and heavy traffic between the main working areas (e.g. the northern suburbs of Johannesburg and Pretoria) and the major residential areas (e.g. northern and south-western Johannesburg including Soweto) is an everyday phenomenon /UN-Habitat 2008/. This section describes the state of transport in Gauteng in terms of public, private and freight transport in the province.

2.1.1 Public transport

The public transport system can be seen as not well developed compared with how public transport operates in industrialized countries – which typically have regular scheduled bus services and rail networks – since there has been historically little investment in this sector. In South Africa the public transport system offers only low levels of service quality (e.g. in terms of reliability, comfort and safety) and is used mainly by people with a low income /Cervero 2000/. Public transport in South Africa is badly coordinated as the public services are not well connected to each other and are not integrated into an overall transport system. Furthermore, the system cannot cope with transportation demands /Jennings & Covary 2007b/, /Van der Merwe & Vorster 2009/, /Jennings & Covary 2007a/.

The network of independently operated, or informally organized, minibuses is mainly seen as ‘the public transport system’, which makes minibuses account for about 72% of the public transport modal share /Van der Merwe & Vorster 2009/. These vehicles have particular advantages compared with regulated scheduled buses, since they are more flexible – offering an almost door-to-door service – and can move more easily through traffic and on unpaved or bad roads /Cervero 2000/. Occupancy levels are high, easily up to 150% of the official maximum load /De Saint-Laurent 1998/. Figure 6 shows typical minibuses in Gauteng.

Figure 6: Typical minibuses in Gauteng. The left-hand picture shows passengers hopping on and off an older minibus, whereas that on the right shows a modern vehicle. Source: own photos.

Minibuses in the province do not run according to a defined schedule and typically operate only over a limited geographical range. Although the routes are usually set (often along major transport corridors that connect informal settlements with typical urban amenities), routes can be changed in response to traffic congestion or requests by passengers. Many minibuses operate the highly used routes, most frequently during peak times. There are usually no formal stops and commuters signal the driver to stop the vehicle when it comes along, whereas passengers wishing to get out are dropped off on request along the route /Cervero 2000/. This mode of transport is therefore difficult (or practically impossible) for non-local people to use.

In Gauteng, there are more than 180 taxi organizations, which are aligned to the Gauteng Taxi Council (GATACO) or to the Gauteng National Taxi Alliance (GNTA) /GPG 2008a/. Among the minibus organizations violent fights for passengers and lucrative routes occurred, because formal regulation is missing and because minibuses operate without a licence /Walters 2006/. The situation in Gauteng at the end of the 20th century and at the start of the 21st was one of the worst in South Africa /Cervero 2000/. Thus, the government has started to regulate and organize the minibus system. Governmental organizations tried to communicate between rival groups and can claim some success, for example when two rival organizations that had fought each other since the late 1980s then declared to cooperate peacefully together in future /GPG 2009a/.

South Africa has a well-developed railway network in comparison with other African countries. Historically, the rail system was used to connect the ethnically separated areas outside the cities with the city centres and it is still facing problems based on a lack of spatial incorporation into a consistent and integrated land-use and public transport policy. Due to the lack of investment and replacement of stock, the average age of coaches has reached more than 30 years (national average), resulting in inadequate performance in terms of availability and punctuality of the services /Walters 2006/. The rail system is nowadays seen as unreliable and inconvenient as well as unsafe /Jennings & Covary 2007a/, /Walters 2006/.

In consequence, since the 1980s usage of rail services has declined rapidly /UNDP 2007/. The nationwide number of commuter passenger trips by rail dropped by about 50% between 1980 and 2008. Passenger rail traffic reached its maximum in 1982 with about 1300 million passenger journeys per year and has decreased steadily since then. However, the rate of decline has decreased since the early 1990s and in the last ten years the total figure has become relatively stable at about 600 million passenger journeys per year (i.e. about 586 million in 2008, which is the latest information available) /Prozzi et al. 2002/, /De Saint-Laurent 1998/, /DOT 2008b/.

The urban rail services are operated by Metrorail, since passenger rail was separated from Transnet in 1997 /De Saint-Laurent 1998/. It is regulated by the South African Rail Commuter Corporation (SARCC), which took over the responsibility for commuter rail operations from Transnet /Walters 2006/. Metrorail had exclusive service rights until the White Paper on National Transport Policy allowed competitors to participate in the market. However, because of the low profit margins, private market participation remains low /Walters 2006/.

Metrorail in Gauteng has three main hubs in the three JET cities – these are Johannesburg Park Station, Germiston Station and Pretoria Station, which serve most of the central province. The Gauteng network reaches to Vereeniging in the south, Randfontein in the west and connects the highly populated Soweto, as well as many of

Pretoria's suburbs in the north of the province /Metrorail 2012/. Ticket prices differ depending on route and service class. Monthly and weekly tickets are also available. A single ticket from Soweto to central Johannesburg costs about 4–8 ZAR /COJ 2012a/.

The rail system in Gauteng is mainly used for travelling to work or back home; there is only limited travelling at off-peak times, which causes the system to be economically inefficient with a cost recovery of only 28% (national average for the state-owned rail services). Consequently, the rail system is highly subsidised to make the fares affordable for the (mainly poor) passengers /DOT 2008b/, /Walters 2006/, /Prozzi et al. 2002/, /De Saint-Laurent 1998/.

There are a few scheduled bus services, which face the same quality and safety problems as the rail system and also experience a declining modal share /Van der Merwe & Vorster 2009/, /UNDP 2007/. There are two different types of services in operation: private operators (some of them subsidised) and also companies owned by municipalities /De Saint-Laurent 1998/. In Gauteng, the scheduled bus services are split between two main companies: one is Metrobus, owned by the city of Johannesburg, and the other is Putco, a private company, which is subsidised by the province. In addition there are some smaller, privately owned bus services operating in Gauteng /Van der Merwe & Vorster 2009/.

Like the rail system, the bus network was historically used to connect the poorer outlying areas with the city centres. Besides diminishing subsidies and service quality in the 1980s, the deregulation of the minibus sector caused the modal share of bus services to decrease /Prozzi et al. 2002/, /Walters 2006/. Putco and Metrobus operate scheduled bus services throughout Gauteng including the JET cities and their suburbs. As for rail services, there are daily, weekly and monthly tickets available, as well as reduced fares for children, persons with disabilities and pensioners. Depending on the distance travelled, a single ticket for a Metrobus journey costs about 8–20 ZAR /COJ 2012b/.

2.1.2 Individual transport

Even though a large proportion of the provincial population relies on public transport, there is also a very strong dependence on private cars, even greater than in Europe and comparable with the situation in North America, and individual transport has increased steadily in Gauteng /UNDP 2007/, /De Saint-Laurent 1998/.

There are about 3.3 million motor vehicles registered in Gauteng (at the end of 2009, Figure 7), of which 2.3 million are motorcars /RTMC 2011/. These are about 40% of the country's vehicle population and about 44% of all motorcars registered in South Africa /RTMC 2011/. A notable fact is that bigger cars, vans, SUVs (sport utility vehicles) and 4x4s have become ubiquitous on South Africa's roads /De Saint-Laurent 1998/.

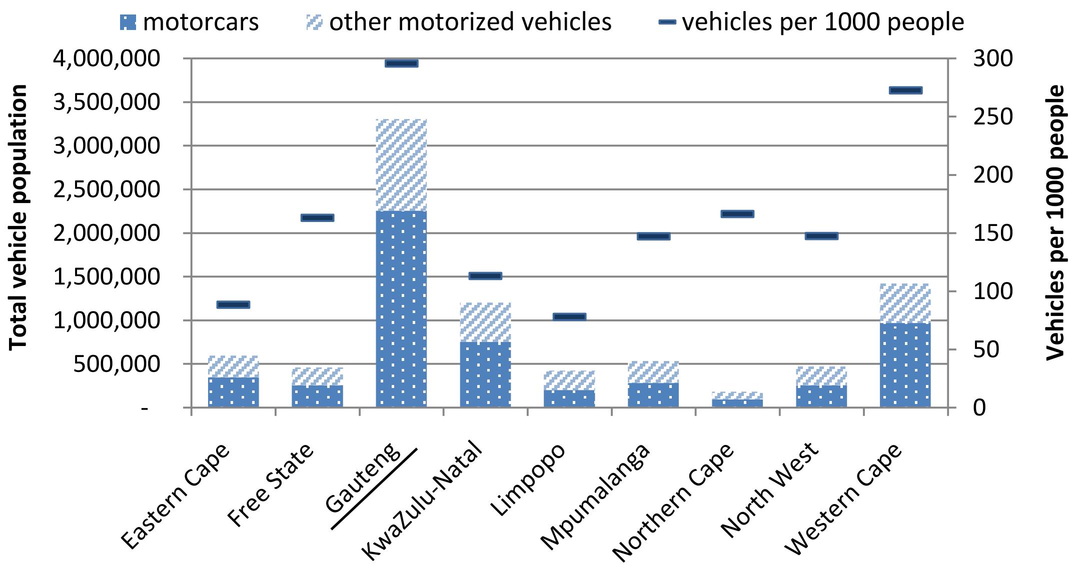


Figure 7: Number of registered vehicles per province in South Africa, at the end of year 2009. Source: own figure based on /RTMC 2011/.

Non-motorized transport (NMT) is an important part of the South African transport scene. In Gauteng one third of all person trips are taken using non-motorized transport, of which the most dominant form is walking /GDPTRW 2006/, /De Saint-Laurent 1998/. About one quarter of all South Africans walk to work /Jennings & Covary 2007b/. From an energy and environmental point of view, walking is an attractive form of mobility for obvious reasons. However, walking has not been included in strategic transport plans for a long time and pedestrian pathways are often non-existent or not usable (since they are blocked or in very bad condition), which makes people have to walk along roads intended for vehicles and even on highways. Sadly, this situation contributes to South Africa's large number of road accidents and transport-related deaths. About 40–50% of all accidents involve pedestrians; an average number of about 15 pedestrians are killed each day in South Africa /Jennings & Covary 2007b/, /DOT 2006/.

Bicycles are not observed often in South Africa, especially in Gauteng, compared with other developing countries. Less than 1% of all person trips are made by bicycle in Gauteng /GDPTRW 2006/. This might be due to image reasons, the long distances involved as well as safety issues /De Saint-Laurent 1998/. As a result, bicycle taxis, which are used in some African countries such as Kenya, are not used in South Africa /Cervero 2000/. However, the province wants to encourage people to use bicycles.

2.1.3 Freight transport

Freight transport faces the same problems as passenger transport in that there are currently only few, unreliable alternatives to road transport. The freight sector was deregulated in 1989; before that time, trucks were not allowed to compete against the government's railway monopoly. However, after the deregulation and with decreasing subsidies, the movement of freight by rail has become less and less important so that goods are currently transported mainly by road /UN-Habitat 2008/, /Prozzi et al. 2002/. Transnet, a state-owned company (see section 2.1.1), is still responsible for general and bulk rail transport since the commuter rail operations were devolved to the South African Rail Commuter Corporation /Walters 2006/.

2.2 Programmes and policies with future impact on the transport sector of Gauteng

The South African government has established several plans to modernize the transport system, regulate the sector and provide more public transport alternatives. These policies and action plans are aimed at modal shifts from private to public transport and from road to rail, as well as on using cleaner fuels or biofuels.

The basic framework is described in the White Paper on National Transport Policy (1996), which focuses on promoting the use of energy-efficient modes of transport. This outline was underlined and extended through the Moving South Africa (1999) long-term strategy. Both documents formulate the need to limit urban sprawl and to increase the population density to reduce travel distances. They point out the importance of investment in public transport, to change the modal split and to enhance the performance of transport operators /UNDP 2007/, /Prozzi et al. 2002/. Moreover, motorized vehicles are recognized as having to decrease energy consumption and increase efficiency /UNDP 2007/, /Prozzi et al. 2002/.

In preparation for the FIFA World Cup 2010 – which took place in South Africa with many games hosted in Johannesburg and Tshwane – Gauteng province and several South African cities elsewhere used this opportunity to take initiatives to improve their transport network. A National Public Transport Infrastructure and System Fund (PTIF) was established in the Framework of the DoT Transport Action Plan for 2010. It granted about 700 million ZAR to Gauteng and an additional 560 million ZAR to the South African Rail Commuter Cooperation and Metrorail to improve the railway system by investing in infrastructure, rolling stock and power systems and also to enhance service quality by increasing security and the attractiveness of the service /DOT 2006/.

A Transport Master plan for 2010 was prepared by the Gauteng provincial government's Department of Public Transport, Roads and Works (GDPTRW), in cooperation with the six local authorities, which aims to establish an environmentally sustainable public transport system, and to make public transport a realistic mobility option /GPG 2009a/, /Jennings & Covary 2007b/, /DOT 2006/, /GPG 2009a/, /GDPTRW 2007/. The road network was expanded through investments in road infrastructure and in new means of transport (e.g. the BRT and Gautrain), which are described in the next section.

In the framework of the transport master plan for 2010, investments in infrastructure were undertaken. Local roads were enhanced, or widened, aiming to provide improved traffic flow within and between the municipalities. A total of 770 million ZAR was budgeted per year for road infrastructure maintenance and rehabilitation /GPG 2009a/. A freeway scheme was set up in Gauteng in order to expand and improve the freeway network. New roads also were built such as the Soweto highway /GPG 2009a/, /GDPTRW 2007/. Even in the first phase of the three-phase project, 180 kilometres of freeways were improved with additional lanes, or intersections made more efficient. The second phase has a budget of about 20 billion ZAR and is scheduled to be completed in 2015; the third and final phase (at a cost of about 23 billion ZAR) is to be finished by 2018 /GPG 2009a/.

2.2.1 Taxi recapitalization and revitalization programme

The minibus taxi recapitalization programme (TRP) was launched in 2006 by the national government as a consequence of the White Paper on National Transport Policy (1996) and Moving South Africa (1998) (see section 2.2). The programme aimed to improve the conditions in the minibus system in terms of quality of its operational service and its safety performance by restructuring and recapitalizing the industry /Walters 2006/.

In this programme, old minibus taxis and old metered taxis were scrapped and replaced by newer, diesel-driven ones, with higher passenger capacities, usually 14–18 seats, and sometimes by vehicles with up to 35 seats (e.g. the Isuzu NQR 500 or Mercedes Sprinter) /Walters 2006/, /Prozzi et al. 2002/. The vehicles had to comply with new safety standards, e.g. by fitting safety belts, new tyres and roll-over protection /Walters 2006/. Thus, 7.7 billion ZAR was made available /Walters 2006/, /GPG 2008a/. In Gauteng, the total funds were 1.6 billion ZAR /GPG 2009a/. An amount of 50,000 ZAR was given to the operator for each scrapped vehicle to assist them in buying new vehicles. Old taxis were destroyed in order to ensure that they were not used on the road again. A “Taxi scrapping Administration” was established by the DoT in order to manage the scrapping process and to help operators with the acquisition of new vehicles /Walters 2006/. Until the end of 2007, about 4,000 applications were received for Gauteng (only 20% of the total national figure of about 20,400) and 1200 old taxis were scrapped in the province (nationally about 12,000) till then /DOT 2008b/. However, the process did not run as intended and by 2011 only about 25% of the goal had been achieved /NPC 2011/. In total there are about 280,000 minibuses registered in South Africa (at the end of 2009) /RTMC 2011/, of which not all necessarily belong to the minibus industry. The number of minibuses registered in Gauteng was about 110,000 at the end of 2009 /RTMC 2011/.

A metered taxi revitalization programme was launched in 2008 to establish a new, safe and comfortable transport system in the province for the FIFA World Cup 2010. The government aimed to set up a professional metered taxi industry /GPG 2008a/. After scrapping old vehicles, the metered taxi operators can lease vehicles – instead of buying them themselves – from the former Government Garage, i.e. known as the G Fleet. The Department of Public Transport, Roads and Works allocated 3 million ZAR in the financial year 2008-2009 for the programme and aimed to have about 10,000 metered taxis operational in the JET cities and Sedibeng for the World Cup. In 2008, the province had about 1,200 metered taxis registered in Gauteng /GPG 2008b/. The programme was not well received because of the complicated financing mechanism and offered little benefit to the taxi operators, who did not find it sufficiently attractive /Tau 2008/.

2.2.2 The Rea Vaya Bus Rapid Transit system (BRT)

Aiming for long-distance coach interchanges within the city of Johannesburg, an express bus line was established, which connects frequently travelled city sections with each other and operates on a scheduled time-table /Muñoz & Gschwender 2008/. The so-called Bus Rapid Transit (BRT) system consists of modern coaches, which are allowed to travel in dedicated bus lanes /Rea Vaya 2012/. BRT systems can also be found in other megacities in developing countries (e.g. Bogotá, Santiago de Chile, and Curitiba) /GPG 2008b/, /Muñoz & Gschwender 2008/, /Wright & Hook 2007/. They can be seen as combining the advantages of rail transport (e.g. by attracting high passenger numbers) with those of road travel (e.g. low implementation costs, short construction time) /Weinstock et al. 2011/. The advantages of a BRT system compared to other mass transport systems such as rail or underground networks are the lower investments costs, i.e. about one fifteenth of the cost per kilometre compared to elevated rail or about one thirteenth of the cost per kilometre for an underground service. Furthermore, the construction time is much shorter. Because of its integration of services, vehicles and fixed facilities in an Intelligent Transport System, BRT can greatly increase the transport efficiency in terms of the construction time needed or energy usage /Bazeley 2007/, /UNDP 2007/, /Currie & Delbosc 2011/.

The BRT system in Gauteng (Figure 8) was established in Johannesburg. It is called Rea Vaya, which means, “We are going” /GPG 2008a/. It is inspired by the Transmilenio system in Bogotá, the capital of Columbia. It aims to improve the public transport system and to reduce congestion, because of quicker travel using the dedicated lanes. The buses approach dedicated BRT terminals, which are set up in the middle of streets to avoid blocking the other traffic /GPG 2009a/. Crosswalks allow people to access the stations /GPG 2008a/. The stations are served by minibus or bus routes, which carry people from outlying areas to the trunk routes. The buses run every 3–5 minutes during peak periods and about every 20 minutes at off-peak times /GPG 2008b/.

The BRT system in Johannesburg is being built in several phases; when completed, the entire network will be 330 km long and will cover about 80% of the population of Johannesburg within 500 m of a trunk or a feeder station. The full BRT system will consist of about 150 bus stations /UNDP 2007/, /Rea Vaya 2012/, /GPG 2008a/. The full phase 1 will consist of 122 km of trunk routes /SUTP 2010/. Phase 1a, the first part to be constructed, was ready in June 2009. It consists of about 26 km of trunk routes and connects Ellis Park with Soccer City and the Soweto Highway /COJ 2011/. In 2007, it consisted of 143 Euro IV diesel buses, of which 41 are articulated and 102 are complementary (solo) buses /Van der Merwe & Vorster 2009/. It is noteworthy that BRT phase 1a did not aim mainly to replace the use of private cars, but instead to attract passengers who normally used minibus taxis. As a result, the introduction of the BRT led to riots among minibus taxi drivers, the reason being that they saw their livelihood threatened by the new competition for their services /GDPTRW 2007/, /Cervero 2000/. Phase 1b (about 44 km of trunk routes) was initially expected to be ready for the FIFA World Cup, but was completed in mid-2012 /Venter 2011/, /GPG 2008a/. Further parts of phase 1 have not yet been decided /COJ 2011/.

Figure 8: The Johannesburg Rea Vaya BRT system. Articulated Euro IV Bus (left) and a BRT station in the middle of a road (right). Source: own photos.

The City of Tshwane, inspired by the Rea Vaya, might follow suit and install a BRT system as the second Gauteng municipality to do so. However, the construction, which was originally scheduled for 2008, was delayed due to planning issues /Venter 2007/. It is now seen that the construction will not start before 2013 /GDPTRW 2012/. The proposed first phase will connect the Mabopane rail terminal in the north-west of the city with Pretoria Station in the south and is intended mainly to transport commuters to and from work /Vorster & van der Merwe 2009/, /COT 2007/. The second phase is planned to start in Belle Ombre, parallel to the first line and going via the Pretoria Stadium and the football stadium to Mamelodi in the east, mainly satisfying off-peak demand for shopping nodes /Vorster & van der Merwe 2009/, /COT 2007/.

2.2.3 The "Gautrain" Rapid Rail Link

Another recent expansion of the transport system is the Gauteng Rapid Rail link, the so-called "Gautrain". The Gautrain project did not originate only because of the FIFA World Cup in 2010. It was also intended to be an important element to satisfy future transport demands /GPG 2009a/.

The construction started in 2006 (Figure 9, right) and the first phase of the network was ready in 2010. This rapid-transit railway interconnects the international airport with the central business districts of the province /Gautrain 2011/, /GPG 2009a/. The route (in 2011 about 80 km) goes from O.R. Tambo International Airport in Ekurhuleni, via the main business district of Sandton – which is one of the main economic areas in Gauteng – to Johannesburg Park Station in the south-west of the province. A second trunk route connects the city of Pretoria and has been extended to Hatfield in the north of the province /Gautrain 2011/, /GPG 2009a/. However, due to problems with ground water during the construction, the route between Rosebank and Park Station, in the southern part of the network, was not ready before mid-2012 /Venter 2012/.

Figure 9: Gautrain in a station (left) and the elevated railway track under construction between Johannesburg and Pretoria (right). Source: own photos.

The Gautrain trains (Figure 9, left) are based on the Bombardier Electrostar series, which operate at a maximum speed of 160 km/h and have a standard gauge of 1,435 mm, which is wider than the South African gauge of 1,067 mm /GPG 2008b/, /Gautrain 2011/. Overall, the complete Gautrain fleet consists of 24 Electrostar train sets with four wagons each, which might be extended to eight wagons in future /GPG 2008b/, /Gautrain 2011/. The network is also to be extended in future with additional stations possibly in Boksburg, Soweto and Randfontain /Railways Africa 2011/.

2.2.4 Green transport initiatives

A greener transport system, increased fuel efficiency of vehicles, better cost effectiveness and reduced GHG emissions are some of the key challenges for the transport sector as pointed out in the Gauteng Integrated Energy Strategy /DLGH 2010/ (see section 1.2). Gauteng sees an opportunity to be a forerunner for South Africa /Madumo 2010/. Therefore, the Department started a project with the South African National Energy Research Institute (SANERI) to investigate the feasibility of alternative energy sources (including natural gas, LPG and biofuels) for the transport sector by converting and testing 12 vehicles /GDPTRW 2010/.

At the end of 2009, the first CNG fuel station opened in Gauteng. It was a newly built facility, connected to an existing pipeline to demonstrate alternative transport fuels during the World Cup 2010. The station was made available to the public and it is planned to set up more stations in the province /Thomaz 2010/. The Gauteng provincial government and the South African Taxi Association Council intensively tested LPG in a 3 million ZAR project. The project was launched in 2011 and 70 minibuses were converted to bi-fuel vehicles. Additionally, 150 minibus taxis were planned for conversion in 2012 /Smit 2011/.

Biofuels are also supported by the Biofuels Industrial Strategy of the Republic of South Africa /DME 2007/. Besides the prospects for reducing GHG emissions by replacing fossil fuels with biofuel, the strategy points out the opportunities to create new jobs and alleviate poverty in rural areas. This should be achieved by establishing a biofuel industry for first-generation biofuels (biodiesel and ethanol from energy crops). Among all the crops suitable for biodiesel production (in general any oil-containing vegetable or nuts could be used) the strategy proposed biodiesel production from soybeans, rapeseed and sunflower seeds /DME 2007/. Jatropha is not considered in the strategy due to the concerns about its water and land requirements /DME 2007/. For ethanol production sugar cane and sugar beet are recommended as suitable crops. Maize was excluded from the feedstock list due to the concerns about food security and its possible impact on food prices /DME 2007/ (see also /Sexton et al. 2008/). The regulated blending mixes allow a maximum volumetric share of ethanol of 10% in the petrol mix (E10) and a minimum concentration of biodiesel of 5% (B5) if biofuels are produced, provided that fuel specifications are met /DOE 2012c/. It is not yet mandatory to produce biofuels in South Africa, but if they are produced, it is mandatory for refineries to blend them into the fuel mix /DOE 2012c/, /DME 2007/.

To finance the maintenance and the expansion of the province's freeway network (see section 2.2), the South African National Roads Agency (SANRAL) plans to introduce a toll road system for the freeways in the province, which was initially intended to be launched in June 2011. However, because of widespread public opposition to the new toll system, its implementation was postponed and was still not operating in May 2013 /Kaplan 2012/. The system will be based on an electronic system which identifies motor vehicles and charges them by vehicle class and travel distance /SANRAL 2012/.

The initial tariff proposed was reduced after consultations. As a result, the intended tariff in 2012 is between 0.18 ZAR/km for motorcycles and 1.50 ZAR/km for large vehicles of more than 12.5 metres length. Passenger cars (length under 6 metres and height less than 2.5 metres) are to be charged at 0.30 ZAR/km. A maximum cap for registered users will limit charges for passenger cars and motorcycles at 550 ZAR/month. The limit for large vehicles is planned at 3,500 ZAR/month. Additionally, exemptions are to be made for public transport services (e.g. scheduled buses and minibuses), which do not have to pay road tolls /SANRAL 2012/.

From 1st September 2010, South Africa has applied an additional charge on vehicle sales prices based on the carbon emission of the vehicle. The tax is collected directly from the vehicle manufacturers and importers. It applies to all new passenger cars and SUVs sold and excludes commercial vehicles. Any vehicle which falls in this category is once-off taxed at 75 ZAR per gram for all carbon emissions above 120 g CO_2/km /Venter 2010/.

2.3 Summary of the state of transport in Gauteng

Table 2 summarizes some of the characteristics of the Gauteng transport system. Road transport – for passengers and freight – clearly dominates the province's transport system. The public transport system is based mainly on privately operated minibuses; however, recent initiatives (Rea Vaya, Gautrain) aim to strengthen the public transport network. Vehicles in use are comparatively old and with relatively low emission standards.

Table 2: Main characteristics of Gauteng transport system.

	Mode	Modal split[1]	Pros	Cons
Non-motorized transport	Walking Bicycle	38%	+ zero emission	– time consuming – safety issues (as not many pedestrian or dedicated bicycle lanes exist)
Individual motorized transport	Cars Motorcycles	35%	+ flexible + safe + convenient	– low emission standards / old vehicles in use – high individual traffic causing congestion and high emissions – currently mainly dependent on fossil fuels
Public transport	Minibus Scheduled bus Train	20% 4% 3%	+ minibus: flexible system + energy efficient (GJ/pkm, if high load figures) + new modes might increase public transport usage	– minibus: often bad safety and technical standards – minibus: mainly non-scheduled services – bus & train: not many services available
Freight transport	Light and heavy duty vehicles Train	n.a.	+ road vehicles are flexible in use + trains offer energy-efficient long-distance services	– high level of road freight may cause congestion and adversely influence air quality – few train services available

Source: own table. [1] Modal split calculated based on /GDPTRW 2006/ (share of annual person trips).

3 Travel demand modelling and transport energy balance

Several factors determine the overall energy use in the transport sector: the number of trips per mode and trip length, load factors, the modal split and the energy consumption of the technologies involved (Figure 4). While those figures are often available in statistical form for industrialized countries (e.g. /BMVBS 2011/), the necessary information for South Africa has yet to be gathered. Previous studies (e.g. /Goyns 2006/) have identified the need for consistent transport databases for South Africa and Gauteng. Thus, this section aims to show how the different parameters for the transport sectors (total fuel use, vehicle efficiency, number of vehicles, etc.) are combined to derive an energy and emission balance for Gauteng.

To give a qualitative database for further modelling, a consistent transport database is developed in this section. Consistent in this case means that relevant parameters (including vehicle numbers, energy efficiency, annual mileage and load figures) are put into perspective so that they sum up to a complete view of the province’s energy consumption and transport activity. To look at future implications for travel demand, a model is developed based on the behaviour of travellers in Gauteng.

In general, final energy use for transport (FEC^{TRA}) in MJ can be described as shown in Equation 1. It is as the total vehicle kilometres (vkm) driven by mode m in km multiplied by the average fuel consumption of each mode η_m in MJ/km. Thirdly, the product of the number of vehicles n of a mode and the average mileage m in km/vehicle leads to total vkm.

$$FEC^{TRA} = \sum_m vkm_m \cdot \eta_m = \sum_m m_m \cdot n_m \cdot \eta_m \qquad \text{Equation 1}$$

The passenger vehicle kilometres vkm can also be derived by division of the total person kilometres (pkm) by mode in km by the average load factor λ. The vehicle kilometres for freight transport and aviation can be determined accordingly (Equation 2). However, for freight transport tkm (tonne kilometre) is used instead of pkm. All different expressions have to be consistent.

$$vkm_m = \frac{pkm_m}{\lambda_m} + \frac{tkm_m}{\lambda_m} \qquad \text{Equation 2}$$

Figure 10 summarizes the approach to how transport energy consumption and travel demand are calculated and forecasted in this thesis. Initially, a full picture of mobility characteristics (e.g. number trips per mode and person, trip distance) is obtained based on mobility surveys, travel velocity patterns, and time of use data. This database is subsequently used to create characteristic travel demand patterns (homogeneous groups of travel behaviour), which are the basis for the forecast. These characteristics include average trip distance and modes used for the homogeneous groups defined (employment and car availability). In combination with vehicle fleet and load factors, the travel demand can be calculated based on the number of persons per group in the base year (2007). The year 2007 was chosen as the base year as most statistics are available for that year. However, the integrated analysis performed later in this research concludes a time horizon up to the year 2040.

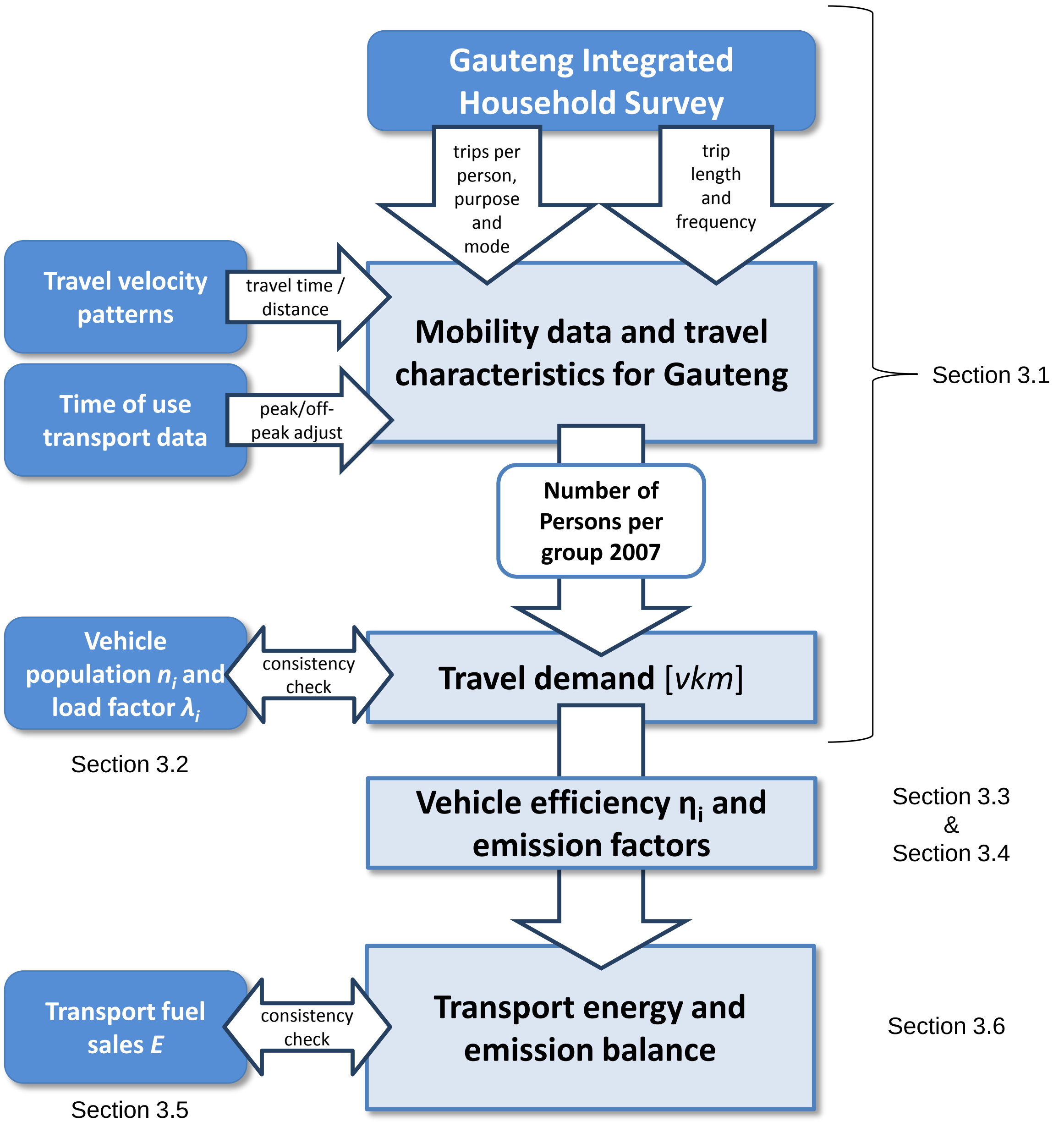


Figure 10: Schematic representation of the approach used in chapter 3.

3.1 Travel demand

Initially, this section shows and evaluates available transport statistics for South Africa and Gauteng (section 3.1.1). After that, available methodologies for calculating travel demand are presented (section 3.1.2). Finally, a travel demand model, which incorporates the socio-economic characteristics and possible development of Gauteng, is created (section 3.1.3).

3.1.1 Travel demand data availability for Gauteng and South Africa

Figures in the literature for vehicle kilometres travelled in South Africa can be found in the studies of De Beer /De Beer & Lötter 2002/ and from the South African Road Traffic Management Corporation (RTMC) /RTMC 2008/. De Beer estimated the total vehicle kilometres travelled in South Africa to be $170 \cdot 10^9$ vkm in 2001, based on total national fuel sales and estimated share of fuel used for road transport (see also section 3.4). Using vehicle registration data from NATIS and estimated specific fuel consumption figures per vehicle type, De Beer calculated the kilometres travelled per vehicle class.

This approach is adopted by the RTMC to estimate the vehicle kilometres travelled in South Africa in later years and also to make estimates for the provinces /RTMC 2008/. However, the RTMC has not updated the method where it seems necessary. The RTMC uses a constant factor to calculate the share of fuel used for road transport (i.e. 98% for petrol and 70% for diesel) /RTMC 2008/, which was originally estimated for the whole of South Africa for the year 2001 by De Beer /De Beer & Lötter 2002/. Moreover, the RTMC takes constant shares (also based on 2001 results) to split fuel use among vehicle categories (e.g. 65% for "cars") for all years and provinces. The result is then multiplied using an assumed specific fuel use per transport mode, which is also not varied over time (e.g. 10 litres/100 km for petrol and diesel cars) to derive total vehicle kilometres travelled. Because of these points of criticism, the RTMC figures are not used in this study and an approach using the original methodology of De Beer has been adopted and extended in terms of socio-economic parameters.

Available travel demand models applied to Gauteng (e.g. GTS 2000 or NATMAP, see section 1.3) do not incorporate all modes analysed in this thesis nor do they correspond to the time horizon needed for further modelling (see chapter 4). Thus, an own model is applied based on the further data needs and specifications. This model does not aim to forecast detailed passenger flows, trip lengths or vehicle speeds; but is used rather to project total mobility by mode for different socio-economic conditions reflecting possible developments of the region.

As described in sections 1.1 and 1.2, wealth and the access to services are not equally distributed among the population, resulting in many people living in poverty. The role of income and living standard for transport (e.g. choice of transport mode, car ownership) has been analysed and underlined in several studies, e.g. /Kenworthy 2003/, /Van der Land 2008/, /Kelly 2007/, /Mokonyama & Venter 2005/, /Mokonyama & Venter 2007/ or /Prozzi et al. 2002/. In South Africa, high growth rates in vehicle numbers are reinforced by government policies that support the use of private vehicles (see sections 2.1 and 2.1.2) and by the poor public transport system available (see section 2.1.1).

Those studies available for South Africa exclude freight transportation or do not provide specific information for the freight sector. NATMAP 2050 includes some information on freight movement but only for the main corridors in Gauteng /DOT 2008a/.

The CSIR states the total freight volume to be $374 \cdot 10^9$ tkm in 2007, which is subdivided into $129 \cdot 10^9$ tkm rail and $245 \cdot 10^9$ tkm road transport /CSIR 2008/. Of these statistics, $2.5 \cdot 10^9$ tkm of the figure for rail transport is declared as “metropolitan” and $61 \cdot 10^9$ tkm as road transport (in 2007) /CSIR 2008/. However, the figure is not subdivided by province. Moreover, no forecasts are given /CSIR 2008/.

In terms of aviation, passenger statistics for Gauteng are available at /ACSA 2012/ (separately for international and domestic passengers). Furthermore, estimates for future passenger numbers in Gauteng are available from NATMAP /DOT 2008a/. Additionally, forecasts for the African continent can be found in /Boeing 2011/ and /Airbus 2011/. However, none of these aviation statistics specifies energy figures or passenger kilometres.

Due to the non-availability of robust figures expressing the travel demand in Gauteng, in the past and for the future, and limitations in consistent and comprehensive transport statistics identified by /Goyns 2006/, a consistent travel demand model calculation seems to be required, which includes the observed dependence of transport demand on socio-economic conditions in order to make projections.

3.1.2 Background to travel demand modelling

Different types of models are available to forecast travel demand. Simple analysis forms are built on the extrapolation of historical trends based on expected growth rates /Wermuth 2005/. Studies that are more complex are regionalized analyses, which are based on the possible decisions of travellers considering their travel needs and socio-economic characteristics /Wermuth 2005/. Many travel demand models split the decision process into four steps: trip generation, trip distribution, modal split and spatial assignment. Four-step models differ in terms of *why* (i.e. aggregated or disaggregated models) and *how* travel demand is generated (i.e. trip based or activity based).

In the first decision step, trip generation, the quantity of travel is analysed. Therefore, the modelled region can be divided into zones (e.g. communities). For each transport zone, the number of trips is calculated based on the socio-economic characteristics of that zone. In consequence, all socio-economic conditions are required to be forecast for each zone /Gorr 1997/, /Jovicic 2001/, /Wermuth 2005/. Secondly, the trips generated are distributed between the zones. This distribution is usually based on a calculated attractiveness (e.g. existence of jobs or shops) of each zone /Gorr 1997/, /Jovicic 2001/, /Wermuth 2005/. The third step, modal choice, splits the trips among the travel modes available. Depending on the details of the model, these can be different individual or public transport modes and include walking. The modal decision is based on the notion of ‘Homo economicus’ – i.e., the concept that human behaviour is based on rational actions aimed at maximising personal wealth, or, in our case, assumes that decisions are taken to minimize travel time or costs. The trips are finally assigned to the network in the fourth step, which generates probable routes between the origin and destination of a journey /Gorr 1997/, /Jovicic 2001/.

In trip-based models, each person’s journey is handled separately, whereas in activity-based models an activity can result in a series of trips. In fact, some decision steps can be dependent on each other or be redundant, for example if several trips follow each other or if only one travel alternative exists /Wermuth 2005/. Thus, in an activity-based model, the activity of “going to work” can result in a sequence of trips such as “go to work, work trip” during the day, and “travel back home”; in a trip-based model these trips are analysed independently /Gorr 1997/, /Jovicic 2001/.

The difference between aggregated and disaggregated (individual behaviour) models lies in the consideration of the traffic reason /Wermuth 2005/. While in aggregated models the reasons for traffic flows are not defined, in disaggregated models travel is based on individual decisions and activities of the traveller based socio-economic and demographic characteristics /Gorr 1997/, /Jovicic 2001/. To do so, in disaggregated four-step models, the total population is separated into homogeneous groups of travel behaviour, according to the assumption that personal indicators correlate with that person’s travel demands /Wermuth 2005/. Significant indicators can, for example, be age, gender, employment and the availability of motor cars /Gorr 1997/, /Wermuth 2005/. Although critics argue that building groups dependent on socio-economic factors might not explain the reason for people travelling, it is recognized that homogeneous groups of travel behaviour result in an appropriate basis on which to project future travel demand /Gorr 1997/. Other points of criticism are seen in the sequential modelling of trip destination and modal choice, which might not reflect reality but make the mathematical basis of the model simpler and easier to operate /Bates 2000/.

The advantages of travel demand modelling based on homogeneous groups can be seen in the relatively simple application of a specific description of travel behaviour /Wermuth 2005/. Conversely, some critics argue that a direct approach to simultaneously forecasting all modes leads to better results because of the interlinkages between travel decision and mode choice /Schaefer 1998/. Modelling based on homogeneous groups can be used for all four decision steps /Wermuth 2005/. However, having too many different groups can result in uncertainties in projecting the population number of each group /Wermuth 2005/.

The following section describes the application of a travel demand model for Gauteng, based on a disaggregated approach using homogeneous groups of travel behaviour.

3.1.3 Travel demand model development and application

Passenger transport

The database for the Gauteng EMME/2 model applications (i.e. GTS 2000 and NATMAP) is used for a trip-based modelling approach /GDPTRW 2006/. The travel demand model application follows in principle the traditional approach (i.e. trip generation, distribution, modal split and network assignment). However, not all steps are necessary, as the energy model used (see chapter 4) requires only aggregated data (total pkm by mode) and no spatial distribution. Thus, it is not necessary to differentiate between transport zones or to distribute the trips spatially to a transport network, so that the data needs and computation efforts can be limited.

A characteristic of the applied travel demand model is that it is a disaggregated approach based on homogeneous groups of travel behaviour. Therefore, it allows forecasting the travel demand for Gauteng considering the development of scenarios for the region considering its socio-economic development. The main challenge for this travel demand model is to prepare the input figures given in various surveys so that they can be used in the proposed method. As stated previously, taking socio-economic indicators into account can improve the possibilities of forecasting travel demand. On the other hand, the data demand is enlarged and so is the mathematical complexity. It seems, therefore, reasonable to limit the descriptive variables for forecasting travel demand based on the required results and data availability. According to /Schaefer 2004/, /Schmiedel 1983/, /Holzapfel 1980/, /Kutter 1972/, two factors are most important for reducing variances and creating homogeneous groups: the availability of a motorcar and the status of personal employment. For that reason the homogeneous groups (meaning that every person belonging to a group shows the same behaviour) in this analysis are defined according to these criteria as reflected in Equation 3, where $p_{m,d}$ is the daily passenger travel per mode (in km/day/person) as a function of employment (e) and car ownership (c). The travel behaviour within each group is taken to be constant over the time horizon of this analysis (i.e. up to the year 2040).

$$p_{m,d} = f(e, c) \qquad \text{Equation 3}$$

In consequence, the total (annual) passenger travel demand (in *pkm*) can be derived by multiplying the number of persons per group ($pop_{e,c}$) by the 365 days in a year (Equation 4).

$$pkm = \sum_{m} p_{m,d}(e, c) \cdot pop_{e,c} \cdot 365\ days \qquad \text{Equation 4}$$

The calculation of personal passenger travel demand ($p_{m,d}$) in this thesis is mainly based on the Gauteng Household Travel survey, which was conducted in 2002/2003 /DOT

2007/, /GDPTRW 2006/. The survey was originally the basis for the Gauteng Transportation Study (GTS 2000), which aimed to simulate the peak-hour traffic for the major transport networks in the province (see section 1.3). The sample size of 84,158 persons represents 55,141 person trips. Expanded to the total population of Gauteng, this reflects more than 5 million daily trips during peak hours. The trip information also includes transport mode, trip purpose, trip frequency and trip time. Furthermore, the survey contains demographic and socio-economic information including car ownership and employment status /GDPTRW 2006/. The survey data are available in the form of three different access databases containing information for people and households surveys and aggregated trip information. These databases are merged in order to allow a coherent analysis. Thus, it has some limitations and does not include all information needed to model total travel demand such as the trip distance in kilometres, which is only measured as trip duration in minutes and does not give all relevant information of total daily travel /GDPTRW 2006/. Another point of criticism is that the survey data for the City of Tshwane is taken from a previous survey conducted in 1998 /GDPTRW 2006/. For the GTS project, it was then merged with the information sampled in the rest of the project, which brings up the question of data consistency. Despite these limitations, the Gauteng travel survey is the most comprehensive travel database available for the province /GDPTRW 2006/.

The employment information obtained from the survey is aggregated into the categories “employed” and “unemployed”, by accumulating all persons who are not formally employed (e.g. students, pensioners) into the latter category. The availability of vehicles is aggregated into the groups none, one, two, and three or more passenger cars. Households that report the availability of five or more vehicles represent only less than 1% of the sample.

Many studies about forecasting car ownership in South Africa are available e.g. /Mokonyama & Venter 2005/, /Mokonyama & Venter 2007/, /Kelly 2007/, /DOT 2009/. The methodologies include regression models, time series extrapolations, cross-classification models and logit models. However, for this study, it is necessary to adopt a forecasting approach which is usable for the travel demand model (see section 3.1) and incorporates the general socio-economic framework of the scenarios (chapter 6).

Johansson and Schipper summarized the main variables influencing car ownership from various studies /Johansson & Schipper 1997/. They found that car availability is mainly dependent on the average income of a household (elasticities of 0.75 to 1.25). Based on the 2003 South African National Travel Survey /DOT 2003/, a matrix of car availability is generated for different income groups. The income groups are aggregated in terms of “poor”, “low”, “middle” and “high income” as defined by /Hector et al. 2009/, and 2003 income levels are adjusted according to this study.

The availability of vehicles is given in the travel survey for the groups none, one, two and more than two vehicles /DOT 2003/. To expand the category “more than two” into two new categories (i.e. two, and three or more cars available), the income and expenditure of households survey 2005/2006 /StatsSA 2005/ is used. The total number of cars is adjusted to the numbers given under vehicle registrations for the years 2003–2007. The figure for available cars per person is merged with the employment figures using an iterative process assuming that the split of cars between employed and unemployed people remains constant. The resulting probability of car availability per income group in Gauteng is shown in Figure 11 for the base year of 2007. For future years, the figures have been adjusted to take account of decreasing household size, which increases availability.

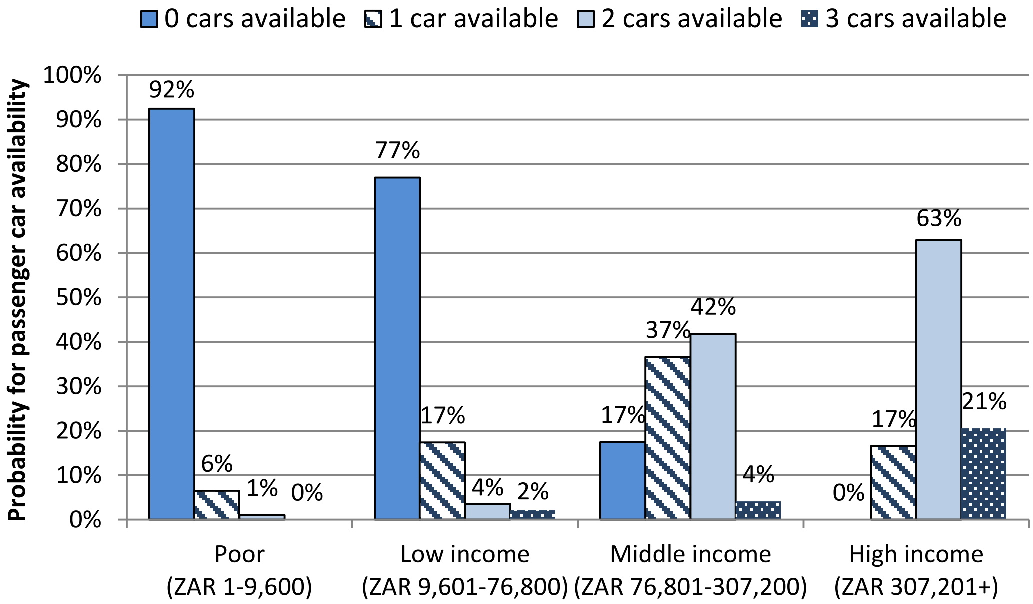


Figure 11: Probability of passenger car availability in Gauteng for the base year 2007. Source: own calculations based on /DOT 2003/, /StatsSA 2005/ and /Hector et al. 2009/.

The number of trips stated in the travel survey has to be adjusted for the total number of daily trips ($p_{m,d}$) from the information available for peak hours. The survey documentation states that the three-hour morning peak period contributes about one quarter of the daily traffic /GDPTRW 2006/. However, this information is quite vague. More detailed information can be found in /DOT 1998/ and /Goyns 2006/. The first study reports the modal trip distribution of annual passenger trips by time of day for the modes bus, train and minibus taxi. In the second study, measurements of vehicles were conducted in Johannesburg, resulting in the daily trip distribution for the measured vehicle sample. By digitising both figures the share of trips during peak hours from the GTS study was calculated /GDPTRW 2006/ and then applied to all modes reported in the GTS (Table 3). It can been seen that the results reflect the initial statement that the three-hour morning peak period contributes about one quarter of the daily traffic, but differs slightly according to transport mode.

Table 3: Adjustment factors (a_m) for total daily personal travel based on peak travel by mode.

Main Mode in GTS 2000	Peak share	Adjustment factor a_m
Bus	22.0%	4.54
Car (drivers and passengers)	19.1%	5.24
Minibus taxi (including lift clubs and company transport)	24.1%	4.14
Motorcycle	24.1%	4.14
Train	25.7%	3.88
NMT (walking and bicycle)	22.0%	4.54
Missing and other	22.0%	4.54

Sources: own calculations, own assumptions based on /Goyns 2006/, /DOT 1998/.

Finally, an assumption is needed to convert the travel duration (in minutes) given in the survey into distances. /GDPTRW 2006/ states the average simulated vehicle speed in the GTS2000 model as 51 km/h in the year 2000, which is estimated to decrease to 26 km/h in 2025. /Goyns 2006/ recorded the average speed of cars as 41 km/h during a two-week measurement period. /Schaefer & Victor 1999/ assumes the average speed of a passenger car in Africa to be 45 km/h, a bus as 20 km/h and a train to be 30 km/h in 1990. In this analysis, the following average driving speeds are assumed (Table 4).

Table 4: Assumed average driving speeds per mode (v_m) in Gauteng.

Main mode	Speed v_m [km/h]
Bus	25
Car (driver and passengers)	35
Company transport and lift clubs	30
Minibus	25
Motorcycle	35
Train	40
Walk	3
Bicycle	10
Missing and other	20

Sources: /Goyns 2006/, /Schaefer & Victor 1999/, own assumptions.

In consequence, it is possible to calculate total volume of daily person travel $p_{m,d}$ (in km/day/person) based on the number of peak trips (τ^{peak}) per mode (m) and per day in 1/day, the adjustment factor a_m, travel time (t) of each trip τ (in min) and travel speed per mode (v_m) (in km/h) (Equation 5).

$$p_{m,d} = \sum_{\tau_{c,e}} \left(\frac{\tau_m^{peak} \cdot a_m \cdot t_\tau \cdot v_m}{60 \, \frac{min}{h}} \right) \cdot \frac{1}{pop_{c,e}} \qquad \text{Equation 5}$$

Equation 5 allows also verification of the assumptions of vehicle speed v_m and off-peak adjustment a_m by illustrating average travel time per trip ($\bar{t}_\tau$) and average trip distances. Table 5 summarizes those mobility characteristic for Gauteng and shows the number of daily trips per person, average travel time per trip and average trip distances for aggregated modes that are used in subsequent modelling, i.e. by merging the car-based modes into one group.

Table 5: Mobility characteristics for Gauteng, showing number of daily trips per person, average travel time per trip and average trip distances.

Main mode	**number of trips per person [trips/day/person]**	**average travel time per trip [min]**	**average trip distance [km/trip]**
Bus	0.11	50.3	25.1
Car	0.92	25.5	14.8
Motorcycle	0.00	17.5	10.2
Taxi	0.53	44.4	25.9
Train	0.08	65.2	43.5
NMT	0.99	24.0	1.3
Total	**2.62**	**30.9**	**13.2**

Sources: own calculations

As a result, a person in Gauteng makes about 2.6 daily trips on average over an average distance of 13.2 km. In comparison, /Goyns 2006/ measured the average distance per car trip in Johannesburg as 11.5 km, excluding long-distance trips, which can be seen as consistent with the finding of this study. This means that the average travel-distance per person in Gauteng is about 31 kilometres per day, or 11,296 kilometres annually. Schaefer analysed the travel time budget (i.e. the total time spent on travelling per person per day) for different countries and studies /Schaefer 1998/. He came to the result that on average about 1.0 to 1.5 h/person/day is spent on travel, regardless of the country, mode of travel or income level. The corresponding result of this study is about 1 h 21 min, which is within this range.

An overview of the travel characteristics of the homogeneous groups ($p_{m,d}$) is presented in Figure 12. The average daily travel almost triples from 19.0 km to 58.0 km/person/day if a person changes his working status from being unemployed to employed. The average travel distance also increases when the number of available cars increases. The average trip distances travelled per day by a person, who has none, one, two or three and more cars available are 23.8, 37.4, 46.0 and 51.1 km/person/day, respectively (average between employed and unemployed). In comparison, a field survey in Johannesburg came to the comparable result of 61.5 km/day for car drivers /DOT 2009/. Another important finding is that the modal split changes drastically as soon as at least one car is available. While the main mode for persons who do not have a car available is minibus taxi and train, the use of cars becomes dominant as soon as one car is available. People with two or more cars available use virtually only cars as their mode of travel (> 96%).

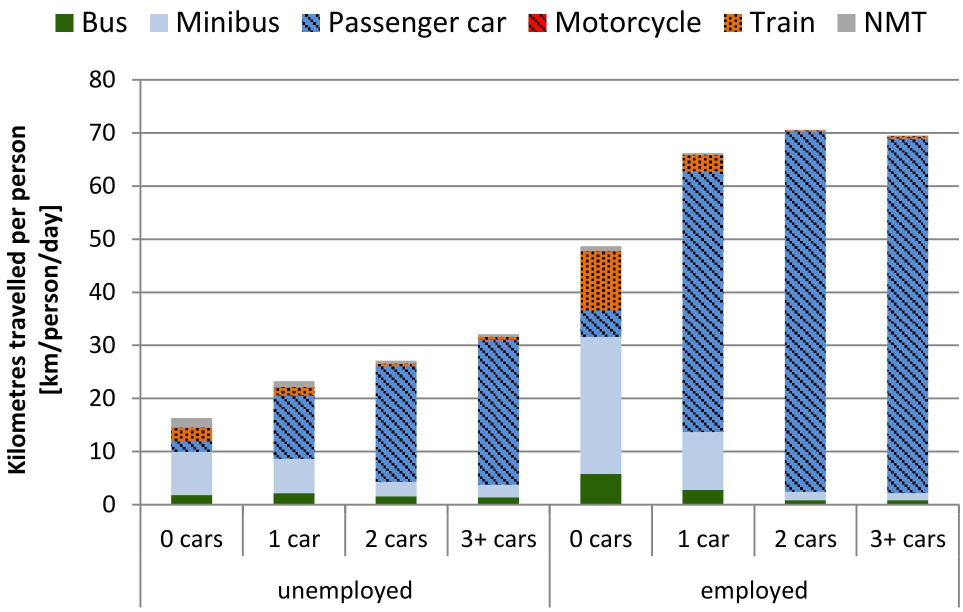


Figure 12: Travel characteristics of the homogeneous groups defined.
Source: own calculations.

Multiplication of the calculated travel characteristics by the number of persons per group leads to the total passenger travel demand of Gauteng in 2007 as $131.9 \cdot 10^9$ pkm, of which about $4.2 \cdot 10^9$ pkm corresponds to NMT (walking and cycling). The travel characteristics of the homogeneous groups are assumed to be constant over the time horizon of this analysis (i.e. up to 2040). However, expanding the public transport system in different ways allows the TIMES-GEECO model to alter the resulting modal shift (see section 4.3)

Freight transport

The Gauteng Household Travel survey includes only passenger travel by road and rail and did not investigate aviation or freight transport /GDPTRW 2006/. However, there are many studies available which show the dependence of freight transport volume on the gross domestic product (e.g. /Farahmand-Razavi et al. 2004/, /Tapio 2005/, /Banister & Stead 2002/, /McKinnon 2007/). The relationship between tkm growth and GDP growth has been investigated for many countries. However, the elasticity of tkm growth rate (also referred to as transport intensity /Banister & Stead 2002/) with respect to growth in GDP is found to depend on the composition of the GDP (i.e. if a country's economy is focused on the first, second or third sector) /McKinnon 2007/. Some studies found that as more of the economy shifts to the third sector (i.e. services), the growth in freight transport declined with respect to growth in GDP /McKinnon 2007/, /Banister & Stead 2002/. The annual growth in tonne kilometres (tkm) can therefore be expressed as (Equation 6):

$$tkm(t) = \varphi \cdot tkm(t-1) \qquad \text{Equation 6}$$

where φ is the transport intensity in $\left[\frac{tkm}{GDP}\right]$. Transport intensities for this thesis are based on /Fulton & Eads 2004/ for industrialized countries and taken as $\varphi = 1$ for 2010 and $\varphi = 0.9$ for 2030 and later years. It is assumed that in intervening years φ changes linearly.

Aviation

Future air travel is not analysed as comprehensively as road travel in this thesis, as it is found that Gauteng may not influence future aviation legislation to any extent. Instead it is calculated as a projection of final energy consumption (FEC) based on passenger volume (pv) and specific energy consumption (e) per passenger and year (Equation 7). The calculation is performed separately for domestic (d) and international passengers (i).

$$FEC^{aviation} = \sum_{i,d} FEC_{i,d}^{aviation} = pv_{i,d} \cdot e_{i,d} \qquad \text{Equation 7}$$

Dividing the consumption of aviation fuel in Gauteng in 2008 (available at /DOE 2009b/) by the passenger volume for that year (available at /ACSA 2012/) leads to the corresponding specific energy consumption (e), which has been calculated as 3.2 GJ/passenger/a (international) and 3.1 GJ/passenger/a (domestic).

Historical passenger statistics for Gauteng available at /ACSA 2012/ are found to have a strong coefficient of regression ($R^2 > 0.96$ for international and $R^2 > 0.99$ for domestic passengers) with GDP/capita for the province. Thus, the forecast of future passenger volumes (pv) is based on these regression curves. If future GDP figures for Gauteng (e.g. /Wehnert et al. 2011/) are applied, the resulting passenger numbers are in line with forecasts available from NATMAP /DOT 2008a/. However, NATMAP assumes that growth is limited by current airport capacity /DOT 2008a/, which is not assumed in this thesis. Annual passenger growth rates can be calculated as 5.2% and 4.6% for international and domestic passenger travel, respectively, which is in line with expected growth for Africa in /Boeing 2011/ and /Airbus 2011/.

Specific energy consumption (e) in the aviation sector decreased continuously in past decades; Peeters calculated an average annual reduction in specific consumption of 1.4% by jet aircraft /Peeters et al. 2005/. This trend has been assumed to continue in future and has been applied to the baseline figures for Gauteng for the year 2008. As a result, specific fuel consumption is assumed to decrease from 3.2 GJ/passenger/a (international) and 3.1 GJ/passenger (domestic) in 2008 to 2.1 GJ/passenger and 2.0 GJ/passenger in 2040 for international and domestic passengers, respectively.

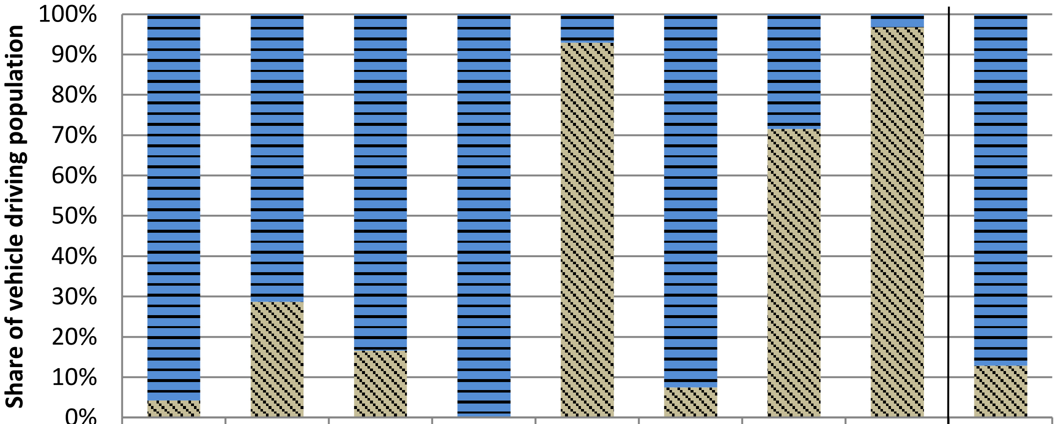
3.2 Vehicle population and vehicle load

About 3 million motorized vehicles were registered in Gauteng in 2007, which is about 38% of the South African vehicle population /RTMC 2008/. Two-thirds of the fleet are motorcars and station wagons and about 18% are light duty vehicles (LDVs) and bakkies. The remainder splits among other categories such as buses, trucks and motorcycles /RTMC 2008/. However, the differentiation of the fleet among fuel types is not stated in the literature. Furthermore, the percentage of the registered fleet, which is capable of being driven and of those vehicles which are simply not deregistered at the end of the vehicles' lifetime), is unknown. /Goyns 2006/ used the Gauteng registration database to deduce the fuel types of vehicles in Johannesburg for his research. This approach was found to be valuable and a similar approach was adopted in this study.

Thus, the Gauteng Vehicle Registration database, which is available for the years 2007 and 2009, was used to calculate the shares of diesel and petrol vehicles /NATIS 2009/. The vehicle base is limited to all vehicles first registered after 1970, in order to assume a database of drivable vehicles, which reduces the database by about 1%. Furthermore, it is possible to subdivide the category "motorcars and station wagons" into two categories, representing smaller cars with an engine size of less than 2.5 litres (in the following they are referred to as passenger cars) and big cars with engine size greater than 2.5 litres (subsequently referred to as SUVs). Vehicles with no information on their fuel type or engine size are distributed equally among those where the information was available.

Buses are subdivided into two categories ("small bus", i.e. buses < 6 litres engine size and "big bus" for the remainder). The total number of registered big buses (~6,000) is adjusted to the number of provincially operating subsidised and municipal buses (in total about 3,000 vehicles) according to /GDPTRW 2004/ and /DOT 2008a/.

Figure 13 shows the calculated vehicle population of 2007 by fuel type. The highest share of the total fleet are motorcars subdivided into the categories passenger cars (PCs) and SUVs, which account for 64% and 6% of the total, respectively. About 19% of the fleet are LDVs. The total share of diesel vehicles is relatively low at only 13% of the fleet running on diesel. Obviously, the share of diesel vehicles is higher for vehicles with a bigger engine size. However, a small number of older heavy-duty vehicles (HDVs) and buses running on petrol are still registered. Furthermore, there were almost no vehicles running on other fuels than petrol and diesel registered in 2007. Until 2012, this state of affairs changed only little: only a few vehicles have been converted to use LPG, CNG and biofuels as a result of government initiatives (see section 2.2.4). Moreover, about 2,000 hybrid electric vehicles had been registered in South Africa by 2011, of which some are likely to be registered in Gauteng /Schmidt 2012/.



	Pass. car	LDV	SUV	Motor-cycle	HDV	Minibus	Small Bus	Big Bus	Total
Petrol	1827	399	157	115	7	95	2	0	2603
Diesel	82	161	32	0	98	8	4	3	388

Figure 13: Relative proportions of vehicles by fuel type in Gauteng in 2007 in 1,000 vehicles. Source: own calculations based on /TÜV 2012b/ and /NATIS 2009/.

Vehicle load factors (occupancy rates) are based on the South African literature available. However, many figures in the literature seem outdated or are not reported for Gauteng specifically but for other areas in South Africa. In 2009, the Gauteng City-Region Observatory (GCRO) conducted a survey to measure social characteristics of the city region /GCRO 2009/. In this so-called “Quality of life survey”, 6,000 people living in the province were surveyed /GCRO 2009/. Some questions were contributed to the survey (such as the average number of people in a vehicle per trip) by the author of this thesis, to deduce Gauteng-specific load figures for minibus and for cars and SUVs. The effect of the minibus taxi recapitalization programme (see section 2.2.1) is included as the occupancy rate of minibuses is assumed to increase from 10.0 persons/trip in 2007 to 12.0 persons/trip in 2015 and later.

Table 6: Assumed load factors for Gauteng according to mode of transport.

Mode	**load [person/trip]**	**load [tonne/trip]**
Bus	28.0	-
BRT	45.0	
Passenger car & SUV	2.6	-
Minibus	10.0-12.0*	-
Motorcycle	1.0	-
LDV	-	1.6
HDV	-	15.0

*12.0 applies to the year 2015 and later

Source: /GCRO 2009/, /Bubeck 2012/, /Winkler 2007/, /GDPTRW 2006/, own assumptions.

3.3 Vehicle emission factors and specific energy consumption

The emission inventory and specific energy consumption for the modes of transport considered in this analysis are a result of the work of TÜV Carbon Services, Cologne, and were developed within the EnerKey research group “Transport and Mobility Patterns” (see also www.enerkey.info). The basis for this inventory is the *Handbook of Emission Factors* (HBEFA), which includes emission factors and fuel efficiencies for different modes and driving conditions. Those values were adjusted by TÜV for emission standards and engine sizes based on the Gauteng registration database (NATIS). Finally, the data were assigned to EMME/2 traffic flow data. As a result, weighted emission factors were obtained for average traffic situations in the province (see /Kober et al. 2011/ and /Tomaschek & Fahl 2013/ for a detailed description of this process).

The efficiencies and tank-to-wheel (TTW) GHG emissions of the base year fleet in 2007 are shown in Table 7. A detailed representation of all emission factors for all vehicle types is given in Appendix B. To determine these figures, the TÜV emissions inventory had to be recalculated from emissions per km to emissions per MJ fuel used to make the data model compliant using the calorific values shown in Appendix A. Subsequently, the vehicle fleet of 2007 (see section 3.2) is divided according to emission standards based on /TÜV 2012b/ by applying the corresponding standard to each vehicle registered in a particular year. Furthermore, the figures are adjusted by taking higher emission standards of imported vehicles into account. As a result, only 6.6% of the total fleet of 2007 was compliant with Euro 4 or higher emission standards, whereas more than 62% of the fleet was running on pre-Euro emission standards. By building weighted averages for each vehicle class and fuel types for the fleet composition (e.g. Euro 1, Euro 2, etc.), it is possible to show a vehicle’s average fuel consumption in a specific year. This procedure was undertaken for the base year of 2007, on the one hand, and for average new vehicles on the other hand.

Table 7: Specific TTW energy consumption and GHG emissions per km of the vehicle fleet in Gauteng in 2007.

Mode	Diesel		Petrol	
	Specific energy consumption[1)]	GHG emissions[2)]	Specific energy consumption[1)]	GHG emissions[2)]
	MJ/km	g CO_2eq/km	MJ/km	g CO_2eq/km
Passenger car	2.5	187	3.5	252
SUV	3.5	261	4.6	335
Motorcycle	-	-	1.6	116
Minibus	4.6	338	5.5	395
Small bus	11.8	869	5.4	387
Big bus	19.2	1,416	9.1	652
LDV	3.7	275	4.1	300
HDV	16.7	1,231	8.4	607

1) average from highway, urban, rural
2) non-GHG emissions are shown in Appendix B

Source: own calculations based on /TÜV 2012a/, /TÜV 2012b/ and /NATIS 2009/.

3.4 Future development of the base year fleet of 2007

When calculating the future composition of the 2007 base year vehicle fleet, without considering vehicle replacements, it is likely that older vehicles (with mostly lower fuel efficiency and emission standards) will be replaced sooner than newer ones. The performance of the base year fleet is therefore expected to improve with time independently of the type of vehicle used to replace scrapped stock or to satisfy new transport demand (which is a result of the TIMES-GEECO model, see chapter 6.2).

The survival of a technology can be expressed by Weibull functions, which allow the estimation of technological reliability and failure probabilities (e.g. /Wilker 2004/, /Mittag & Rinne 2008/, /Chen & Niemeier 2005/). Zachariadis presented a modified Weibull function in which the original three-parameter function is reduced to two parameters, resulting in a transformed S-curve /Zachariadis et al. 1995/, /Zachariadis et al. 2001/. Using such a modified Weibull function, the future number of vehicles v from the base year fleet of an emission standard s can be calculated by Equation 8.

$$v_s(t) = exp\left[-\left(\frac{t+b_s}{T_s}\right)^{b_s}\right] \cdot v_s(t=0) \qquad \text{Equation 8}$$

In this equation t is the time in years, T the characteristic service life in years of a vehicle of type s, and b is the failure rate of a vehicle of that type. According to the study of /Zachariadis et al. 1995/, T_s is usually found to be equal to the expected lifetime of a vehicle and b_s can be approximated to the average age of the vehicle.

Figure 14 illustrates the future number of petrol-driven passenger cars surviving from the 2007 base year fleet (left side) and the resulting changes in the fuel consumption as older vehicles progressively retire (right side). As a consequence of the retirement of older vehicles, the average fuel consumption – which for petrol cars in the 2007 base year was about 3.5 MJ/km – will fall to less than 3.2 MJ/km in 2025 (Figure 14).

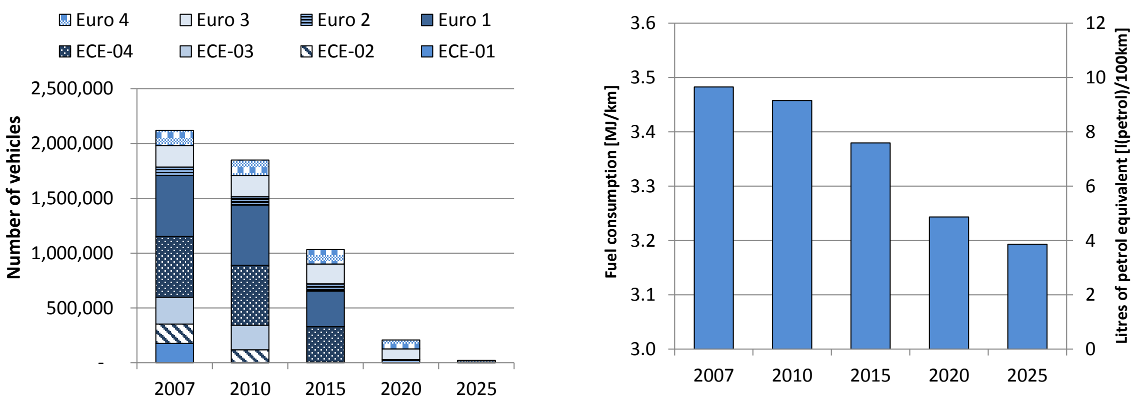


Figure 14: Future size and composition of the residual fleet of petrol-driven cars, starting with the 2007 base year, in terms of emission standard (left) and average fuel consumption per km (right). Source: own calculations.

3.5 Transport fuel use

The fuel used for transport is used to cross-check and calibrate the results of transport energy consumption previously calculated. However, as stated above, this figure for Gauteng cannot be found directly from available statistics or in the literature. De Beer developed a method to account for fuel sales for road use (FEC^{road}) and to other sectors in South Africa /De Beer & Lötter 2002/. This approach is based on guidelines given by the Department of Minerals and Energy Affairs (DME), the South African Revenue Service (in the diesel refund guide) and Spoornet. As a result, they demonstrated that the share of diesel for road use in South Africa rose from 65% to 75% between 1996 and 2001. The share of petrol for road use was assumed to be 98% /De Beer & Lötter 2002/.

The methodology presented in /De Beer & Lötter 2002/ is applied in this thesis to the fuel sales figures for Gauteng, which can be found at /SAPIA 2011/. While /De Beer & Lötter 2002/ used a fixed share for petrol for road use, in this thesis the same procedure used for allocating diesel sales is assumed to be applicable also for petrol sales. The analysis shows that the share of diesel for road use in the province rose from 68% in 2002 to 83% in 2007, while the share of petrol for road transport remained almost constant between 98% and 99%, which is consistent with the initial finding of /De Beer & Lötter 2002/. In absolute numbers, the amount of fuel used for road transport rose from 158 PJ in 2002 to about 204 PJ in 2007 (an increase of 29%) (Figure 15).

Total energy consumption for aviation ($FEC^{aviation}$) is derived from fuel sales for kerosene given by the DME (about 58.5 PJ in 2008) /DOE 2009b/. For rail transport (FEC^{rail}), electricity and diesel consumption are estimated based on /IEA 2008a/ and /DNT 2003/, which result in about 4.1 PJ_{diesel} and 0.8 $PJ_{electricity}$ in 2007.

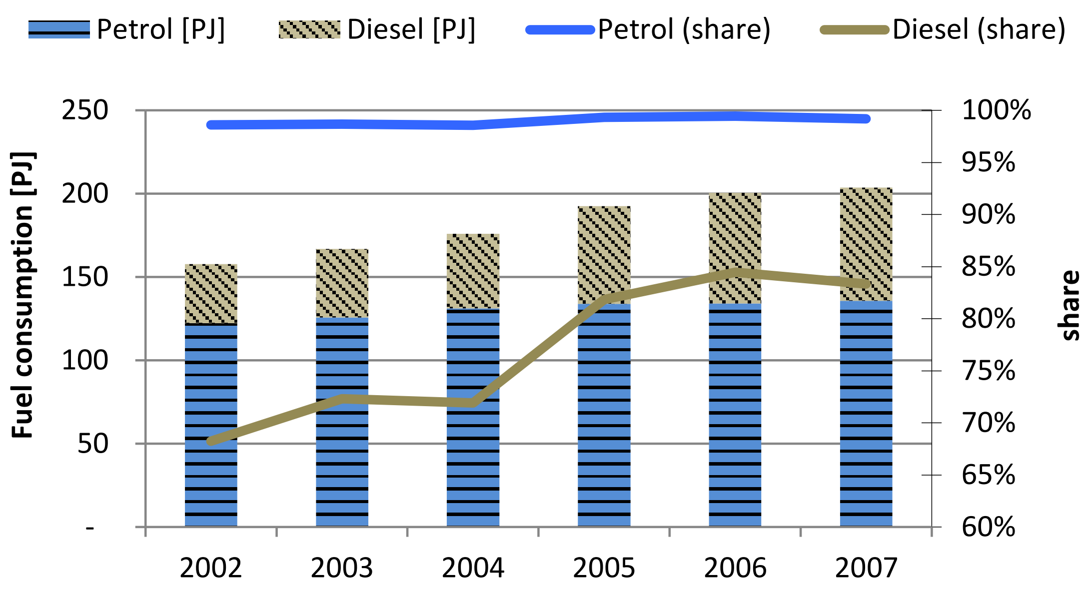


Figure 15: Fuel used for road transport in Gauteng (left axis) and transport fuel use as share of total provincial fuel consumption (right axis). Source: own calculations based on /SAPIA 2011/ and /De Beer & Lötter 2002/.

3.6 Transport energy and GHG emission balance for Gauteng in 2007

Combining the information gathered above (travel demand, vehicle population, vehicle load factors, vehicle fuel efficiency and total energy use for road transport), as well as the calculation for rail transport and aviation, it is possible to deduce a complete energy balance for the Gauteng transport sector. Based on the GHG emission factors of the TÜV emission inventory for Gauteng /TÜV 2012a/ and the calorific values given in Appendix A, it is furthermore possible to deduce the total tank-to-wheel GHG emissions corresponding to the transport sector (Figure 16). GHG emissions corresponding to international aviation have not been allocated to Gauteng, whereas 50% of emissions related to domestic aviation have been allocated to the province.

In total, the final energy consumption of the transport sector in Gauteng in 2007 was calculated as 270.6 PJ. This figure corresponds to about 35% for private passenger transport (i.e. passenger cars, SUVs and motorcycles), of which passenger cars are the greatest consumers at 83.1 PJ. Road freight (LDVs, HDVs) contributes about 85.8 PJ to the total final energy consumption, of which about 60% is HDVs. Public transport, including minibuses, contributes only 27.4 PJ (about 10.1%) to the total final energy consumption. The tank-to-wheel GHG emissions from transport in Gauteng in 2007 represent 16.1 Mt CO_2eq; 6.8 Mt CO_2eq of this is generated by individual passenger transport. The second largest contribution is due to road freight, which corresponds to about 6.2 Mt CO_2eq. Public transport (including minibuses) contributes only 1.6 Mt CO_2eq (about 9.9%) to the total of direct GHG emissions in the province.

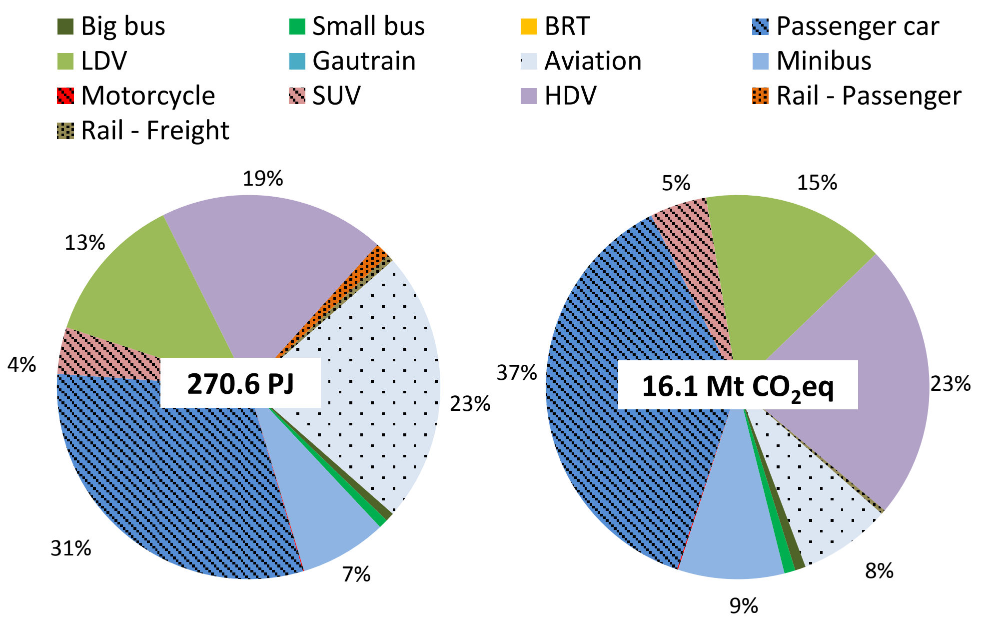


Figure 16: Final energy consumption (left) and TTW GHG emissions (right) of the transport sector in Gauteng in 2007. Source: own calculations based on /TÜV 2012a/, /TÜV 2012b/, /SAPIA 2011/, /NATIS 2009/, /GDPTRW 2006/, /Goyns 2006/, /DOT 1998/, /Schaefer & Victor 1999/ and /De Beer & Lötter 2002/.

4 The energy system model TIMES-GEECO

According to /Voß 2009/, energy system analysis can be described as "investigation of the structural characteristics of a system through analysing the descriptive representation of its functions" (see also /Möst & Fichtner 2009/). It aims to support decisions (e.g. in energy politics or energy-related research) by scientifically quantifying the characteristics of the system elements under given conditions. A system represents a part of the real world and can be understood as an "aggregation of elements which are interdependent and impartial to their environment" /Voß 2009/. However, the experimental analysis of (real world) systems might be impractical or even impossible, since interventions in the real system might be immeasurable or would result in high costs. One possibility is to use mathematical models to analyse potential effects of measures or possible future development of systems. A model can be defined as a simplified representation of reality or of a fictitious system /Voß 2009/, /Möst & Fichtner 2009/.

The necessity of using models for energy system analysis becomes evident when considering the characteristics of energy systems. These include:

- its long-running nature (a common project lifetime of 20 years or longer)
- high investment costs (e.g. in the case of power plants, refineries)
- complexities (e.g. relationships in the energy system). The use of some energy carriers might require additional infrastructure investments such as new or extra investments in fuel stations
- uncertainties (e.g. future costs of primary energy or economic and demographic developments)
- conflicting aims (e.g. use of limited resources. Biomass, for example, could be used in the supply sector for electricity generation, to produce liquid fuels or for gasification. Since land for cultivation is limited, sectoral targets might be in conflict).

The application of an energy system model can be used as a quantitative tool to support political decision making scientifically. However, even though results can be quantified, modelling aims "to provide insight and not numbers" /Huntington et al. 1982/. Thus, energy system analysis is essential as rational decision support tool and for deriving policy recommendations by showing both the selection of plausible measures to reach certain targets within a set of alternatives and by quantifying the effects of those measures /Grunwald 2008/.

Scenario analysis is a method which is often used in energy planning /Remme 2011/, /Schönfelder et al. 2011/. Looking at the long-term perspective and the uncertainties in some assumptions (e.g. the costs of future energy carriers) modelling results cannot be and do not claim to be a prediction of future development. Different plausible "futures" /Grunwald 2008/ can be compared in a scenario analysis. A scenario comprises a set of assumptions about the future (e.g. the availability of technology, oil price, etc.), which should be consistent with other assumptions in the scenario (e.g. the development of sectoral GDP and the related working population). Generally, scenarios can be normative or explorative. While an explorative scenario looks at how a future might look under certain conditions (e.g. 20% electricity contribution from wind power), a normative scenario investigates how to reach targets (e.g. a 20% reduction of GHG emissions).

Thus, scenario results can be seen as quantitative representation of a plausible development of the energy system under a given set of assumptions /Remme 2006/. Comparing scenarios with different framework conditions makes it possible to deduce sets of measurements, which are consistent within all scenarios. Those measures will be considered as robust options, which are independent of possible development of the scenario framework /Voß 2009/. Finally, it is possible to include robust measures in an action plan for future development, which can be a basis for formulating policy recommendations /Möst & Fichtner 2009/, /Remme 2006/. In the following sections, the TIMES model generator and its application for Gauteng are presented in detail.

4.1 The TIMES model generator and its features

Despite other tools available for system analysis (e.g. life-cycle assessment, the Delphi method, cross-impact analyses, see e.g. /Möst & Fichtner 2009/, /Hendrickson et al. 2006/ or /Horne et al. 2009/ for further information), in this thesis an energy system model is used. There are different models available to illustrate energy demands or impacts of certain energy technologies in the future in order to support policy-making processes. According to /Van Beeck 1999/ and /Möst & Fichtner 2009/, energy models can be classified in several categories. An overview of those characteristics is given in Figure 17, which shows how model components can be classified by purpose (e.g. to explore the impacts of policies or to normatively investigate how to achieve policy goals); by analytical approach (i.e. whether technology-based bottom-up, or economy-based top-down); by methodology (e.g. optimization, simulation, econometrics or general equilibrium models); by geographical coverage (i.e. how many regions can be modelled), by geographical representation (e.g. local, national, international, etc.); by sectoral coverage (i.e. modelling the whole economy or only the energy system); by time horizon (from short, which can be up to one year, to long term, which is up to 50 years or longer) and by the model time resolution /Van Beeck 1999/, /Möst & Fichtner 2009/.

The Integrated MARKAL-EFOM System (TIMES) model is a least-cost optimization, bottom-up energy system analysis tool designed to analyse the impacts of policies/measures (e.g. the phasing out of nuclear energy) as well as how to achieve policy goals (e.g. climate mitigation targets) /Remme et al. 2009/. The TIMES model has been developed within the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA) as it was found that the technical features of

MARKAL were no longer sufficient (e.g. the length of time segments was not variable, storage processes were not explicitly representable, age of processes (vintage) was not easily to model) /Loulou et al. 2005a/.

The TIMES model is widely used and has been applied by more than 250 institutions in more than 70 countries /Schönfelder et al. 2011/. The features of the model are highlighted in the outer circle of Figure 17, from which it should be noted that further model variations exist (e.g. TIMES-MACRO or Mixed-integer programming /IEA 2011b/). Additionally, some features (such as geographical coverage, time resolution, and time horizon) are dependent on the specific application of the model. In those cases, typical features of the TIMES model are highlighted in the outer circle of Figure 17.

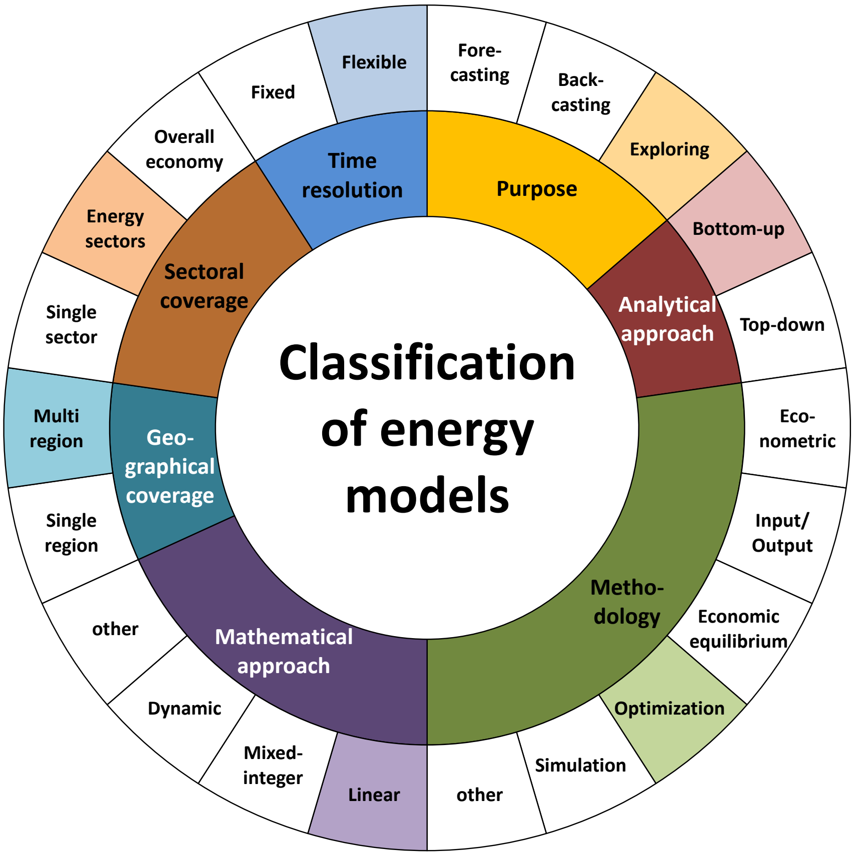


Figure 17: Classification of energy models. Source: own figure based on /Möst & Fichtner 2009/ and /Van Beeck 1999/.

The TIMES model generator is implemented within the General Algebraic Modelling System (GAMS). While the model generator is available free of charge, two commercial software interfaces exist to allow the user to input information, store and handle data and analyse model results (namely, ANSWER and VEDA /Noble-Soft 2011/, /Kanors 2011/). While these software packages allow user-friendly working with the TIMES model, the provision of necessary data sets (i.e. energy service demands, primary energy resource potentials, structure of the energy system, policy settings, and full techno-economic description technologies used and possible alternatives) are fully dependent on the model developer /Loulou et al. 2005a/. The TIMES model is flexible in terms of the number of regions and geographical scale which is shown in applications which vary from cities or municipalities to world modelling approaches /Schönfelder et al. 2011/.

The TIMES model generator is a technology based partial equilibrium model that assumes perfect foresight and perfect competition /Loulou et al. 2005a/. In TIMES the objective is to minimise the total system costs (Equation 9), which include capital costs $INV_{p,t}$ for investing into or dismantling a process p in time period t; fixed operating and maintenance costs and other annual costs ($FOM_{p,t}$); variable costs that are dependent on the activity (production level) of a process expressed by $ACT_{p,t}$ as well as those costs dependent on commodity flows ($FLO_{p,t}$, e.g. due to a CO_2 tax). Furthermore, the objective function accounts for and import expenditures and export revenues ($IMPEXP_{p,t}$). $SALV_{p,t}$ represents the salvage value of processes at the end of the planning horizon T. All costs are discounted to the beginning of the base year z using discount factor $DF(t,z)$.

$$Obj(z) = \sum_{t=1}^{T} DF(t,z) \cdot \left[\sum_{p} \left(INV_{p,t} + FOM_{p,t} + ACT_{p,t} + FLO_{p,t} + IMPEXP_{p,t} - SALV_{p,t} \right) \right] \stackrel{!}{=} min \qquad \text{Equation 9}$$

The strengths of the model are, for example, the detailed representation of interlinkages in the energy system and the flexibility in applying the model /Schönfelder et al. 2011/, /Möst & Fichtner 2009/. On the other hand, the effects in other sectors of the economy (e.g. the influence of politics on the demand for energy) are not, or are only partly, represented within the model as some parameters (such as the demand for energy services) are given exogenously /Möst & Fichtner 2009/. In addition, the assumptions of perfect foresight and of perfect competition are seen negatively by some critics (e.g. /Schönfelder et al. 2011/). However, model variations such as a myopic version (where only certain time steps are optimized together, not the whole time horizon) try to address such criticism. The TIMES model generator as applied to Gauteng is described in the following section.

4.2 General model structure of TIMES-GEECO

Choosing system boundaries according to the research question is essential for expressing interrelationships relevant to the system. For example, only about 3% of the 43 GW installed electric power plant capacity (in 2007) is located within the Gauteng provincial boundaries /Platts 2008/ (see also section 5.1.8). Moreover, other fuel conversion and primary energy supplies (e.g. coalmines, oil and gas excavation, and crude oil refineries) are completely outside Gauteng (see section 5.1). It is therefore obvious that the province's economic activity requires energy from other parts of South Africa, which goes in hand with emissions and costs in the production chain. For example, petrol used in Gauteng is responsible for expenses related to transport and distribution within the province. However, fuel production – which is associated with significant GHG emissions (see sections 5.1.1 and 5.1.2) – takes place in oil refineries elsewhere in the country and crude oil has to be extracted or imported. Both processes require electricity, which itself is associated with additional efforts and emissions.

Given those upstream emissions and expenses, it seems self-evident that Gauteng has to account for those as well. Following a strictly territorial approach for Gauteng, only the emissions generated within the provincial boundaries would be taken into account, which would minimize GHG emissions for the province. This would be a trivial approach, because electricity, petroleum products and other energy carriers are provided "emission free" from the rest of South Africa. Thus, system boundaries are chosen in such a way that they include the conversion technologies and primary energy supplies of South Africa that are used for energy provision for the province (Figure 18). To do so, the residual fuel provision capacities of South Africa have been scaled according to the demand that is used in Gauteng (e.g. 29.9% of the electricity consumption of South Africa in 2007 was consumed in the province /StatsSA 2012b/).

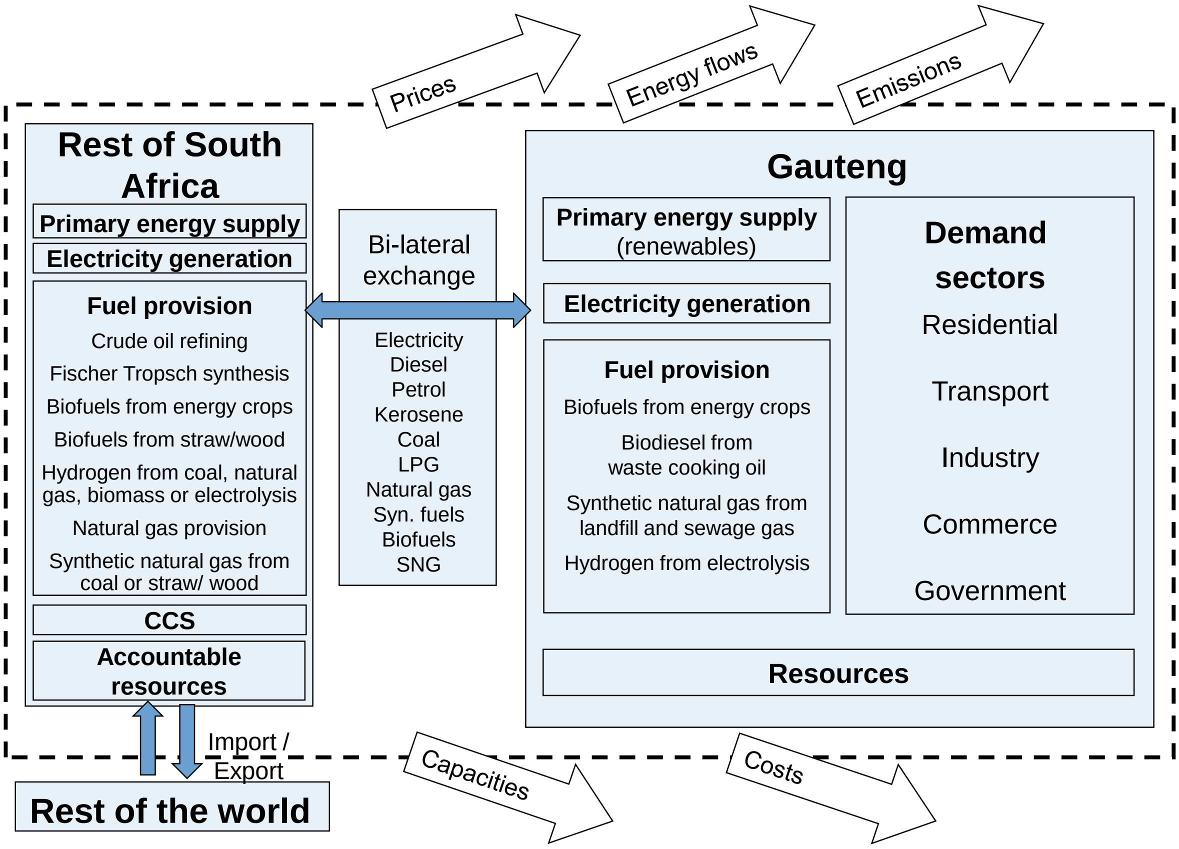
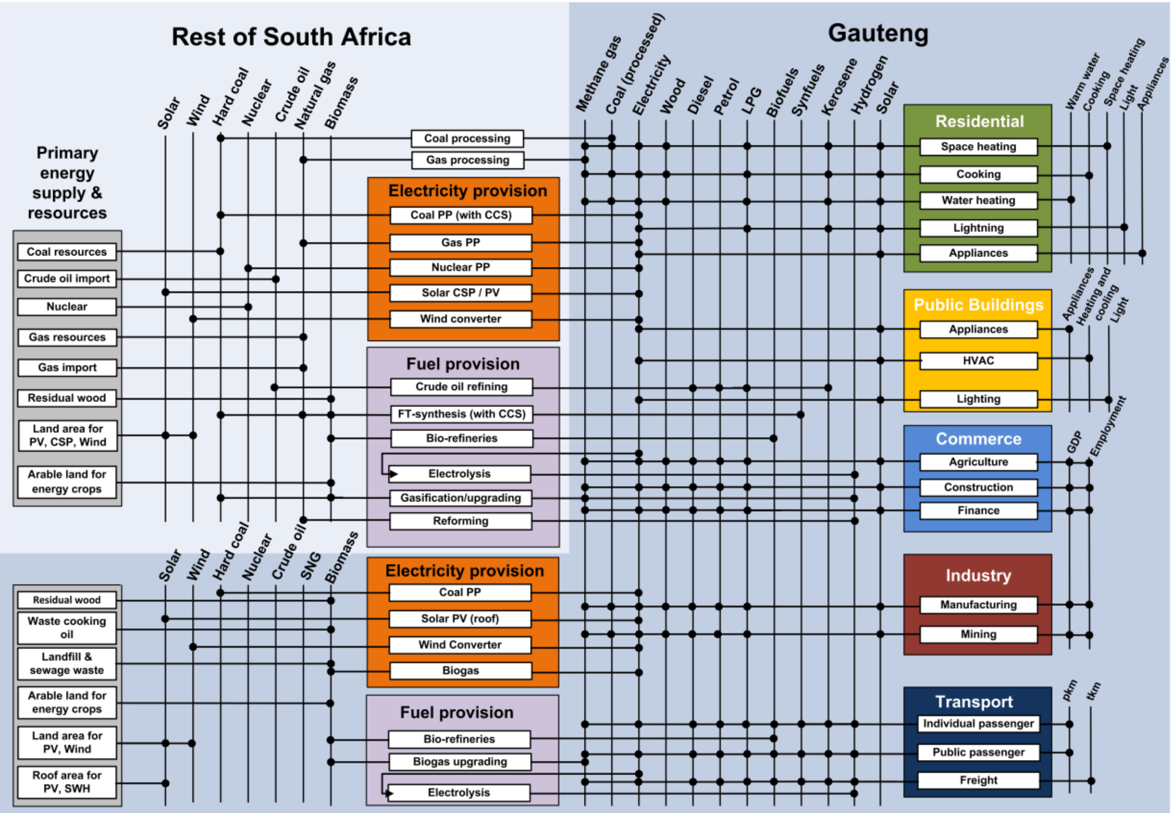


Figure 18: Costs, energy flows, capacity and emission balance in TIMES-GEECO. Source: own figure.

Figure 19 represents the reference energy system (RES) of the TIMES-GEECO model application. This figure shows in aggregate how the different sectors are interlinked within the energy system. Vertical lines represent the commodities used in the energy system, while the boxes represent energy provision and conversion processes and end-use technologies. All demand sectors (i.e. residential, government/public buildings, commerce, industry and transport) compete for different energy carriers.

On the left-hand side, the primary energy supply is shown separately for Gauteng and the rest of the country. Gauteng only directly supplies renewable primary energy carriers like residual wood and land area for energy crops or renewable electricity provision. However, fossil primary energy sources are extracted or imported from other regions in South Africa, where they are processed.



Abbreviations: PV = photovoltaic, CSP = concentrated solar power, PP = power plant, FT = Fischer-Tropsch, CCS = carbon capture and storage, pkm = person kilometres, tkm = tonne kilometres.

Figure 19: Reference energy system of TIMES-GEECO. Source: own figure.

In Figure 19, it can furthermore be seen that final energy is provided by the electricity sector and the fuel sector implemented in TIMES-GEECO as well as by the processing of coal and natural gas as shown in the middle part of the figure. In the electricity sector, diverse alternatives are given as different coal-fired power plants as well as other technologies such as concentrated solar power (CSP), open field photovoltaic (PV) or wind converters. As for the demand sectors, this representation can also be understood only in aggregate; many more technologies have been implemented in detail in the TIMES-GEECO model. Detailed information on implemented power plants, as well as their techno-economic description, are given in Appendix C and in /Telsnig et al. 2012/. Different options and different conditions are given (such as the level of solar radiation), depending on the region examined, i.e. Gauteng or the rest of South Africa, as described previously. The fuel conversion sector is represented by crude oil conversion, synthetic fuels, biofuels (first and second-generation) and hydrogen production. Additionally, the possibility of using carbon capture and storage (CCS) technologies is implemented in the model, i.e. in the electricity generation sector for coal power plants, and in fuel liquefaction for both new CTL and GTL facilities. A detailed description of the assumptions made CCS application costs for Gauteng and South Africa can be found in /Telsnig et al. 2013b/.

On the right-hand side of the figure, the demand sectors are shown with their associated sub-sectors. These are, for example, for the residential sector space heating, cooking, water heating, lighting (indoor and outdoor) and appliances. The transport sector can be subdivided into individual transport, public transport and freight. All subsectors are driven by their demand for energy services, shown on the right-hand side of the figure. Note that these subdivisions are only an aggregated representation of the information within the sector. /Tomaschek et al. 2012a/ gives more detailed information on the non-transport sectors of the model.

The time horizon of the model is the year 2040; 2007 was selected as the base year. The reason for choosing the year 2007 as the base year was that many South African statistics refer to this point in time (e.g. the community survey of 2007), so that 2007 seemed to be a good basis for further calculations /Tomaschek et al. 2012a/, /Tomaschek et al. 2012d/. Further milestone years were defined as 2010, 2012, 2015, 2020, 2025, 2030 and 2035, such that the early ones are also used to calibrate the model.

The TIMES-GEECO model includes a sub-annual time resolution in order to allow better modelling of fluctuations in energy supply (e.g. of photovoltaic or wind energy) and service demand. Figure 20 represents the temporal disaggregation of one year in the TIMES-GEECO model. The smallest implemented time slice has a duration of one hour and corresponds to the peak hour between 19:00 and 20:00. A total of 42 time slices have been implemented in the model.

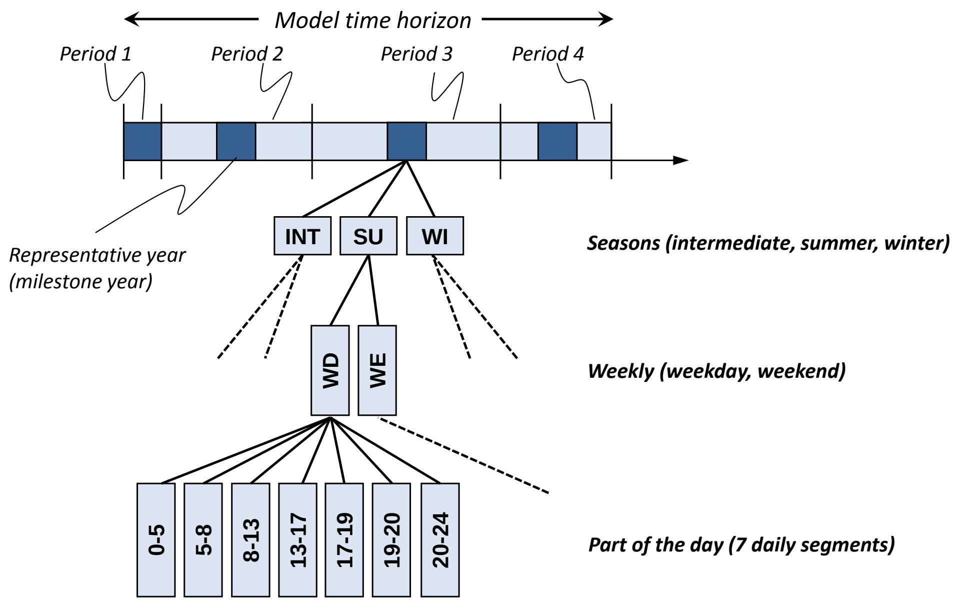


Figure 20: Temporal resolution implemented in the TIMES-GEECO model. Source: own figure based on /Remme 2006/.

These sub-annual time slices are defined as three per season (i.e. summer, winter, and intermediate), two per week (i.e. weekday and weekend) and eight per day, which express the typical aspects of the South African energy system based on /Rosin 2005/. The characteristic demand curves have been implemented for all sub-sectors (i.e. transport, residential, industry, commerce, and government) as well as for fluctuating primary energy supply (i.e. including wind and solar energy).

4.3 The transport sector in the TIMES-GEECO model

The transport sector in the TIMES-GEECO model is divided into individual, public and freight transport (Figure 21). It has been modelled in a way that includes those transport modes that express the characteristics of a developing region such as Gauteng, for example minibus taxis (see section 2.1). Additionally, different vehicle sizes/ engine sizes for passenger cars (e.g. SUVs) have been incorporated. Splitting motorized individual travel into different modes allows the use of different technologies to describe each one to demonstrate the effects of trends to vehicles with larger engine capacities (see also section 2.1.2). Furthermore, recently introduced new forms of transport in the province, such as the BRT and Gautrain (see section 2.2) are included as separate modes. Railway-based modes have also been modelled for passenger and freight rail. All rail-based forms of travel are shown hatched in the figure. Moreover, the TIMES-GEECO model incorporates all the other transport modes that comprise the transport system, e.g. scheduled bus services, LDVs, HDVs and air travel.

All modes have been analysed for different emission categories, ranging from pre-Euro emission classes (ECE1) over Euro 6 to possible future standards /TÜV 2012a/. This information was then modelled in the form of average (or typical) vehicles in TIMES-GEECO (see also section 3.3). Furthermore, each road-based mode was defined for different driving profiles, namely, highway, urban, and rural.

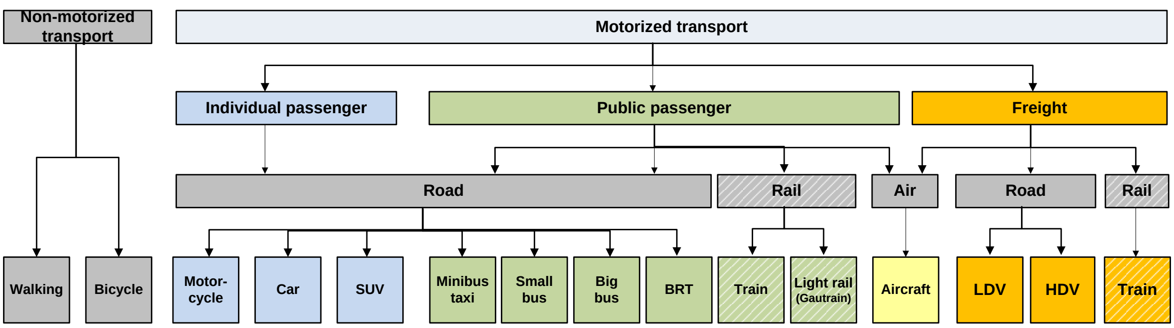


Figure 21: Transport modes considered in the TIMES-GEECO model.
Source: own figure.

For all modes addressed in the model, different powertrain technologies and fuel options are available. For example, a passenger car could be running on an internal combustion engine (ICE), could additionally be powered by an electric engine (as in a hybrid) or be completely dependent on alternative sources of energy, e.g. natural gas, LPG or electricity (see section 5.2). The possibility of using hydrogen either in spark ignition internal combustion engines (ICE–SI) or in fuel cells hybrid electric vehicles (FCHEV) has also been modelled. The different options are shown in Figure 22. However, not all technologies are applicable for each mode of transport. For example, petrol-fuelled hybrid engines will probably not be used for heavy-duty vehicles (see also section 5.2.1) or grid-based electricity supply can only be used for a track-based system such as trains or trolley buses. On the other hand, options like natural gas or biofuels can in theory be applied to numerous modes of transport.

Additionally, fuel-blending options (e.g. ethanol, biodiesel, and synthetic fuels) have been modelled for all vehicles running on petrol or diesel. The maximum blending proportions implemented are based on national legislation (see section 2.2.4, i.e. $10\%_{vol}$ for ethanol). For biodiesel a maximum of $10\%_{vol}$ was assumed dependent on the technical limitations of conventional vehicles to use higher shares of biofuels (see section 5.2.2). For higher penetration of biofuel, vehicles such as E85–ICE SI or B100–ICE CI have been modelled.

Fuels	Petrol 1)				Diesel 2)				Ethanol (E85)	Biodiesel (B100)	LPG	CNG/SNG	Electricity		Hydrogen		Kerosene
Vehicle technology/ powertrain	ICE SI	Mild hybrid SI	Full hybrid SI	PHEV SI	ICE CI	Mild hybrid CI	Full hybrid CI	PHEV CI	ICE SI	B100 - ICE CI	ICE SI	ICE SI	BEV	Trolley/Grid	ICE SI	FCHEV	Jet turbine
Motorcycle	✓																
Car (small)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Car big (SUV)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Minibus	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Bus (small)	✓ 3)				✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	
Bus (big)	✓ 3)				✓	✓	✓	✓		✓	✓	✓			✓	✓	
BRT					✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	
Train (passenger)					✓									✓			
Light rail (Gautrain)														✓			
LDV	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Truck	✓ 3)				✓	✓	✓	✓		✓	✓	✓			✓	✓	
Train (freight)					✓									✓			
Aviation																	✓

ICE = Internal combustion engine
SI = Spark ignition
CI = Compressed ignition
PHEV = Plug-in hybrid electric vehicle
BEV = Battery electric vehicle
FCHEV = Fuel cell hybrid electric vehicle

1) Can be blended with ethanol and synthetic petrol (fossil or bio)
2) Can be blended with biodiesel or synthetic diesel (fossil or bio)
3) Petrol implemented only for base year fleet

Figure 22: Vehicle technologies considered in the TIMES-GEECO model.
Source: own figure.

Figure 23 shows how road transport processes have been modelled in TIMES-GEECO in the case of a conventional passenger car using a diesel compressed-ignition (CI) ICE. The possibility of using different fuels is shown in the left-hand side of the figure. In this example, the diesel car can run on diesel derived from crude oil as well as on synthetic fuels or biodiesel. However, biodiesel cannot be blended in a high proportion without modifying the vehicle (see section 5.2.2).

The right-hand side of the figure shows that road vehicles are modelled in such a way that they have distinct commodity outputs in relation to highway, urban and rural travel, respectively. As expressed in chapter 5, alternative technologies have certain disadvantages depending on the driving profile – for example, the most energy efficient use of electric vehicles is under urban driving conditions. The way of modelling the process with different efficiencies for each driving profile includes these characteristics in the model. Furthermore, the eight pollutants considered, namely, CO_2, CH_4, N_2O, CO, hydrocarbons, NO_x, particulates and SO_2, are outputs of each transport process. Consequently, a transport vehicle process requires up to 32 emissions factors for the different (blending) fuel options (i.e. crude oil fuels, fossil Fischer-Tropsch fuels, biogenic Fischer-Tropsch fuels and biodiesel/ethanol) and the corresponding pollutants to be considered.

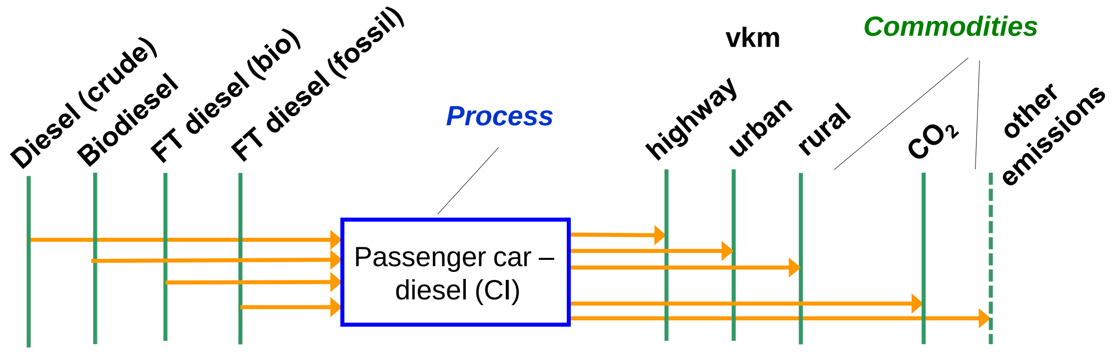


Figure 23: Schematic illustration of the passenger car diesel process to illustrate input and output flows in the TIMES-GEECO model. Source: own figure.

Energy supply options that are relevant to transport have been modelled in TIMES-GEECO and are illustrated in Figure 24. Different colours indicate the different primary energy sources for transport fuel and electricity provision.

The energy supply options analysed include fossil fuels, fuels from biomass as well as other energy sources such as electricity. The model takes account of fossil fuels produced from crude oil, natural gas and coal. As crude oil refining products, petrol, diesel LPG and kerosene have been modelled. Natural gas can be used in the transport sector either in compressed form in road vehicles or for providing synthetic fuels via Fischer-Tropsch synthesis and can furthermore be used for hydrogen provision. Fuels from coal originate via Fischer-Tropsch synthesis, hydrogen synthesis and via gasification and upgrading to methane gas as substitute natural gas (SNG). Fuels from biomass consist of products from thermo-chemical processes (i.e. synthetic fuels derived via Fischer-Tropsch synthesis and substitute natural gas via gasification), biochemical processes (i.e. ethanol from alcoholic fermentation and SNG from anaerobic fermentation) as well as fuel provided by physiochemical processes (i.e. biodiesel via transesterification). This includes fuels that are characteristic or might explicitly be an option for South Africa like biodiesel from waste cooking oil or ethanol from sugar beet. The production of hydrogen has been modelled for various pathways including coal and biomass gasification and upgrading, natural gas reforming, and electrolysis (Figure 24). All modelled pathways for transport fuel provision are explained and analysed in section 5.1.

Numerous options for electricity generation have also been modelled in TIMES-GEECO, which include electricity provision from fossil sources such as coal, natural gas and diesel, renewable sources such as biomass, hydropower, wind and solar energy as well as electricity provision from nuclear energy. The reader is referred to Appendix C and /Telsnig et al. 2012/ for an overview of all types of power plants included in the model.

Input	Process (simplified)	Output								
		Petrol [1)]	Diesel [1)]	Ethanol	Biodiesel	Kerosene	LPG	CNG/SNG	Hydrogen	Electricity
Crude oil	Refining	✓	✓			✓	✓			
Coal	Gasification, FT-synthesis	✓	✓							
Coal	Gasification, FT-synthesis, CCS	✓	✓							
Coal	Gasification, upgrading							✓	✓	
Coal	Gasification, upgrading, CCS								✓	
Coal	Power plants									✓
Coal	Power plants, CCS									✓
Natural gas	Compression							✓		
Natural gas	Reforming, upgrading								✓	
Natural gas	Reforming, upgrading, CCS								✓	
Natural gas	Reforming, FT-synthesis	✓	✓							
Natural gas	Reforming, FT-synthesis, CCS	✓	✓							
Natural gas	Power plants									✓
Rape seeds	Extraction, transesterification				✓					
Soybeans	Extraction, transesterification				✓					
Sunflower seeds	Extraction, transesterification				✓					
Sugar beet	Fermentation, distillation			✓						
Sugar cane	Fermentation, distillation			✓						
Waste cooking oil	Preparation, transesterification				✓					
Waste (organic)	Anaerobic digestion, upgrading							✓		
Waste (organic)	Anaerobic digestion, gas turbine									✓
Straw/ wood	Gasification, FT-synthesis	✓	✓							
Straw/ wood	Gasification, upgrading							✓	✓	
Straw/ wood	Hydrolysis, fermentation, distillation			✓						
Straw/ wood	Power plants									✓
Solar irradiation	Power plants (CSP, PV)									✓
Wind	Power plants									✓
Diesel	Power plants									✓
Hydropower	Power plants									✓
Nuclear	Power plants									✓
Electricity	Electrolysis (centralized)								✓	
Electricity	Electrolysis (de-centralized)								✓	

[1)] Including synthetic petrol and provided via Fischer-Tropsch synthesis

Figure 24: The energy supply options for the transport sector considered in this study. Source: own figure.

The model incorporates the possibility of vehicle-to-grid (V2G) energy storage by electric vehicles. V2G has been discussed in several studies as a possibility to supplement peak electricity demand, backup storage, to improve grid efficiency and reliability, especially when incorporating large amounts of fluctuating electricity like wind power and photovoltaics (PV), see e.g. /Mullan et al. 2012/, /Clement-Nyns et al. 2011/, /Kempton &

Tomic 2005/. The idea behind modelling V2G capability in TIMES-GEECO is that the model can explicitly select having electric vehicles as part of a model solution and use them as storage for excess electricity, which can be fed back into the grid if required. Obviously, this is only possible when the vehicle is not being driven and is connected to the grid.

To incorporate the V2G storage capability into the TIMES-GEECO model, an additional storage process had to be considered. Electricity storage in the TIMES model consists of three processes: an input and an output process as well as the storage process itself as shown in Figure 25. The capacity of the V2G storage is defined by the battery capacity available for V2G in Gauteng as calculated in Appendix D and the number of private electric passenger vehicles in a scenario. To represent this relation a user constraint is defined, summing over periods and time slices for the region specified /Loulou et al. 2005b/. The V2G capacity can then be calculated via the left-hand-side multiplier, which is given in kWh for each type of electric vehicle (i.e. c_s, see Appendix D). Additionally, storage efficiency and the cost of battery degeneration have been taken into account. Further energy storages considered in the model are pump storage, compressed air storage, molten salt storages for concentrated solar power plants (CSP) and the possibility of converting electricity into other energy carriers such as hydrogen via electrolysis.

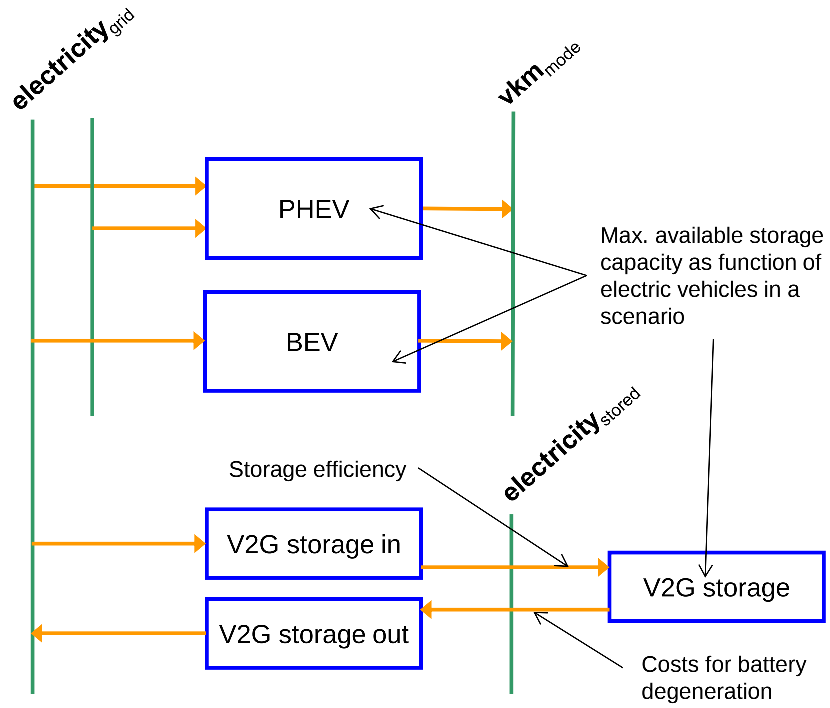


Figure 25: Representation of vehicle-to-grid (V2G) electricity storage in the TIMES-GEECO model. Source: own figure.

The current public transport network – the system of roads and railways – is expected to change over the model time horizon as some expansion projects are currently in hand (e.g. the BRT, see section 2.2.2) or thinkable in future (e.g. expansion of the

Gautrain or of trolley-bus infrastructure). Thus, the additional investment costs as well as the effects of implementing such systems on the modal shift have been included as explicit model options. Specific growth in the public transport system is modelled for the BRT in Tshwane and Johannesburg and for the Gautrain (see sections 2.2.2 and 2.2.3) in the TIMES-GEECO model. Additional investment costs comprise, in the case of the BRT, the expansion and modification of roads, bus stops, bus depots, feeder lines and control centres. To enlarge the Gautrain system, investment costs include expenditures on railway tracks, bridges, tunnels, feeder lines, etc. Obviously, the investment and operation of vehicles and rolling-stock lead to further costs. These are dependent on the vehicle powertrain used and the associated fuel costs and thus are not discussed here. However, these expenses are included in the TIMES-GEECO model.

Additionally, the TIMES-GEECO model developed in this thesis also includes grid-based road vehicles (trolley buses, see section 5.2.4) as possible expansion of the BRT network. As trolley buses offer the advantages of electric engines (e.g. no local pollution, high initial torque), they do not require large sets of batteries, which increase the costs of electric vehicles in comparison with conventional combustion engines (see section 5.2.4). However, catenaries are obviously required to operate trolley buses as well as additional equipment such as transformer stations.

Consideration has been given to expanding the current Gautrain network in two further stages. The BRT in Johannesburg is assumed to have four possible expansion stages. For the BRT in Tshwane, five phases have been analysed. Additionally, it has been incorporated that the BRT operation can potentially be upgraded as a trolley bus system. In total, these alternatives add up to 180 different options (5 options in Johannesburg, i.e. no expansion at all or up to 4 expansion stages; 3 options for the Gautrain; 6 options for the BRT in Tshwane, i.e. no construction or up to 5 phases and the possibility of establishing the infrastructure for trolley buses. These correspond to $5 \cdot 3 \cdot 6 \cdot 2 = 180$ possible transport options).

For incorporation in the TIMES framework, the resulting modal split of each option and the corresponding costs have been assigned to different processes, which represent particular plans for investment (e.g. expansion of the Rea Vaya to include phases 1C and 1D and further extension of the Gautrain). That means that the times at which expansions can occur are defined ex ante. By doing so, we consider that a further expansion cannot be realized before the previous one (e.g. phase 1D before 1C). Investment costs, which arise in a certain period (e.g. expanding the Gautrain network in 2020), have to be expressed as specific costs based on the change of process activity between the two affected milestone years.

To eliminate the possibility of switching between different options/investment plans (e.g. if one option involves no investment costs in a particular year), user constraints have been modelled for each public transport expansion plan, which ensures that an option once started will still be used subsequently. To do so, a dynamic user constraint is needed which can be expressed as shown in Equation 10, in which VAR_NCAP is the new capacity investment, VAR_CAP is the (total) installed capacity, GR the annual growth rate in period t for a specified region r and process p, and c is a constant of the user constraint. $D(t)$ is the period involved:

$$VAR\_NCAP_{r,t+1,p} \leq GR^{D(t)} \cdot VAR\_CAP_{r,t,p} + c \qquad \text{Equation 10}$$

As the total process activity (i.e. total travel demand) is model input (here it is defined by the socio-economic framework and the travel demand model, see section 3.1) the parameter GR can be calculated as shown in Equation 11 with pkm the total passenger kilometres in period t and Δt the timespan in years between two succeeding periods.

$$GR = e^{\frac{\ln\left(\frac{pkm_{t+1}}{pkm_t}\right)}{\Delta t}} \qquad \text{Equation 11}$$

Figure 26 illustrates schematically how the TIMES-GEECO model is used to describe the expansion of a public transport system.

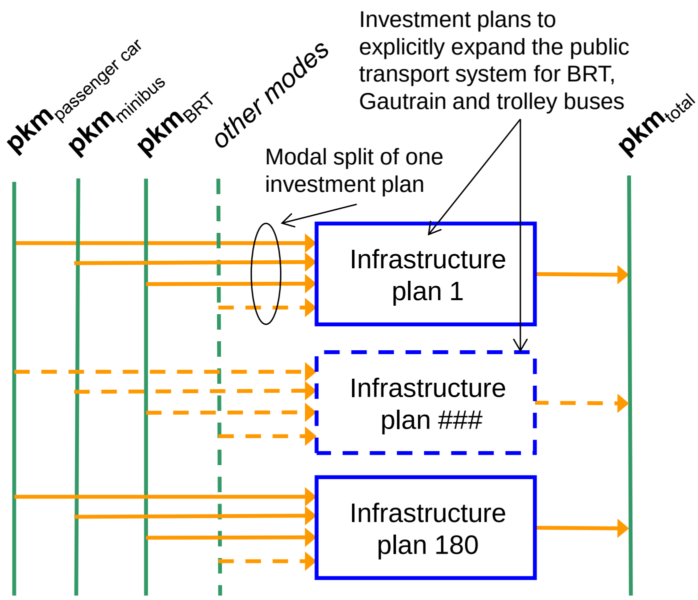


Figure 26: Schematic representation of explicitly expanding the public transport system in the TIMES-GEECO model. Source: own figure.

To summarize, the TIMES-GEECO model is used to analyse the costs and GHG mitigation potential of alternative transport technologies, alternative fuels and expansions of the public transport system, while also taking into account the interlinkages and interconnections with the whole energy system of South Africa. The model accounts for:

- Energy supply and GHG mitigation options in Gauteng and in the rest of South Africa
- A time horizon up to the year 2040 with 42 time slices for sub-annual time resolution

- Full consideration of process chain emissions and costs of energy provision
- Numerous transport fuel and electricity provision technologies, including those which are characteristic of developing countries (e.g. fuels from bio waste)
- Many vehicle technologies, including those which are relevant for the local transport system (e.g. minibus taxis) and those that might be feasible in an urban area such as Gauteng (e.g. trolley buses)
- Modelling of different road types – namely, highway, urban, and rural – including corresponding fuel efficiencies and emission factors to include the advantages and disadvantages of technologies under certain operating modes
- Explicit expansion of public transport systems (considering full costs)
- V2G electricity storage options for private passenger vehicles, as well as pumped storage, compressed air storage, molten salt storage for CSP power plants, and converting electricity into other energy carriers, e.g. hydrogen.

4.4 Comparison of TIMES-GEECO with other transport energy system models

This section describes previous applications of energy system models, in greater detail in the transport sector, and compares them with the one undertaken in this study. The IEA gives an excellent overview of recent advances in energy system models in their Annex XI "Joint Studies for New and Mitigated Energy Systems" /IEA 2011d/, in which they summarize over 350 publications for the years 2008–2010, focusing on applications of the TIMES-MARKAL model generator. Most of the references presented are applications of global (about 70) or national (about 190) models, where the focus lies clearly on European countries and the United States /IEA 2011d/. Only about 6% of the references describe applications of sub-national or local models /IEA 2011d/, which demonstrates the need for research in this field. Furthermore, little focus has been given to transport or transport-related studies, with the exception of hydrogen supply and use (e.g. /Gül et al. 2009/, /Contreras et al. 2009/, /Contaldi et al. 2008/ and /Rosenberg et al. 2010/). However, some applications can be identified, with a high level of detail in modelling and analysing the transport sector (i.e. /Bruchof 2013/, /Özdemir 2012/, /Gül 2008/), which focus on applications of alternative fuels or vehicle types for Germany and elsewhere in Europe.

In his thesis, Bruchof analysed the possible contributions of alternative fuels and powertrains as part of an energy-economics transport strategy for Germany and Europe in relation to energy and climate targets /Bruchof 2013/. He compared the technical, economic and environmental characteristics of alternative fuels including first and second-generation biofuels, synthetic fuels, electricity and hydrogen /Bruchof 2013/. In terms of alternative powertrains for the German transport sector, Bruchof evaluated the costs and emissions of a variety of technologies, e.g. hybrid-electric and battery-electric vehicles, natural gas and LPG engines and vehicles adapted for pure biofuel usage /Bruchof 2013/. His analysis covered all relevant transport modes for Germany and Europe in respect of passenger and freight transport /Bruchof 2013/. Using the TIMES-PanEU model, which covers the 27 countries of the European Union as well as three other regions, he was, for example, able to evaluate the German targets for biofuel blending as well as to give recommendations for future policy making /Bruchof 2013/.

Özdemir analysed the future role of alternative powertrains and fuels in the German transport sector with respect to technical, economic and environmental aspects /Özdemir 2012/. He thereby compared these powertrains in terms of investment costs, energy consumption and environmental performance /Özdemir 2012/. His analysis covered conventional spark ignition and compressed ignition engines as well as electric motors, hybrid electric vehicles and fuel cells /Özdemir 2012/. In terms of alternative fuel options for Germany, Özdemir analysed several production methods for biofuels, methane gas, synthetic diesel, hydrogen and others /Özdemir 2012/. Using the TIMES-D model, which is an application of the TIMES model generator, for the German energy system, he concluded that the transport sector is not the first one to address in order to achieve Germany’s climate targets /Özdemir 2012/. According to his results, alternative powertrains were not likely to play a major role in the German transport sector in future, but public bus transport is the most likely to do so /Özdemir 2012/. In terms of alternative fuels, Özdemir concluded that the use of ethanol from lignocellulosic biomass, SNG, biogas, ETBE and hydrogen can cost-effectively reduce GHG emissions, which allowed him to derive policy implications for the future of the German transport sector /Özdemir 2012/.

Gül conducted a detailed analysis of hydrogen production and delivery pathways for the German transport sector as part of the national energy system /Gül 2008/. Furthermore, Gül considered biofuels as alternatives for the transport sector /Gül 2008/. To do so, he applied the European MARKAL model EHM, which includes the 27 EU countries as well as Norway and Switzerland /Gül 2008/. In his analysis, he focused on private passenger transport and laid emphasis on hydrogen provision /Gül 2008/. He identifies hydrogen as a cost-effective option for GHG mitigation, especially if produced using carbon capture or via electrolysis based on low-carbon generation methods (e.g. wind energy and nuclear energy) /Gül 2008/.

The MARKAL model presented in the Long-term Mitigation Scenarios (LTMS) has been applied to South Africa /Winkler 2007/. However, the level of detail in the analysis of the transport sector presented in the study is significantly lower than for the rest of the energy system as the LTMS study focuses more on a general view of the energy system and does not present a highly detailed description of the transport sector /Winkler 2007/. As the available model documentation states that the transport sector was “tightly constrained” /Winkler 2007/ and that it “does not optimise in the way that it does in the rest of the energy system”/Winkler 2007/, it is presumed that only relatively few details are available. However, it is the most recent optimization model available for the South African context and it is, thus, included in this comparison.

Table 8 presents the energy system models analysed and compares them by different categories with the TIMES-GEECO model used in this study. All models presented use an optimization approach (e.g. TIMES or MARKAL) and have a long-term time horizon. In terms of the transport modes incorporated in the model, this study extends the modes analysed to those which are characteristic of a developing country and an urban region (i.e. different engine sizes for passenger cars, minibus taxis, the BRT and trolley buses), which are not covered in the detailed representations in /Bruchof 2013/, /Özdemir 2012/. Gül, on the other hand, analysed only passenger cars /Gül 2008/.

Table 8: Comparison of this study with other transport energy system modelling.

		This study	/BRUCHOF 2013/	/ÖZDEMIR 2012/	/GÜL 2008/	/WINKLER 2007/
Model		**TIMES-GEECO**	TIMES-PAN EU	TIMES-D	MARKAL-EHM	MARKAL
Time horizon		**2007-2040**	2010-2050	1995-2030	2000-2100	2003-2050
Modes analysed	Car	✓	✓	✓	✓	✓
	SUV	✓				✓
	Minibus	✓				✓
	Bus	✓	✓	✓		✓
	BRT	✓				
	Trolley bus	✓				
	LDV	✓	✓	✓		✓
	HDV	✓	✓	✓		✓
	Rail	✓	✓	✓		✓
	Aviation	✓	✓	✓		?
Incorporation of road types		✓				
Transport infrastructure investments		✓				
Fuels included	Crude oil based	✓	✓	✓	✓	✓
	Energy crops	✓	✓	✓	✓	✓
	Waste cooking oil	✓				?
	Synthetic fuels	✓	✓	✓	✓	?
	Hydrogen	✓	✓	✓	✓	?
	Sewage & landfill gas	✓				?
Possibility for CCS		✓	✓		✓	✓
Scenario-dependent travel demand modelling		✓				
Possibility for V2G		✓				

Source: own table.

As far as the alternative transport fuels analysed are concerned, the available analysis of the German transport sector shows a very high level of detail and includes a variety of crude oil-based fuels, biofuels from energy crops, synthetic fuels, etc. /Bruchof 2013/, /Özdemir 2012/, /Gül 2008/. However, the TIMES-GEECO model is applied in such a way that it also covers characteristic measures for Gauteng, such as using fuels from waste cooking oil and the use of landfill and sewage gas. The LTMS study does not provide very detailed accounts of alternative transport fuels. Furthermore, it is unclear if alternative fuels were analysed in terms of cost-optimization.

Like most of the studies referred to, this analysis includes the possibility of CCS for electricity generation and fuel provision. However, the TIMES-GEECO model is the only one of the applications presented which accounts for the possibility of vehicle-to-grid (V2G) energy storage. Moreover, none of the applications of energy system models presented here includes the possibility of explicit expansion of the public transport infrastructure. Additionally, taking account of different socio-economic scenarios in the determination of future travel demand seems to be essential as it can substantially affect the overall choice of future transport modes and motorized travel and thus future energy consumption and emissions.

5 Analysis of transport energy supply and vehicle powertrain technologies for Gauteng

This chapter analyses alternative transport technologies for Gauteng and South Africa. Initially, this chapter focuses on alternative fuels (section 5.1). These include options that can be used with existing technologies and infrastructure (such as biofuels) as well as those transport fuels, which go in hand with additional needs for fuel delivery infrastructure and vehicle powertrain technology (e.g. methane gas or LPG for use in vehicles). Moreover, different production pathways are analysed for most fuels. The second part of the chapter describes alternative powertrains (e.g. hybrid, battery electric or natural gas vehicles), which are analysed and compared with ICEs as reference technology (section 5.2).

5.1 Energy supply options for transport fuels

This section presents current and alternative energy supply options for the transport sector in Gauteng. The techno-economic and environmental descriptions of technologies currently used and plausible for future use in South Africa and Gauteng are described here after a thorough review of the literature. The information derived includes cost data (i.e. investment, fixed and variable operating and maintenance costs) as well as conversion efficiencies and direct GHG emissions.

Cost data from different studies are converted to South African rand (ZAR) and normalized to the base year of 2007, according to Appendix A, which indicates the exchange rates and consumer price indices (CPI). Investment costs for different capacities follow the cost regression assumption of /Henniges 2006/, namely, that investment costs increase by 60% as the capacity doubles, which is also applied in other studies e.g. /Özdemir 2012/, /Tomaschek et al. 2012c/. The resulting cost figures are presented as they are used in the TIMES-GEECO model.

At the end of the section, the transport energy supply options are compared in terms of their total production costs and of their GHG well-to-tank (WTT) emissions.

5.1.1 Crude oil refining

Crude oil consists mainly of carbon, hydrogen and sulphur in different proportions, depending on its source /Gary & Handwerk 2001/. South African crude oil imports mostly originate from the Middle East and are delivered by tanker to the ports of Durban and Port Elizabeth, where they are refined or delivered via pipeline to the interior of the country to be refined there /EIA 2011/. Crude oil extraction, processing and piping to the refinery accounted for 3.6 g $CO_2eq/MJ_{crude\ oil}$ of GHG emissions and an auxiliary energy demand of 0.01 $MJ_{electricity}/MJ_{crude\ oil}$ according to /Edwards et al. 2011a/.

The first stage of the oil refining process is to separate the hydrocarbons, i.e. the paraffins, olefins, naphthenes, and aromatics. This is done by fractional distillation and vacuum distillation based on the higher boiling points of hydrocarbons with a longer chain length. The products of the refining process can be grouped in different categories of petroleum distillates (i.e. light, middle and heavy distillates) and residuals such as asphalt and tar. Light distillates consist of petrol, naphtha and LPG, whereas middle distillates are kerosene and diesel. LPG (liquefied petroleum gas) is a refinery by-product, consisting mainly of butane and propane gases /Gary & Handwerk 2001/.

To change the product shares of the refining process according to fuel needs and to increase the share of higher value fuels, several conversion and conditioning processes are used in a refinery. These processes include, for example, the cracking of long-chain hydrocarbons into smaller molecules to decrease the proportion of heavy residuals, the catalytic reforming of low octane products into higher octane ones by altering their molecular structure, and hydro-treating to clean the products from contamination with sulphur, nitrogen and metals /Gary & Handwerk 2001/.

South Africa has a crude oil refining capacity of about 513,000 bbl/day, which is the second largest capacity on the African continent /EIA 2011/, /SAPIA 2009/. The building of a new crude oil refinery with a capacity of 400,000 bbl/d is under discussion, because South Africa is currently also a net importer of petroleum products /EIA 2011/, /IEA 2008a/. The project is estimated to cost 10 billion USD and would be located at Coega, Port Elizabeth /Dalmini 2011/. However, it is not certain if, and when, the project will be started /Dalmini 2011/. Refineries in South Africa were upgraded several times in the past to increase their capacity, adapt the product spectrum and to comply with modern fuel specifications. The last major upgrades were undertaken in the early 2000s and included installation of sulphur-recovering units and gas treating facilities /MBI 2010/. In 2010, all South African refineries were equipped with cracking units, catalytic reformers, and sulphur recovery and alkylation units /ICF 2009/.

Table 9 summarizes the techno-economic and environmental parameters of crude oil refining in South Africa. It indicates that the major differences between the expected new expansion options and existing oil refineries are the product shares, as it is assumed that new investments would be made according to the anticipated increase in demand for diesel. The national production statistics /JODIDB 2011/ are used to calculate the historical share of products of South Africa’s existing oil refineries. The production statistics are adjusted according to the calculated production of synthetic fuels as they include all the petroleum products generated in South Africa (see also section 5.1.2). The product range for new investments is based on /Kavalov & Peteves 2005/ and /Bultitude 2012/.

Direct GHG emissions from the crude oil refining process are taken from /Edwards et al. 2011a/ and /IAÖ 2011/ and adjusted for the South African refinery efficiencies. It is assumed that refining light distillates causes GHG emissions at the refinery of about 7.1 g $CO_2eq/MJ_{product}$ and middle distillates of about 8.7 g $CO_2eq/MJ_{product}$. The GHG emissions from middle distillates production are higher than from light distillates because /Edwards et al. 2011a/ assumes that greater effort is required to produce high quality, sulphur-free diesel which will be required in South Africa in future, too. The cost of crude oil refining is calculated on the basis of the estimated cost of the proposed new oil refinery at Coega as about 81,000 $ZAR_{2007}/(TJ/a)_{cap}$ for investment and 3,650 $ZAR_{2007}/(TJ/a)_{cap}$ for fixed operating and maintenance (FOM) costs. The lifetime of the technology is assumed to be 30 years with a construction time of 4 years /IEA 2010e/. Auxiliary energy requirements and the efficiency of the refining process are calculated based on the energy balances for South Africa available from the IEA /IEA 2008a/. The availability is considered to be 8,160 h/a /Bruchof 2013/.

Table 9: Techno-economic and environmental characteristics of refining processes in South Africa for all residual facilities operating in 2007 and new investments in 2010 and 2040.

Process	Crude oil refining		
Feedstock	Crude oil		
Output	Petrol, diesel, kerosene, LPG		
		2007 (all existing)	2010 2040
Capacity	bbl/day	513,000	400,000
	PJ/a	1,066	831
Availability	h/a	8,160	8,160
Construction time	a	-	4
Lifetime	a	-	30
Efficiency	MJ_{out}/MJ_{in}	0.90	0.90
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.028	0.028
Product shares (fuels)			
Light distillates	$MJ_{light\ dist}/MJ_{out}$	34% – 51%	40% – 75%
Middle distillates	$MJ_{middle\ dist}/MJ_{out}$	49% – 65%	45% – 65%
LPG	MJ_{LPG}/MJ_{out}	0% – 7%	0% – 6%
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	-	81,116
	$EUR_{07}/(TJ/a)_{cap}$	-	8,397
FOM	ZAR_{07}/TJ_{cap}	3,650	3,650
	EUR_{07}/TJ_{cap}	378	378
Direct GHG emissions			
Light distillates	$g\ CO_2eq/MJ_{out}$	7.1	7.1
Middle distillates	$g\ CO_2eq/MJ_{out}$	8.7	8.7

Abbreviations: out = output; in = input; cap = capacity; elec = electricity; dist = distillate.

Sources: own calculations and assumptions based on /SAPIA 2009/, /Bruchof 2013/, /IEA 2010e/, /Dalmini 2011/, /Edwards et al. 2011a/, /IEA 2008a/, /JODIDB 2011/, /IAÖ 2011/, /Kavalov & Peteves 2005/, /Bultitude 2012/.

5.1.2 Thermo-chemical production of synthetic fuels from coal (CTL), natural gas (GTL) and biomass (BTL)

Modern thermo-chemical processes for converting fossil (e.g. coal and natural gas) and renewable resources (e.g. wood, agricultural residues and solid waste) into liquid fuels are based on Fischer-Tropsch synthesis (FTS) /IEA 2010c/. Those fuels are named synthetic fuels, FTS fuels, XTL fuels or designer fuels. Because they are produced synthetically, they can be generated according to desired specifications. Synthetic fuels have a low sulphur content and a small proportion of aromatics, which results in fewer pollutants such as HC, SO_2 or particulates, when used as vehicle fuel, compared to crude oil based fuels /Beiermann 2010/. Furthermore, the cetane and octane numbers are higher than for crude oil diesel and petrol, respectively /Beiermann 2010/.

The pathways for producing Fischer-Tropsch synthetic fuels from different feedstock (coal, natural gas and biomass) are shown in Figure 27. The first stage in Fischer-Tropsch synthesis is the production of a synthesis gas (CO and H_2) by gasification of a solid or liquid hydrocarbon (in some cases after separated pyrolysis) or by the reforming of natural gas /IEA 2010c/. The product gas of a gasification process consists mainly of carbon dioxide (CO_2), carbon monoxide (CO) and molecular hydrogen (H_2), but also of smaller proportions of other products such as CH_4, N_2, H_2O, tar and particulates /NPC 2007/. The composition of the product gas is dependent on the feedstock, the oxidant used, as well as on the pressure and temperature in the reactor, and the type of reactor used. Available rector types are inter alia moving-bed gasifiers, fluidized bed gasifiers (e.g. at Güssing) or entrained flow gasifiers (e.g. Carbo-V). Air, steam or pure oxygen can be used as oxidant /Beiermann 2010/, /IEA 2010e/, /NPC 2007/, /IEA 2010c/.

After gasification, the product gas is cleaned and prepared by removing ash and undesired components. In the following water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) the share of hydrogen and carbon monoxide in the gas can be adjusted according to the further process needs /Michel 2008/. Subsequently the CO_2 is removed by a washing process such as Selexol or Gensorb process (see also section 5.1.4 for a description of CO_2 removal techniques).

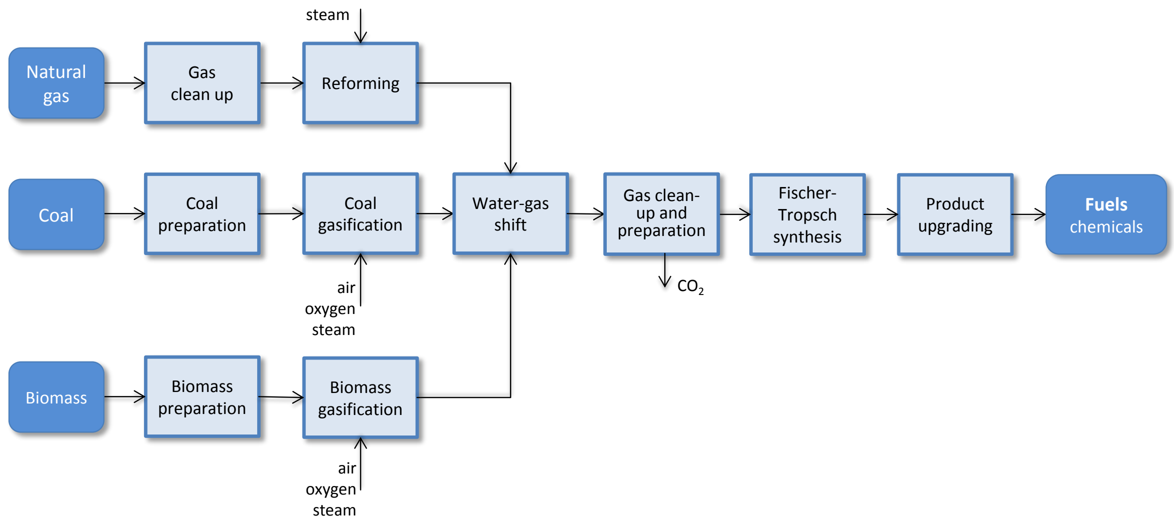


Figure 27: Different pathways for synthesis gas production and Fischer-Tropsch synthesis. Source: own figure adapted from /Sasol 2010a/, /Beiermann 2010/ and /NPC 2007/.

The synthesis gas obtained can be used flexibly, for example, for methanol synthesis, ammonia production (Haber-Bosch process), hydroformylation, synthetic natural gas (SNG) production or for Fischer-Tropsch synthesis /IEA 2010e/, /IEA 2010c/, /Anderson 1984/, /NPC 2007/. Only Fischer-Tropsch synthesis is currently used on a commercial scale to produce transport fuels /Beiermann 2010/.

Several reactor designs are available for Fisher-Tropsch synthesis, which can be distinguished into high-temperature processes that yield lighter hydrocarbons and low-temperature process that increase the share of longer hydrocarbons and waxes. Typically an iron or cobalt catalyst is used to achieve the chemical reactions (e.g. for paraffins: $n\,CO + (2n+1)\,H_2 \leftrightarrow C_nH_{2n+2} + n\,H_2O$; and for naphthenes: $n\,CO + 2n\,H_2 \leftrightarrow C_nH_{2n} + n\,H_2O$). Fuel outputs of the process are synthetic diesel and naphtha. Naphtha can be used in the chemical industry or can be fed to a conventional refining process to produce high quality petrol (via catalytic reforming). Like a crude oil refinery, an synthetic fuel plant consists of further processes such as hydro-treating and hydrocracking units to maximize the output of the desired components /Beiermann 2010/, /USDOE 2007/.

The Fischer-Tropsch synthesis was used on a commercial scale during the Second World War. After the war, the availability of cheap crude oil and petroleum products caused further research on the processes to remain little. In response to the world oil crisis, South Africa largely invested in Fischer-Tropsch synthesis – due to its abundance of coal and minimum oil reserves (see section 1.1) – and increased the capacities of Sasol (which stands for Suid-Afrikaanse Steenkool en Olie), the company founded in 1955 /Anderson 1984/. Sasol is nowadays a world market leader in fossil liquefaction processes (CTL, GTL), /Sasol 2010a/.

Coal-to-liquid (CTL)

In 2010, Sasol produced about the equivalent of 150,000 barrels/day (bbl_{eq}) in fuels and chemicals via CTL at Secunda (Sasol II & Sasol III) /Sasol 2010c/. Sasol II and Sasol III have been refitted several times to improve the production processes and fuel qualities /NPC 2007/. In 1996, all reactors at Secunda were replaced with new Sasol Advanced Synthol (SAS) reactors, which involves a high temperature process (operating at about 350°C) using Fe as catalyst and produces mainly light distillates and chemical feedstock /Sasol 2010a/, /Gibson 2007/, /Collings 2006/.

Investment costs for existing and new plants have been published in several studies, e.g. /Sasol 2010a/, /Sasol 2010b/, /Telsnig et al. 2013b/, /Geertsema 2006/, /Gibson 2007/, /IEA 2010e/, /IEA 2010c/, /NPC 2007/, /USDOE 2007/, /Creamer 2007/ and /Edwards et al. 2011a/ and show a significant range of figures. For example, the Conservation of Clean Air and Water in Europe (CONCAWE) research group gives the investment costs for a CTL plant (greenfield) as about 401,000 ZAR_{2007}/(TJ/a) with an uncertainty range of ± 40% /Edwards et al. 2011a/. Costs in this thesis are according to a proposed new CTL project, called Mafutha (the Nguni word for “energy”), to be built in Limpopo province, and have been calculated based on /Telsnig et al. 2013b/. The facility is planned to produce 80,000 bbl/day and – like the other CTL plants – has a coalmine nearby /Sasol 2010a/. Those investment costs are 12% lower than CONCAWE /Edwards et al. 2011a/. As South Africa is the world leader in the production of Fischer-Tropsch fuels, this cost saving is found to be plausible. Investment costs for the years 2010 and 2040 are expected to improve based on the postulated increase in the efficiency of the process. Thus, it is estimated that the capital costs of greenfield investment will decrease from about 353,000 ZAR_{2007}/(TJ/a) in 2010 to about 332,000 ZAR_{2007}/(TJ/a) in 2040 (Table 10).

The overall efficiency of the CTL process in Secunda is assumed to be 39% (coal to fuel) /Goosen 2010/, which is clearly lower than the anticipated efficiency of modern CTL applications of about 50–55% /Edwards et al. 2011a/, /USDOE 2007/, /NPC 2007/. In South Africa the efficiency for new CTL plants is assumed to increase from 49% in 2010 to 52% based on /Telsnig et al. 2013b/. Furthermore, it is expected that new CTL plants will generate 100% of their own electricity needs due to a different set-up of the process and higher process efficiency. Product shares of the Sasol plants at Secunda have been obtained from /Fabris 2011/ and are calculated for fuels only. Fuel outputs for new CTL plants are taken from /Kavalov & Peteves 2005/ and /Bultitude 2012/ and assume a higher diesel yield due to a low-temperature process.

Table 10: Techno-economic and environmental characteristics of CTL processes in South Africa.

Process	**Coal-to-liquid (CTL)**			
Input	Coal			
Output	Synthetic fuels			
		2007 (all existing)	2010	2040
Capacity	bbl_{eq}/day	150,000	80,000	80,000
	PJ/a	305	163	163
Availability	h/a	8,000	8,000	
Construction time	a	-	4	
Lifetime	a	-	30	
Efficiency	MJ_{out}/MJ_{in}	0.39	0.49	0.52
Auxiliary energy input	GJ_{elec}/GJ_{out}	0.03	0.00	
Product shares (fuels)				
Synthetic diesel	MJ_{SD}/MJ_{out}	0.40 – 0.44	0.45 – 0.85	
Synthetic naphtha	MJ_{SN}/MJ_{out}	0.54 – 0.58	0.00 – 0.35	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	-	353,186	332,810
	$EUR_{07}/(TJ/a)_{cap}$	-	36,563	34,454
FOM	ZAR_{07}/TJ_{cap}	19,969	15,893	14,976
	EUR_{07}/TJ_{cap}	2,067	1,645	1,550
VOM	ZAR_{07}/TJ_{out}	22,844	18,182	17,133
w/o auxiliary energy	EUR_{07}/TJ_{out}	2,365	1,882	1,774
Direct GHG emissions	g CO_2eq/MJ_{out}	172.1	122.6	111.4

Abbreviations: out = output; in = input; cap = capacity; elec = electricity; SD = synthetic diesel; SN = synthetic naphtha.

Sources: own calculations and assumptions based on /Telsnig et al. 2013b/, /Edwards et al. 2011a/, /Goosen 2010/, /IEA 2010e/, /Fabris 2011/, /Creamer 2007/, /Sasol 2010a/, /Kavalov & Peteves 2005/, /Bultitude 2012/.

Direct GHG emissions are calculated using the carbon content of the feedstock and the fuels produced as well as figures for methane leakage, which were obtained from /IEA 2010e/. It was found that the total GHG emissions of the existing CTL process are about 172 g $CO_{2eq}/MJ_{product}$ /Telsnig et al. 2013b/. However, GHG emissions would be considerably less in future plants due to their expected higher efficiency.

Gas-to-liquid (GTL)

The small amounts of natural gas (NG) which are produced in South Africa are almost all used to produce synthetic fuels (GTL) /EIA 2011/, /Geertsema 2006/. PetroSA operates South Africa's GTL refinery with a capacity of 45,000 bbl_{eq}/day, which is located in Mossel Bay /EIA 2011/. The plant is supplied by natural gas from offshore sources, whose reserve capacity is uncertain. New offshore gas fields are currently under development or under investigation, which could prolong the project's lifetime /Creamer 2012/, /Creamer 2010/. On the other hand, the company is also investigating the possibility of importing liquefied natural gas (LNG) to extend the plant's lifetime /Creamer 2012/. Additionally, some quantities of natural gas are being used at Secunda /Sasol 2010c/, /Sasol 2010a/, which has been allocated to the residual GTL capacities in this thesis. New GTL capacities are also conceivable, for example, at Secunda /Telsnig et al. 2013b/.

The efficiency of the current GTL process is found to be 55% (Table 11) /Goosen 2010/, which is lower than the proposed efficiency of new plants of 60–65%, /IEA 2010e/, /IEA 2010c/. Here the efficiency of new investments is estimated to be 62% in 2010 and 64% in 2040 for South Africa /Telsnig et al. 2013b/. As for the CTL process, it is expected that new GTL plants will self-generate all their electricity needs.

The availability of existing and new plants is assumed to be 8,000 h/a /Bruchof 2013/, /Özdemir 2012/. Fuels product shares are based on /Kavalov & Peteves 2005/ and /Bultitude 2012/ as for CTL products. The investment costs of GTL facilities are assumed to be considerably lower than for CTL plants at about 88,000 ZAR/(TJ/a) in 2010 and about 84,000 ZAR/(TJ/a) in 2040, based on /Telsnig et al. 2013b/. However, the expected technology learning is less. The GHG emissions of the process are calculated based on the carbon content of the feedstock and the fuel produced as for the CTL process, resulting in 34.1 g $CO_2eq/MJ_{product}$ for the current process, which is expected to decrease by about 50% in the case of future investments according to the anticipated increase in efficiency (Table 11).

In comparison with the CTL process, investment costs as well as direct GHG emissions are significantly lower for the GTL process. Investment costs are assumed to decline considerably between 2010 and 2040 as they reflect the expected improvement in efficiency of 2 percentage points.

Table 11: Techno-economic and environmental characteristics of GTL processes in South Africa.

Process	Gas-to-liquid (GTL)			
Input	Natural gas			
Output	Synthetic fuels			
		2007 (all existing)	2010	2040
Capacity	bbl_{eq}/day	52,380	34,000	34,000
	PJ/a	106	69	69
Availability	h/a	8,000	8,000	
Construction time	a	-	2	
Lifetime	a	-	30	
Efficiency	MJ_{out}/MJ_{in}	0.55	0.62	0.64
Auxiliary energy input	GJ_{elec} / GJ_{out}	0.01	0.00	
Product shares (fuels)				
Synthetic diesel	MJ_{SD}/MJ_{out}	0.54 – 0.58	0.45 – 0.85	
Synthetic naphtha	MJ_{SN}/MJ_{out}	0.42 – 0.46	0.00 – 0.35	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	-	87,787	84,411
	$EUR_{07}/(TJ/a)_{cap}$	-	9,088	8,739
FOM	ZAR_{07}/TJ_{cap}	4,417	3,950	3,798
	EUR_{07}/TJ_{cap}	457	409	393
VOM	ZAR_{07}/TJ_{out}	16,198	14,486	13,921
w/o auxiliary energy	EUR_{07}/TJ_{out}	1,677	1,500	1,441
Direct GHG emissions	g CO_2eq/MJ_{out}	34.1	23.1	19.4

Abbreviations: out = output; in = input; cap = capacity; elec = electricity; SD = synthetic diesel; SN = synthetic naphtha.

Sources: own calculations and assumptions based on /Telsnig et al. 2013b/, /Bruchof 2013/, /Özdemir 2012/, /Goosen 2010/, /Kavalov & Peteves 2005/, /EIA 2011/, /Sasol 2010a/.

Biomass-to-liquid (BTL)

Biomass-to-liquid processes are still on a pre-commercial scale /Sunde et al. 2011/, /IEA 2008b/. Some promising concepts applied to thermo-chemical use of biomass are currently under investigation such as the fast, internally circulating fluidized bed (FICFB) gasification of wood and straw with steam at Güssing, Austria, for power generation (8 MW_{th}) /Rauch 2010/. Others are the Bioliq entrained flow gasification with oxygen using straw, and the Carbo-V process by Choren (at Freiberg, Germany), using wood for entrained flow gasification (with oxygen) after pyrolysis, which is designed to produce Fischer-Tropsch fuels /Schütte 2010/. The Choren process is found to be the most promising one for Fischer-Tropsch fuels in terms of efficiency and specific production costs /Stahlschmidt et al. 2010/. However, continuing problems forced Choren to petition for insolvency proceedings in mid-2011. Linde Engineering Dresden licensed the Carbo-V process in 2012 /Ernhofer 2012/.

Table 12 summarizes the expected techno-economic and environmental characteristics of BTL processes in South Africa. For BTL the literature gives a range of available figures for costs and efficiencies as identified for the production of CTL and GTL fuels (see e.g. /Swanson et al. 2010/, /IEA 2010e/, /Bruchof 2013/, /Özdemir 2012/, /IEA 2008b/, /IEA 2009a/). In this thesis investment costs are assumed to be about

588,000 ZAR/(TJ/a) in 2010 and about 356,000 ZAR/(TJ/a) in 2040, based on /Edwards et al. 2011a/ and /Swanson et al. 2010/ and given the expected increase in production capacity and efficiency over that time span. The efficiency of the process is assumed to increase from 41% in 2010 to 44% in 2040, based on /Swanson et al. 2010/ and the expected efficiency improvement for the CTL process. Furthermore, the availability is expected to increase from 7,400 h in 2010 to 8,000h/a in 2040, based on /Swanson et al. 2010/ and /Özdemir 2012/. Expected production shares for BTL in South Africa are based on /Kavalov & Peteves 2005/ and /Bultitude 2012/ in consistence to the assumptions for CTL and GTL production in South Africa. Construction time and lifetime of the BTL process are according to /Bruchof 2013/ and /Swanson et al. 2010/. GHG emissions for BTL production are taken from /Özdemir 2012/ and are a result of methane leakages.

Table 12: Techno-economic and environmental characteristics of BTL processes.

Process	Biomass-to-liquid (BTL)		
Input	Straw, Wood		
Output	Synthetic fuels		
		2010	2040
Capacity	PJ/a	1.1	4.1
Availability	h/a	7,400	8,000
Construction time	a	4	
Lifetime	a	20	
Efficiency	MJ_{out}/MJ_{in}	0.41	0.44
Product shares (fuels)			
Synthetic diesel	MJ_{SD}/MJ_{out}	0.45 – 0.85	
Synthetic naphtha	MJ_{SN}/MJ_{out}	0.00 – 0.35	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	587,961	356,002
	$EUR_{07}/(TJ/a)_{cap}$	60,868	36,855
FOM	ZAR_{07}/TJ_{cap}	29,439	17,825
	EUR_{07}/TJ_{cap}	3,048	1,845
VOM	ZAR_{07}/TJ_{out}	21,677	20,202
	EUR_{07}/TJ_{out}	2,244	2,091
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	0.01	0.01

Abbreviations: out = output; in = input; cap = capacity; SD = synthetic diesel; SN = synthetic naphtha.

Sources: own calculations and assumptions based on /Swanson et al. 2010/, /Bruchof 2013/, /Özdemir 2012/, /Kavalov & Peteves 2005/, /Bultitude 2012/.

Compared with the CTL and GTL processes, BTL generation has the lowest efficiency. Investment costs are found to be the highest of the three Fischer-Tropsch processes analysed but show significant potential reductions in investment costs as the technology matures and higher capacities are achieved. Moreover, BTL manufacturing is assumed to generate only low direct GHG emissions.

5.1.3 Hydrogen production

Even though hydrogen is one of the most abundant elements on the planet, it is found mostly in chemical combination (e.g. as H_2O) /Rühle & Geitmann 2005/. Molecular hydrogen (H_2) can be produced through different pathways of which the most technically mature processes are the reforming of natural gas (about 49% of world H_2 production) or of other light hydrocarbons (29%), the gasification of coal (18%) and generation via electrolysis (4%) /Suresh et al. 2010/, /Michel 2008/. However, biomass can also be used for hydrogen production via biochemical (e.g. fermentation, algae) or thermo-chemical processes (e.g. gasification) /Rühle & Geitmann 2005/, /Geitmann 2006/.

Various processes that produce molecular hydrogen are available (Figure 28). For steam reforming, the hydrocarbon (commonly natural gas) has to be pre-processed in order to remove sulphur or other non-desirable components. Subsequently, the feedstock is catalytically reformed (using Ni) with steam to produce synthesis gas ($CH_4 + H_2O \leftrightarrow CO + 3\,H_2$). The feedstock used can be partly oxidized in order to yield energy for the endothermic reaction /Geitmann 2006/. In a water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$), most of the carbon monoxide is converted to form H_2 and CO_2 /Michel 2008/.

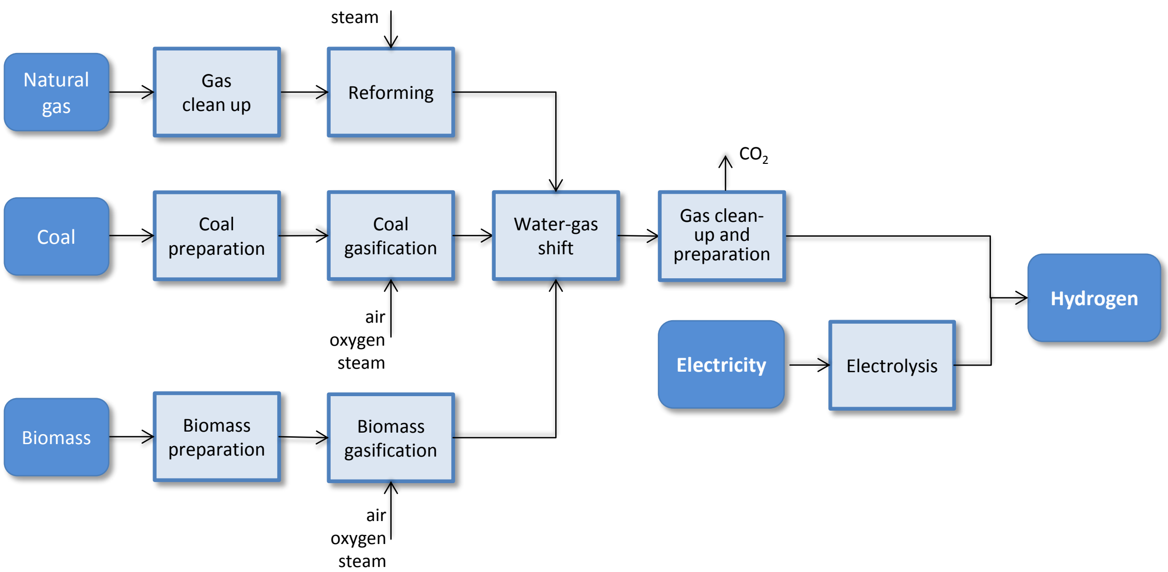


Figure 28: Hydrogen production from natural gas, coal and biomass via thermo-chemical pathways and from the electrolysis of water. Source: own figure adapted from /Sasol 2010a/, /Beiermann 2010/, /NPC 2007/.

The technical and economic parameters for hydrogen production from natural gas have been obtained from the hydrogen analysis project (H2A) of the U.S. Department of Energy /USDOE 2012/. The capacity of the process is taken as 5.8 PJ/a in 2010 and is anticipated to increase to 10.5 PJ/a in 2040 /Özdemir 2012/ (Table 13). The efficiency of the process is assumed to increase from 73% in 2010 to 77% in 2040 /Özdemir 2012/, /USDOE 2012/.

The investment costs are assumed to be about 86,000 ZAR_{2007}/(TJ/a) in 2010 according to /USDOE 2012/ and are expected to decrease to about 67,000 ZAR_{2007}/(TJ/a) based on the expected increase in capacity and efficiency. VOM costs are calculated based on H2A (about 1,500 ZAR_{2007}/TJ) /USDOE 2012/ and considered to change based on the efficiency of the process. The CO_2 emissions are calculated in relation to the carbon content of the feedstock and the fuel produced as shown in /WEC 2007/. All other figures are taken from /USDOE 2012/, see Table 13. As a result, the steam reforming of natural gas to hydrogen shows relatively high efficiency and low investment costs compared with hydrogen production from coal or biomass. However, further energy needs and expenses due to transport and delivery of the hydrogen have to be considered. This is done in section 5.1.9.

Table 13: Techno-economic and environmental characteristics of natural gas steam reforming for hydrogen production in South Africa.

Process	**Natural gas steam reforming and gas upgrading**		
Input	Natural gas		
Output	Hydrogen		
		2010	2040
Capacity	PJ/a	5.8	10.5
Availability	h/a	7,884	
Construction time	a	3	
Lifetime	a	40	
Efficiency	MJ_{out}/MJ_{in}	0.73	0.77
Auxiliary energy input	GJ_{elec}/GJ_{out}	0.017	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	85,560	67,005
	$EUR_{07}/(TJ/a)_{cap}$	8,857	6,937
FOM	ZAR_{07}/TJ_{cap}	4,349	3,406
	EUR_{07}/TJ_{cap}	450	353
VOM	ZAR_{07}/TJ_{out}	1,528	1,449
w/o auxiliary energy	EUR_{07}/TJ_{out}	158	150
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	79.0	74.9

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /USDOE 2012/ and /Özdemir 2012/.

Gasification of solid products (hard coal, and also lignite or biomass) is described above (section 5.1.2), that addresses Fischer-Tropsch synthetic fuels. In the case of hydrogen production, the gasification processes and the subsequent water-gas shift reaction are designed according to a high yield of H_2. Table 14 and Table 15 summarize the technical, economic and environmental characteristics of hydrogen production from coal and biomass via gasification and synthesis gas upgrading in South Africa. The average efficiency of hydrogen production using solid feedstock is less than for gaseous feedstock /Geitmann 2006/. The efficiencies in 2010 and 2040 are taken as 51%–57% for coal as feedstock (Table 14) and 48%–58% using cellulosic biomass as feedstock (Table 15), based on /USDOE 2008/, /USDOE 2012/ and /Özdemir 2012/.

The investment costs for 2010 of the two processes are found to be higher than for reforming natural gas and have been calculated based on /USDOE 2008/ and /USDOE 2012/. Future costs are calculated on the expected improvement in the efficiency and capacity of the processes. For coal gasification and upgrading the same capacity has been chosen as for hydrogen production from natural gas /Özdemir 2012/. However, the capacity for biomass gasification and upgrading to hydrogen is considered to be smaller (i.e. 3.3 PJ/a and 6.0 PJ/a in 2010 and 2040, respectively) /Özdemir 2012/.

Table 14: Techno-economic and environmental characteristics of coal gasification and upgrading for hydrogen production in South Africa.

Process	Coal gasification and upgrading		
Input	Coal		
Output	Hydrogen		
		2010	2040
Capacity	PJ/a	5.8	10.5
Availability	h/a	7,884	
Construction time	a	3	
Lifetime	a	40	
Efficiency	MJ_{out}/MJ_{in}	0.51	0.57
Energy surplus	GJ_{elec}/GJ_{out}	0.095	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	214,842	158,809
	$EUR_{07}/(TJ/a)_{cap}$	22,241	16,440
FOM	ZAR_{07}/TJ_{cap}	15,845	11,713
	EUR_{07}/TJ_{cap}	1,640	1,213
VOM	ZAR_{07}/TJ_{out}	2,604	2,330
w/o auxiliary energy	EUR_{07}/TJ_{out}	270	241
Direct GHG emissions	g CO_2eq/MJ_{out}	185.4	165.9

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /USDOE 2008/ and /Özdemir 2012/.

Table 15: Techno-economic and environmental characteristics of biomass gasification and upgrading for hydrogen production in South Africa.

Process	Biomass gasification and upgrading		
Input	Straw, wood		
Output	Hydrogen		
		2010	2040
Capacity	PJ/a	3.3	6.0
Availability	h/a	7,884	
Construction time	a	3	
Lifetime	a	40	
Efficiency	MJ_{out}/MJ_{in}	0.48	0.58
Auxiliary energy input	GJ_{elec}/GJ_{out}	0.030	
	GJ_{ng}/GJ_{out}	0.052	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	156,025	106,477
	$EUR_{07}/(TJ/a)_{cap}$	16,152	11,023
FOM	ZAR_{07}/TJ_{cap}	13,575	9,264
	EUR_{07}/TJ_{cap}	1,405	959
VOM	ZAR_{07}/TJ_{out}	3,460	2,863
w/o auxiliary energy	EUR_{07}/TJ_{out}	358	296
Direct GHG emissions	g CO_2eq/MJ_{out}	3.0	3.0

Abbreviations: out = output; in = input; cap = capacity; elec = electricity; ng = natural gas.

Sources: own calculations and assumptions based on /USDOE 2012/ and /Özdemir 2012/.

Comparing the two processes, biomass gasification and upgrading is found to require more auxiliary energy (the process using coal as feedstock is designed to generate surplus electricity) and has lower efficiency /USDOE 2008/, /USDOE 2012/. GHG emissions are calculated based on the carbon content of the feedstock and auxiliary energy requirements.

The separation of the hydrogen and oxygen of water using electricity is called electrolysis. If direct current is applied to an electrically conducting aqueous solution, e.g. of a salt or acid, gaseous oxygen is produced at the (positive) anode and gaseous hydrogen at the (negative) cathode according to the chemical reactions 2 H_2O + 2 e^- → H_2 + OH^- and 2 H_2O → O_2 + 4 H^+ + 4 e^-, respectively /Geitmann 2006/. A catalyst, such as platinum, is needed to start the reaction and a separator is used to prevent the gases from mixing /Geitmann 2006/. Only about 4% of the world's molecular hydrogen is produced by electrolysis /Suresh et al. 2010/, /Michel 2008/. Different variations of the process exist such as high pressure electrolysis (which involves increasing the pressure in the cell in order to eliminate the necessity of subsequent compression of the gas) or high temperature electrolysis using steam and ceramic materials to operate at temperatures of 900–1000°C, which achieve about 90% efficiency /Gül 2008/, /Geitmann 2006/. Yet, those processes have not been applied on a commercial scale /USDOE 2011a/, /Gül 2008/. Hydrogen electrolysis is also discussed for small-scale, de-centralized production, which minimizes transportation and distribution costs and losses (see section 5.1.9). However, due to the smaller scale, specific investment costs are found to be higher and production efficiency less than for centralized production /USDOE 2012/, /Bruchof 2013/. Table 16 and Table 17 summarize the characteristics of hydrogen production via electrolysis in South Africa. The efficiency of centralized hydrogen production via alkaline electrolysis is taken as 67–75% (2010–2040) (Table 16) and as 57–65% (Table 17) for de-centralized production, based on /USDOE 2012/, /Özdemir 2012/ and /IEA 2005/.

Table 16: Techno-economic and environmental characteristics of centralized hydrogen production via alkaline electrolysis in South Africa.

Process	**Alkaline electrolysis – centralized**		
Input	Electricity		
Output	Hydrogen		
		2010	2040
Capacity	PJ/a	2.2	4.5
Availability	h/a	7,500	
Construction time	a	1	
Lifetime	a	20	
Efficiency	MJ_{out}/MJ_{in}	0.67	0.75
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	127,321	90,701
	$EUR_{07}/(TJ/a)_{cap}$	13,181	9,390
FOM	ZAR_{07}/TJ_{cap}	10,678	7,607
	EUR_{07}/TJ_{cap}	1,105	787
VOM	ZAR_{07}/TJ_{out}	0	0
w/o auxiliary energy	EUR_{07}/TJ_{out}	0	0
Direct GHG emissions	g CO_2eq/MJ_{out}	0.0	0.0

Abbreviations: out = output; in = input; cap = capacity.

Sources: own calculations and assumptions based on /USDOE 2012/, /IEA 2005/ and /Özdemir 2012/.

The investment costs in 2010 are assumed to be about 127,000 ZAR_{2007}/(TJ/a) and about 237,000 ZAR_{2007}/(TJ/a) for centralized and de-centralized production, respectively /USDOE 2012/. Future investment costs are calculated, with the capacity and efficiency of the processes – which are taken to be 2.2 PJ/a in 2010 and 4.5 PJ/a in 2040 for centralized production and 0.06 PJ/a and 0.11 PJ/a for de-centralized production in these years – based on /USDOE 2012/ and /Özdemir 2012/. The annual availability of 7,500 h/a is taken from /USDOE 2012/.

There are no direct GHG emissions due to hydrogen production via electrolysis. However, it should be noted that the process chain emissions of hydrogen production from electrolysis are dependent on the source of the electricity.

Table 17: Techno-economic and environmental characteristics of de-centralized hydrogen production via alkaline electrolysis in South Africa.

Process	**Alkaline electrolysis – de-centralized**		
Input	Electricity		
Output	Hydrogen		
		2010	2040
Capacity	PJ/a	0.06	0.11
Availability	h/a	7,531	
Construction time	a	1	
Lifetime	a	20	
Efficiency	MJ_{out}/MJ_{in}	0.57	0.65
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	237,359	165,890
	$EUR_{07}/(TJ/a)_{cap}$	24,572	17,174
FOM	ZAR_{07}/TJ_{cap}	13,793	9,640
	EUR_{07}/TJ_{cap}	1,428	998
VOM	ZAR_{07}/TJ_{out}	0	0
w/o auxiliary energy	EUR_{07}/TJ_{out}	0	0
Direct GHG emissions	g CO_2eq/MJ_{out}	0.0	0.0

Abbreviations: out = output; in = input; cap = capacity.

Sources: own calculations and assumptions based on /USDOE 2012/, /IEA 2005/, /Özdemir 2012/ and /Bruchof 2013/.

Besides the commercially available processes described for H_2 production, there is the option of producing molecular hydrogen by biochemical means. Thus, bacteria or certain algae can be used which generate hydrogen by photosynthesis, or enzymatic production by fermentation of monosaccharide sugars /Cheng et al. 2011/, /Foglia et al. 2010/. This option is not considered in this thesis as research is still at an early developmental stage.

Furthermore, hydrogen can be used as an option for storing renewable electricity (see e.g. /IEA 2005/), if excess electricity is used for electrolysis. The hydrogen produced might later be used in a fuel cell if the electricity demand increases or if the electricity supply is interrupted. However, these conversions go hand in hand with reductions in the overall energy efficiency and an increase in costs, which are considered in TIMES-GEECO.

5.1.4 Carbon capture and storage (CCS)

Carbon capture and storage (CCS) is discussed as an option for reducing GHG emissions by the sequestration into underground storage of CO_2 generated in combustion processes /Kuckshinrichs et al. 2010/. Different geological sites seem to be suitable, such as depleted oil and gas fields, saline aquifers or deep coal beds /Fischedick et al. 2007/. Furthermore, the CO_2 can be used for enhanced oil and gas recovery /Kuckshinrichs et al. 2010/, /Fischedick et al. 2007/.

South Africa recognized the option of CCS to limit CO_2 emissions, as the Long-term Mitigation Scenarios (see section 1.3) proposes carbon capture and storage for new liquefaction plants and for future IGCC coal-fired power plants /Winkler 2007/. A Centre for Carbon Capture and Storage was established within the South African National Research Energy Institute (SANERI) to investigate the potential storage sites and sources for CCS as well as to establish the technical and human basis for commercial CCS projects /Surridge & Cloete 2009/. On the technical side, South Africa plans to establish a demonstration CCS plant operational by the year 2020 and commercial plants in 2025 /CGS 2010/. CO_2-enhanced coal-bed methane recovery, on the other hand, is not seen as a likely option for South Africa due to the disaggregated storage potential /CGS 2010/.

The main steps of the CCS process are the capture of the CO_2 and its compression, transport to the storage site (most probably by pipeline or ship) and, thirdly, pumping the CO_2 underground for storage (Figure 29). Several options for capturing the carbon dioxide are feasible, which can be separated with respect to the capture point of the CO_2 (pre- or post-combustion) and the oxidant used. Even though enhanced oil and gas recovery is already used in practice, and CO_2 transport has been used since the 1970s in the USA, the potential CCS applications are at an early stage of development /Kuckshinrichs et al. 2010/, /Fischedick et al. 2007/.

Post-combustion is the most developed process and can been applied via various available gas treatment processes. These are for example physical processes using van der Vals Bounds to adsorb the CO_2 on a solid surface (as in pressurized swing adsorption processes) or by absorbing the CO_2 in a solvent (as in pressurized water scrubbers). The Selexol and Gensorb processes use additional washing-fluids to increase the capture performance and allow for simple regeneration of the solvent. Further options are chemically removing the CO_2 from the flue gas via absorption as for example by using amine gas treatment. Using mineral adsorption or the use of membranes for CO_2 removal in CCS processes are still the subject of research /IEA 2009b/, /Esken et al. 2010/, /Fischedick et al. 2007/. Further processes, such as enzymatic or algae-based sequestration, are in an early stage of development /Esken et al. 2010/.

In pre-combustion processes, the CO_2 is removed from the syngas (e.g. in IGCC or Fischer-Tropsch synthetic fuel plants) mostly by chemical or physical washing or by membranes /Kuckshinrichs et al. 2010/, /Fischedick et al. 2007/, /Esken et al. 2010/. Pre-combustion has not yet been applied on a large scale but the technology has been proven in several industrial processes /IEA 2009b/.

The use of pure oxygen for a combustion process (instead of air) increases the CO_2 content of the flue gas (to about 80%), reduces the need of flue gas cleaning (e.g. NO_x) and thus makes capturing the CO_2 easier /Esken et al. 2010/. This technology is called the oxyfuel combustion process. Oxyfuel combustion has not yet been applied on a large scale due to the high energy needs for pure oxygen provision, but has been demonstrated in industrial projects in the steel industry with capacities up to 250 MW /IEA 2009b/, /Fischedick et al. 2007/. It is expected that CCS will be available on a commercial scale in 2020–2025 /Kuckshinrichs et al. 2010/, /Esken et al. 2010/, /IEA 2009b/, /Fischedick et al. 2007/.

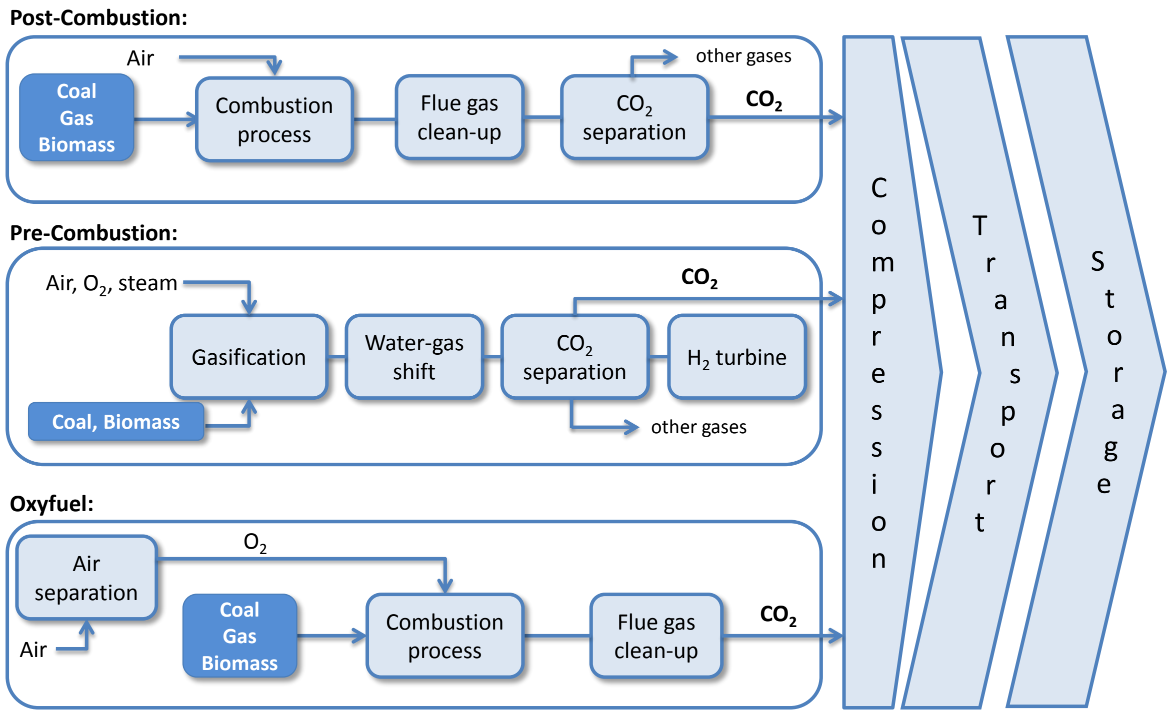


Figure 29: Promising options for the application of carbon capture and storage. Source: own figure based on /Kuckshinrichs et al. 2010/, /Esken et al. 2010/, /Fischedick et al. 2007/ and /Metz et al. 2005/.

Typically, about 80% to 95% of the CO_2 can be separated and captured /IEA 2011a/, /Kuckshinrichs et al. 2010/. In principle, any combustion process could be used with CCS but large amounts of CO_2 are needed to make the process economically feasible. Therefore, CCS is primarily discussed for application in coal-fired power plants, Fischer-Tropsch synthetic fuel processes (see section 5.1.2), hydrogen production from coal or natural gas (see section 5.1.3) and for large industrial emitters (such as petrochemical or cement producers) /Fischedick et al. 2007/. However, energy is needed to capture and purify the CO_2, compressing and transporting and finally for pumping it underground independently from the capture method. Thus, the overall efficiency of a power plant is expected to be reduced by about 6–12 percentage points /Kober 2013/, /IEA 2011a/.

Additionally, about 3 percentage points are lost due to the transport and storage /Kuckshinrichs et al. 2010/.

For CCS application in South Africa the reduction in efficiency due to CO_2 capture is taken as 4.5 percentage points for CTL, which corresponds to an additional electricity demand of 0.206 $MJ_{electricty}/MJ_{product}$ in 2010 and 0.182 $MJ_{electricty}/MJ_{product}$ in 2040 /Telsnig et al. 2013b/ (Table 18). For GTL, these figures are adjusted according to the lower CO_2 emissions of the process. Thus, the corresponding auxiliary electricity requirement is considerably lower at 0.039 $MJ_{electricty}/MJ_{product}$ in 2010 and 0.032 $MJ_{electricty}/MJ_{product}$ in 2040 /Telsnig et al. 2013b/, which equals a reduction in efficiency of about 1.5 percentage points (Table 19). Given the comparatively low electricity prices and high prices for petroleum products in South Africa, it is assumed that the additional electricity requirement is taken from the grid. The additional investment costs of the plants are relatively low and mainly results from extra compressor stations, taken from /Kreutz et al. 2008/. Fixed operating and maintenance costs (FOM) are assumed to be 4.5% of the investment, which is similar to the plants without CCS. Variable operating and maintenance costs (VOM) include costs for CO_2 transport and storage, based on /Telsnig et al. 2013b/.

Table 18: Techno-economic and environmental characteristics of CTL processes with CCS in South Africa including transport and storage.

Process	**CTL with CCS**		
Input	Coal		
Output	Synthetic fuels		
		2010	2040
Capacity	bbl_{eq}/day	80,000	80,000
Availability	h/a	8,000	
Construction time	a	4	
Lifetime	a	30	
Efficiency	MJ_{out}/MJ_{in}	0.49	0.52
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.206	0.182
Product shares (fuels)			
Synthetic diesel	MJ_{SD}/MJ_{out}	0.45 – 0.85	
Synthetic naphtha	MJ_{SN}/MJ_{out}	0.00 – 0.35	
Specific investment cost	$ZAR_{07}/(TJ/a)_{cap}$	359,414	339,038
	$EUR_{07}/(TJ/a)_{cap}$	37,208	35,099
FOM	ZAR_{07}/TJ_{cap}	16,174	15,241
	EUR_{07}/TJ_{cap}	1,674	1,579
VOM	ZAR_{07}/TJ_{out}	30,339	28,494
w/o auxiliary energy	EUR_{07}/TJ_{out}	3,147	2,950
Direct GHG emissions	g CO_2eq/MJ_{out}	16.1	14.6

Abbreviations: out = output; in = input; cap = capacity; elec = electricity; SD = synthetic diesel; SN = synthetic naphtha.

Sources: own calculations and assumptions based on /Telsnig et al. 2013b/, /Edwards et al. 2011a/, /Goosen 2010/, /IEA 2010e/, /Fabris 2011/, /Creamer 2007/, /Sasol 2010a/, /Kavalov & Peteves 2005/, /Bultitude 2012/, /Kreutz et al. 2008/, /IEA 2011a/.

Table 19: Techno-economic and environmental characteristics of GTL processes with CCS in South Africa, including transport and storage.

Process	GTL with CCS		
Input	Natural gas		
Output	Synthetic fuels		
		2010	2040
Capacity	bbl_{eq}/day	89,116	89,116
Availability	h/a	8,000	
Construction time	a	2	
Lifetime	a	30	
Efficiency	MJ_{out}/MJ_{in}	0.62	0.64
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.039	0.032
Product shares (fuels)			
Synthetic diesel	MJ_{SD}/MJ_{out}	0.45 – 0.85	
Synthetic naphtha	MJ_{SN}/MJ_{out}	0.00 – 0.35	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	94,015	90,639
	$EUR_{07}/(TJ/a)_{cap}$	9,733	9,383
FOM	ZAR_{07}/TJ_{cap}	4,231	4,079
	EUR_{07}/TJ_{cap}	438	422
VOM	ZAR_{07}/TJ_{out}	17,408	16,564
w/o auxiliary energy	EUR_{07}/TJ_{out}	1,802	1,715
Direct GHG emissions	g CO_2eq/MJ_{out}	3.1	2.6

Abbreviations: out = output; in = input; cap = capacity; elec = electricity; SD = synthetic diesel; SN = synthetic naphtha.

Sources: own calculations and assumptions based on /Telsnig et al. 2013b/, /Bruchof 2013/, /Özdemir 2012/, /Goosen 2010/, /Kavalov & Peteves 2005/, /EIA 2011/, /Sasol 2010a/, /Kreutz et al. 2008/.

Hydrogen production with CCS via steam reforming of natural gas and water-gas shift, and hydrogen from coal-based synthesis gas provision and subsequent gas upgrading with CCS, are summarized in Table 20 and Table 21, respectively. Additional investment costs for hydrogen production with CCS are to be found in /IEA 2005/ and /Kreutz et al. 2008/. As for the production of Fischer-Tropsch fuels, the additional investment costs of the hydrogen plants are relatively low and result mainly from extra compressor stations, because it is assumed that electricity is taken from the grid and thus no further production capacity has to be built /Telsnig et al. 2013b/, /IEA 2005/. In accordance with the previous assumptions, the auxiliary energy requirement for carbon capture is expressed as equivalent additional electricity requirement. For natural gas reforming to hydrogen with CCS the auxiliary electricity requirement results in a reduction of process efficiency of 3.5 percentage points /Gül 2008/. For coal-based hydrogen production with CCS the corresponding reduction in efficiency is 3.0 percentage points /Gül 2008/. However, it is a coupled process that produces hydrogen and electricity (0.038 MJ_{elec}/MJ_{out}), whereas the pathway considered for steam reforming of natural gas requires auxiliary energy of 0.068 MJ_{elec}/MJ_{out} /USDOE 2012/, /USDOE 2008/.

The calculation of emissions from CCS processes is according to /Telsnig et al. 2013b/, in which a detailed analysis of various applications of CCS for fuel production (i.e. CTL and GTL) and electricity generation (via coal IGCC) was reported for different plant locations in South Africa. In comparison with the processes without CCS (see sections 5.1.2 and 5.1.3), direct GHG emissions are calculated to be considerably lower at a reduction of about 87% for the processes considered. In absolute terms, the reduction in direct GHG emissions is highest for new investments in CTL and hydrogen from coal at about 106 g CO_2eq/MJ and 163 g CO_2eq/MJ, respectively.

Table 20: Techno-economic and environmental characteristics of natural gas steam reforming with CCS for hydrogen production in South Africa.

Process		**Natural gas steam reforming and gas upgrading with CCS**	
Input		Natural gas	
Output		Hydrogen	
		2010	2040
Capacity	PJ/a	5.8	10.5
Availability	h/a	7,884	
Construction time	a	3	
Lifetime	a	40	
Efficiency	MJ_{out}/MJ_{in}	0.73	0.77
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.068	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	91,788	73,233
	$EUR_{07}/(TJ/a)_{cap}$	9,502	7,581
FOM	ZAR_{07}/TJ_{cap}	5,125	4,182
	EUR_{07}/TJ_{cap}	531	433
VOM	ZAR_{07}/TJ_{out}	11,695	11,821
w/o auxiliary energy	EUR_{07}/TJ_{out}	1,211	1,224
Direct GHG emissions	g CO_2eq/MJ_{out}	9.5	9.0

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /USDOE 2012/, /IEA 2005/, /Kreutz et al. 2008/, /Bruchof 2013/ and /Özdemir 2012/.

Table 21: Techno-economic and environmental characteristics of coal gasification and gas upgrading with CCS for hydrogen production in South Africa.

Process		**Coal gasification and gas upgrading with CCS**	
Input		Coal	
Output		Hydrogen	
		2010	2040
Capacity	PJ/a	5.8	10.5
Availability	h/a	7,884	
Construction time	a	3	
Lifetime	a	40	
Efficiency	MJ_{out}/MJ_{in}	0.51	0.57
Energy surplus	MJ_{elec}/MJ_{out}	0.038	
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	221,070	165,037
	$EUR_{07}/(TJ/a)_{cap}$	22,886	17,085
FOM	ZAR_{07}/TJ_{cap}	16,638	12,298
	EUR_{07}/TJ_{cap}	1,722	1,273
VOM	ZAR_{07}/TJ_{out}	21,323	19,467
w/o auxiliary energy	EUR_{07}/TJ_{out}	2,207	2,015
Direct GHG emissions	g CO_2eq/MJ_{out}	22.2	19.9

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /USDOE 2008/, /IEA 2005/, /Kreutz et al. 2008/, /Bruchof 2013/ and /Özdemir 2012/.

Costs for transport and storage have been calculated for proposed or likely locations of the plants; i.e. for CTL and hydrogen production using coal in Limpopo, for GTL and hydrogen via natural gas reforming at Secunda, and for a large-scale application of CCS with IGCC power generation at Majuba /Creamer 2007/, /DOE 2011/, /Telsnig et al. 2013b/. Transport and storage costs add up to 115 ZAR_{2007}/t CO_2(stored) for CTL and H_2 from coal, 146 ZAR_{2007}/t CO_2(stored) for GTL and H_2 from natural gas and to about 74 ZAR_{2007}/t CO_2(stored) for IGCC, based on /Telsnig et al. 2013b/. The electricity requirement for transport and storage is less than 0.01 $GJ_{electricity}/GJ_{product}$ for all applications /Telsnig et al. 2013b/.

The CO_2 storage capacity of South Africa has been discussed in several studies with the result that large storage possibilities are evident around the country (see e.g. /Surridge & Cloete 2009/, /Engelbrecht et al. 2004/). A comprehensive study can be found in the *Atlas on Geological Storage of Carbon Dioxide in South Africa* by the Council for Geoscience /CGS 2010/. The most promising storage sites – in terms of data availability and substrate heterogeneity – are deep saline formations near Swaziland and near the city of Port Elizabeth, with a storage potential of about 500 Mt each /CGS 2010/, /Telsnig et al. 2013b/. Moreover, large capacities of about 148 Gt are estimated in offshore deep saline formations /CGS 2010/. However, lower soil quality is projected for these sites and only limited data are available /CGS 2010/. Furthermore, these sites are problematic due to the relatively large distances to significant CO_2 sources /CGS 2010/. The CCS storage capacity usable for fuel production for Gauteng is estimated to be about 25.7 Mt CO_2/a, which assumes that only onshore storage is used for CCS projects in the model time horizon. For example, the proposed CTL plant in Limpopo (see section 5.1.2) would require about 19 Mt CO_2/a /Telsnig et al. 2013b/. In comparison for an IGCC power plant of 1.3 MW, the CO_2 captured annually would amount to about 5.9 Mt CO_2/a /Telsnig et al. 2013b/. CCS is assumed to be available for the energy system modelling (see chapter 6) from 2020 onwards.

5.1.5 Physiochemical production of biofuels

Biodiesel can be produced from oil or fat-containing crops such as soybeans, sunflower seeds, rapeseeds, certain nuts and other seeds /Romano & Sorichetti 2011/. Figure 30 shows the general process of biodiesel production. Initially, the vegetable oil is produced by physical extraction (milling and pressing) with an additional chemical extraction stage to maximize the oil yield /Moser 2009/, /Widmann et al. 2009/. The chemical extraction is usually realized by using hexane as solvent (C_6H_{14}) /Widmann et al. 2009/. The hexane has to be removed after the extraction, which can be done by distillation due to its low boiling point /Widmann et al. 2009/. By-products of this process are oil cakes, which can be used as an energy source (after dehydration) or as animal food /Moser 2009/. On the other hand, it is also possible to use waste cooking oil as feedstock for biodiesel production. This is already being done in Gauteng on a small scale /GAIN 2009/. In the case of producing biodiesel from waste oil, extraction is not needed in the process but the feedstock has to be filtered from foreign material and dehydrated.

Vegetable oils and fats are esters, i.e. trivalent alcohols (glycerine) chemically bound to three long-chain fatty acids /Moser 2009/. This complex molecular structure is the reason for their undesirable characteristics (e.g. high viscosity) compared to fossil diesel. Using a monovalent alcohol, usually methanol (or also ethanol), and a catalyst, the triglyceride can be replaced by transesterification. The products are monovalent esters: fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE) and glycerine /Widmann et al. 2009/. The by-product glycerine is used in the chemical, pharmaceutical and cosmetics industries, or can be used as an energy source, which is not common today /Marshall & Haverkamp 2008/. FAME, commonly known as biodiesel, is comparable to fossil diesel in its density, viscosity and ignition characteristics /Widmann et al. 2009/.

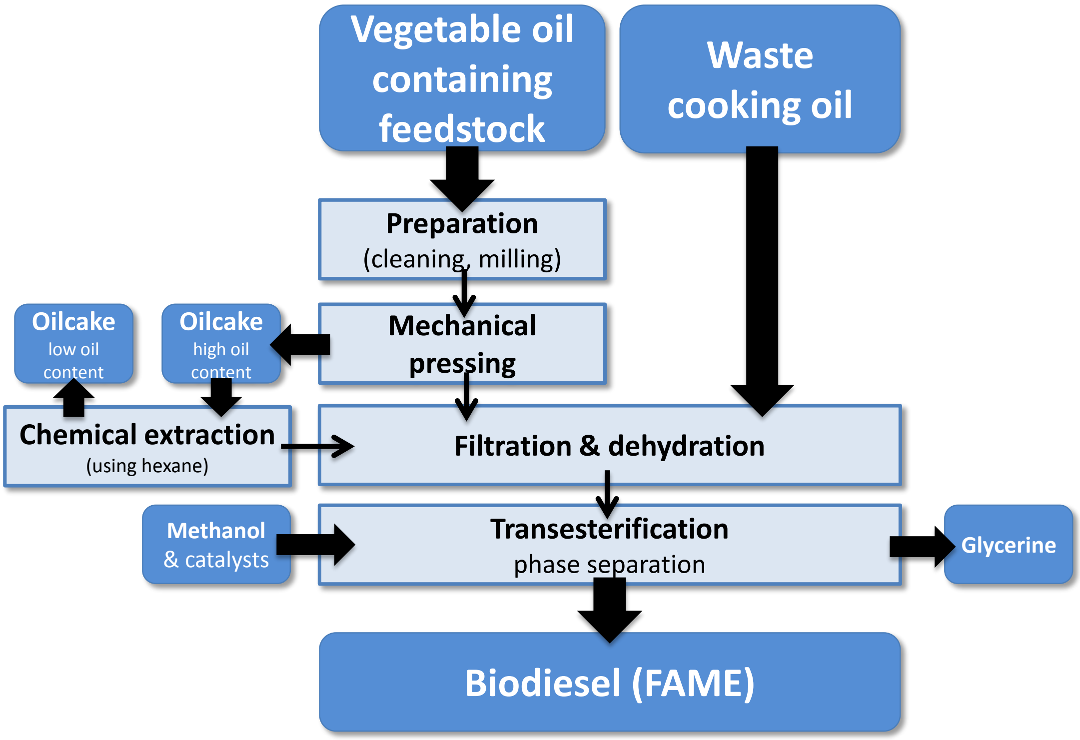


Figure 30: Simplified process of converting vegetable oil and waste cooking oil via transesterification to produce FAME. Source: own figure, adapted from /Widmann et al. 2009/, /Moser 2009/.

The main biodiesel producers in the world in 2008 were Germany, the United States and France, with production of about 2.8, 2.4 and 1.8 million tons, respectively /Romano & Sorichetti 2011/. South Africa had no industrial-scale biodiesel production until 2009 /F.O. Licht 2008c/. Only relatively small quantities of biodiesel are produced from waste cooking oil from larger restaurants and used for their company vehicles /GAIN 2009/. However, South Africa has the potential for large-scale production and has planned to increase its efforts to establish a biofuel industry: the Industrial Biofuel Strategy (see also section 2.2.4) identified relevant crops as feedstock for biodiesel production, e.g. sunflowers (with 810,000 t production in 2008) and soybeans (282,000 t in 2008) /FAO 2011/. Furthermore, rapeseeds are proposed for biodiesel production which have been cultivated since 2002 but only in relatively small quantities (30,800 t in 2008) /FAO 2011/.

A detailed account of the costs of generating biofuels from energy crops in South Africa, analysed for the whole production chain including crop production and transport, conversion and fuel distribution, as well as all the economic assumptions made, is published in /Tomaschek et al. 2012c/. There the costs of provisions for biofuels are calculated according to the assumption that the biofuel producer buys the energy crops or the waste oil at market prices and does not necessarily cultivate the required feedstock himself. This approach allows the use of available statistics for crop prices in South Africa (i.e. /FAO 2011/, /Brent et al. 2010/ and /Stephenson et al. 2010/), which already include the cost of land, fertilizers, machines, labour and profit margins for farmers.

The techno-economic specifications of biodiesel production in South Africa using energy crops are summarized in Table 22 and in Table 23 using waste cooking oil as feedstock. The production capacity of the processes is assumed to increase from 0.8 PJ/a in 2010 to 3.3 PJ/a in 2040 /Tomaschek et al. 2012c/. The efficiency of the conversion of energy crops to fuels is dependent on the oil content of the crop used; figures are taken from /Letete 2009/. Conversion rates for biodiesel from waste cooking oil are based on /Özdemir 2012/. Coal is used for direct heating in the transesterification process and electricity to run the machines /Tomaschek et al. 2012c/.

The investment costs for biodiesel production from energy crops and waste oil are taken from the South African Biofuel Industrial Strategy (/DME 2007/, see also section 2.2.4) and /Nolte 2007/. Variable costs including expenditures for methanol and catalysts are taken from /Nolte 2007/ and adjusted by more recent figures for revenues from glycerine sales taken from /Oleoline 2011/. Furthermore, VOM costs given in /Nolte 2007/ have been reduced by the costs for auxiliary energy consumption of the production process, which is analysed separately in this thesis, according to /Roth 2010/ and /Stephenson et al. 2010/. A separate analysis of auxiliary energy requirements allows the effects of changing prices and emission factors in the future to be included. GHG emissions from these processes are based on the analysis presented in /Roth 2010/ and /Stephenson et al. 2010/ and adjusted to take account of the auxiliary energy demand, which is different in these sources.

As shown in Table 22 and Table 23, the investment costs of new plants are estimated to decrease until 2040, which can be explained by the assumed increase in production capacity. Comparing the investment costs of biodiesel production from energy crops with that produced from waste cooking oil, the investment costs of the latter process are considerably lower due to the easier handling of the production process (e.g. no milling is requirement and no oil extraction).

Table 22: Techno-economic and environmental characteristics of biodiesel production from energy crops in South Africa.

Process	**Biodiesel production from energy crops**		
Input	Vegetable oil containing energy crops (SO, SF, RS)		
Output	Biodiesel		
		2010	2040
Capacity	Ml/a	25	100
	PJ/a	0.8	3.3
Availability	h/a	8,000	
Construction time	a	3	
Lifetime	a	20	
Conversion rates	kg_{SO}/MJ_{out}	0.165	
	kg_{SF}/MJ_{out}	0.078	
	kg_{RS}/MJ_{out}	0.074	
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.026	
	MJ_{coal}/MJ_{out}	0.016	
Investment costs	$ZAR_{07}/(TJ/a)_{cap}$	104,252	66,721
	$EUR_{07}/(TJ/a)_{cap}$	10,793	6,907
FOM	ZAR_{07}/TJ_{cap}	17,622	11,582
	EUR_{07}/TJ_{cap}	1,824	1,199
VOM w/o auxiliary energy	ZAR_{07}/TJ_{out}	6,212	
	EUR_{07}/TJ_{out}	643	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	1.5	

Abbreviations: SO = soybeans; SF = sunflower seeds; RS = rapeseeds; out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Tomaschek et al. 2012c/, /DME 2007/, /Henniges 2006/, /OSEC 2010/, /Nolte 2007/, /Macedo et al. 2008/, /Stephenson et al. 2010/, /Letete 2009/, /Roth 2010/, /Oleoline 2011/.

Table 23: Techno-economic and environmental characteristics of biodiesel production from waste cooking oil in South Africa.

Process	**Biodiesel production from waste cooking oil**		
Input	Waste cooking oil		
Output	Biodiesel		
		2010	2040
Capacity	Ml/a	25	100
	PJ/a	0.8	3.3
Availability	h/a	8,000	
Construction time	a	2	
Lifetime	a	20	
Conversion rate	MJ_{out}/MJ_{in}	0.9	
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.012	
	MJ_{coal}/MJ_{out}	0.015	
Investment costs	$ZAR_{07}/(TJ/a)_{cap}$	15,699	10,048
	$EUR_{07}/(TJ/a)_{cap}$	1,625	1,040
FOM	ZAR_{07}/TJ_{cap}	4,752	3,123
	EUR_{07}/TJ_{cap}	492	323
VOM w/o auxiliary energy	ZAR_{07}/TJ_{out}	1,323	
	EUR_{07}/TJ_{out}	137	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	1.4	

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /DME 2007/, /Henniges 2006/, /OSEC 2010/, /Nolte 2007/, /Macedo et al. 2008/, /Stephenson et al. 2010/, /Özdemir 2012/, /Letete 2009/, /Roth 2010/, /Oleoline 2011/.

Direct GHG emissions from both processes are low, but auxiliary energy is needed for process heat and electricity. Conversion emissions for FAME production from energy crops are determined as 1.5 g CO_2eq/MJ_{output}, which is only slightly higher than direct emissions from biodiesel production from waste cooking oil. However, additional emissions from crop cultivation and transport occur (without considering the effects of changes in land use). These are calculated as 71.7 g CO_2eq/MJ_{output} (in 2010) and 60.0 g CO_2eq/MJ_{output} (in 2040) for soybeans; 73.9 g CO_2eq/MJ_{output} (in 2010) and 34.7 g CO_2eq/MJ_{output} (in 2040) for sunflower seeds; and 68.8 g CO_2eq/MJ_{output} (in 2010) and 40.0 g CO_2eq/MJ_{output} (in 2040) for rapeseeds, based on /Stephenson et al. 2010/ and /Brent et al. 2010/. The future reduction of GHG emissions is primarily a result of improved production techniques, which are also expressed to take account of increased yields (i.e. 1.23 t/ha and 2.52 t/ha for soybeans, 0.97 t/ha and 1.70 t/ha for sunflower seeds, and 1.14 t/ha and 1.58 t/ha for rapeseeds in 2010 and 2040, respectively, based on /Tomaschek et al. 2012c/ and /Brent et al. 2010/).

5.1.6 Biochemical production of biofuels

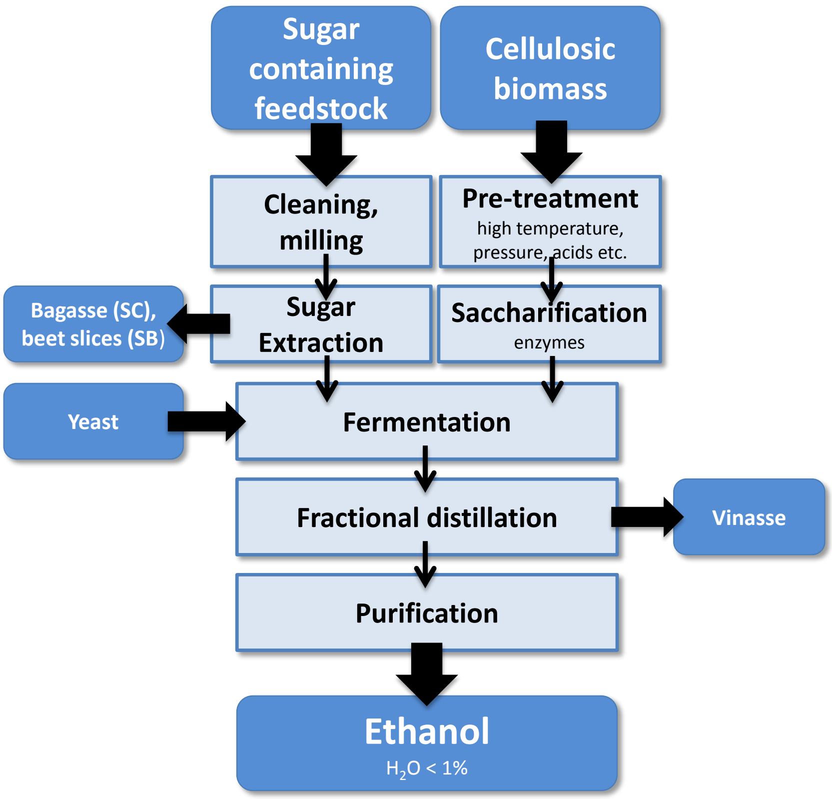
Ethanol can be produced synthetically (e.g. by hydration of ethylene) or from biomass (by fermentation of sugars). South Africa is one of the world's largest producers of synthetic ethanol (0.6% of global ethanol production in 2007 /F.O. Licht 2008b/), using ethane gas from Sasol's coal liquefaction process (see section 5.1.2) /Berg 2010/. In 2007, about $400 \cdot 10^6$ litres of ethanol (8.4 PJ) were produced in South Africa /F.O. Licht 2008b/ of which $260 \cdot 10^6$ litres (5.5 PJ) were exported /F.O. Licht 2008a/. However, it is unclear how much of this production is currently used in the South African petrol mix, if at all. Even if the total remainder of 2.9 PJ was blended into the petrol mix, it would account for only a 0.7% energy share (or 1.2% share by volume) of the total petrol sales in 2007 /SAPIA 2011/, which implies minor significance for the transport sector.

For ethanol production via fermentation, sugar is needed as a source. Sugar cane and sugar beet are commonly used as feedstock and also proposed by the Industrial Biofuel Strategy of South Africa (see also section 2.2.4) /Rutz & Janssen 2007/. Moreover, feedstock which contains starch (such as maize or wheat) can be used, as the starch can be converted into fermentable sugars /Senn et al. 2009/. However, maize as feedstock is politically unacceptable by the South African government and thus is not considered further in this study (see section 2.2.4) /DME 2007/.

In 2011, more than 99% of the world's ethanol production was provided from energy crops /USDOE 2011b/. The main producers of ethanol from crops are the United States and Brazil /REN21 2010/. South Africa also has huge potential for ethanol production from energy crops, as it is one of the major sugar cane producers in the world (14th largest in 2010), with more than $16 \cdot 10^6$ t of cane production in 2010 (i.e. about 18% of the total African production and about 1% of world sugar production) /FAO 2011/. On the other hand, sugar beet is not yet cultivated on a commercial scale in South Africa /FAO 2011/. However, a first pilot project has been started in Cradock in the Eastern Cape to demonstrate the feasibility of sugar beet production in South Africa /CEF 2010/.

On the other hand, cellulosic biomass can be used as feedstock for the biochemical production of biofuels, which are also referred to as second-generation biofuels /IEA 2008b/. However, so far only first-generation biofuels have been produced on a commercial scale globally as the upscaling of plants has been found to be problematic /Nigam & Singh 2011/, /Bullis 2012/. In 2010, the world's largest producers of second-generation ethanol were the United States, with a production capacity of about $15 \cdot 10^6$ litres/a (from 12 plants), and Canada, with $19 \cdot 10^6$ litres/a from 3 plants /REN21 2010/. In 2011, the construction of a $49 \cdot 10^6$ litres/a plant was started in Italy, and is scheduled for completion in 2012 /Comyns 2011/. However, this plant will partially be supplied with energy crops /Comyns 2011/.

Figure 31 shows the basic production chain for ethanol from sugar-containing feedstock and for cellulosic biomass. Initially, the sugar-containing feedstock is milled and the sugar is extracted. The starch-containing and cellulosic materials have to be converted into monosaccharide sugars (e.g. glucose). For cellulosic materials, acids or enzymatic hydrolysis (in the iogen process) can be used to break down the complex polysaccharidic molecular structure /Senn et al. 2009/.



Abbreviations: SC = sugar cane, SB = sugar beet.

Figure 31: Simplified scheme for the production of ethanol from sugar-containing feedstock or cellulosic biomass. Source: own figure based on /Senn et al. 2009/, /Rutz & Janssen 2007/, /Weitz 2006/.

The following fermentation process is conducted using yeast. The resulting mash has to be separated by removing the water by fractional distillation and subsequent dehydration by adding absorbents /Senn et al. 2009/. The by-product of this process is vinasse, which can be used as an animal feed, for biogas production, as fertilizer or could be burned for energy use after dehydration /Rutz & Janssen 2007/, /Weitz 2006/. If sugar cane is used as a feedstock for this purpose, the bagasse is also a valuable by-product for electricity production, which is already an established practice in the South African sugar industry /Peacock & Cole 2009/. Sugar beet usage results in the by-product of beet slices, which can be used as a protein-rich animal food /Rutz & Janssen 2007/.

The conversion rates for ethanol production from energy crops in South Africa are taken from /Roth 2010/ and /Letete 2009/ (Table 24). As for biodiesel production in South Africa (see section 5.1.5), it was assumed that coal is used to provide process heat (e.g. for the distillation process) if sugar beet is used as feedstock /Tomaschek et al. 2012c/. In producing ethanol from sugar cane, the bagasse is used for heat provision and to generate surplus electricity (about 0.02 MJ_{elec}/MJ_{EOH}) /Tomaschek et al. 2012c/.

Table 24: Techno-economic and environmental characteristics of ethanol production from energy crops in South Africa.

Process	**Ethanol production from energy crops**		
Input	Sugar containing feedstock (SB, SC)		
Output	Ethanol		
		2010	2040
Capacity	Ml/a	500	2,000
	PJ/a	1.1	4.2
Availability	h/a	8,000	
Construction time	a	3	
Lifetime	a	20	
Conversion rate	kg_{SC}/MJ_{out}	0.604	
	kg_{SB}/MJ_{out}	0.450	
Auxiliary energy input			
Sugar cane	MJ_{elec}/MJ_{out}	–0.020*	
Sugar beet	MJ_{elec}/MJ_{out}	0.029	
	MJ_{coal}/MJ_{out}	0.142	
Investment costs	$ZAR_{07}/(TJ/a)_{cap}$	330,874	104,905
	$EUR_{07}/(TJ/a)_{cap}$	34,253	10,860
FOM	ZAR_{07}/TJ_{cap}	19,362	12,725
	EUR_{07}/TJ_{cap}	2,004	1,317
VOM	ZAR_{07}/TJ_{out}	20,227	
w/o auxiliary energy	EUR_{07}/TJ_{out}	2,094	
Direct GHG emissions			
Sugar cane	$g\ CO_2eq/MJ_{out}$	0.0	0.0
Sugar beet	$g\ CO_2eq/MJ_{out}$	13.5	13.5

*negative value states surplus energy generated by bagasse burning which is fed to the grid
Abbreviations: SB = sugar beet; SC = sugar cane; out = output; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Tomaschek et al. 2012c/, /Roth 2010/, /DME 2007/, /Henniges 2006/, /OSEC 2010/, /Macedo et al. 2008/, /Ecoinvent 2007/, /Letete 2009/.

Investment and FOM costs for ethanol production from energy crops can be found in /DME 2007/ and /Henniges 2006/. The investment costs of the plant are expected to decrease significantly between 2010 and 2040 due to increasing production capacity but also because of anticipated technology learning; this will result in the investment costs in South Africa in 2040 being comparable with those in Brazil in 2010 /Tomaschek et al. 2012c/. Variable costs from /Henniges 2006/ are adjusted by the auxiliary energy consumption, which is excluded from VOM costs, based on /Macedo et al. 2008/, /Ecoinvent 2007/ as described in /Tomaschek et al. 2012c/.

Crop cultivation makes a significant contribution to additional GHG emissions, with 53 g CO_2eq/MJ_{output} (in 2010) and 38 g CO_2eq/MJ_{output} (in 2040) for sugar cane, and 38 g CO_2eq/MJ_{output} (in 2010) and 27.5 g CO_2eq/MJ_{output} (in 2040) for sugar beet, based on /Roth 2010/. The improvement of the production process is also reflected in the increase in yield, which, according to /Roth 2010/, is calculated to be 32.5 t/ha and 47.2 t/ha for sugar beet and 47.6 t/ha and 63.3 t/ha for sugar cane in 2010 and 2040, respectively.

The efficiency of ethanol production from wood and straw (Table 25) is assumed to increase from 35% in 2010 to 40% in 2040, based on /Humbird et al. 2011/, /Kabir Kazi et al. 2010/ and /Özdemir 2012/. Additionally, ethanol provision from cellulosic biomass is anticipated to produce about 0.08 MJ_{elec}/MJ_{EOH} surplus electricity /Humbird et al. 2011/. The figures for availability and for the production capacity the process have been assumed to be similar to those for ethanol production from energy crops /Tomaschek et al. 2012c/. Investment, fixed and variable costs are taken from /Humbird et al. 2011/ and /IEA 2009a/ and have been adapted to the capacity. Direct GHG emissions are taken from /Özdemir 2012/, /Bruchof 2013/. Compared with ethanol production from energy crops, the specific investment costs are significantly higher. However, direct GHG emissions are only low.

Table 25: Techno-economic and environmental characteristics of ethanol production from wood and straw in South Africa.

Process	Ethanol production from cellulosic biomass		
Input	Straw, wood		
Output	Ethanol		
		2010	2040
Capacity	Ml/a	500	2,000
	PJ/a	1.1	4.2
Availability	h/a	8,000	
Construction time	a	4	
Lifetime	a	20	
Efficiency	MJ_{out}/MJ_{in}	0.35	0.40
Energy surplus	MJ_{elec}/MJ_{out}	0.08	
Investment costs	$ZAR_{07}/(TJ/a)_{cap}$	760,757	432,469
	$EUR_{07}/(TJ/a)_{cap}$	78,757	44,771
FOM	ZAR_{07}/TJ_{cap}	34,234	19,461
	EUR_{07}/TJ_{cap}	3,544	2,015
VOM	ZAR_{07}/TJ_{out}	28,968	25,347
w/o auxiliary energy	EUR_{07}/TJ_{out}	2,999	2,624
Direct GHG emissions	g CO_2eq/MJ_{out}	0.34	0.29

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Humbird et al. 2011/, /Kabir Kazi et al. 2010/, /IEA 2009a/, /DME 2007/, /Henniges 2006/, /Özdemir 2012/, /Bruchof 2013/.

5.1.7 Methane gas supply

Methane gas (CH_4) can be can be sourced in different ways, of which the most common is natural gas /Cerbe 2008/. Other options analysed in this thesis are CH_4 from fermentation processes (here from sewage plants and landfill sites) and from the gasification of coal and biomass.

Methane from the latter sources is often referred to as SNG, where the meaning of this abbreviation is sometimes not clearly distinguished in the literature. Some sources refer to SNG as synthetic natural gas (e.g. /Chandel & William 2009/, /Gray et al. 2007/), while others refer to SNG as substitute natural gas (e.g. /Tuna 2008/, /Özdemir 2012/). To distinguish SNG from fossil or renewable energy sources, the term bio-SNG can also be found in the literature (e.g. /Rönsch et al. 2009/, /Chandel & William 2009/). In this thesis, SNG refers to all substitutions of natural gas (possessing the necessary quality to be fed into the gas grid); the feedstock is indicated to show the source.

Natural gas as the main source of methane gas

Methane is the main component of natural gas, amongst others including ethane, propane and carbon monoxide /Cerbe 2008/. Natural gas can be distinguished for its different qualities, depending on the composition and methane content of the source gas, which is also referred to as dry (about 80% CH_4) and wet natural gas (about 60% CH_4), of which the latter is mostly found in the USA /Flottmann et al. 2003/. Excavated natural gas has to be processed before it is used. The most important intervention is dehydration by removing water as well as separation of CO, H_2S and higher hydrocarbons. Natural gas is commonly transported via pipelines (94% of the total) or ships (about 6% of the world's natural gas was so transported in 2005) /Kelkar 2008/. For transportation the volume of natural gas is usually minimized by compression (when conveyed by pipeline) or liquefaction (in ships) at about –161°C /Cerbe 2008/.

The natural gas reserves of South Africa are located near the western and southern coasts and are currently used for liquefaction (refer to section 5.1.2) /Sweto 2009/, /DME 2005/. Additionally, natural gas is imported via an 865-km-long pipeline from Mozambique with a peak capacity of 240 PJ/a (in 2009, South Africa imported about 120 PJ of natural gas) /Allix 2008/. The proven onshore natural gas reserves of Mozambique are about 5 Tcf (more than 5.4 EJ) /EIA 2010/, so that it is assumed that the supply can be ensured over the time horizon of this analysis (until 2040). Natural gas from Mozambique is sold to customers (principally industrial consumers) in Gauteng, corresponding to about 50 PJ in 2007 /Tomaschek et al. 2012b/, /Sasol 2010a/, /Singh 2011/. Gauteng has a relatively dense distribution network, which is especially concentrated in the south of the province, and connects major cities such as Johannesburg, Germiston and Boksburg but also Pretoria in the north /DME 2005/. It is anticipated that the costs of pipeline expansion are included in the tariff-based price for natural gas considered in this thesis (Table 31). It is assumed that about 0.04 MJ electricity per MJ natural gas is needed to pipe and transport natural gas in South Africa, based on /Edwards et al. 2011a/.

Anaerobic digestion for methane gas supply

Methane gas can also be obtained by anaerobic digestion of biomass. The process is based on the initial transformation of the feedstock (e.g. carbohydrates, fats or proteins) to sugars fatty acids and amino acids via hydrolysis and secondly to alcohols and organic acids via acidogenesis /Scholwin et al. 2009/, /Cerbe 2008/. In a third step (acetogenesis), acetic acid, hydrogen and carbon dioxide are produced. Finally, the acids and hydrogen are converted to methane. Different types of bacteria, which use the respective transformation products, are responsible for the conversion chain. The conversion rate of digestion of organic components to gas depends mainly on the composition of the feedstock as well as the possible presence of inhibitive components in the waste, which can limit the reaction. The resulting product gas consists mainly of CH_4 and CO_2, and is referred to as (raw) biogas.

In order to use biogas in technical appliances it is usually cleaned of sulphur and dehydrated in order to avoid corrosion. Removal of other undesirable components such as CO_2 depends on the further use of the gas. For electricity generation (e.g. in a gas motor) medium-quality gas (in which sulphur and other pollutants have been removed) is suitable. The gas can then be further upgraded to natural gas quality (SNG) from which CO_2 has to be removed via available gas treatment processes (refer to sections 5.1.2 and 5.1.4) /Scholwin et al. 2009/, /PDG 2004/ /Cerbe 2008/.

The main sources of biogas in Europe are energy crops (e.g. maize) and manure /Scholwin et al. 2009/. Maize is explicitly excluded in the South African biofuel strategy from the list of suitable feedstock for producing biofuels (see section 2.2.4) due to competition with the food market. The production of biogas from maize is therefore not considered further in this thesis.

Other possible sources of organic biomass are sewage sludge or organic waste. The resulting digestion gas is a product of bacterial activity within the landfill site. Like biogas, it mainly consists of CH_4 and CO_2 but also includes other organic and non-organic components such as silicate and chlorofluorocarbons /Scholwin et al. 2009/, /Cerbe 2008/. Landfill sites, especially those which process relatively large amounts of organic waste, are suitable sources for CH_4 production /Scholwin et al. 2009/, /Cerbe 2008/.

The digestion of sewage sludge as the basis of electricity production is commonly applied in Europe /Cerbe 2008/. However, in South Africa electricity from sewage gas is not produced on a larger commercial scale /Knote et al. 2008/. Gas from landfill sites in South Africa is mostly flared or not processed at all as only passive ventilation is a mandatory requirement /PDG 2004/. On the other hand, electricity production from landfill gas, has been adopted in CDM (clean development mechanism) projects, corresponding to total electric power of 9.9 MW in South Africa (of which 4 MW applies to Gauteng) /Schon 2012/, /UNFCCC 2010/, /UNFCCC 2006/. SNG from landfill or sewage gas is currently not produced on a commercial scale in South Africa as well. However, a demonstration project in Gauteng showed the feasibility for producing SNG from upgraded landfill gas for industrial and vehicle use /NERSA 2011/.

Cost and efficiency data for the processing of landfill (Table 26) and sewage gas (Table 27) and the subsequent upgrading to SNG are taken from /Schon 2012/ who analysed cost and potentials of landfill and sewage gas utilisation in South Africa and from /Weidner et al. 2008/. These figures include the gathering of raw gas and flaring units. The upgrading of raw gas is based on pressure scrubbing as this option is found to be the cheapest for South Africa due to the low electricity prices /Schon 2012/. Investment costs for SNG provision from landfill gas are expected to decrease from about 371,000 ZAR_{2007}/(TJ/a) in 2010 to about 258,000 ZAR_{2007}/(TJ/a) in 2040. Investment costs for SNG provision from sewage gas are assumed to be higher (i.e. about 802,000 ZAR_{2007}/(TJ/a) in 2010 and 449,000 ZAR_{2007}/(TJ/a)in 2040), mainly due to the smaller production capacity /Schon 2012/. The capacity of a typical plant to produce SNG from landfill sites and sewage plants was chosen corresponding to small to medium-sized utilities in South Africa (i.e. 0.05–0.15 PJ/a for landfill gas processing and upgrading and 0.02–0.10 PJ/a for sewage gas processing and upgrading) /Schon 2012/. The potential of raw gas provision for such plants was calculated to be of the magnitude of 0.6–1.8 PJ (Table 41) /Schon 2012/.

Table 26: Techno-economic and environmental characteristics of SNG from landfill sites in South Africa.

Process	Landfill gas gathering, processing and upgrading		
Input	Biogas (landfill)		
Output	SNG (biomass)		
		2010	2040
Capacity	PJ/a	0.05	0.15
Availability	h/a	8,000	
Construction time	a	3	
Lifetime	a	15	
Efficiency	MJ_{out}/MJ_{in}	0.97	0.97
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.084	0.084
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	371,066	257,668
	$EUR_{07}/(TJ/a)_{cap}$	38,414	26,675
FOM	ZAR_{07}/TJ_{cap}	16,698	11,595
	EUR_{07}/TJ_{cap}	1,729	1,200
VOM	ZAR_{07}/TJ_{out}	10,461	10,461
	EUR_{07}/TJ_{out}	1,083	1,083
Direct GHG emissions	g CO_2eq/MJ_{out}	14.23	14.23

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Schon 2012/ and /Weidner et al. 2008/.

Table 27: Techno-economic and environmental characteristics of SNG from sewage plants in South Africa.

Process	Sewage gas gathering, processing and upgrading		
Input	Biogas (sewage)		
Output	SNG (biomass)		
		2010	2040
Capacity	PJ/a	0.02	0.10
Availability	h/a	8,000	
Construction time	a	3	
Lifetime	a	15	
Efficiency	MJ_{out}/MJ_{in}	0.97	0.97
Auxiliary energy input	MJ_{elec}/MJ_{out}	0.117	0.117
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	801,726	448,949
	$EUR_{07}/(TJ/a)_{cap}$	82,998	46,477
FOM	ZAR_{07}/TJ_{cap}	36,078	20,203
	EUR_{07}/TJ_{cap}	3,735	2,091
VOM	ZAR_{07}/TJ_{out}	8,009	8,009
	EUR_{07}/TJ_{out}	829	829
Direct GHG emissions	g CO_2eq/MJ_{out}	14.23	14.23

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Schon 2012/ and /Weidner et al. 2008/.

The efficiency of both processes is 97%, as only minor leakage of methane occurs during the pressure scrubbing /Schon 2012/. Direct GHG emissions are the result of methane leakages and are calculated as 14.2 g CO_2eq/MJ_{out}. Electricity production from landfill and sewage gas is described in Appendix C.

Thermo-chemical gasification of biomass or coal for methane provision

Lastly, this section describes methane gas from thermo-chemical gasification of biomass or coal. The gasification of coal and biomass is also addressed in section 5.1.2 for Fischer-Tropsch fuel production and in section 5.1.3. for hydrogen production. Figure 32 illustrates the production of SNG from coal or biomass via a thermo-chemical pathway.

Gasification of coal or biomass produces a syngas that can be upgraded to SNG, by treatment in a water-gas shift reactor and, finally, by cleaning and upgrading by removing undesirable gases (e.g. CO_2 and H_2S). Different reactor designs are suitable for the gasification of solid hydrocarbons and the production of syngas (see section 5.1.2). The syngas is then methanated in a catalytic reaction (typically using nickel) at high temperatures to CH_4 and H_2O ($CO + 3\,H_2 \leftrightarrow CH_4 + H_2O$) /Gray et al. 2007/, /Chandel & William 2009/, /Rönsch et al. 2009/. If biomass is used for gasification, the feedstock has to be milled and dried to ensure a low moisture content /Rönsch et al. 2009/. Moreover, high tar content can make additional gas treatments necessary /Tuna 2008/, /Chandel & William 2009/. After methanation, the product has to be dried and adjusted to the specifications of the natural-gas pipeline network /Rönsch et al. 2009/. Gasification of biomass is at the demonstration stage and only small-scale operations have been set up, such as those at Güssing in Austria with a capacity of 8 MW_{th} /Rönsch et al. 2009/.

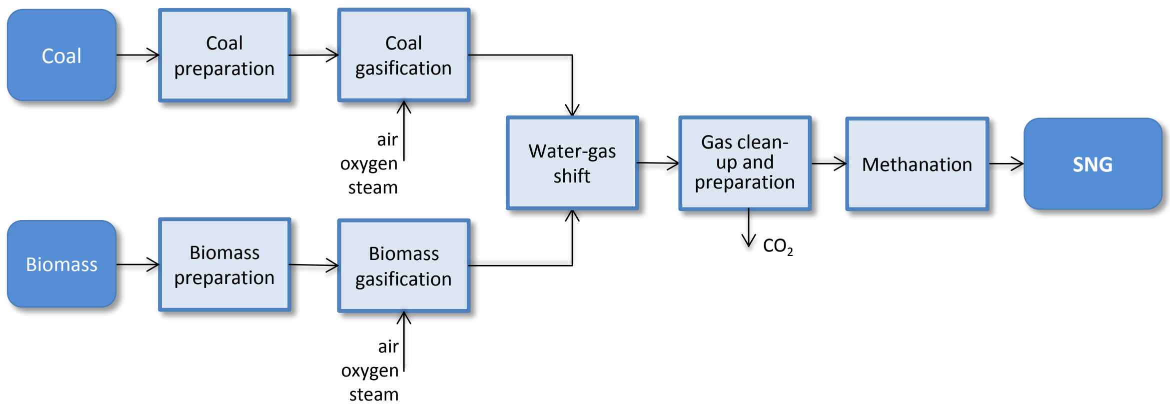


Figure 32: Schematic supply chain of SNG production from coal and biomass. Source: own figure adapted from /Sasol 2010a/, /Beiermann 2010/, /NPC 2007/.

Table 28 summarizes the techno-economic and environmental specifications for biomass gasification and methanation. Specifications for coal gasification and methanation can be found in Table 29. The efficiency of biomass gasification, methanation and gas treatment is taken as 52% for current applications and as 55% in 2040, according to the expected improvements in the BTL process (section 5.1.2) and /Gray et al. 2007/. The capacity of a typical plant in 2010 has been chosen based on the gasification process at Güssing; larger capacities in the future have been based on assumptions made in /Özdemir 2012/. GHG emissions for biomass gasification (9.2 g CO_2eq/MJ_{out}), which include methane leakage, are taken from /Özdemir 2012/.

Table 28: Techno-economic and environmental characteristics of biomass gasification and methanation in South Africa.

Process	Biomass gasification and methanation		
Input	Straw, wood		
Output	SNG (biomass)		
		2010	2040
Capacity	PJ/a	0.7	2.0
Availability	h/a	8,000	
Construction time	a	3	
Lifetime	a	25	
Efficiency	MJ_{out}/MJ_{in}	0.48	0.52
Energy surplus	MJ_{elec}/MJ_{out}	0.013	0.018
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	569,901	372,921
	$EUR_{07}/(TJ/a)_{cap}$	58,998	38,606
FOM	ZAR_{07}/TJ_{cap}	28,535	18,672
	EUR_{07}/TJ_{cap}	2,954	1,933
VOM	ZAR_{07}/TJ_{out}	14,330	13,355
	EUR_{07}/TJ_{out}	1,483	1,383
Direct GHG emissions	g CO_2eq/MJ_{out}	9.20	9.20

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Gray et al. 2007/, /Swanson et al. 2010/, /Özdemir 2012/, /Bruchof 2013/.

Table 29: Techno-economic and environmental characteristics of coal gasification and methanation in South Africa.

Process	Coal gasification and methanation		
Input	Coal		
Output	SNG (coal)		
		2010	2040
Capacity	PJ/a	26	26
Availability	h/a	8,000	
Construction time	a	3	
Lifetime	a	25	
Efficiency	MJ_{out}/MJ_{in}	0.58	0.60
Energy surplus	MJ_{elec}/MJ_{out}	0.015	0.021
Investment cost	$ZAR_{07}/(TJ/a)_{cap}$	162,009	155,172
	$EUR_{07}/(TJ/a)_{cap}$	16,772	16,064
FOM	ZAR_{07}/TJ_{cap}	8,112	7,769
	EUR_{07}/TJ_{cap}	840	804
VOM	ZAR_{07}/TJ_{out}	12,203	11,688
	EUR_{07}/TJ_{out}	1,263	1,210
Direct GHG emissions	g CO_2eq/MJ_{out}	115.0	108.0

Abbreviations: out = output; in = input; cap = capacity; elec = electricity.

Sources: own calculations and assumptions based on /Gray et al. 2007/, /Swanson et al. 2010/, /Özdemir 2012/.

By comparison, GHG emissions for coal gasification are considerable higher (115 g CO_2eq/MJ_{out} in 2010 and 108 g CO_2eq/MJ_{out} in 2040) relative to biomass gasification and methanation. However, specific investment costs for coal gasification are clearly lower, which is a result of easier processing and use of coal in comparison to cellulosic biomass and also of the significantly higher production capacity.

5.1.8 Electricity generation

South Africa had installed electricity generation capacity in 2011 of about 45.5 GW, of which about 1.3 GW was in Gauteng (Figure 33) /DOE 2011/, /Platts 2008/. This figure includes about 1.6 GW of pumped storage capacity. About 86% of the total generation capacity is based on coal, which is responsible for high GHG emissions /Platts 2008/, /Schulz 2003/. South Africa has the only nuclear power plant on the African continent (at Koeberg, near Cape Town), which is the second largest facility in terms of capacity installed in the country, at almost 2 GW (in two units) /EIA 2011/, /Platts 2008/. Most of the gas turbines in South Africa (~3.2 GW) have been built in recent years in response to electricity shortages (see also section 1.1). The electricity generation capacity in Gauteng consists of 1.1 GW coal-fired power plants, 200 MW oil open cycle gas turbines (OCGT) and only 3 MW of installed hydro capacity (hatched parts in Figure 33).

Furthermore, there are some power plants currently being built and which will be completed within the next few years. A recently published Integrated Resource Plan Electricity (IRP) describes the electricity generation projects that are planned for the near future. Besides an additional 4.3 GW of coal-fired power plants currently under construction and 4.3 GW planned to be built by 2019, about 1.5 GW of old capacity is scheduled to return to service by 2014 /DOE 2011/. Moreover, there are plans to build about 200 MW of concentrated solar power (CSP) and ~700 MW wind power plants by 2014 /DOE 2011/. Both these residual capacities as well as power plants currently under construction are considered in the TIMES-GEECO model.

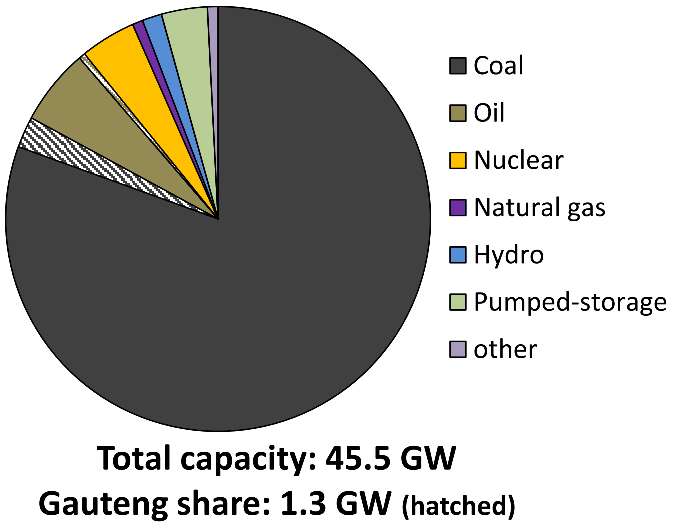


Figure 33: Total electric power generation capacity installed in South Africa in 2011. Sources: own calculations based on /Platts 2008/ and /DOE 2011/.

The investment costs and efficiencies of fossil-fuelled power plants are calculated on the basis of /IEA & NEA 2010/, /DOE 2011/, /Marquard et al. 2008/, /Winkler 2006/ and /Winkler 2007/. Analysing those studies, it is found that the efficiency of such power plants in South Africa is on average 2 percentage points less than a comparable power plant in Europe or in North America due to the higher ambient air temperatures. The investments costs given in the South African studies for current construction are taken as investment costs in 2010. These are combined with the predictions given in /IEA & NEA 2010/ for future cost trajectories. Techno-economic descriptions of electricity generation from renewables (such as CSP, open-field PV and wind power) are according to /Telsnig et al. 2012/. Emission factors are taken from /Schulz 2003/ and /Telsnig et al. 2012/. All relevant parameters are to be found in Appendix C and in /Telsnig et al. 2012/.

5.1.9 Energy delivery costs and emissions

The costs of production of secondary energy carriers, e.g. LPG, CNG, petrol, diesel and electricity, are calculated endogenously in the TIMES-GEECO model. However, further costs can apply, such as those for transport and delivery or taxes. As taxes reflect a re-allocation of money and this analysis uses a macro-economic perspective, taxes have been excluded. All transport and distribution costs are assumed to be constant (at their value in the year 2007) over the time horizon of this analysis (i.e. up to 2040).

The costs for transport and distribution of petrol (about 22 ZAR_{2007}/GJ) and diesel (about 19 ZAR_{2007}/GJ) are taken from /DOE 2012a/ and /DOE 2012b/. LPG transport cost to Gauteng can be found in /DOE 2010/. The transport costs of compressed methane gas (CNG/SNG_{coal}) are calculated in terms of the pipeline length involved and cost data from /Mayer-Spohn 2009/ and /DOT 2008a/. Transport costs for SNG from biomass are expected to be higher than for SNG from coal as the expected distance of the plant locations from Gauteng is greater. Distribution costs for LPG and for methane gas are calculated based on /IEA 2010j/ and /IGU 2009/. Total transport and distribution costs add up to about 28 ZAR_{2007}/GJ for CNG and SNG from coal and to about 32 ZAR_{2007}/GJ for SNG from biomass (Table 30). In addition, electricity is required to compress the gas (i.e. 0.03 $GJ_{elec}/GJ_{CNG/SNG}$) /Pölz & Salchenegger 2005/.

Transport and distribution costs for biodiesel and for ethanol transport to Gauteng have been calculated based on the distance of probable production sites, given in /Jewitt et al. 2009/, to a refinery close to Gauteng, where the fuel can be blended. The total costs for transport and distribution amount to about 43 ZAR_{2007}/GJ for ethanol and to about 24 ZAR_{2007}/GJ for biodiesel (Table 30, see also /Tomaschek et al. 2012c/).

Hydrogen supply costs are calculated using the Hydrogen Delivery Scenario Model (HDSAM) of the U.S. Department of Energy /USDOE 2010/, which was also used for other comprehensive studies focusing on hydrogen supply and use (e.g. /Gül 2008/). The calculation is performed based on the distance of the prospective hydrogen production sites to Gauteng (for centralized production). It is assumed that the hydrogen is distributed in compressed form (at 350 bar) in trucks because distribution in that way is cheaper than as liquid /USDOE 2010/ (see also /Gül 2008/). As a result, the transport and distribution of centrally produced hydrogen costs about 295 ZAR_{2007}/GJ /USDOE 2010/. When production is de-centralized only the distribution costs apply, i.e. about 130 ZAR_{2007}/GJ /USDOE 2010/. About 0.13 MJ_{elec}/MJ_{H2} (centralized production) and 0.04 MJ_{elec}/MJ_{H2} (de-centralized production) are needed for compression /USDOE 2010/ (Table 30). Additionally, it is assumed that about 1% of the hydrogen is lost during transport and distribution to Gauteng /USDOE 2010/.

Table 30: Assumed average cost of transport and distribution of fuels to Gauteng.

Fuel	Transport and, distribution costs* [ZAR_{2007}/GJ]	GHG emissions* [g/MJ]	Auxiliary energy requirement [$GJ_{electricity}/GJ_{product}$]
Petrol	22.3	1.1	
Diesel	19.3	1.0	
Biodiesel	23.9	1.0	
Ethanol	42.6	1.7	
LPG	44.4	1.3	
CNG and SNG (coal)	28.3	0.0	0.03
SNG (biomass)	32.3	0.0	0.03
Hydrogen (centralized)	295.3	9.9	0.13
Hydrogen (de-centralized)	130.1	0.0	0.04

* Without costs and emissions for auxiliary energy requirement

Sources: own calculations and assumptions based on /DOE 2010/, /DOE 2012a/, /DOE 2012b/, /DOE 2010/, /Edwards et al. 2011a/, /IEA 2010j/, /Tomaschek et al. 2012c/, /Pölz & Salchenegger 2005/, /USDOE 2010/.

GHG emissions for diesel distribution are taken as 1.0 g/MJ_{diesel} from /Edwards et al. 2011a/ and have been recalculated for the other liquid fuels, based on the volumetric energy density. GHG emissions for hydrogen distribution are calculated using the HDSAM model /USDOE 2010/. GHG emissions for hydrogen transport and distribution are significantly higher than for the other fuels because of its transportation as a gas (Table 30).

5.1.10 Cost and GHG emissions of fuel provision to Gauteng

To compare the economics of the fuel options, the fuel provision costs *C* of each technology *i* are calculated. Fuel provision costs include the annual investment ($ANF \cdot INV_i$) of the technology, specific fixed and variable operating and maintenance costs (FOM_i and VOM_i) as well as annual expenditures on feedstock. Annual feedstock expenditures are calculated based on the feedstock price ($P_{Feedstock}$) and the conversion efficiency η_i of the process. Furthermore, auxiliary energy (*a*) inputs and outputs have to be considered. Equation 12 summarizes total fuel costs of a fuel, where *E* is the auxiliary energy demand or supply per unit of energy generated by the process and *P* is the price of the auxiliary energy carrier. *AFA* represents the annual availability factor and *D* is the transport and distribution costs of the fuel.

$$C_{Fuel,i} = ANF \cdot \frac{INV_i}{AFA} + \frac{FOM_i}{AFA} + VOM_i + \frac{1}{\eta_i} \cdot P_{Feedstock} + \sum_a E_a \cdot P_a + D_{Fuel} \qquad \text{Equation 12}$$

The annuity factor (*ANF*) is defined in Equation 13 for annual payments of an investment, where *n* is the number of years (i.e. the lifetime of a process) and *i* is the interest rate. The interest rate *i* used throughout this thesis is 8%.

$$ANF_{i,n} = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \qquad \text{Equation 13}$$

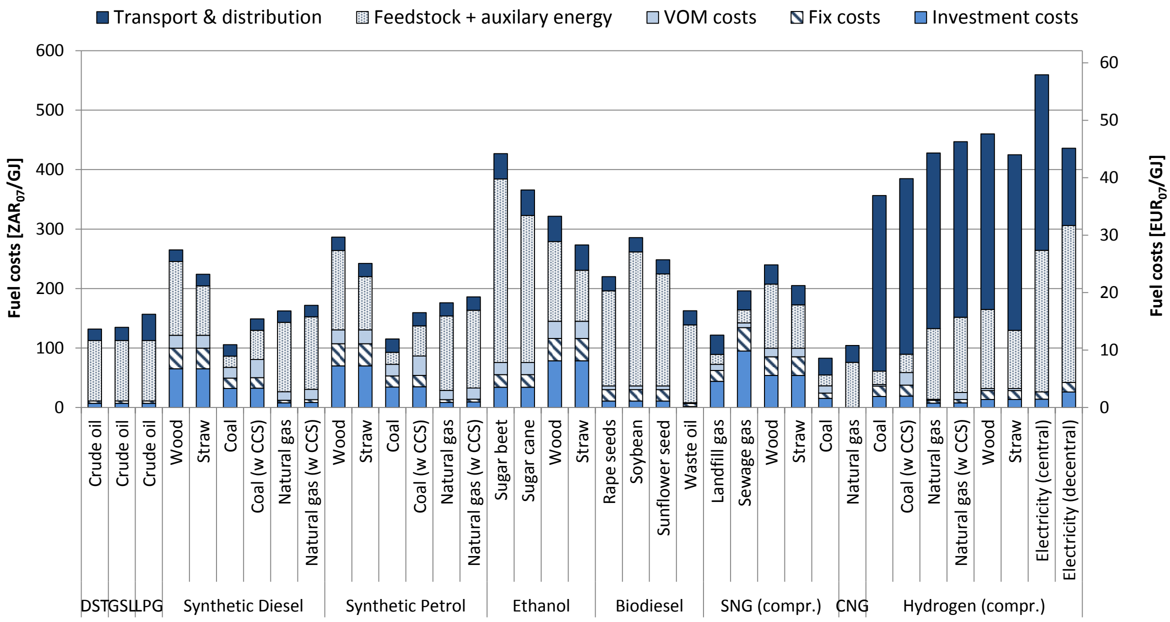
The feedstock prices considered for the calculation can be found in Table 31 and are based on a regression analysis of the price development for primary energy carriers considered in relation to the crude oil price (see section 6.1.3). The figures presented here reflect those of the high energy carrier price scenario (see section 6.1). The electricity price is anticipated to be about 147 ZAR_{2007}/GJ in 2010 and about 207 ZAR_{2007}/GJ in 2040 /Telsnig et al. 2013b/. GHG emissions for electricity are assumed as 291 g CO_2eq/MJ in 2010 and 142 g CO_2eq/MJ in 2040 /Telsnig et al. 2013b/.

Table 31: Assumed feedstock prices (without taxes) and inclusive transport for the years 2010 and 2040 for industrial consumers in Gauteng and South Africa.

	Unit	2010	2040
Crude oil	USD_{10}/bbl	78.1	123.0
	ZAR_{07}/GJ	87.6	139.2
Coal	ZAR_{07}/GJ	9.3	14.5
Natural gas	ZAR_{07}/GJ	71.6	118.5
Electricity	ZAR_{07}/GJ	146.7	207.0
Wood	ZAR_{07}/GJ	51.0	51.4
Straw	ZAR_{07}/GJ	34.2	34.6
Pressed sugar beet slices	ZAR_{07}/kg	1.9	1.8
Pressed oil cake rapeseed	ZAR_{07}/kg	2.2	3.1
Pressed oil cake soy	ZAR_{07}/kg	2.4	3.1
Pressed oil cake sunflower	ZAR_{07}/kg	1.4	2.0
Sugar cane	ZAR_{07}/kg	0.4	0.4
Sugar beet	ZAR_{07}/kg	0.8	0.8
Rapeseeds	ZAR_{07}/kg	3.3	4.5
Sunflower seed	ZAR_{07}/kg	3.2	4.3
Soybean	ZAR_{07}/kg	3.2	4.1
Waste oil	ZAR_{07}/GJ	116.0	154.9

Sources: own calculations and assumptions based on /DOE 2009a/, /Tomaschek et al. 2012c/, /Nolte 2007/, /IEA 2011c/ and /Telsnig et al. 2013b/.

Figure 34 shows the 2010 fuel provision costs calculated for South Africa. Results are shown differentiated for the same cost components as in Equation 12, although in the figure the costs for feedstock and auxiliary energy have been added. As a result, costs for liquid and gaseous fuels are considerably lower if produced from fossil sources than from renewable sources, with the single exception being biodiesel from waste cooking oil. Petrol from crude oil costs about 134.9 ZAR_{2007}/GJ, whereas the cost of crude oil diesel is about 131.9 ZAR_{2007}/GJ. The lowest fuel costs for liquid fuels are for CTL, namely, synthetic diesel at 105.8 ZAR_{2007}/GJ and for synthetic petrol at 115.3 ZAR_{2007}/GJ. The costs of SNG from coal (83.0 ZAR_{2007}/GJ) are lower than of CNG at 104.3 ZAR_{2007}/GJ. Using biomass as feedstock for SNG results in fuel costs between 121.7 ZAR_{2007}/GJ (landfill gas) and 239.8 ZAR_{2007}/GJ (wood). For biofuels from energy crops, the provision of ethanol from sugar cane or sugar beet corresponds to 365.7 ZAR_{2007}/GJ and 426.9 ZAR_{2007}/GJ, respectively. Fuel prices of biodiesel (produced from sunflower seeds, rapeseeds or soybeans) are between 220.1 ZAR_{2007}/GJ and 285.7 ZAR_{2007}/GJ; the cheapest production would be realized with biodiesel from rapeseeds. However, biodiesel from waste cooking oil can be produced significantly more cheaply (162.9 ZAR_{2007}/GJ), due to the low feedstock costs. Costs for second-generation biofuels are expected to be lower than those of first-generation processes, with 297.6 ZAR_{2007}/GJ and 244.5 ZAR_{2007}/GJ for ethanol from lignocellulosic biomass and BTL diesel, respectively, on average for straw and wood. The cost of hydrogen provision in 2010 is between 356.5 ZAR_{2007}/GJ for that from coal and 559.6 ZAR_{2007}/GJ for hydrogen from centralized electrolysis.

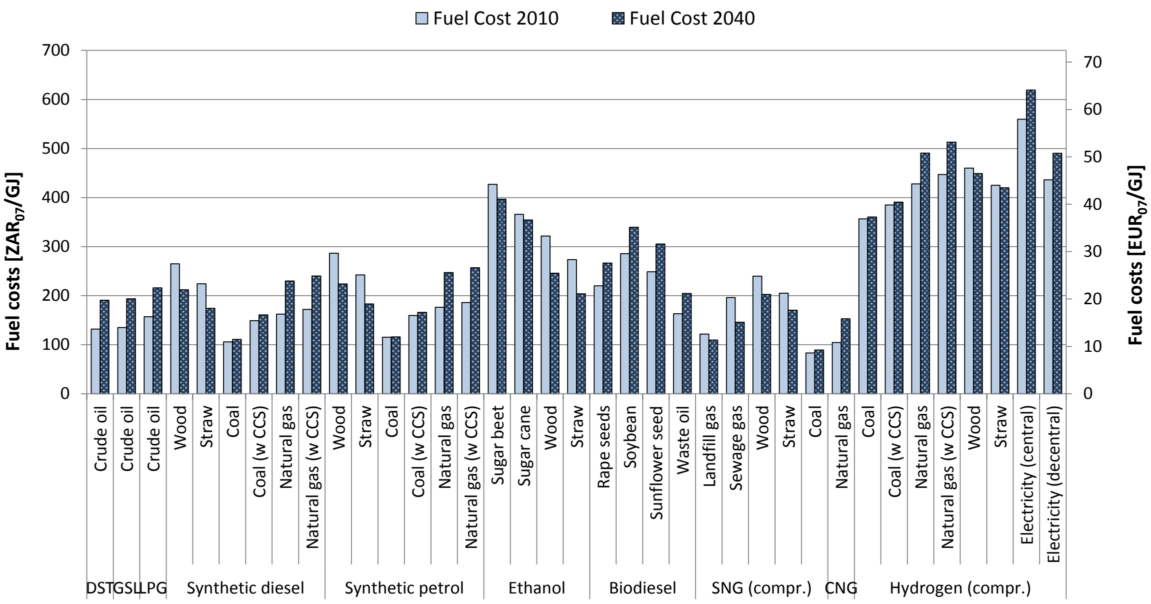


Abbreviations: DST = diesel; GSL = petrol; SNG = substitute natural gas, CNG = compressed natural gas.

Figure 34: Fuel provision costs in South Africa in 2010. Source: own calculations.

By examining fuel cost composition, it is obvious that feedstock prices, including revenues from by-product sales and auxiliary energy, have a significant impact on the costs of providing first-generation biofuels in South Africa, accounting for 68% to 80% of the total fuel costs. The lowest share of feedstock costs corresponds to processes that use coal as feedstock (6–33%) and for SNG from upgraded sewage or landfill gas (11–14%). For hydrogen, distribution costs make a big contribution to the fuel price, most significantly for centrally produced hydrogen. The highest share of plant-related costs (i.e. investment, FOM and VOM costs) are seen for the CTL process, at 54–64%, ethanol from cellulosic biomass (45–53%) and for biogas upgrading from sewage (73%) and landfill gas (60%). In the case of the refinery production of diesel, petrol and LPG from crude oil, the plant-related costs are only about 8%.

Figure 35 compares fuel costs in South Africa in 2040 with those in 2010. Future fuel costs are expected to increase for most energy carriers. A large increase can be seen for petrol and diesel from crude oil at 44% and 45%, respectively, which corresponds to 193.9 ZAR_{2007}/GJ and 190.9 ZAR_{2007}/GJ in 2040. Fuel costs for LPG increase from 157.0 ZAR_{2007}/GJ in 2010 to 216.0 ZAR_{2007}/GJ in 2040. Not surprisingly, fuels using natural gas as feedstock are also expected to increase significantly, as prices for natural gas are assumed to rise from 71.6 ZAR_{2007}/GJ in 2010 to 118.5 ZAR_{2007}/GJ (Table 31). CNG costs are about 153.0 ZAR_{2007}/GJ in 2040 (+47%) and the cost of synthetic fuels from natural gas will increase about 38–42%. Smaller increases can be seen for biodiesel from energy crops, which cost between 266.5 ZAR_{2007}/GJ (FAME from rapeseeds) and 339.7 ZAR_{2007}/GJ (FAME from soybeans) in 2040, i.e. +19–23%. A decrease in fuel costs can be expected for those fuels using wood or straw as feedstock as well as for ethanol from energy crops, and SNG from landfill and sewage gas. Therefore, biofuels from sugar cane or sugar beet would be priced at about 354.5 ZAR_{2007}/GJ and 396.8 ZAR_{2007}/GJ, which corresponds to a reduction of 3–7% in comparison with 2010. Fuel costs for ethanol from cellulosic biomass diminish to about 203.9–245.8 ZAR_{2007}/GJ; the corresponding values for BTL fuels are 174.3–224.1 ZAR_{2007}/GJ. The cost of hydrogen provision from coal or biomass remains almost constant as changes in fuel costs and auxiliary energy costs are nearly compensated for by the changes in efficiency and investment costs anticipated. Hydrogen produced via reformation of natural gas or via electrolysis, on the other hand, is calculated to cost about 11–15% more in 2040 than in 2010 due to the assumed increase in electricity and natural gas prices.



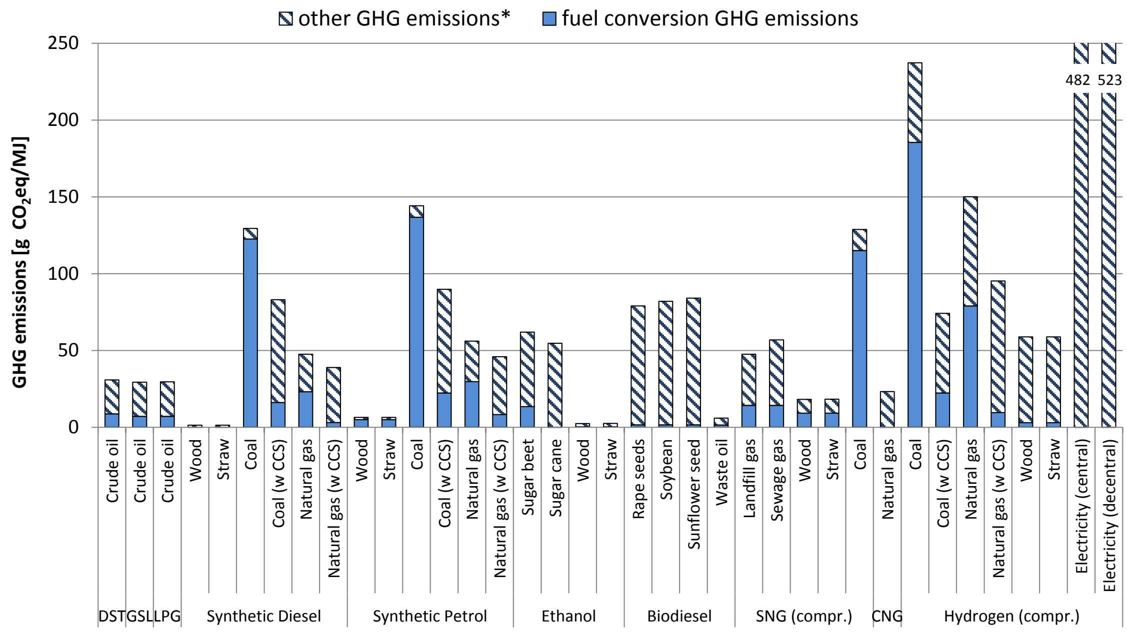
Abbreviations: DST = diesel; GSL = petrol; SNG = substitute natural gas.

Figure 35: Fuel provision costs in South Africa in 2040 compared to 2010.
Source: own calculations.

Figure 36 shows well-to-tank (WTT) GHG emissions in 2010 for the fuel options considered for Gauteng. They differentiate between emissions from the fuel conversion process and other GHG emissions, which include auxiliary energy consumption, crop cultivation, transport and distribution as in in Equation 14. There $EF_{Fuel,i}$ is the WTT emission factor for fuels produced via technology i; E_a corresponds to the consumption of auxiliary energy, for which the emission factors of energy use ($EF_{a,con}$) and energy provision ($EF_{a,prov}$) have been accounted for; η_i is the conversion efficiency of process i, EF_{Prim} is the emission factor for primary energy provision and EF_{Dist} the emission factor of fuel distribution. No credit has been given for the provision of auxiliary electricity.

$$EF_{Fuel,i} = EF_{conv} + \sum_a E_a \cdot (EF_{a,con} + EF_{a,prov}) + \frac{1}{\eta_i} \cdot EF_{Prim} + EF_{Dist} \qquad \text{Equation 14}$$

The highest WTT emissions are associated with hydrogen production via electrolysis, which accounts for about 482–523 g CO_2eq/MJ. Furthermore, hydrogen production using coal or natural gas and CTL fuels using coal are associated with high GHG emissions of about 130–237 g CO_2eq/MJ if produced without CCS. Compared to crude diesel (30.9 g CO_2eq/MJ) and petrol (29.4 g CO_2eq/MJ), WTT emissions for CTL fuels are about four to five times higher, and for hydrogen from electrolysis more than 15 times greater. Of course, the results for WTT emissions for current (2010) hydrogen production via electrolysis in South Africa are based on the high GHG emissions of coal-based electricity production. WTT GHG emissions for coal gasification and methanation are, at 129 g CO_2eq/MJ, only slightly lower. Biofuels from energy crops indicate WTT emissions of 54.7–61.9 g CO_2eq/MJ for ethanol and 79.0–84.1 g CO_2eq/MJ for biodiesel. Furthermore, most of the WTT emissions of biofuels can be attributed to crop cultivation and auxiliary energy input. It can also be seen that CCS can cause considerable indirect emissions if the auxiliary electricity is acquired from coal-fired sources (e.g. about 81% of the total WTT emissions of 83.1 g CO_2eq/MJ for CTL diesel with CCS). Second-generation biofuels from wood and straw, as well as biodiesel from waste oil, show only small WTT emissions.

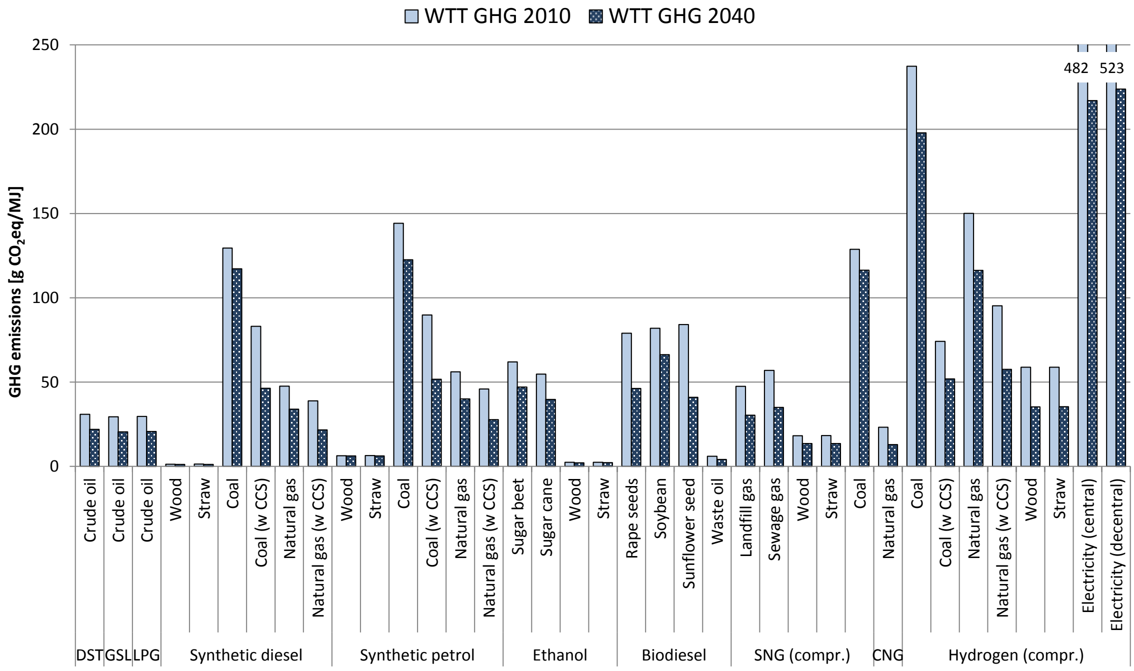


*other GHG emissions comprise crop cultivation, feedstock production and transport, auxiliary energy consumption and fuel distribution
Abbreviations: DST = diesel; GSL = petrol; SNG = substitute natural gas.

Figure 36: Well-to-tank (WTT) greenhouse gas emissions in 2010 for fuels considered. Source: own calculations.

All fuels will generate reduced WTT GHG emissions in 2040 compared with 2010 (Figure 37). The highest absolute reductions are found for those processes which are dependent on electricity, such as hydrogen electrolysis and the application of CCS for CTL due to the assumed reduction in GHG emissions for electricity production (i.e.

291 g CO_2eq/MJ in 2010 according to /Telsnig et al. 2013b/). For CTL with CCS the reduction between 2010 and 2040 is about 37–38 g CO_2eq/MJ (about 42–44%) for synthetic diesel and petrol, respectively. GHG emissions for first-generation biofuels are calculated to decrease between 19% (soybean) and 51% (sunflower seeds) in the same period. In comparison, WTT GHG emissions of fossil fuels from crude oil decrease by 29–30%, to 22.0 g CO_2eq/MJ and 20.5 g CO_2eq/MJ for diesel and petrol, respectively. Smaller reductions can be expected for compressed SNG, with SNG from coal at 116.5 g CO_2eq/MJ in 2040 (–10%), SNG from straw or wood at 13.6 g CO_2eq/MJ in 2040 (–25%), and SNG from organic waste at 30.5–35.0 g CO_2eq/MJ in 2040 (–36% to –38%). In comparison, CNG accounts for WTT GHG emissions of 13.0 g CO_2eq/MJ (–44%) in 2040. As in 2010, the lowest WTT GHG emissions are found for second-generation biofuels as well as for biodiesel from waste cooking oil.



Abbreviations: DST = diesel; GSL = petrol; SNG = substitute natural gas.

Figure 37: Well-to-tank (WTT) greenhouse gas emissions in 2040 compared to 2010. Source: own calculations.

For a concluding comparison of the different fuel options, the tank-to-wheel (TTW) emissions also have to be considered as well as the cost of running vehicles on those fuels. Section 5.2 discusses those alternative powertrain technologies when applied to Gauteng. The chapter concludes with an integration of WTT and TTW emissions as well as mitigation potential and cost (section 5.3).

5.2 Techno-economic analysis of vehicle powertrains

In this section, current and alternative powertrains for the transport sector in Gauteng are analysed. As in the previous section, the description of the present state of each technology and the plausible future development are based on an extensive review of the literature. To do so, each vehicle is considered in terms of its main cost components. For consistency with the analysis of energy supply options for transport fuels, cost data from different studies are converted to South African rand (ZAR) and normalized to the base year of 2007, according to Appendix A, which indicates the corresponding exchange rates and consumer price indices (CPI). This section concludes with a comparison of total vehicle costs for the different technologies in 2010 and in 2040. Furthermore, the tank-to-wheel (TTW) emissions are calculated and put into perspective (section 5.2.7).

5.2.1 Internal combustion engines (ICEs)

Internal combustion engines (ICEs) are the common technology for motorized transport, which can be explained by the long period of cheap and widely available fossil fuels. These are comparatively easy to handle and to store and make the operation of vehicles running with ICEs more flexible than other technologies /Heywood et al. 2003/.

Mostly applied combustion engines concepts used for vehicles are spark-ignition (SI) engines, which usually run on petrol as fuel; and diesel engines, which ignite the fuel through compression heat (CI: compression-ignition). Diesel engines have a higher fuel efficiency than petrol engines due to their higher compression ratio and are more reliable than petrol engines /Heywood et al. 2003/. For that reason, they are mostly used for larger vehicles, such as trucks and buses. On the other hand, smaller vehicles (including passenger cars) are often powered by petrol SI engines because these engines are cheaper and run more quietly /Heywood et al. 2003/. The cost of a diesel ICE is about 50–80% greater than that of a petrol SI-engine (including transmission and engine improvements) /Edwards et al. 2011b/.

As ICEs benefit from a long history, they are constantly being improved to increase engine efficiency and fuel consumption. Promising measures for further efficiency improvement include downsizing, for example, which means that the engine capacity is reduced while maintaining the torque and power, or turbochargers, which generate higher loads during operation and improve the air/fuel mixture in the engine /IEA 2010d/, /IEA 2010f/, /WEC 2007/. Additionally, better pumping efficiency and increased mechanical efficiency are usually included in downsizing and turbocharging measures. The potential for improvement for these measures goes hand in hand with an increase in fuel efficiency of about 3–12% /IEA 2010d/, /IEA 2010f/, /McKinsey 2009/. Furthermore, additional measures can be used to reduce specific fuel consumption. These include employing a higher share of aluminium or composite materials, aerodynamic measures, and tyres with reduced rolling friction. These measures can result in a 5–10% reduction in specific fuel consumption at a small increase in cost /Edwards et al. 2011b/, /Rueger 2009/, /IEA 2010d/, /IEA 2010f/, /McKinsey 2009/. Further potential is seen in homogeneous charge compression ignition (HCCI) technologies, which are a new design of the ICE and combine the advantages of SI and CI engines /WEC 2007/. In HCCI engines, the fuel and air are pre-mixed to a homogeneous mixture (as in SI engines) and the fuel is ignited by compression (like in CI engines) while the ignition occurs throughout the entire volume of the fuel-air mixture, which leads to cleaner combustion. Reductions in specific fuel consumption reductions forecast for these measures are in the order of about 10–20% compared to diesel or petrol engines /Edwards et al. 2011b/, /Rueger 2009/, /IEA 2010d/, /IEA 2010f/, /WEC 2007/.

On the other hand, improvements in efficiency will be partly compensated for because of higher emission standards and necessary after-treatment technologies as well as a trend to heavier vehicles /Heywood et al. 2003/, /Rueger 2009/. Studies vary in forecasting the total potential in fuel efficiency increase and different base year and time horizons make it complicated to compare the forecasts. Figure 38 shows various forecasts of future ICE performance from the literature. The studies summarized in the figure forecast a performance improvement of about 36% and 21% for new petrol and diesel ICE passenger cars, respectively. The calculated specific energy consumption of new vehicles in Gauteng is 3.2 MJ/km in 2010 and 2.0 MJ/km in 2040 for the case of a petrol-driven passenger car; and 2.3 MJ/km in 2010 and 1.8 MJ/km in 2040 for the case of a diesel-driven passenger car (calculation based on /TÜV 2012a/, see also sections 3.3 and 3.4). Both expected developments of the specific energy consumption are within the calculated performance ranges.

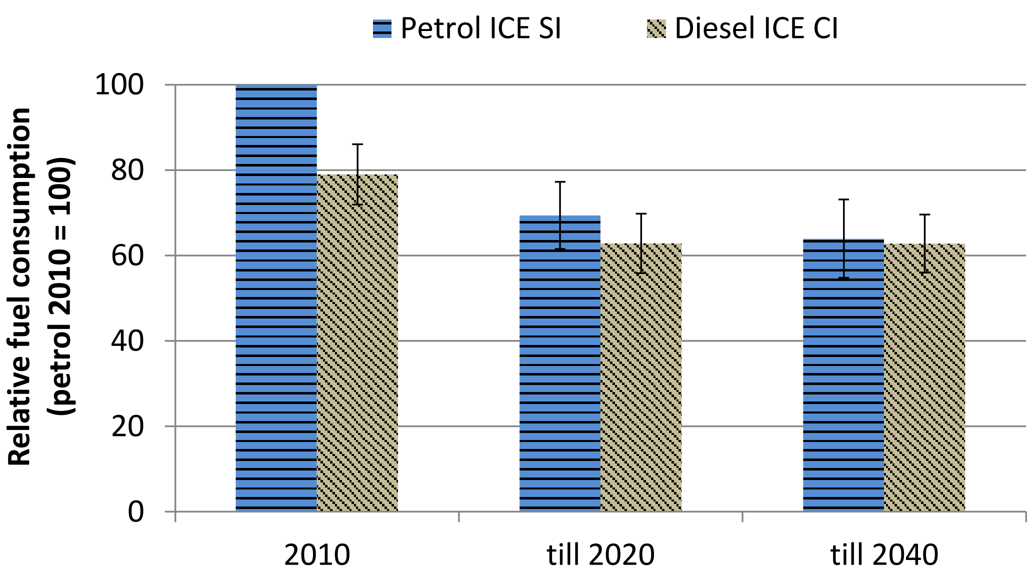


Figure 38: Performance ranges of new ICE passenger cars for various forecast years. (ICE petrol 2010 = 100). Error bars show standard deviation.
Sources: own calculations based on /Sperling & Cannon 2009/, /Bandivadekar et al. 2008b/, /Bandivadekar et al. 2008a/, /Bodek & Heywood 2008/, /Fulton & Eads 2004/, /Schaefer et al. 2006/, /Heywood et al. 2003/, /Özdemir 2012/, /Bruchof 2013/, /McKinsey 2009/.

Costs for petrol ICE SI engines were taken as 287 ZAR_{2007}/kW in 2010 /Edwards et al. 2011b/. It is expected that by 2040 ICE engines will be equipped with turbocharging, improved transmission, start-stop technology (i.e. mild hybrid, see section 5.2.5) and further emission treatment, which increases ICE SI costs from 287 ZAR_{2007}/kW in 2010 to 406 ZAR_{2007}/kW in 2040, according to /Edwards et al. 2011b/, /Özdemir 2012/, /Bruchof 2013/. For CI engines those figures are assumed as 507 ZAR_{2007}/kW in 2010 and 613 ZAR_{2007}/kW in 2040, respectively, based on /Edwards et al. 2011b/, /Özdemir 2012/, /Bruchof 2013/.

5.2.2 Modified ICE for biofuel usage

Pure vegetable oils can only be used in adapted diesel engines that can handle their high density and viscosity and the different ignitability compared to fossil diesel. For that reason vegetable oils are not commonly used directly as fuel but upgraded to biodiesel via transesterification /Rutz & Janssen 2007/.

CI engines can be operated with biodiesel, and ethanol can be used to replace petrol in SI engines when mixed in relatively low proportions (< 5–15$\%_{vol}$ mixture) without the need to modify the piping and injection system /ADAC 2011a/, /Widmann et al. 2009/, /IEA 2010g/. For higher blending shares or for the direct use of biodiesel or ethanol, adaptions are needed, e.g. in the engine or its piping and modifications to the injection system /Widmann et al. 2009/, /ADAC 2011b/. Flexible-fuel vehicles, which can run on high blending shares of ethanol (E85) as well as on traditional petrol are an option to use with high ethanol content in the fuel mix /IEA 2010g/.

Although the calorific value of ethanol is lower than that of petrol (about 40% lower, based on LHV MJ/litre), the heating value of the air/fuel mixture is comparable due to the lower requirements of air in the combustion process /Senn et al. 2009/. The overall efficiency of an SI engine increases up to 10% (in terms of MJ/km) if run on ethanol compared to petrol /IEA 2010g/. However, specific fuel consumption is not expected to change if the fuel is blended in small proportions for non-modified vehicles /Özdemir 2012/. Biodiesel vehicles, on the other hand, have about the same efficiency as diesel vehicles in terms of MJ/km /Krüger 2002/.

The additional costs for dedicated biodiesel vehicles (B100) are taken as 4,830 ZAR_{2007}/vehicle (500 EUR_{2007}/vehicle) for small vehicles, and as 18,836 ZAR_{2007}/vehicle (1,950 EUR_{2007}/vehicle) for heavy vehicles in the year 2010, based on /Özdemir 2012/ and /Krüger 2002/. In 2040, these additional costs are expected to decrease to 2,415 ZAR_{2007}/vehicle (250 EUR_{2007}/vehicle) for light vehicles and 7,245 ZAR_{2007}/vehicle (750 EUR_{2007}/vehicle) for heavy vehicles. This reduction is based on the assumption that future biofuel vehicles will be available on the market directly from the manufacturer /Özdemir 2012/, /Krüger 2002/. Extra costs for dedicated vehicles running on ethanol (E85) are taken as 7,728 ZAR_{2007}/vehicle (800 EUR_{2007}/vehicle) in

2010; these are expected to decrease to 2,898 ZAR_{2007}/vehicle (300 EUR_{2007}/vehicle) in 2040, due also to the assumption that more dedicated biofuel vehicles will be available on the market /IEA 2010g/. For modelling the energy system (see chapter 6), it is assumed that modified ICE were available from 2010.

5.2.3 Gas SI engines

This section discusses SI engines that run on LPG, CNG or hydrogen. SI IC engines that run on gas have an approximately 10% higher efficiency than ICEs using petrol as fuel /Özdemir 2012/, /Verhelst & Wallner 2009/.

In LPG-fuelled vehicles a cylinder made of steel or composite is used to store the gas at about 10 bars /IEA 2010j/. LPG as a transport fuel is mainly used for smaller vehicles and most of the LPG vehicles on the market today are refits of conventional petrol vehicles /IEA 2010j/. To allow a range comparable to conventional petrol vehicles, the storage tank is bigger because of the lower volumetric energy content of LPG. The fuel gas is usually injected as a liquid into the combustion chamber can but can also be evaporated before ignition /IEA 2010j/.

In vehicles powered by methane gas, the gas is usually stored in compressed form at 200–270 bars (CNG) /IEA 2010j/. Vehicles powered purely by gas, and bi-fuelled vehicles that run on methane and on gasoline, are available on the market, where bi-fuelled vehicles are more common /IEA 2010j/.

Hydrogen can be used in SI combustion engines, too, with only minor changes necessary /IEA 2005/. However, vehicles using hydrogen gas engines are still under development and only a limited number of them have been produced for demonstration purposes /Verhelst & Wallner 2009/. To store hydrogen for a vehicle, different concepts are possible (e.g. compressed or liquid storage, in a solid material or on-board hydrogen generation), which are discussed in section 5.2.6.

Vehicles running on natural gas or LPG gas benefit from a lower carbon content per MJ of fuel (i.e. in South Africa about 61 g CO_2/MJ_{LPG} and about 58 g $CO_2/MJ_{natural\ gas}$ compared to about 74 g CO_2/MJ_{diesel} /TÜV 2012a/), and the combustion of hydrogen results in zero CO_2 emissions /IEA 2005/, /Verhelst & Wallner 2009/. LPG offers the advantage of easier transportation (it liquefies at low pressure), and higher energy density, compared with CNG. However, it is based on crude oil whereas methane gas can be produced from biomass. Natural gas and hydrogen, furthermore, offer the advantages of lower particulate, CO and nitrogen oxide (NO_x) emissions than petrol or diesel-powered engines. LPG-fuelled engines still have a smaller advantage in terms of non-GHG emissions than diesel ICEs /Bräuninger et al. 2008/, /Engerer & Horn 2008/, /Engerer & Horn 2010/, /IEA 2005/, /Verhelst & Wallner 2009/.

The additional costs of refitting a light gasoline vehicle to bi-fuel CNG or LPG are calculated based on the storage capacity (i.e. fuel tank) as 157 ZAR_{2007}/kWh for CNG and

107 ZAR_{2007}/kWh in 2010. In 2040 these costs are assumed to fall to 138 ZAR_{2007}/kWh and 86 ZAR_{2007}/kWh for CNG and LPG, respectively /IEA 2010a/, /Deininger 2011/, /Engerer & Horn 2008/, /Blesl et al. 2005/, /IEA 2010j/, /SWD 2011/, /Edwards et al. 2011b/, /SWD 2011/, /Wiedemann 2008/, /Lienin 2009/. As emission treatment is easier for hydrogen ICE engines, the costs of a SI ICE running on H_2 are calculated as 369 ZAR_{2007}/kW in 2040 according to /Edwards et al. 2011b/, /Özdemir 2012/, /Bruchof 2013/. Compressed hydrogen storage is considered as 212 ZAR_{2007}/kWh and 199 ZAR_{2007}/kWh in 2010 and 2040, respectively, based on /Blesl et al. 2009/ and /Edwards et al. 2011b/.

For modelling the energy system (see chapter 6), it is assumed that gas SI engines were available from 2007 for LPG and CNG. Hydrogen-using ICE SI vehicles are assumed to be available from 2015.

5.2.4 Battery electric vehicles and grid-connected systems

Vehicles with electric motors (EM) are seen as a possibility to increase transport energy efficiency and to reduce GHG emissions, although the concept is not new /Nischler et al. 2011/, /Smole 2009/, /Brown et al. 2010/, /Maerz et al. 2005/. Besides electric vehicles that use a battery for energy storage, this section also refers to grid-connected systems.

Arguments supporting electrical mobility include reduced local emissions (depending on the degree of electrification, down to zero for pure electric vehicles), high acceleration and quieter operation. Electric motors have, in comparison with IC engines, the advantage of high initial torque, high energy efficiency and the possibility of overloading them for a short period /Horst 2009/. If used in reverse mode, they perform as generators and can recharge the electrical storage unit. The advantages of electric motors in terms of high-energy efficiency are most evident in a stop-and-go environment like a bus service or in the urban rush hour /Horst 2009/.

Additionally, electrical vehicles are being considered to help optimize the load of existing power plants by being charged at night using an intelligent load system /Horst 2009/. However, the management of the load system is seen as a crucial aspect by some authors as mismanagement can even increase the load /Özdemir & Hartmann 2012/. Important for the success of electric vehicles is the development of an energy storage technology, which is competitive with conventional ICEs in terms of capacity, allows for fast recharge with low energy losses, and guarantees long lifetime even when subject to many loading cycles /Blesl et al. 2009/, /Horst et al. 2009/, /Krüger 2002/.

Battery electric vehicles

Battery electric vehicles (BEV) are purely electrically-powered vehicles, which are not equipped with an ICE and use a battery for energy storage. Different battery technologies exist or are being discussed for those vehicles. Lead acid batteries, which are usually used as starter batteries in conventional ICE vehicles, were used in early battery electric vehicles and studies. However, due to their low specific energy storage capacity and long recharge time, they are no longer the focus of battery research /Blesl et al. 2009/, /Stan 2005/. Today, the battery electric vehicles available are run mainly on Ni-MH batteries and lithium-ion (Li-ion) batteries /Duleep 2009/. In comparison with Ni-MH batteries, Li-ion batteries offer almost double the gravimetric (Wh/kg) and volumetric (Wh/litre) density. Additionally, Li-ion batteries do not suffer the so-called “memory effect”, which reduces the storage capacity in conventional batteries with each loading cycle /Blesl et al. 2009/, /Duleep 2009/, /IEA 2010i/. However, the batteries are sensitive to fast and to deep discharge as well as to mechanical damage, which can result in catching fire or explosion. Lithium-polymer (Li-Po) batteries are considered as a further improvement, as they are comparably robust and have an even higher specific storage capacity /Stan 2005/, /Blesl et al. 2009/, /Duleep 2009/. Additionally, different charging technologies for battery electric vehicles have been proposed, ranging from local recharging using an electrical connection at home or work, fuel stations – which have to be constructed – to allow more flexible recharging options, or replacing the whole battery or electrolyte for quick recharging, which requires new infrastructure /WEC 2007/.

To cope with battery degeneration due to battery age and the load-cycles performed, vehicle manufacturers make the battery larger than that required for the driving range over the vehicle’s lifetime /Özdemir & Hartmann 2012/. Moreover, it is forecasted that significant improvement will be achieved (especially in the field of Li-ion batteries) in the relatively near (about 10 years) future /Duleep 2009/. However, the lifetime of a battery is limited. In this study a battery lifetime is assumed to be 250,000 vkm, based on /Lave & MacLean 2002/ and /Özdemir 2012/, which is an optimistic assumption in comparison to e.g. /Özdemir & Hartmann 2012/. However, as a consequence, only the passenger cars and SUVs considered can be operated on a battery pack without replacement as the battery lifetime does not exceed the lifetime of those vehicles (i.e. about 230,000 vkm, see chapter 3). Other vehicles require battery replacement, up to twice for an HDV. Battery replacement costs have been considered in the cost calculation.

Specific battery costs are anticipated to decrease from about 7,656 ZAR_{2007}/kWh in 2007 (800 EUR_{2007}/kWh) to 2871 ZAR_{2007}/kWh (300 EUR_{2007}/kWh) in 2040; these costs include those for the oversizing needed to compensate for battery ageing, based on /Schädlich 2011/, /Özdemir & Hartmann 2012/, /Özdemir 2012/, /IEA 2010h/ and /Blesl et al. 2009/. Costs for converters and controllers are taken from /Özdemir & Hartmann 2012/.

For modelling the energy system (see chapter 6), it is assumed that battery electric vehicles are available from 2012. Furthermore, due to the uncertainty about further battery costs, different battery costs have been calculated for various scenarios (see section 6.6).

Grid-connected systems – Trolley buses

Trolley buses have been successfully introduced in cities all over the world, for example, in Solingen (Germany), Salzburg (Austria), Landskrona (Sweden), San Francisco (USA), Minsk (Belarus) and Moscow (Russia) /Murray 2001/. Trolley buses can have the same chassis as a conventional (diesel) bus or electrically powered bus. Like other electric vehicles, they have the advantages of no local emissions from combustion and are much quieter. Unlike battery electric vehicles, trolley buses acquire their energy (electricity) not from internal storage (at least not as the main source) but via electric supply structures mounted on the roof. A catenary is used to connect the vehicles to the grid during operation. In contrast to light rail systems, trolley buses do not need separate tracks or railway lines, which clearly reduces investment costs /Schuchmann 2009/, /Schuchmann 2007/, /Kühne 2010/. Modern trolley buses can return braking energy to the grid, which may reduce energy consumption by an additional 10% /Schuchmann 2009/. Proposed future systems can be equipped with supercapacitors, which makes it unnecessary to erect wires along the whole track, but to store energy only at the stops /Kühne 2010/.

As trolley buses are produced in only relative small numbers and require some modification, their investment costs are higher than those of conventional diesel buses. Furthermore, there are additional costs for infrastructure (e.g. poles, the catenary system, electric power substations). The costs for 1 km of catenary system (including poles, separators, crossings, etc.) are considered to be 8.5 million ZAR_{2007}/km in 2010 and are assumed to be about 6.2 million ZAR_{2007}/km in 2040. The additional equipment needed (e.g. substations) is about 4.1 million ZAR_{2007} per system, which is expected to decrease by 270,000 ZAR_{2007} in 2040 based on /Kühne 2011/, /Mackinger 2004/, /Mackinger 2007/, /Steiner 2008/, /Stadt St. Gallen 2007/, /Schuchmann 2007/, /Schuchmann 2009/. For modelling the energy system (see chapter 6), it is assumed that existing and new BRT infrastructure can be converted to trolley bus lines after 2012.

5.2.5 ICE-hybrid electric vehicles

Hybrid-electric vehicles combine the advantages of both technologies: electric motors and internal combustion engines. Hybrid vehicles include two powertrains, e.g. a conventional engine and also an electric engine, and two energy storage systems (e.g. battery and fuel tank). The advantages of such systems are that they benefit from the high efficiency of electric engines while using a (smaller) conventional ICE, which allows long driving distance and flexibility. In commercially available vehicles, the non-electric part usually consists of an IC engine (petrol or diesel) but it could also be represented by other technologies like fuel cells or CNG /Edwards et al. 2011b/, /IEA 2010h/. The electrical part consists of one or more electric motors. The engines can be arranged in different powertrain architectures. In a serial configuration, there is no mechanical connection of the IC engine with the powertrain. In a parallel architecture, both the ICE and EM are connected to the propulsion unit, working either independently or simultaneously. Furthermore, there are mixed configurations, involving a power-split to use the torque of the IC engine to propel wheels and run the generator /Heywood et al. 2003/, /Blesl et al. 2009/, /IEA 2010h/.

Depending on the degree of electric motorization, several forms can be differentiated. They are commonly distinguished between micro, mild, full hybrid and plug-in hybrid electric vehicles (PHEV), although different studies use different definitions of a hybrid /WBCSD 2004/, /Horst et al. 2009/, /Blesl et al. 2009/, /IEA 2010h/. In the smallest hybridization form, a *micro hybrid*, the electric engine does not support the powertrain. It is a start-stop system in which the IC engine is switched off during de-acceleration and at zero load times (e.g. at traffic lights) and is restarted immediately and not noticeably by the driver. The additional costs of this technology are relatively low (about 2000 ZAR_{2007}/vehicle /Edwards et al. 2011b/). With a micro hybrid system, it is possible to reduce fuel consumption by up to 10% in urban traffic situations. On average a 6% efficiency gain is achieved /Blesl et al. 2009/, /IEA 2010h/. However, since the electric motor is not used for propulsion it is not considered to be a hybrid vehicle in all studies /WBCSD 2004/, /Horst et al. 2009/, /Duleep 2009/, /Blesl et al. 2009/, /IEA 2010h/.

Mild hybrid vehicles are also not capable of pure electric driving. However, the electric motor is used to support the conventional engine during peak load with additional torque. The power of the electrical unit has therefore to be higher (about 10–15 kW compared with 3–4 kW for the micro hybrid system) /Blesl et al. 2009/. Mild hybrids, like all hybrid concepts, also include the start-stop system and return of braking energy to increase the fuel efficiency. Mild hybrid systems can result in a decrease in fuel consumption of about 10–20% compared to the non-hybrid, depending on the driving cycle /Bruchof 2013/, /Özdemir 2012/, /IEA 2010h/, /Blesl et al. 2009/.

In a *full hybrid* vehicle the electric motor and battery are bigger and it is, therefore, possible to drive the vehicle totally electrically in a low- to mid-speed operation for a short distance of 2–5 km /Blesl et al. 2009/. In addition, the battery capacity has to be enlarged in comparison with mild hybrid systems, which increases the costs of the vehicle. The bigger electrical motor allows further downsizing of the conventional engine. Depending on the driving cycle, a full hybrid systems can result in more than a 20% increase in fuel efficiency /Bruchof 2013/, /Özdemir 2012/, /IEA 2010h/, /Duleep 2009/.

All the hybrid vehicles described (micro, mild, full) have in common that they generate their electricity by recovering braking energy or excess energy from the combustion engine. In addition, *plug-in hybrid vehicles (PHEV)* are capable of recharging their batteries directly from the grid. Additionally, modifications of this concept have been developed in which the IC engine is used as a range-extender, by its recharging the batteries. A plug-in hybrid electric vehicle is defined as being able to drive at least 10 miles (i.e. 16.1 kilometres) in a purely electrical operation /IEEE 2007/. Commercially available plug-in hybrid electric vehicles – like the Chevrolet Volt or the Toyota Prius –

are able to drive about 20–55 km without the backup of a combustion engine /Chevrolet 2011/, /Toyota 2012/. The achievable reduction in fuel consumption in comparison to an ICE vehicle depends on the share of electric driving and battery electric charge /Blesl et al. 2009/. ICEs for plug-in hybrid electric vehicles are considered to be 10% cheaper due to the gearing /Blesl et al. 2009/.

Most of the technological measures for IC engines to increase fuel efficiency are also applicable to hybrid vehicles /IEA 2007b/, /Blesl et al. 2009/, /Duleep 2009/. It is, therefore, reasonable that the fuel efficiency trajectory of hybrid vehicles will be comparable to that of ICE vehicles in the long term /Oba et al. 2004/. Additionally, hybrid vehicles are expected to benefit from technological progress of the electrical components such as reduced internal resistance of batteries /IEA 2007b/, /Blesl et al. 2009/, /Duleep 2009/. However, the decrease in fuel consumption depends on the degree of electrification and driving cycle /IEA 2007b/, /Blesl et al. 2009/, /Duleep 2009/. Figure 39 shows the trajectories for the expected future fuel consumption of hybrid vehicles compared to petrol engines for the base year of 2010. The figure does not distinguish between mild and full hybrid motorization.

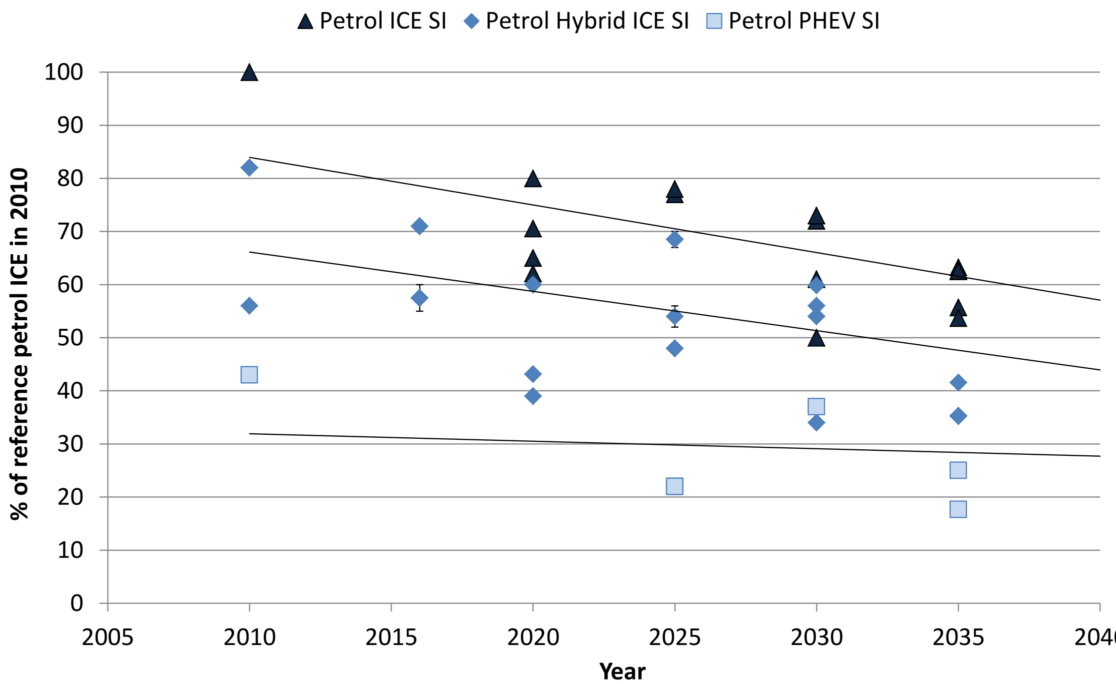


Figure 39: Projected efficiency of hybrid electric vehicles relative to the current performance of petrol-fuelled ICEs.
Sources: own calculations based on /Sperling & Cannon 2009/, /Bandivadekar et al. 2008b/, /Bandivadekar et al. 2008a/, /Bodek & Heywood 2008/, /Fulton & Eads 2004/, /Schaefer et al. 2006/, /Heywood et al. 2003/, /Özdemir 2012/, /Bruchof 2013/, /McKinsey 2009/.

The costs of electric motors (i.e. 177 ZAR_{2007}/kW in 2010; 115 ZAR_{2007}/kW in 2040) and of conventional fuel tanks (1196 ZAR_{2007}/unit) were taken from /Blesl et al. 2009/. Battery costs are defined as for fully electric vehicles (see section 5.2.4, i.e. about

7,656 ZAR_{2007}/kWh (800 EUR_{2007}/kWh) in 2007 and about 2871 ZAR_{2007}/kWh (300 EUR_{2007}/kWh) in 2040). For modelling the energy system (see chapter 6), it is assumed that mild and full ICE-hybrid electric vehicles are available from 2007 for passenger cars. For LDVs, SUVs and buses availability is assumed for 2010. Mild and full ICE-hybrid electric HDVs are expected to be available after 2012. Plug-in hybrid electric vehicles are assumed to be available after 2012 for passenger cars. For other modes, availability is considered for 2015.

5.2.6 Fuel cell hybrid electric vehicles

Fuel cells (FC) directly convert the chemical energy content of an energy carrier into electricity and, therefore, have a higher energy efficiency than combustion engines (i.e. about 50–70% less specific energy consumption than an ICE) /Bruchof 2013/, /Özdemir 2012/, /Blesl et al. 2009/, /Verhelst & Wallner 2009/. Fuel cells can be operated with different feedstock including hydrogen, natural gas and methanol and different oxidants (mostly air, but also oxygen, chlorine or chlorine dioxide) /Blesl et al. 2009/, /IEA 2005/. One can differentiate between low, middle and high temperature fuel cells /Blesl et al. 2009/, /IEA 2005/. Most of those proposed for vehicle use are proton membrane fuel cells (PEMFC), which combine flexible operating patterns with low operating temperature and high specific energy storage capacity /Stan 2005/, /IEA 2005/.

However, a disadvantage of hydrogen is its low specific energy content (volumetric), which causes major efforts for storage. In fuel cell vehicles, hydrogen is stored in either compressed form (currently at about 350 bar and up to 700 bar at an early development stage) or in liquid form at about –253°C /IEA 2005/. Alternatively, the hydrogen can be absorbed in a solid medium for storage, which is currently in a developmental stage /Krüger 2002/, /WEC 2007/, /Blesl et al. 2009/. Furthermore, it also possible to derive the hydrogen through reformation of natural gas (see section 5.1.3) on-board the vehicle /Edwards et al. 2011b/. In this thesis, only compressed hydrogen storage is considered. As with electric vehicles, the GHG reduction potential of hydrogen-propelled vehicles depends on how the fuel is produced.

The cost of compressed hydrogen storage is considered to be 212 ZAR_{2007}/kWh and 199 ZAR_{2007}/kWh in 2010 and 2040, respectively, as for hydrogen ICE SI vehicles (see section 5.2.3). Fuel cells costs are defined as 3,541 ZAR_{2007}/kW (2010) and 478 ZAR_{2007}/kW (2040) based on /Blesl et al. 2009/. For the energy system modelling (see chapter 6), it is assumed that fuel cell hybrid electric vehicles are available from 2015.

5.2.7 Overview of investment costs, fuel efficiency and tank-to-wheel GHG emissions for passenger cars

Vehicle costs have been calculated based on the specific costs of vehicle components given in section 5.2, which are summarized in Table 32 for the years 2010 and 2040 for the example of a passenger car. The reference vehicle for a passenger car is assumed to be a VW Golf 1.4 litres (63 kW). Furthermore, a minimum driving range of 200 km has been considered for passenger cars to calculate the capacity of energy storage systems (e.g. batteries or fuel tanks). The fuel efficiency and emission factors are according to /TÜV 2012a/ and are shown averaged over road distribution and aggregated for emission standards. The range of plug-in hybrid electric vehicles is taken as 65 km for passenger cars, based on /Özdemir & Hartmann 2012/, /Özdemir 2012/, /Bruchof 2013/ and /Blesl et al. 2009/. Total battery costs of electric vehicles include battery replacement costs and have been calculated as expressed in section 5.2.4. A detailed overview of all calculated vehicle costs is given in Appendix B.

Table 32: Specific costs for the considered vehicle components for 2010 and 2040.

Concept	Unit	2010	2040
ICE–SI*	EUR_{07}/kW	30.0	42.5
	ZAR_{07}/kW	287	406
ICE–CI*	EUR_{07}/kW	53.0	64.1
	ZAR_{07}/kW	507	613
Electric engine	EUR_{07}/kW	18.5	12.0
	ZAR_{07}/kW	177	115
Fuel tank (conventional)	EUR_{07}	125	125
	ZAR_{07}	1,196	1,196
Fuel tank (CNG)	EUR_{07}/kWh	16.4	14.4
	ZAR_{07}/kWh	157	138
Fuel tank (LPG)	EUR_{07}/kWh	11.2	8.9
	ZAR_{07}/kWh	107	86
H_2 tank	EUR_{07}/kWh	22.2	20.8
	ZAR_{07}/kWh	212	199
Fuel cell	EUR_{07}/kW	370	50
	ZAR_{07}/kW	3,541	478
Battery (Li-Ion)	EUR_{07}/kWh	800	300
	ZAR_{07}/kWh	7,656	2,871
Converter and controller (including AC/DC)	EUR_{07}	4,274	2,482
	ZAR_{07}	40,903	23,755
Converter and controller (excluding AC/DC)	EUR_{07}	2,415	1,240
	ZAR_{07}	23,108	11,864

* Costs of ICEs for PHEVs (no gearing) as well as for ICE–H_2 SI in 2040 (easier emission treatment) are about 10% lower.
Sources: /Edwards et al. 2011b/, /Blesl et al. 2009/, /Schädlich 2011/, /Özdemir & Hartmann 2012/, /SWD 2011/, /Wiedemann 2008/, /Lienin 2009/, /IEA 2010a/, /Deininger 2011/, /Engerer & Horn 2008/, /Blesl et al. 2005/, /IEA 2010j/, /Özdemir 2012/, /Bruchof 2013/, own calculations.

Figure 40 illustrates the trend in vehicle costs for a passenger car. The constituents of all vehicle costs are shown in detail in Appendix B. The investment costs of battery electric vehicles and fuel cell hybrid electric vehicles are clearly highest in 2010. However, the expected learning curves reduce the investment costs for a battery electric vehicle from about 670,000 ZAR_{2007} in 2010 to about 343,000 ZAR_{2007}/vehicle in 2040. For fuel cell hybrid electric vehicles, investment costs are expected to fall to about 206,000 ZAR_{2007} in 2040, which is about 53% less than the calculated 443,000 ZAR_{2007} in 2010. Other alternative vehicle technologies are expected to lead to reduced investment costs, too, although to a smaller extent. On the other hand, the investment in conventional ICEs (petrol and diesel) increases in 2040 compared to 2010 due to new legislation regarding emissions and technical adaptions (see section 5.2.1). However, even in 2040 conventional combustion engines are still the cheapest option as far as investment costs are concerned.

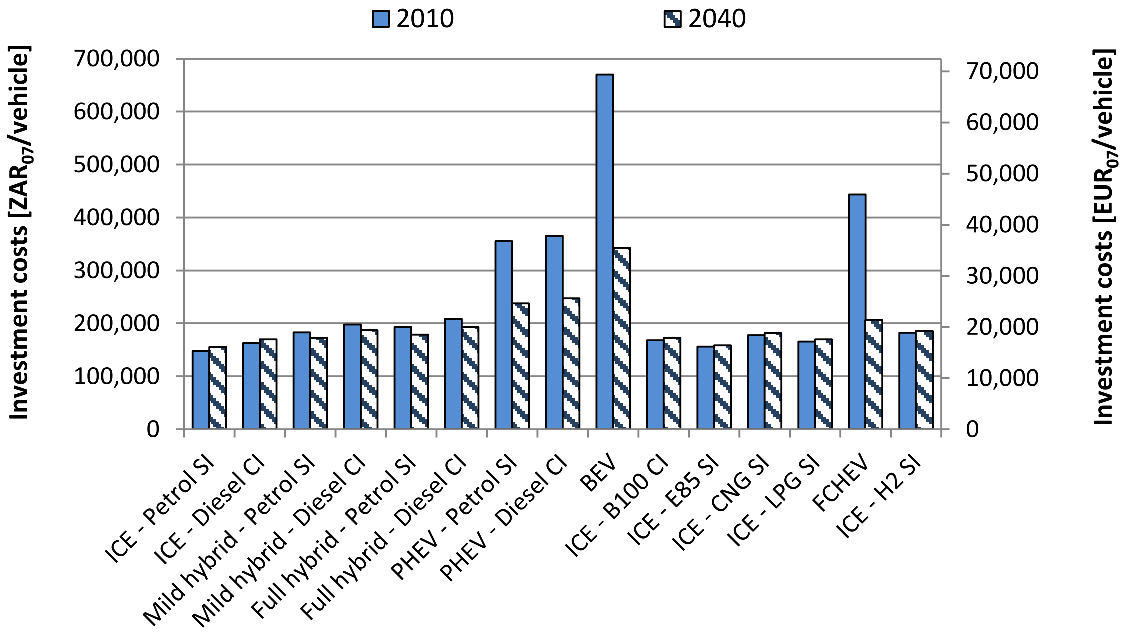


Figure 40: Investment costs of passenger cars in 2010 and 2040 for different powertrain technologies. Source: own calculations.

The efficiencies of all vehicles are calculated based on the emission and vehicle efficiency inventory for Gauteng /TÜV 2012a/ (see section 3.3). For the example of a passenger car is can be seen that electric engines offer significantly higher efficiency than internal combustion engines (Figure 41). The expected fuel consumption in 2010 was 0.6 MJ/km for battery electric vehicles and 0.8–0.9 MJ/km for plug-in hybrid electric vehicles (diesel CI and petrol SI, respectively). In comparison, conventional ICEs are seen to have a fuel consumption of 3.2 and 2.3 MJ/km for petrol SI and diesel CI engines in 2010. Ethanol vehicles (E85) as well as CNG and LPG vehicles offer small efficiency benefits compared to the petrol-driven reference vehicle.

The fuel efficiency of ICEs improves, between 2010 and 2040, by 38% and 23% for petrol SI and diesel CI engines, respectively. The calculated efficiency improvement is in line with the projections in the literature (see section 5.2.1). Electric vehicles are not likely to reduce their fuel consumption much (about 0.2 MJ/km for battery electric vehicles and about 0.2–0.3 MJ/km for plug-in hybrid electric vehicles). The fuel consumption of fuel cell hybrid electric passenger cars is expected to decrease from 1.8 MJ/km in 2010 to 1.3 MJ/km in 2040 (–25%) The fuel efficiency of biodiesel is expected to be similar to fossil diesel. The fuel consumption of ethanol-powered SI engines is expected to decline from 3.1 MJ/km in 2010 to 1.9 MJ/km in 2040, whereas the fuel consumption of SI engines running on LPG is likely to fall from 3.0 MJ/km in 2010 to 1.8 MJ/km in 2040. CI ICEs running on B100 show the same fuel consumption as conventional CI ICEs running on (fossil) diesel.

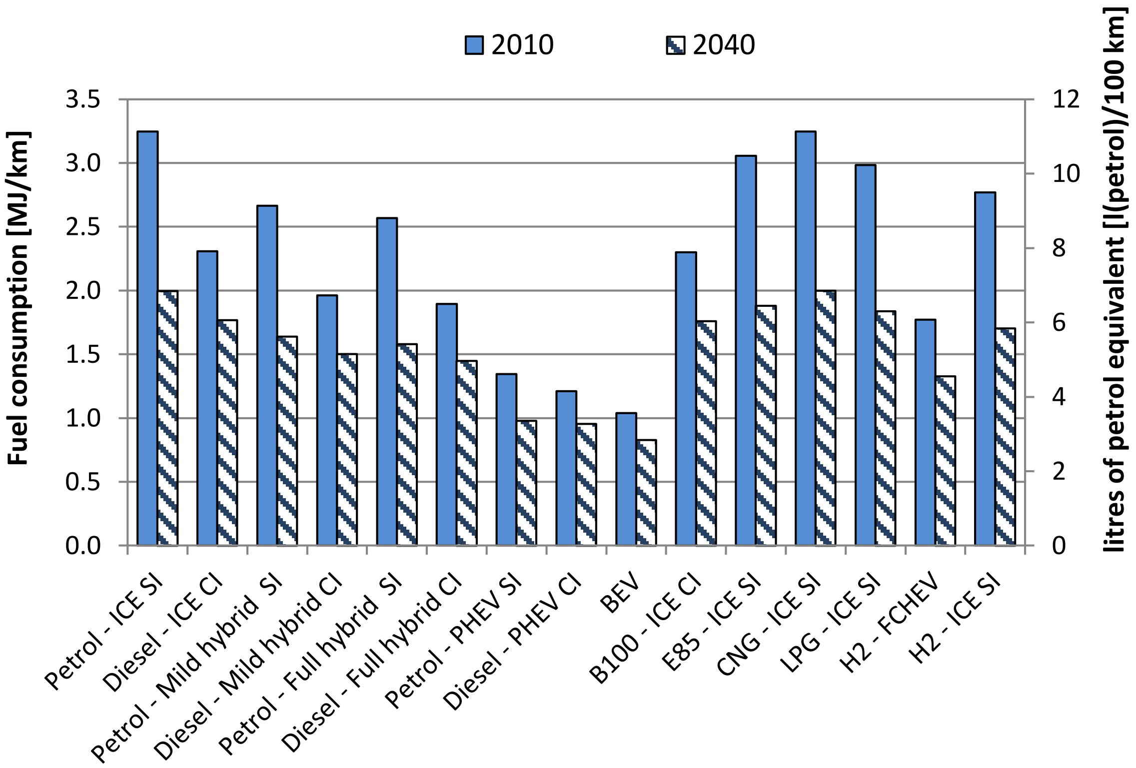


Figure 41: Calculated fuel efficiency of new passenger cars in Gauteng in 2010 and 2040. Source: own calculations based on /TÜV 2012a/.

Tank-to-wheel (TTW) GHG emissions vary by vehicle type (Figure 42). The highest such emissions for new passenger cars in 2010 have been calculated for conventional internal combustion engines. These amount to about 231.8 g CO_2eq/km for petrol-fuelled ICE SI vehicles and to about 169.9 g CO_2eq/km for diesel-fuelled ICE CI passenger cars. In comparison, the TTW GHG emissions of mild hybrids are about 15–18% lower, although full hybrids are not expected to result in significant further reductions of these emissions. Battery electric vehicles and those vehicles using hydrogen do not generate GHG emissions, whereas CO_2 emissions from biogenic sources are balanced as zero based on the assumption that the carbon is accumulated in biomass cultivation. Up to 2040, reductions are estimated for all the fuel–powertrain combinations (with non-zero TTW emissions). Thus, TTW GHG emissions for conventional ICEs are expected to decline to about 142.8 g CO_2eq/km (petrol) and 130.2 g CO_2eq/km (diesel). As in 2010, plug-in hybrid electric vehicles (PHEV) show comparatively low TTW GHG emissions (e.g. about 19.2 g CO_2eq/km in 2010 and 14.0 g CO_2eq/km in 2040 if using petrol as fuel).

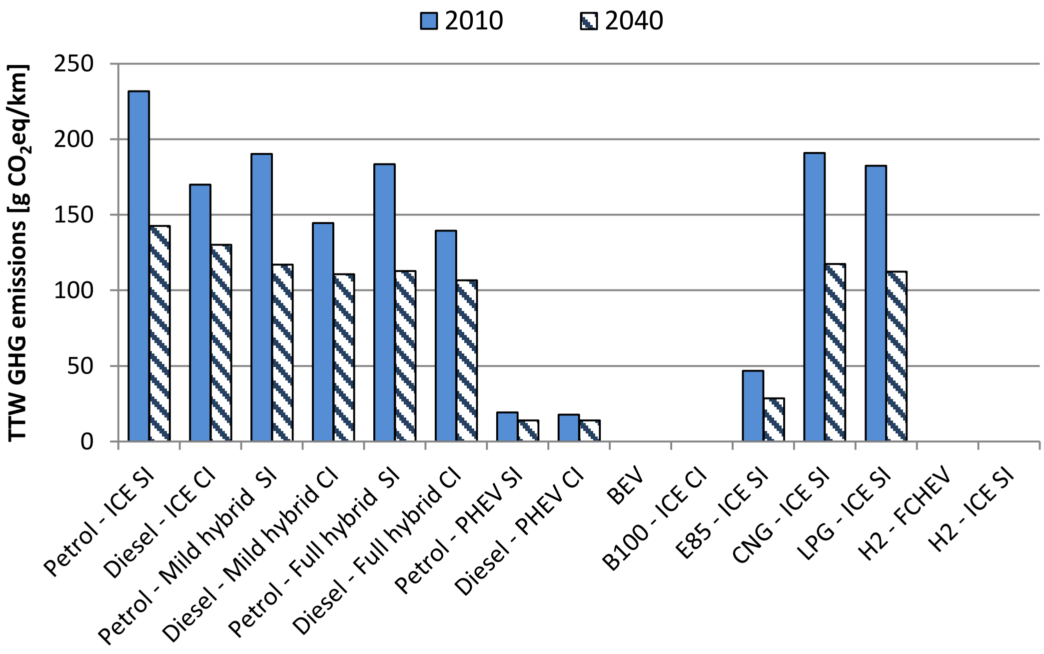


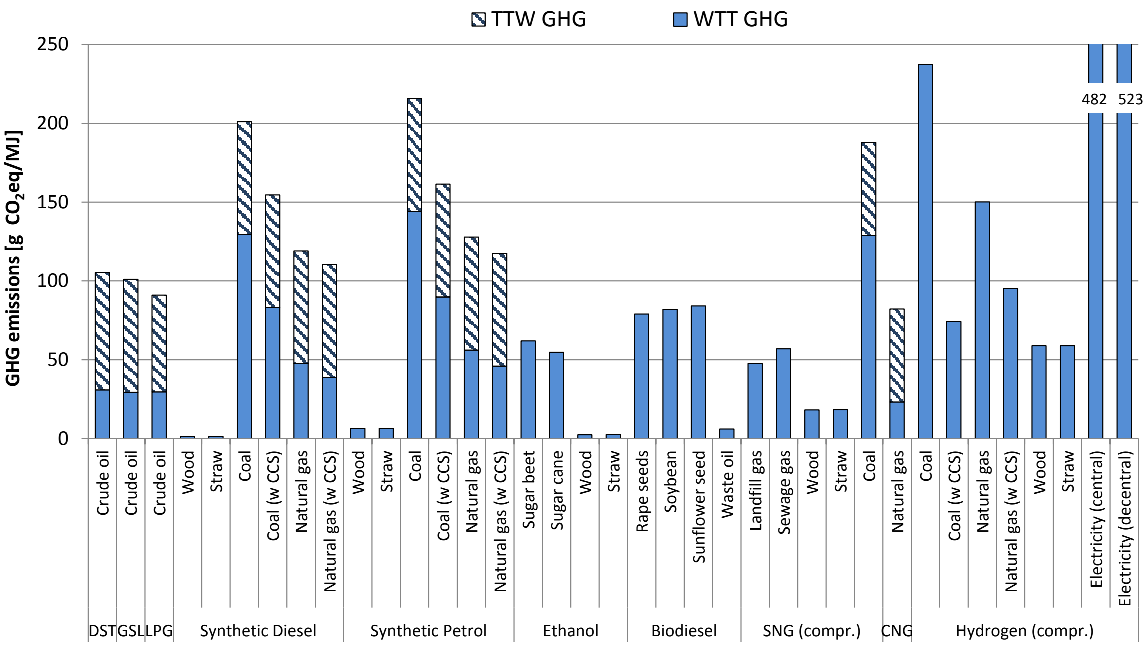
Figure 42: Tank-to-wheel GHG emissions of new passenger cars in Gauteng in 2010 and 2040. Source: own calculations based on /TÜV 2012a/.

In summary, alternative vehicle technologies have been identified that present the opportunity to reduce transport GHG emissions and final energy consumption. The costs, on the other hand, are very different among these options and change with time. To conclude the comparison of these technologies, fuel supplies (well-to-tank emissions) also have to be analysed. This is done in the next section.

5.3 Well-to-wheel GHG emissions of transport energy supply options and vehicle powertrain technologies analysed for Gauteng

In this section, well-to-wheel GHG emissions are presented for the example of a new passenger car. The analysis is based on the results of the well-to-tank (section 5.1) and tank-to-wheel (section 5.2) application of alternative powertrain technologies and fuels for Gauteng. All transport energy supply and vehicle powertrain options are analysed for the years 2010 and 2040, even if not all are yet commercially available (e.g. such as fuel cell hybrid electric vehicles). Finally, a marginal abatement cost curve (MACC) is derived for a passenger car by calculating the well-to-wheel (WTW) GHG mitigation costs and the GHG mitigation potential (expressed per vehicle, assuming an annual driving distance of 12,632 km/a) for passenger cars in Gauteng.

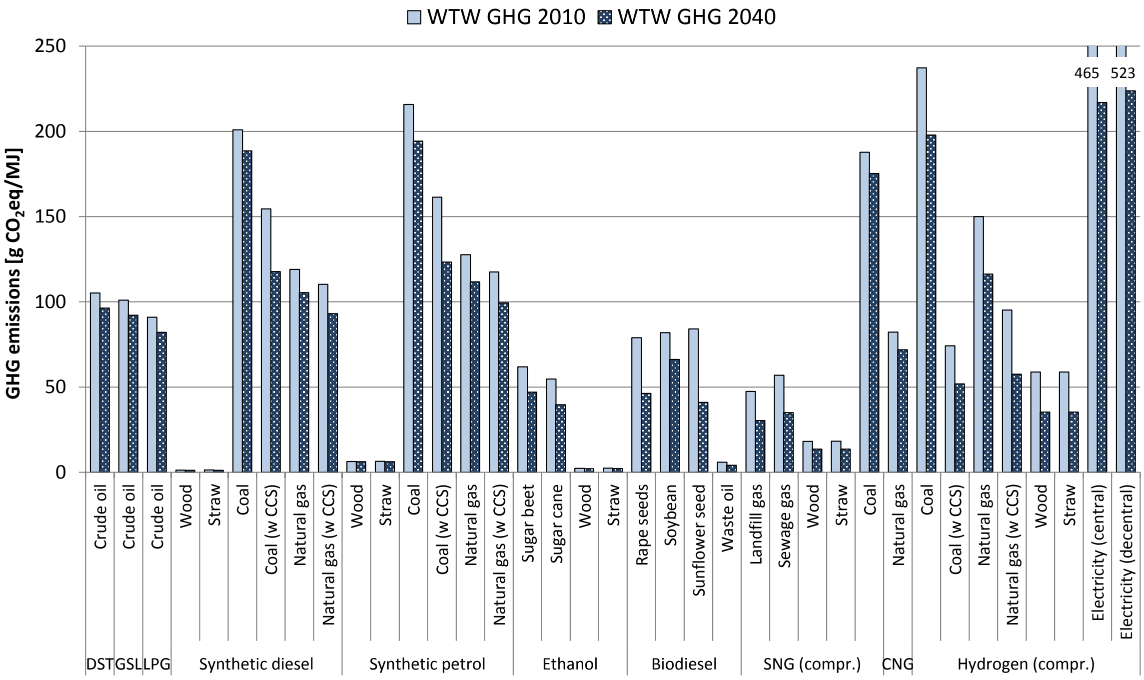
In the case of WTW GHG emissions of the fuels analysed and relevant vehicle technologies for the year 2010 (Figure 43), the highest figures have been identified as resulting from the application of hydrogen generated by electrolysis (i.e. 482–523 g CO_2eq/MJ). This is due to the high WTT emissions factor for the electricity mix in South Africa, which is predominantly based on coal (i.e. 291 g CO_2eq/MJ in 2010, see also section 5.1.10). Furthermore, CTL fuels without CCS (i.e. about 201 g CO_2eq/MJ and 216 g CO_2eq/MJ for synthetic diesel and petrol, respectively), and SNG using coal as feedstock (about 188 g CO_2eq/MJ), also show high WTW GHG emissions. In comparison, crude oil-based diesel accounted for WTW emissions of about 105 g CO_2eq/MJ in 2010, whereas crude oil-based petrol accounted for about 101 g CO_2eq/MJ. CNG generates total GHG WTW emissions of about 82 g CO_2eq/MJ, which are clearly higher than WTW GHG emissions of SNG from landfill or upgraded sewage gas (47.5–56.9 g CO_2eq/MJ). Significantly lower are the WTW GHG emissions of fuels from biomass, as they do not account for WTT GHG emissions due to the use of biogenic sources. Thus, total WTW emissions of biofuels from energy crops are between 54.7 g CO_2eq/MJ for ethanol from sugar cane and 84.1 g CO_2eq/MJ for biodiesel from sunflower seeds. As for the WTT analysis (see section 5.1.10), the lowest WTW emissions were found for second-generation biofuels from straw and wood (i.e. 1.3–6.4 g CO_2eq/MJ) as well as for biodiesel from waste cooking oil (i.e. 6.0 g CO_2eq/MJ).



Abbreviations: DST = diesel; GSL = petrol; SNG = substitute natural gas.

Figure 43: Well-to-wheel (WTW) GHG emissions of passenger cars in 2010 for various South African fuels. Source: own calculations.

Between 2010 and 2040, WTW GHG emissions decline for all fuels (Figure 44). In 2040, the use of CCS for CTL and GTL fuels shows WTW emissions comparable to those from crude petrol and diesel (e.g. 93.2 g CO_2eq/MJ for GTL synthetic diesel compared to 96.4 g CO_2eq/MJ for diesel from crude oil refining). WTW emissions for hydrogen from electrolysis decline by 55–57% to about 220 g CO_2eq/MJ. This result is also based on the assumed GHG emission factor for electricity (i.e. 142 g CO_2eq/MJ in 2040, see section 5.1.10) and might show an even better result if the electricity is sourced with low CO_2 emissions (e.g. using a nuclear or renewable option). The lowest WTW GHG emissions for hydrogen in 2040 can be seen for hydrogen generated from biomass gasification (i.e. 35.4 g CO_2eq/MJ). WTW GHG reduction for SNG from organic waste declines by 36–38% to 30.5 g CO_2eq/MJ and 35.0 g CO_2eq/MJ for SNG from landfill and sewage gas, respectively. WTW GHG emissions for SNG from cellulosic biomass in 2040 are 13.6 g CO_2eq/MJ (–25%) compared with SNG from coal (175.4 g CO_2eq/MJ) and with CNG from natural gas (71.9 g CO_2eq/MJ). WTW emissions of biofuels from energy crops in 2040 are between 39.7 g CO_2eq/MJ (for ethanol from sugar cane) and 66.3 g CO_2eq/MJ (for biodiesel from soybeans). However, WTW GHG emissions for ethanol from lignocellulosic biomass and for BTL fuels are calculated to be significantly less (about 1.2–6.3 g CO_2eq/MJ). The highest reduction of total WTW GHG emissions from liquid fuels is for biodiesel from sunflower seeds, which declines by 43.1 g CO_2eq/MJ (–51%). The lowest absolute WTW emissions from liquid fuels in 2040 are calculated for synthetic fuels from cellulosic biomass and for biodiesel based on waste cooking oil.



Abbreviations: DST = diesel; GSL = petrol; SNG = substitute natural gas.

Figure 44: Well-to-wheel (WTW) GHG emissions of passenger cars for various fuels and vehicle technologies in 2040 compared with 2010. Source: own calculations.

GHG mitigation costs and GHG mitigation potential per vehicle, assuming an annual driving distance of 12,632 km/a, have been calculated for alternative transport energy supply options and powertrain technologies for the example of a new passenger car in Gauteng. This has been done according to Equation 15, where *A* is the GHG mitigation cost in ZAR/t, *R* is the running cost of vehicle technology *i* with fuel *j*, and *E* is WTW emissions in t/km. The reference technology *ref* is chosen as the new conventional petrol SI-ICE vehicle (see section 5.2.7) running on the South African fuel mix as given in

/Tomaschek et al. 2012c/ (i.e. 71% crude oil petrol, 24% CTL and 5% GTL in the fuel mix).

$$A_{i,j} = \frac{R_{i,j} - R_{ref}}{E_{ref} - E_{i,j}} \qquad \text{(for all } E_{i,j} < E_{ref}\text{)} \qquad \text{Equation 15}$$

The running cost *R* in ZAR/km of a specific vehicle *i* includes the investment annuity (INV_i) and fixed operating and maintenance costs (FOM_i) based on annual mileage m_i as well as fuel expenditure based on the fuel price P_F in ZAR/GJ and the vehicle fuel efficiency η_i in GJ/km (see Equation 16).

$$R_i = \frac{1}{m_i}(ANF \cdot INV_i + FOM_i) + P_F \cdot \eta_i \qquad \text{Equation 16}$$

The annuity factor is defined as in Equation 13, where *n* is the lifetime of the vehicle [a] and *i* is the interest rate, which is assumed to be 8%. Vehicle investment costs (INV_i) for passenger cars are taken from the analysis in section 5.2.7. FOM_i has been considered as 5% of the investment costs. The fuel price (P_F) is taken from the analysis described in section 5.1.10 and from Table 31 for electricity

The results of GHG abatement costs are shown in Table 33 for the year 2010 and in Table 34 for the year 2040. Table 35 and Table 36 show the corresponding mitigation potential per vehicle for 2010 and 2040, respectively. For easier comparison, the results have been ranked:

- Lowest abatement costs are shown in **green** (≤ 1,000 ZAR_{2007}/t CO_2eq).
- Intermediate abatement costs (1,000–2,500 ZAR_{2007}/t CO_2eq) are shown in **yellow**.
- Highest abatement costs (> 2,500 ZAR_{2007}/t CO_2eq) are shown in **red**.
- Mitigation potentials per car less than 1 t CO_2eq/a are shown in **red**.
- **Yellow** indicates an annual mitigation potential per car of 1–5 t CO_2eq/a.
- **Green** indicates an annual mitigation potential per car of more than 5 t CO_2eq/a.

The lowest GHG abatement costs for passenger cars in Gauteng in 2010 were identified as being for crude oil-based fuels, replacing the synthetic components in the South African fuel mix (Table 33). GHG mitigation costs for crude oil-based petrol in conventional ICEs are 81 ZAR_{2007}/t CO_2eq and mitigation costs for crude oil-based diesel are 355 ZAR_{2007}/t CO_2eq. The mitigation potential is only about 1.2–2.2 t CO_2eq/a (Table 35). GHG mitigation costs in 2010 are highest for hydrogen from natural gas without CCS (i.e. 244,714 ZAR_{2007}/t CO_2eq) and remain the highest in 2040, although they decline significantly to about 23,451 ZAR_{2007}/t CO_2eq (Table 34). The high abatement costs are also based on the small mitigation potential as only about 0.1 t CO_2eq/a and 2.8 t CO_2eq/a can be avoided in 2010 and 2040, respectively, which is among the lowest mitigation potentials in both years (Table 35 and Table 36).

Table 33: GHG mitigation costs for passenger cars in Gauteng in 2010 [ZAR/t CO_2eq] (reference = new conventional petrol ICE SI on the South African fuel mix).

	Vehicle powertrain	ICE - GSL SI	ICE - DST CI	Mild hybrid - GSL SI	Mild hybrid - DST CI	Full hybrid - GSL SI	Full hybrid - DST CI	PHEV - GSL SI	PHEV - DST CI	BEV	ICE - B100 CI	ICE - E85 SI	ICE - CNG SI	ICE - LPG SI	FCHEV	H_2 ICE
Fuel	**Feedstock**															
Diesel	Crude oil		355		2,121		2,603		8,282							
Petrol	Crude oil	81		2,413		2,999		8,163								
LPG	Crude oil													1,770		
Synthetic Diesel	Wood		887		1,710		1,980		6,180							
	Straw		660		1,519		1,795		6,062							
	Coal		x		15,383		13,138		13,513							
	Coal (w CCS)		1,611		4,159		4,757		10,488							
	Natural gas		917		2,748		3,248		8,915							
	Natural gas (w CCS)		938		2,609		3,079		8,628							
Synthetic Petrol	Wood	1,249		1,906		2,159		6,135								
	Straw	892		1,616		1,880		5,993								
	Coal	x		x		x		17,641								
	Coal (w CCS)	x		x		88,582		11,587								
	Natural gas	23,401		5,931		6,368		9,567								
	Natural gas (w CCS)	4,425		4,671		5,174		9,116								
Ethanol	Sugar beet	4,350		4,476		4,716		8,056				4,228				
	Sugar cane	3,114		3,569		3,843		7,593				3,123				
	Wood	1,486		2,084		2,324		6,170				1,589				
	Straw	1,108		1,775		2,027		6,016				1,234				
Biodiesel	Rape seeds		1,119		2,361		2,742		7,801		1,381					
	Soybean		1,806		2,909		3,267		8,134		2,071					
	Sunflower seed		1,468		2,673		3,050		8,060		1,741					
	Waste oil		331		1,259		1,551		5,965		488					
SNG (compr.)	Landfill gas												1,260			
	Sewage gas												2,449			
	Wood												1,989			
	Straw												1,677			
	Coal												x			
CNG	Natural gas												1,815			
Hydrogen (compr.)	Coal														x	x
	Coal (w CCS)														13,563	4,957
	Natural gas														25,843	240,714
	Natural gas (w CCS)														16,009	7,898
	Wood														12,815	4,945
	Straw														12,622	4,570
	Electricity (central)														x	x
	Electricity (decentral)														x	x
Electricity	(Grid)							80,506	35,820	52,580						

Legend: ≤ 1,000 $ZAR_{2007}/t\ CO_2$ eq; > 1,000 $ZAR_{2007}/t\ CO_2$ eq ∧ ≤ 2,500 $ZAR_{2007}/t\ CO_2$ eq; > 2,500 $ZAR_{2007}/t\ CO_2$ eq

Abbreviations: ICE = internal combustion engine; GSL = petrol; DST = diesel; CNG = compressed natural gas; PHEV = Plug-in hybrid electric vehicle; BEV = Battery electric vehicle; FCHEV = Fuel cell hybrid electric vehicle. Source: own calculations

Table 34: GHG mitigation costs for passenger cars in Gauteng in 2040 [ZAR/t CO_2eq] (reference = new conventional petrol ICE SI on the South African fuel mix).

Fuel	Vehicle powertrain / Feedstock	ICE - GSL SI	ICE - DST CI	Mild hybrid - GSL SI	Mild hybrid - DST CI	Full hybrid - GSL SI	Full hybrid - DST CI	PHEV - GSL SI	PHEV - DST CI	BEV	ICE - B100 CI	ICE - E85 SI	ICE - CNG SI	ICE - LPG SI	FCHEV	H_2 ICE
Diesel	Crude oil		2,474		3,612		4,035		6,755							
Petrol	Crude oil	611		2,125		2,635		5,913								
LPG	Crude oil													2,602		
Synthetic Diesel	Wood		846		1,529		1,775		4,211							
	Straw		557		1,284		1,539		4,056							
	Coal		x		x		x		16,306							
	Coal (w CCS)		4,004		4,843		5,312		7,650							
	Natural gas		4,743		5,037		5,383		7,473							
	Natural gas (w CCS)		3,521		4,211		4,564		6,936							
Synthetic Petrol	Wood	410		1,010		1,254		3,858								
	Straw	43		711		967		3,684								
	Coal	x		x		x		17,662								
	Coal (w CCS)	x		4,082		4,804		7,265								
	Natural gas	12,158		5,161		5,494		7,239								
	Natural gas (w CCS)	4,386		3,933		4,319		6,673								
Ethanol	Sugar beet	3,104		3,241		3,464		5,579				2,936				
	Sugar cane	2,265		2,600		2,840		5,161				2,184				
	Wood	585		1,135		1,368		3,884				629				
	Straw	221		838		1,082		3,708				287				
Biodiesel	Rape seeds		1,915		2,651		2,938		5,436		2,112					
	Soybean		3,593		4,057		4,320		6,450		3,837					
	Sunflower seed		2,229		2,868		3,132		5,486		2,413					
	Waste oil		805		1,508		1,759		4,230		942					
SNG (compr.)	Landfill gas												1,064			
	Sewage gas												1,564			
	Wood												1,789			
	Straw												1,479			
	Coal												x			
CNG	Natural gas												2,988			
Hydrogen (compr.)	Coal														x	x
	Coal (w CCS)														4,754	4,656
	Natural gas														11,490	23,451
	Natural gas (w CCS)														6,007	6,512
	Wood														4,611	4,473
	Straw														4,407	4,191
	Electricity (central)														x	x
	Electricity (decentral)														x	x
Electricity	(Grid)							9,081	9,885	18,324						

Legend: ≤ 1,000 ZAR_{2007}/t CO_2 eq; > 1,000 ZAR_{2007}/t CO_2 eq ∧ ≤ 2,500 ZAR_{2007}/t CO_2 eq; > 2,500 ZAR_{2007}/t CO_2 eq

Abbreviations: ICE = internal combustion engine; GSL = petrol; DST = diesel; CNG = compressed natural gas; PHEV = Plug-in hybrid electric vehicle; BEV = Battery electric vehicle; FCHEV = Fuel cell hybrid electric vehicle. Source: own calculations.

Table 35: GHG mitigation potential for a passenger car in Gauteng in 2010 [t CO_2eq/a] (reference = new conventional petrol ICE SI on the South African fuel mix).

Fuel	Feedstock	ICE - GSL SI	ICE - DST CI	Mild hybrid - GSL SI	Mild hybrid - DST CI	Full hybrid - GSL SI	Full hybrid - DST CI	PHEV - GSL SI	PHEV - DST CI	BEV	ICE - B100 CI	ICE - E85 SI	ICE - CNG SI	ICE - LPG SI	FCHEV	H_2 ICE
Diesel	Crude oil		2.2		2.7		2.8		3.7							
Petrol	Crude oil	1.2		1.9		2.0		3.6								
LPG	Crude oil													1.9		
Synthetic Diesel	Wood		5.3		5.3		5.3		5.3							
	Straw		5.3		5.3		5.3		5.3							
	Coal		x		0.3		0.5		2.2							
	Coal (w CCS)		0.8		1.5		1.6		3.0							
	Natural gas		1.8		2.4		2.5		3.5							
	Natural gas (w CCS)		2.1		2.6		2.7		3.6							
Synthetic Petrol	Wood	5.1		5.1		5.1		5.2								
	Straw	5.0		5.1		5.1		5.2								
	Coal	x		x		x		1.6								
	Coal (w CCS)	x		x		0.1		2.6								
	Natural gas	0.1		1.0		1.2		3.1								
	Natural gas (w CCS)	0.5		1.4		1.5		3.3								
Ethanol	Sugar beet	2.8		3.2		3.3		4.3				2.9				
	Sugar cane	3.1		3.5		3.5		4.4				3.2				
	Wood	5.2		5.2		5.2		5.3				5.2				
	Straw	5.2		5.2		5.2		5.3				5.2				
Biodiesel	Rape seeds		3.0		3.4		3.4		4.1		3.0					
	Soybean		2.9		3.3		3.4		4.1		2.9					
	Sunflower seed		2.9		3.2		3.3		4.0		2.9					
	Waste oil		5.1		5.2		5.2		5.2		5.1					
SNG (compr.)	Landfill gas												3.4			
	Sewage gas												3.0			
	Wood												4.6			
	Straw												4.6			
	Coal												x			
CNG	Natural gas												1.9			
Hydrogen (compr.)	Coal														x	x
	Coal (w CCS)														3.7	2.7
	Natural gas														2.0	0.1
	Natural gas (w CCS)														3.2	2.0
	Wood														4.0	3.3
	Straw														4.0	3.3
	Electricity (central)														x	x
	Electricity (decentral)														x	x
Electricity	(Grid)							0.4	0.9	1.5						

Legend: < 1 t CO_2 eq/a (red); ≥ 1 t CO_2 eq/a ∧ ≤ 5 t CO_2 eq/a (yellow); > 5 t CO_2 eq/a (green)

Abbreviations: ICE = internal combustion engine; GSL = petrol; DST = diesel; CNG = compressed natural gas; PHEV = Plug-in hybrid electric vehicle; BEV = Battery electric vehicle; FCHEV = Fuel cell hybrid electric vehicle. Source: own calculations.

Table 36: GHG mitigation potential for a passenger car in Gauteng in 2040 [t CO_2eq/a] (reference = new conventional petrol ICE SI on the South African fuel mix).

Fuel	Feedstock	ICE - GSL SI	ICE - DST CI	Mild hybrid - GSL SI	Mild hybrid - DST CI	Full hybrid - GSL SI	Full hybrid - DST CI	PHEV - GSL SI	PHEV - DST CI	BEV	ICE - B100 CI	ICE - E85 SI	ICE - CNG SI	ICE - LPG SI	FCHEV	H_2 ICE
Diesel	Crude oil		3.2		3.5		3.5		4.1							
Petrol	Crude oil	3.0		3.4		3.5		4.2								
LPG	Crude oil													3.4		
Synthetic Diesel	Wood		5.3		5.3		5.3		5.3							
	Straw		5.3		5.3		5.3		5.3							
	Coal		x		x		x		3.0							
	Coal (w CCS)		2.7		3.1		3.2		3.9							
	Natural gas		3.0		3.3		3.4		4.0							
	Natural gas (w CCS)		3.2		3.5		3.6		4.2							
Synthetic Petrol	Wood	5.2		5.2		5.2		5.2								
	Straw	5.2		5.2		5.2		5.2								
	Coal	x		x		x		2.9								
	Coal (w CCS)	x		2.8		2.8		3.8								
	Natural gas	2.5		3.0		3.1		3.9								
	Natural gas (w CCS)	2.8		3.3		3.3		4.1								
Ethanol	Sugar beet	4.1		4.3		4.4		4.7				4.2				
	Sugar cane	4.3		4.5		4.5		4.8				4.4				
	Wood	5.3		5.3		5.3		5.3				5.3				
	Straw	5.3		5.3		5.3		5.3				5.3				
Biodiesel	Rape seeds		4.3		4.4		4.5		4.8		4.3					
	Soybean		3.8		4.1		4.1		4.5		3.8					
	Sunflower seed		4.4		4.5		4.6		4.8		4.4					
	Waste oil		5.2		5.2		5.2		5.3		5.2					
SNG (compr.)	Landfill gas												4.5			
	Sewage gas												4.4			
	Wood												5.0			
	Straw												5.0			
	Coal												x			
CNG	Natural gas												3.5			
Hydrogen (compr.)	Coal														x	x
	Coal (w CCS)														4.4	4.2
	Natural gas														3.4	2.8
	Natural gas (w CCS)														4.3	4.1
	Wood														4.7	4.6
	Straw														4.7	4.5
	Electricity (central)														x	x
	Electricity (decentral)														x	x
Electricity	(Grid)							3.6	3.6	3.8						

Legend: < 1 t CO_2 eq/a; ≥ 1 t CO_2 eq/a ∧ ≤ 5 t CO_2 eq/a; > 5 t CO_2 eq/a

Abbreviations: ICE = internal combustion engine; GSL = petrol; DST = diesel; CNG = compressed natural gas; PHEV = Plug-in hybrid electric vehicle; BEV = Battery electric vehicle; FCHEV = Fuel cell hybrid electric vehicle. Source: own calculations.

Battery electric vehicles and plug-in hybrid electric vehicles running on electricity show GHG abatement costs from 35,820 ZAR_{2007}/t CO_2eq (PHEV–diesel CI) to 80,506 ZAR_{2007}/t CO_2eq (PHEV–petrol SI) in 2010, which reduce to 9,885 ZAR_{2007}/t CO_2eq and 9,081 ZAR_{2007}/t CO_2eq in 2040. These results are obviously dependent on the assumed costs and GHG emissions for electricity provision (see section 5.1.10). This can also be seen in the relatively low annual GHG mitigation potential, which is calculated as 0.4 t CO_2eq/a (PHEV–petrol SI) and 0.9 t CO_2eq/a (PHEV–diesel CI) in 2010. For 2040 the mitigation potential is about 2.6 t CO_2eq/a for plug-in hybrid electric vehicles and 3.8 t CO_2eq/a for battery electric vehicles.

For crude oil-based fuels, hybrid vehicles show costs per tonne of CO_2eq mitigated of about 2,100 ZAR_{2007}/t CO_2eq to 8,280 ZAR_{2007}/t CO_2eq in 2010, where mild hybrids have the lowest and plug-in hybrids the highest mitigation costs. In 2040 the corresponding figures change to about 2,125–6,755 ZAR_{2007}/t CO_2eq based on the diminishing cost penalty for hybrid vehicles but also taking into account the smaller mitigation potential as the reference vehicle evolves and thus reduces the absolute difference in fuel efficiency between the vehicle concepts. Mitigation costs for CNG passenger cars increase from about 1,815 ZAR_{2007}/t CO_2eq in 2010 to about 2,990 ZAR_{2007}/t CO_2eq in 2040. Mitigation costs for LPG increase from about 1,770 ZAR_{2007}/t CO_2eq to about 2,600 ZAR_{2007}/t CO_2eq, in this period, based on the only slightly reduced cost penalty for vehicle investment and lower absolute emission reduction in 2040.

In 2010, biofuels used in passenger cars show the lowest mitigation costs for biodiesel from waste cooking oil (about 330 ZAR_{2007}/t CO_2eq in conventional ICEs and about 490 ZAR_{2007}/t CO_2eq for B100 CI vehicles, Table 33). The annual mitigation potential for biofuels from waste cooking oil is among the highest at 5.1 t CO_2eq/a (if used in conventional diesel ICEs) as shown in Table 35. In 2040, the lowest GHG mitigation costs for biofuels used in passenger cars with conventional IC engines were calculated for second-generation biofuels to be 43–846 ZAR_{2007}/t CO_2eq for BTL fuels and 221–585 ZAR_{2007}/t CO_2eq for ethanol from lignocellulosic biomass (Table 34). The annual mitigation potential for second-generation biofuels is in the highest category (i.e. > 5 t CO_2eq/a) in 2010 as well as in 2040.

Finally, a static marginal abatement cost curve (MACC) has been derived to identify fuel–powertrain combinations for passenger cars in Gauteng, which have high GHG mitigation potential with lowest costs, as summarized in Figure 45. It can be seen that BTL and ethanol from lignocellulosic biomass as well as biodiesel from waste cooking oil provide high mitigation potential at comparatively low mitigation costs (sector I). However, these technologies are not available on a commercial scale today. The mitigation option with the lowest costs identified is the substitution of the current fuel mix with crude oil-based fuels, but the mitigation potential (on a single vehicle) is less than for previous options (sector II). Most of the combinations of alternative transport fuels and powertrains that mitigate GHG emissions of passenger car show only a modest annual abatement potential at medium mitigation costs (sector V). These include hybrid electric vehicles, first-generation biofuels as well as methane gas and LPG use in the transport sector. The application of hydrogen-fuelled vehicles and plug-in hybrid electric vehicles for passenger cars shows medium annual GHG mitigation potential at comparatively high cost (sector VIII). However, the mitigation potential would be higher if electricity with lower corresponding GHG emissions were used.

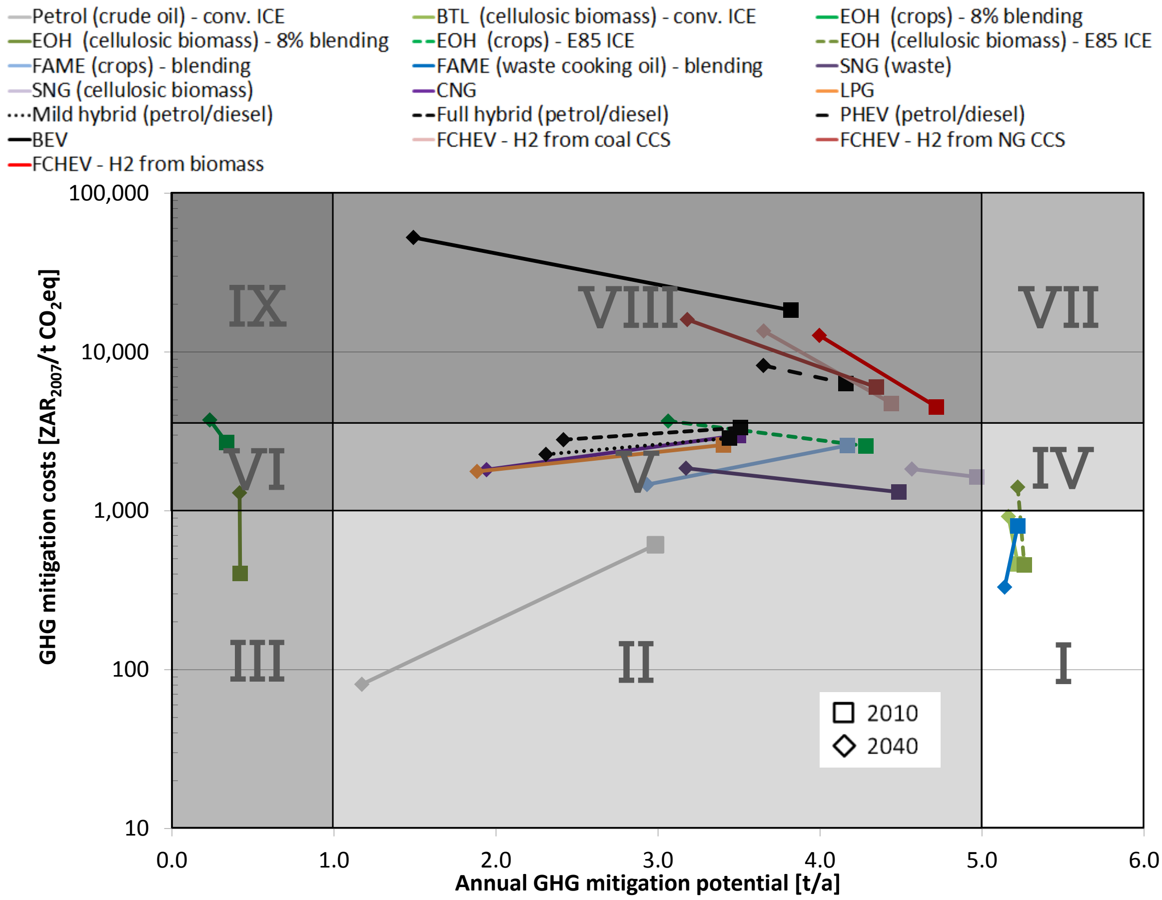


Figure 45: Well-to-wheel (WTW) GHG mitigation costs for a passenger car in Gauteng in 2010 and 2040 for different fuel options and vehicle technologies.
Source: own calculations.

It has to be kept in mind that the calculated mitigation costs for the example of a passenger car are strongly determined by the reference vehicle (in this case the new petrol ICE SI), the reference fuel mix (here the fuel mix according /Tomaschek et al. 2012c/) and the upstream GHG emission of the energy used (e.g. the electricity mix). Moreover, different assumptions for the costs of future technology (e.g. batteries for electric vehicles, see section 5.2.7) are possible. To consider all the possible combinations of alternative powertrains and different sources of transport energy, an analysis was conducted using the energy system model TIMES-GEECO, as described in the next chapter.

6 Integrated analysis of the energy system of Gauteng with emphasis on the transport sector

It has been shown that the need to mitigate greenhouse gas emissions generated in Gauteng is obvious (see section 3.6) and a particular concern of the provincial and national governments (see chapter 1 and section 2.2.4). South Africa has declared its intention to reduce its carbon emissions by 34% in 2020 and by 42% in 2025 (compared to business as usual) during the Copenhagen accord in the context of the United Nations Framework Convention on Climate Change (UNFCCC) /DNT 2010/, /Winkler 2007/. Gauteng province, as the economic hub of South Africa, sees its chance to be a forerunner for South Africa to develop strategies and implement measures to reduce its energy consumption and GHG emissions /Madumo 2010/, /DLGH 2010/. The transport sector is of special interest for GHG mitigation and Gauteng has already investigated several options including LPG and CNG vehicles as well as possibilities for biofuel production and utilization /Madumo 2010/, /GDPTRW 2010/, /Smit 2011/.

Although those strategies recognize the urgency of taking action in the transport sector, they do not represent clear policies for how this sector should develop in the future, nor have they critically analysed cost-optimal measures for transport energy supply and use to achieve national and provincial mitigation targets /Winkler 2007/, /DLGH 2010/.

One of the proposed measures for reducing greenhouse gas emissions in South Africa is the implementation of carbon taxes as recommended in the Long-term Mitigation Scenarios (LTMS) and in the National Climate Change Response Green Paper /Winkler 2007/, /DNT 2010/. It is suggested that implementing carbon taxes should be based on CO_2 equivalents for all energy-consuming sectors /DNT 2013/. However, discussion continues on the rate at which such a tax should be applied (it has been proposed as 120 ZAR/t CO_2eq) and if there should be exemption for energy intensive industries /DNT 2013/.

Many options exist to increase energy efficiency in the transport sector (see sections 4.3 and 5.2) or to switch to alternative fuels with lower climate impact than the current energy system, which is dominated by fuels derived from crude oil and coal (CTL) (see section 5.1). However, as demonstrated in sections 5.1.10 and 5.2.7, the different options cannot only be analysed separately as they are dependent on each other. An integrated approach can help to evaluate and coordinate the measures available and put them in the context of the whole energy system in the light of limited resources (e.g. of potential renewables or of finance). This chapter addresses the idea of integrated analysis of energy systems and shows how the TIMES-GEECO model is applied to Gauteng. In the following, scenarios are presented to show the development under a defined future (e.g. regarding population development, and energy carrier prices). Lastly, the results are compared and significant parameters varied in order to identify robust measures (those which are independent from the analysed uncertainties) for policy recommendation.

6.1 Scenario assumptions and variations

This section describes the relevant scenario assumptions when applying the TIMES energy system model. Within the TIMES model (chapter 4), a scenario is described, according to /Loulou et al. 2005a/, by:

- the demand for energy services (which could also be determined endogenously by socio-economic drivers such as population growth or GDP development)
- the potentials and prices of primary energy provision (involving import and production limitations as well as renewable energy potential)
- policies (relating to quotas, subsidies or climate targets), and
- the techno-economic description of technologies currently in use as well as possible alternatives in a long-term time horizon (here taken to be 2040).

While the techno-economic description of technologies relevant to the transport sector in Gauteng are described in detail in chapter 5, the other aspects such as service demand drivers as input for the travel demand model (section 3.1.3), prices for primary energy provision, potentials for renewable energy provision and policy implications, are presented in the following sections.

Table 37 shows the scenarios analysed in this thesis. The reference scenario analysed is called the **business as usual (BAU) scenario**, which investigates the energy system under current policies and expected technological progress. This includes policies that affect the energy system and which have been implemented, such as the taxi recapitalization programme (see section 2.2.1). The reference scenarios do not take GHG mitigation targets into account.

To derive a set of measures for Gauteng to reduce GHG emissions at minimal cost based on alternative transport technologies, fuels and implicit expansions of the BRT and Gautrain, an approach has been chosen based on GHG taxes for the various **GHG mitigation scenarios**. Using the TIMES model, it is possible to restrict GHG emissions by different means. By setting fixed quotas, the dual variables of the GHG emission-limiting constraint will show the corresponding GHG certificate price related to the emission abatement target formulated. However, the formulation of such quotas can be normative. Moreover, results might be sensitive to the chosen target and a minor deviation from the abatement target might affect a measure to be considered or not. Thus, in this analysis GHG emissions are limited by acknowledging different costs of GHG emissions (similar to carbon taxes). These have been calculated within multiple scenario runs to derive model-based **marginal abatement cost curves (MACCs) for GHG emissions**. Using MACCs it is possible to identify quantitatively which sectors and measures to reduce GHG emissions should be considered in which order, to achieve any given mitigation target at least cost (see also section 1).

To generate a MACC for GHG emissions, taxes have been applied system-wide to CO_2, CH_4 and N_2O emissions, ranging from 25 to 2,500 ZAR_{2007}/t CO_2eq. In between, smaller steps are chosen for the lower GHG taxes as most changes in the energy system are expected there. GHG taxes have been increased over the model time-horizon (i.e. 2007–2040) with a discount rate of 8%, which is inherent to the TIMES-GEECO model. 18 model runs are performed per scenario with GHG taxes starting from the year 2018.

As future socio-economic development such as economic growth, population development and income inequality is found to be uncertain (see also section 1.2), two different socio-economic scenario frameworks have been analysed, in terms of **low growth (LG)** and **high socio-economic growth (HG)**. Section 6.1.2 gives a detailed account of the socio-economic framework. Both socio-economic frameworks have been considered for the BAU scenarios as well as for each GHG mitigation cost curve (Table 37).

Table 37: Scenario tableau for the reference scenario and GHG tax scenarios.

Scenario name	Scenario description	Socio-economic growth	GHG tax	Primary energy price	Other implications
BAU_LG	**Reference scenario**: Business as usual – **low** socio-economic **growth**	**low** see Table 39	none	**high** see Table 38	none
BAU_HG	**Reference scenario**: Business as usual – **high** socio-economic **growth**	**high** see Table 39	none	**high** see Table 38	none
	Role of the transport sector for GHG mitigation				
GHG_LG	**GHG tax**: **low** socio-economic **growth**	**low** see Table 39	varied from 25 to 2,500 ZAR_{07}/t CO_2eq	**high** see Table 38	none
GHG_HG	**GHG tax**: **high** socio-economic **growth**	**high** see Table 39	varied from 25 to 2,500 ZAR_{07}/t CO_2eq	**high** see Table 38	none
	Scenario variations for high socio-economic growth				
GHG_HG-MP	**GHG tax**: **moderate primary energy carrier prices**	**high** see Table 39	varied from 25 to 2,500 ZAR_{07}/t CO_2eq	**moderate** see Table 38	none
GHG_HG-No CCS	**GHG tax**: **no CCS**	**high** see Table 39	varied from 25 to 2,500 ZAR_{07}/t CO_2eq	**high** see Table 38	**CCS not available until 2040**
GHG_HG-CV	**GHG tax**: **cost variation**	**high** see Table 39	varied from 25 to 2,500 ZAR_{07}/t CO_2eq	**high** see Table 38	**Variation of cost parameters for a) cellulosic biomass b) battery costs**

The reference for all scenarios is the assumption of a higher growth in crude oil price. However, its future trend is unknown and, thus, based on the assumption that global climate efforts can limit the growth of the crude oil price in the future (see e.g. /Remme et al. 2008/); a variation for the GHG_HG scenario with **moderate primary energy carrier prices (MP)** corresponding to a lower oil price is also analysed (Table 37). The prices of primary energy carriers are found furthermore to be dependent on the crude oil price (see section 6.1.3) and thus varied accordingly.

CCS is considered as an option from 2020 onwards for all scenarios, according to /CGS 2010/ and /Telsnig et al. 2013b/ except for the GHG_HG–**no CCS scenario** (Table 37). In this scenario, CCS technologies are assumed not to be available until 2040, to demonstrate the possible role of CCS for GHG mitigation in South Africa.

Lastly, the costs of some technologies and commodities, which are identified as being promising measures for GHG mitigation (see section 5.3), are varied in order to account for uncertainties. These scenarios are referred to as **cost variation (CV) scenarios**. Thus, costs of providing lignocellulosic biomass (such as straw and wood) are increased by 50% (see also section 6.1.4), which is of reasonable magnitude given the uncertainty in provision costs found in the literature (see e.g. /Damm & Triebel 2008/, /Eisentraut 2010/ and /DWAF 2003/). Additionally, specific battery costs are varied. The figure of 300 €/kWh used in this study (see chapter 5) is based on several literature sources. However, there are studies available (e.g. /Hartmann et al. 2012/, /Özdemir & Hartmann 2012/) which state lower costs. A recent study by McKinsey & Company postulates specific battery investment costs of 130 €/kWh for 2025 /VDI 2012/. However, this figure is not uncontroversial /VDI 2012/. Thus, in a cost variation, specific battery investment costs have been reduced by 50% to 150 $€_{2007}$/kWh in 2040 (Table 37).

The calculations in this analysis exclude the application of taxes and subsidies and indicate a macro-economic view; taxes reflect a re-allocation of resources and, thus, should not influence the optimal solution for a minimal-cost objective. The discount rate in all scenarios is taken as 8%. When calculating the annuities, the technical lifetime of technologies is seen to be equal to the economic lifetime.

On the electricity supply side, in all scenarios it is considered that up to 1.2 GW_{el} of new nuclear capacity attributable to Gauteng can be built /IER 2012/.

The effects of the minibus taxi recapitalization programme (TRP) (see section 2.2.1) are expected to lead to at least 55% of new registered minibuses in 2040 using CI engines (refer to section 6.1.3). Furthermore, the average load factor of minibuses is assumed to increase from 10 in 2007 to 12 person/trip from 2015 onwards (see Table 6).

The possible effects of the Gauteng e-tolling system on motorized travel on the province's main highways are not measurable at this time. However, it is assumed that it will result in more passengers using the Gautrain and BRT system in future, which has been taken into account when estimating future passenger volumes (see section 4.3)

/Bubeck 2012/. No further assumptions have been made on possible effects of the system on the travel demand or load factors of other transport modes.

A minimum biofuel quota as proposed by the National Strategy (see section 2.2.4) has not been included in the scenarios as it is not yet mandatory. However, based on the strategy and technical restrictions of biofuel usage in non-modified vehicle engines (see section 5.2.2), the maximum blending shares for biofuels without vehicle modifications have been set at B10 and E10 for biodiesel and for ethanol, respectively (see sections 2.2.4 and 4.3).

6.1.1 Prices of primary energy carriers and crops

A regression approach is used to estimate future trends in primary energy prices. Historical prices for coal and natural gas in South Africa (available at /DOE 2009a/) are found to be correlated with the world crude oil price derived from /OPEC 2011/. To do so, all values are adjusted for inflation using the South African Consumer Price Index (CPI) (see Appendix A). The same method is applied to feedstock prices. Historical figures for feedstock prices have been published in /FAO 2011/. The price of oil seeds is found to correlate quite well with the crude oil price. On the other hand, the price of sugar cane seems to be independent of the crude oil price. The sugar cane price was relatively stable between the years 2000 and 2008 (around 205 ZAR_{2007}/t) but rose greatly (by about 85%) in 2009 and remained at high levels in 2010 (at about 370 ZAR_{2007}/t) /FAO 2010/, /FAO 2011/. The sugar price level later fell again and was around 300 ZAR_{2007}/t in May 2011 /Jayes 2011/. Missing values for South African crop prices are calculated using data for countries with comparable conditions (cf. /Tomaschek et al. 2012c/ for a detailed account of the determination of crop prices in South Africa). The price of waste cooking oil is taken as 116 ZAR_{2007}/GJ (5 ZAR_{2010}/litre) in 2010, including expenditure on collection /Le Roy 2011/. Table 38 shows the prices calculated for primary energy carriers and crops in Gauteng for the industrial consumer’s inclusive transport and distribution in terms of both medium and high oil prices. The prices of secondary energy carriers (e.g. LPG, CNG, petrol, diesel and electricity) including delivery costs are calculated endogenously in the model.

The forecasts of the crude oil price are based on the World Energy Outlook 2011 (WEO) published by the International Energy Agency /IEA 2011c/. The reference crude oil price is chosen based on the IEA’s new policies scenario, assuming a (real) crude oil price of about 123 USD_{2010}/bbl in 2040 /IEA 2011c/. Assuming an annual inflation rate of 3.3% – which is the average rate in the US over the last 30 years /BLS 2012/ – this corresponds to a nominal oil price in 2040 of about 326 USD_{2040}/bbl. For the moderate primary energy carrier price (MP) a lower oil price is assumed based on the 450 ppm scenario (i.e. about 97 USD_{2010}/bbl or 257 USD_{2040}/bbl in 2040) /IEA 2011c/, /BLS 2012/.

Table 38: Prices for primary energy carriers and crops in Gauteng in 2010 and 2040.

	Unit	2010	Medium energy price 2040	High energy price 2040
Crude oil	USD_{10}/bbl	78.1	97.0	123.0
	ZAR_{07}/GJ	87.6	109.7	139.2
Coal	ZAR_{07}/GJ	9.3	11.5	14.5
Natural gas	ZAR_{07}/GJ	71.6	94.9	118.5
Sugar cane	ZAR_{07}/kg	0.4	0.4	0.4
Sugar beet	ZAR_{07}/kg	0.8	0.8	0.8
Rapeseeds	ZAR_{07}/kg	3.3	3.9	4.5
Sunflower seed	ZAR_{07}/kg	3.2	3.7	4.3
Soybean	ZAR_{07}/kg	3.2	3.6	4.1
Waste oil	ZAR_{07}/GJ	116.0	132.7	154.9

All prices shown for industrial consumers inclusive of transport and distribution.

Sources: own calculations and assumptions based on /DOE 2009a/, /OPEC 2011/, /FAO 2011/, /Jayes 2011/, /FAO 2010/, /Tomaschek et al. 2012c/, /Nolte 2007/, /Telsnig et al. 2013b/, /Le Roy 2011/.

6.1.2 Socio-economic framework

In past years, the economy has been growing faster in Gauteng than the national average. Furthermore, it is still projected to grow faster than this average, making it not only dominant in South Africa currently but will also strengthen its position in the future. While South Africa's average GDP growth rate was between 3% and 6% per annum from 2001 to 2007, Gauteng's GDPR has grown on average about half a percentage point higher /GPG 2009b/. In addition, Gauteng's population growth has been on average 0.6% higher than the national average /GPG 2009b/. However, different estimates for the future development are available. According to /Landau & Gindrey 2008/ and /UN-Habitat 2008/, the 2008 population of an estimated 10.5 million is projected to grow in a medium growth scenario on average by 1.6% annually, reaching about 13.3 million people in 2018. In a high socio-economic growth rate scenario – with increasing migration and decreasing mortalitiy figures – the provincial population is forecasted to reach 13.7 million in 2018 at an annual growth rate of 2% /Landau & Gindrey 2008/. The growth is essentially driven by migration due to the economic dominance of the province, leading many people to move to Gauteng /Landau & Gindrey 2008/. However, the number of households is projected to grow significantly faster than the population itself, with household growth rates about four times the population growth rate between 2001 and 2021 /Van Aardt 2007/, resulting in a decline of the average household size from about 4.5 in 1996 to 3.3 in 2007 /Van Aardt 2007/, /StatsSA 2007/. There are currently about 3 million households in Gauteng /UN-Habitat 2008/, /StatsSA 2007/.

The Institute for Future Studies and Technology Assessment (IZT) consolidated various existing forecasts and created a "mildly optimistic socio-economic scenario frame" for Gauteng /Wehnert et al. 2011/. In their framework, they conclude that Gauteng will have become a megacity region with about 20 million inhabitants in 2040 with a corresponding, approximately 3.7-fold increase in GDP /Wehnert et al. 2011/. The income inequality in Gauteng in 2040 is still described as “dramatic”, but less than that in 2010 /Wehnert et al. 2011/. As those projections are based on the assumption of high socio-economic growth, the figures are used for the high socio-economic growth scenarios, whereas the low socio-economic growth scenarios assume lower population and GDP growth and higher income inequality. The key figures for the socio-economic scenarios considered in this analysis are summarized in Table 39.

Table 39: Socio-economic framework for the scenario analysis.

Population growth and household size

	High socio-economic growth		Low socio-economic growth	
	Population [million]	Household size [person/hh]	Population [million]	Household size [person/hh]
2007	10.5	3.3	10.5	3.3
2010	11.3	3.2	11.3	3.2
2020	14.1	3.1	12.9	3.1
2030	16.6	2.9	13.7	2.9
2040	19.1	2.8	14.4	2.8

Economic framework

	High socio-economic growth		Low socio-economic growth	
	GDP [2007=100%]	Employment [million]	GDP [2007=100%]	Employment [million]
2007	100%	3.9	100%	3.9
2010	108%	3.7	108%	3.7
2020	166%	4.8	140%	4.3
2030	253%	6.0	179%	4.9
2040	374%	7.2	229%	5.5

Household income distribution

	High socio-economic growth		Low socio-economic growth	
	Group I: < 9,600 ZAR_{07}/hh/a	Group II: 9,600 – 76,800 ZAR_{07}/hh/a	Group I: < 9,600 ZAR_{07}/hh/a	Group II: 9,600 – 76,800 ZAR_{07}/hh/a
2007	22%	45%	22%	45%
2010	22%	47%	22%	47%
2020	18%	48%	21%	44%
2030	15%	44%	21%	42%
2040	11%	39%	20%	40%
	Group III: 76,800 – 307,200 ZAR_{07}/hh/a	Group IV: > 307,200 ZAR_{07}/hh/a	Group III: 76,800 – 307,200 ZAR_{07}/hh/a	Group IV: > 307,200 ZAR_{07}/hh/a
2007	21%	12%	21%	12%
2010	20%	12%	20%	12%
2020	18%	15%	21%	13%
2030	21%	20%	23%	14%
2040	25%	25%	25%	15%

Sources: /Wehnert et al. 2011/ and own assumptions.

In comparison, the high-growth scenarios assume a total population of more than 19 million in Gauteng in 2040, whereas in the corresponding low socio-economic growth scenarios the population is estimated at about 14.4 million. Both scenarios also assume a significant increase in total GDP. However, the GDP in 2040 is about 374% of the base year (2007) value in the high-growth variant and 229% in the low socio-economic growth model. Consequently, GDP per capita increases from about 65,300 ZAR_{2007}/cap in 2007 to about 133,800 ZAR_{2007}/cap, in the case of high socio-economic growth, and to about 108,600 ZAR_{2007}/cap under low socio-economic growth. Furthermore, both scenarios show differences in the number of employed people and in income distribution. In 2040, in the high socio-economic growth scenario, the number of employees is about 229% of the figure in 2007 (about 3.9 million people), whereas in the low socio-economic growth scenario the corresponding figure is 142%. Accordingly, the high socio-economic growth scenario assumes a greater proportion of people in the higher income groups (see section 1.2).

6.1.3 Constraints for the future market penetration of CI engines

Market penetration of new technology is not only determined by its costs but also by individual preferences and personal requirements. Thus, it takes time for a new technology to reach a particular market share. However, in a least-cost optimization energy system model one technology would be cost-optimal to serve a given demand at a particular time and thus be the favourite option to invest in. On the other hand, bounds for the market penetration alter the cost-optimal model decision based on assumptions of the modeller. For that reason in this analysis, only a few limits have been defined for the contribution of both diesel (CI) and petrol (SI) engines, and others such as electric motors.

To model the market behaviour in Gauteng, the vehicle registration database /NATIS 2009/ was analysed in detail. For each vehicle type, the share of CI vehicle registrations in all new vehicle registrations was calculated for a time series from 1990 to 2009.

Market penetration rates can be described by a sigmoid function (i.e. S-shaped curves), which expresses bounded growth /Höök et al. 2011/. These curves can describe the different stages of how technologies develop in new markets. The first part is characterized by slow but increasing growth and represents new, emerging technologies. In the second part, growth is almost linear, which corresponds to booming markets. In the third part, the growth rate decreases when the market is saturated /Höök et al. 2011/. These trajectories for each technology *i* can be expressed, for example, using a Gompertz formula (Equation 17).

$$y_i(t) = a_i e^{-b_i e^{-c_i t}} \qquad \text{Equation 17}$$

In Equation 17 t is the time (in years) between t_1 and t_2, a is the saturation value (i.e. the target value for the diesel share of new registrations for the year t_2) for a technology i, and b and c are the gradients of the curve. The parameters b and c can be calculated by transforming the formula into Equation 18 and applying the function to historical values:

$$\ln(b_i) - c_i t = ln\left(-ln\left(\frac{y(t)}{a_i}\right)\right), \qquad with\ a > 0;\ b > 0 \qquad \text{Equation 18}$$

Linear regression provides values for the function parameters b_i and c_i and a corresponding coefficient of determination (R^2). The target value a_i can then be calculated by a maximizing R^2 in an iterative process. An interval for the target values a_i was calculated for $R^2 > 0.85$. The actual market penetration of a technology is the result of the energy system model used and based on the scenario definition. Figure 46 shows the results for the boundaries for the diesel share of passenger car registrations. As a result, the minimum and maximum proportions of CI ICEs in new passenger vehicle registrations in 2040 were calculated as 10.6% and 23.7%, respectively.

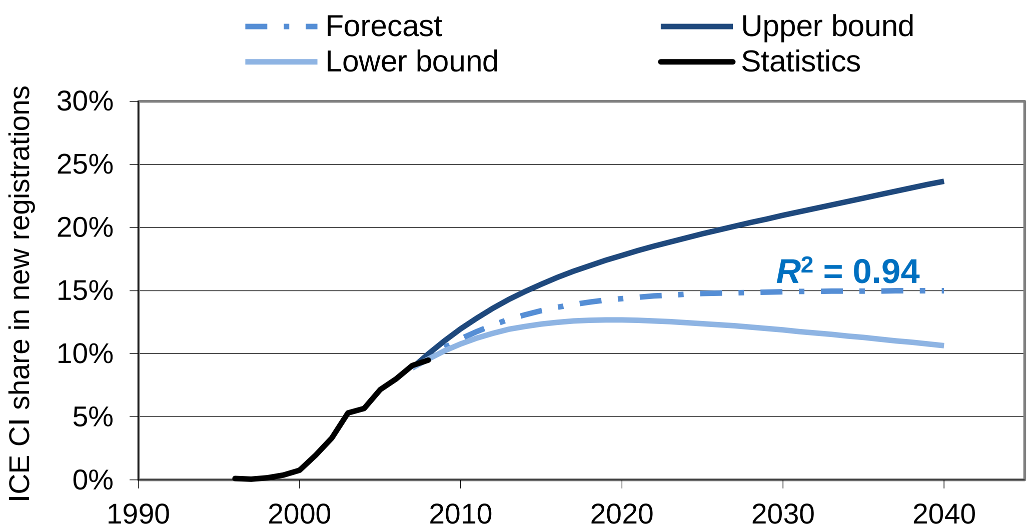


Figure 46: Historical values and forecast bandwidth of the share of ICE CI passenger cars in new vehicle registrations for Gauteng up to the year 2040.
Source: own calculations based on /NATIS 2009/.

The calculation was also carried out for other modes. The corresponding figures for SUVs are calculated as 51.1% and 77.2% in 2040, which also shows the higher share of CI engines for larger vehicles. For LDVs, a minimum share of CI ICEs in new registrations of 47.6% and a minimum of share 72.6% was calculated for the year 2040. For minibus taxis, those figures are calculated as 55.7% and 81.8% (Table 40). No bounds for CI engines are considered for buses and HDVs.

Table 40: Calculated upper and lower bounds for CI engines in Gauteng.

Mode	**Minimum share of CI engines in new registrations**		**Maximum share of CI engines in new registrations**	
	2010	**2040**	**2010**	**2040**
Passenger car	10.8%	10.6%	12.0%	23.7%
SUV	46.4%	51.1%	47.9%	77.2%
LDV	43.7%	47.6%	46.0%	72.6%
Minibus	25.8%	55.7%	28.1%	81.8%

Source: own calculations based on /NATIS 2009/.

6.1.4 Assumptions for renewable energy provision

As described in chapter 4, it is assumed that potential sources of renewable energy, which are located outside the provincial boundaries, are allocated to Gauteng on a pro rata basis according to the province's share of electricity consumption (e.g. 29.9% of the electricity consumption of South Africa in 2007 was consumed in Gauteng /StatsSA 2012b/). The potentials considered for provision of renewable energy can be found in Table 41 and in Figure 47. All values are based on /Telsnig et al. 2013a/, /Tomaschek et al. 2013/ and /IER 2012/ except the potentials for biogas from landfill sites and sewage plants, which are based on /Schon 2012/ for medium-sized plants.

The land used for building large-scale renewable-energy power plants is not seen as a limiting factor in South Africa. It is assumed that a maximum of 16.3 PJ of renewable electricity from open space PV, CSP and wind generation can be imported by Gauteng (Table 41). In Gauteng, only limited land is available for constructing such power plants (i.e. 502 km^2). However, additionally roof areas are available for PV on residential, commercial and industrial buildings (refer to /Telsnig et al. 2012/ for technology descriptions and land use factors).

Furthermore, arable land is available for the cultivation of energy crops, namely sugar cane, canola, sugar beet, sunflowers and soybeans, of which only the last three can be cultivated in Gauteng. It is assumed that a maximum of 20% of the arable land may be used for energy crop provision, which corresponds to about 544 km^2 in Gauteng (of which only 51 km^2 are suitable for soy cultivation) and about 2,700 km^2 in South Africa which are attributable to Gauteng. Besides, one should be aware of that water availability might be an additional limiting constraint in South Africa /Hoogeveen et al. 2009/.

Table 41: Considered potentials for renewable energy provision.

	Unit	Gauteng	South Africa (Gauteng related)
Land area available for open space power plants	km^2 PJ [a)]	502 max. 220	b)
Area available for PV on roofs of residential buildings	km^2 PJ [a)]	21 max. 12.1	n.a.
Area available for PV on roofs of industrial and commercial buildings	km^2 PJ [a)]	40 max. 24.5	n.a.
Land area available for energy crops	km^2 PJ [a)]	544 [c)] max. 5.6	2,718 max. 29.2
Waste cooking oil available for transesterification	PJ	6.5 – 11.9 [d)]	n.a.
Maximum capacity for hydro electricity	MW	3.2	254
Raw biogas from sewage plants	PJ	0.4 – 1.2 [d)]	n.a.
Raw biogas from landfill sites	PJ	0.2 – 0.6 [d)]	n.a.

a) The potential in PJ depends on the technology applied
b) It is assumed that a maximum of 16.3 PJ of renewable electricity from open space PV, CSP and wind can be imported by Gauteng.
c) Only 51 km^2 are suitable for soy cultivation in Gauteng.
d) Figures are for 2010 and for 2040, respectively.

Sources: /Telsnig et al. 2013a/, /Tomaschek et al. 2013/, /IER 2012/, /Schon 2012/.

The cellulosic biomass potential in South Africa which can be allocated to Gauteng is shown in Figure 47, taken from /IER 2012/ but modified by transport costs. The potential has been analysed for different types of straw and wood quality. The lowest costs of wood are assumed for residual wood and mill residues, which can be provided at about 15–21 ZAR_{2007}/GJ. However, the potential for such resources is low (i.e. about 12 PJ/a). Straw would cost between 17 and 44 ZAR_{2007}/GJ. The total potential of straw and wood, which is available for ethanol production and gasification (see section 5.1) as well as for co-firing in coal-fired power plants, is assumed to be about 80 PJ.

It is anticipated that the wood resources of Gauteng, on the other hand, are too small for fuel use and remain restricted for direct use in the residential, commercial and industrial sectors (less than 5 PJ of local wood is currently consumed in Gauteng /Tomaschek et al. 2012d/).

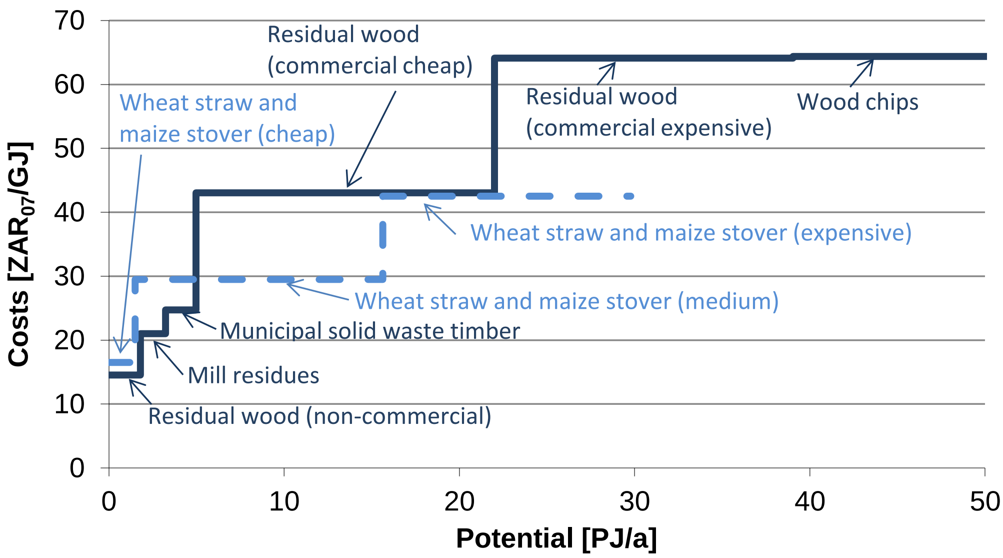


Figure 47: Cost-potential curve for wood and straw in South Africa usable for electricity and fuel provision for Gauteng, inclusive costs of transport and distribution. Source: /IER 2012/, own calculations.

6.2 Model results: The reference scenario – business as usual

In this section, the model results of the reference cases are presented for the low socio-economic growth (LG) and high socio-economic growth (HG) scenarios. The results are analysed and all results are represented graphically for easier comparison.

6.2.1 Primary energy consumption

The primary energy consumption (PEC) of Gauteng increases significantly under reference scenario conditions. Primary energy consumption in the BAU_HG scenario grows from about 1,470 PJ in 2007 to more than 2,700 PJ in 2040 (+84%) as shown in Figure 48. In the BAU_LG scenario, the increase from 2007 to 2040 is 325 PJ (+22%).

Under reference scenario conditions, the dependence on fossil energy carriers is likely to continue. In both scenarios, most of the total primary energy consumption is based on coal (between 74% and 76%), which increases from about 1,079 PJ in 2007 to about 2,020 PJ in BAU_HG and to about 1,360 PJ in BAU_LG in 2040. The second biggest share in primary energy consumption is that of crude oil. Crude oil consumption increases from 262 PJ in 2007 to about 521 PJ and 316 PJ in 2040, for the high and low socio-economic growth scenarios, respectively. In the reference cases, natural gas is found to contribute only about 4–5% of the primary energy consumption in 2040 (i.e. 100 PJ in BAU_HG and 65 PJ in BAU_LG in the year 2040).

The consumption of other primary energy carriers remains low in the reference scenarios. Nuclear energy, in the reference case, slowly declines until 2030. The model does not allow for the building of new nuclear capacity, as electricity provision from coal is cheaper. Even though renewable energy consumption increases drastically (from 10 PJ in 2007 to 59 PJ in BAU_HG and 51 PJ in BAU_LG in 2040), the share remains small. The figure can be disaggregated – for example, for the HG scenario, into 31 PJ wood and straw, 19 PJ solar energy, 8 PJ hydro energy, > 1 PJ for biofuels and > 1 PJ for raw biogas from landfill sites and sewage treatment plants in 2040. In BAU_LG, these figures are similar except for primary solar energy consumption, which is 11 PJ in 2040. Solar energy also shows the highest growth rates for renewable primary energy provision as it was hardly used in 2007. Cellulosic biomass primary energy consumption increases significantly in both reference scenarios (about 4 PJ in 2007). Wind energy remains below 1 PJ under reference scenario conditions for both scenarios.

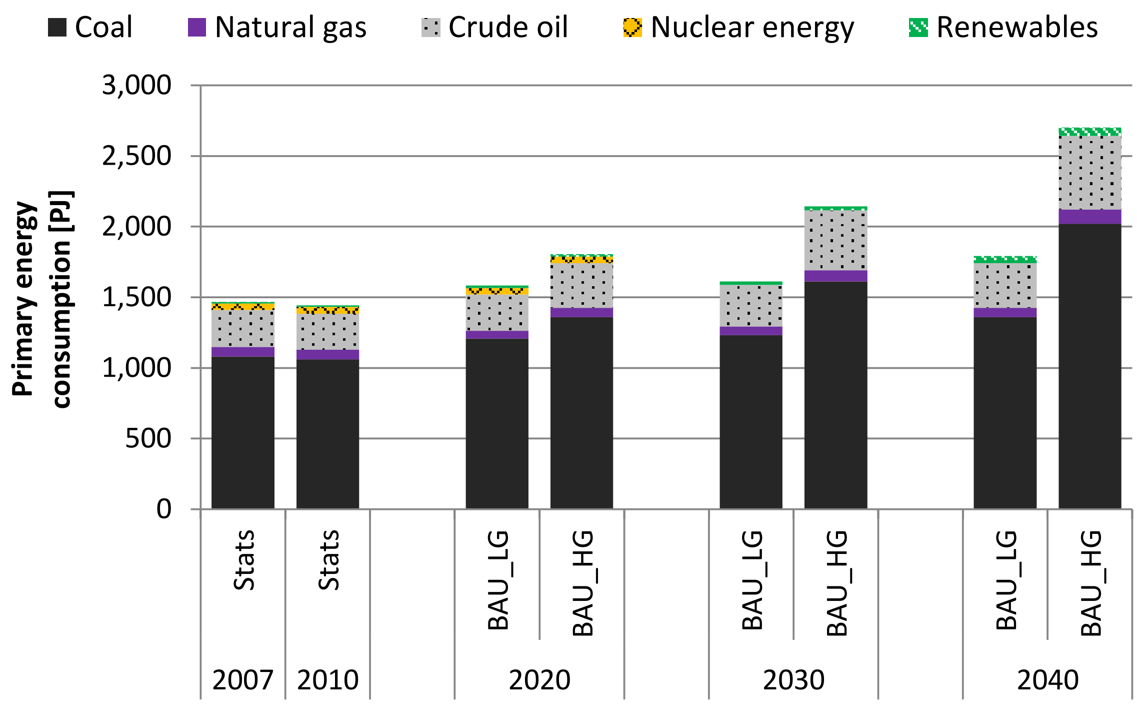


Figure 48: Primary energy consumption in Gauteng under BAU scenario conditions up to 2040. Source: own calculations.

6.2.2 Final energy consumption and provision

Figure 49 shows the total final energy consumption in Gauteng from 2007 to 2040 under reference case conditions. Under these conditions, the final energy consumption increases by 27% and 91% from 758 PJ in the base year to about 960 PJ and 1,450 PJ in 2040, in the low socio-economic growth and high socio-economic growth scenarios, respectively. It is found that under reference scenario conditions, electricity and coal, as well as fossil fuels from crude oil and fossil synthetic fuels, will be an important part of the future final energy mix (about 76–77% of the total in 2040) independently of changes in socio-economic growth. Electricity consumption increases from 231 PJ (64 TWh) in 2007 to 457 PJ in 2040 (127 TWh, +98%) in the BAU_HG scenario, and to 294 PJ (82 TWh, +27%) in BAU_LG. Coal consumption increases from 188 PJ in 2007 to 310 PJ (+64%) and to 209 PJ (+11%) in 2040, in high socio-economic growth and low socio-economic growth conditions, respectively.

Under high socio-economic growth conditions, increases in crude oil based diesel and petrol consumption of 159% and 17% are seen. In the low socio-economic growth scenario diesel consumption (from crude oil) grows only slowly (+24%) and petrol consumption (from crude oil) is reduced by 34 PJ (–34%). This is also a result of the significant contributions of synthetic Fischer-Tropsch fuels to the energy system (i.e. 97 PJ in 2040 (+50%) in both reference scenarios), which increase in both cases in 2020 when new capacities are allowed. The consumption of natural gas increases between 2007 and 2040 by 42 PJ (+90%) and by 11 PJ (+12%) in BAU_HG and BAU_LG, respectively, which is about 6% of the total final energy consumption.

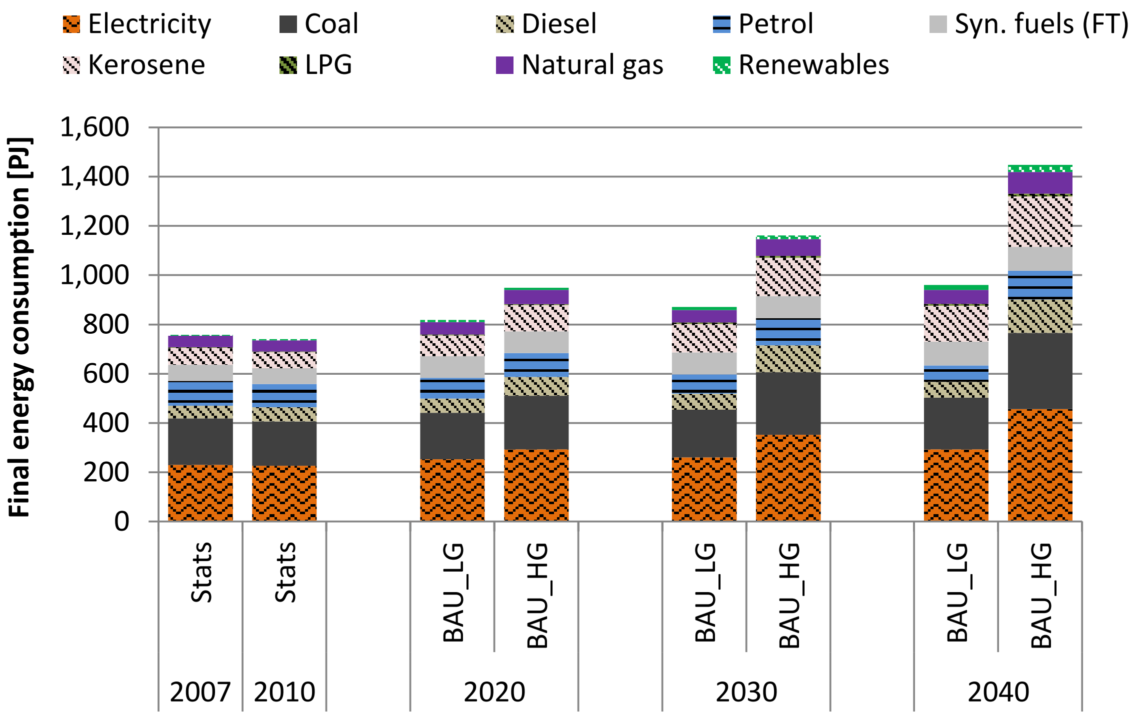


Figure 49: Total final energy consumption of Gauteng by energy carrier under BAU scenario conditions from 2007 to 2040. Source: own calculations.

The highest growth rates in final energy consumption, however, can be seen in both scenarios for renewable energy carriers, which increase from about 4 PJ in 2007 to 28 PJ in 2040 in the BAU_HG scenario (20 PJ in BAU_LG). Solar final energy consumption increases from about 1 PJ in 2007 to 18 PJ in 2040 in the BAU_HG scenario (10 PJ in BAU_LG). Wood final energy consumption also increases significantly by about 184% from 4 PJ in 2007 to 10 PJ in both BAU_LG and BAU_HG in 2040. However, compared to the total final energy consumption in Gauteng these figures are small. Biofuel consumption, which made no contribution to the final energy consumption in 2007, is not expected to expand significantly under reference conditions (< 1 PJ independently of socio-economic growth).

In addition to the high proportion of fossil fuels in final energy consumption, the electricity supply for Gauteng is seen to be based mainly on coal (Figure 50). Total electricity provision increases from about 80 TWh in 2007 to 102 TWh in 2040 (+27%) in the low socio-economic growth, business-as-usual scenario. In BAU_HG, about 157 TWh electricity is provided for Gauteng in 2040. Obviously, electricity provision figures are higher than those for final electricity consumption as distribution losses occur. In addition, electricity is used for the provision and conversion of other energy carriers. Of the total electricity provision, about 93% is supplied by coal-fired power plants in both reference scenarios in 2040. These show a growth in output from 70 TWh in 2007 to 94 TWh (+34%) and to 147 TWh (+109%) in 2040, for BAU_LG and BAU_HG, respectively. New coal-fired power plants continuously replace current capacities, which are progressively decommissioned after 2012.

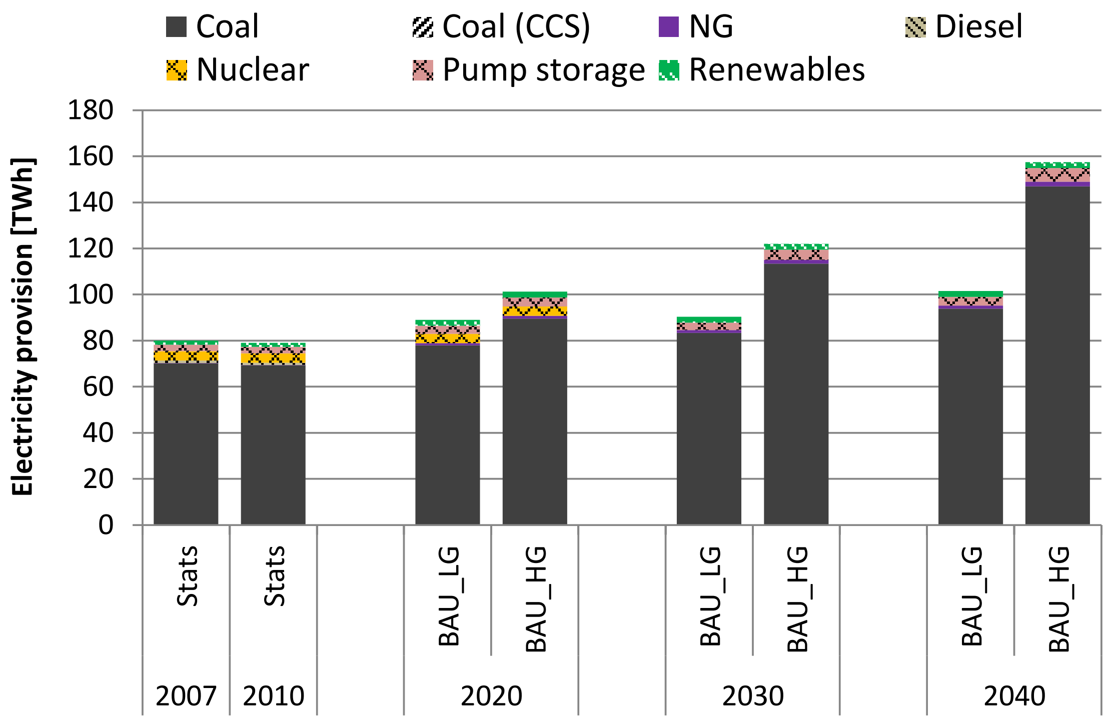


Figure 50: Electricity provision by energy carrier for Gauteng under BAU scenario conditions between 2007 and 2040. Source: own calculations.

Diesel power plants for electricity provision (OCGT), which were built in the 1970s and 1980s and between 2007 and 2009 to help meet peak electricity demand during the energy crisis, are likely to be replaced by natural gas power plants. However, under BAU scenario conditions capacities remain small (about 1 GW in 2040 in BAU_LG and about 2 GW in BAU_HG). The share of renewable electricity provision (i.e. hydro, solar energy, wind energy, combustible renewables and waste) remains less than 2% in the reference scenarios. This small contribution is almost totally provided by hydropower plants. CCS is not used for power plants in the business-as-usual scenarios until 2040 (Figure 50).

All sectors are expected to contribute to the growing energy demand in both scenarios as shown in Figure 51 for sectoral composition of total final energy consumption between 2007 and 2040. However, the contribution of the transport sector declines slightly from about 36% in 2007 to about 35% in 2040 in both scenarios. Thus, the variants in socio-economic growth do not significantly result in sectoral shifts in final energy consumption. The greatest increases in these shares under BAU conditions are in the residential sector (9% contribution to the total final energy consumption in 2007 and about 13% in 2040) and in the commerce sector, which made a 9% contribution to the total final energy consumption in 2007 and about 13% in 2040. In the industry sector, a growth of 217 PJ (high socio-economic growth) and 21 PJ (low socio-economic growth) can be seen, which, similar to the transport sector, is among the highest absolute increases among all demand sectors. In the transport sector, the total final energy consumption in the BAU_HG scenario rises from 271 PJ in 2007 to more than 500 PJ in 2040, which corresponds to an increase of about 88%. In the BAU_LG scenario, the increase in the final energy consumption of the transport sector is still significant at about 73 PJ (+27%).

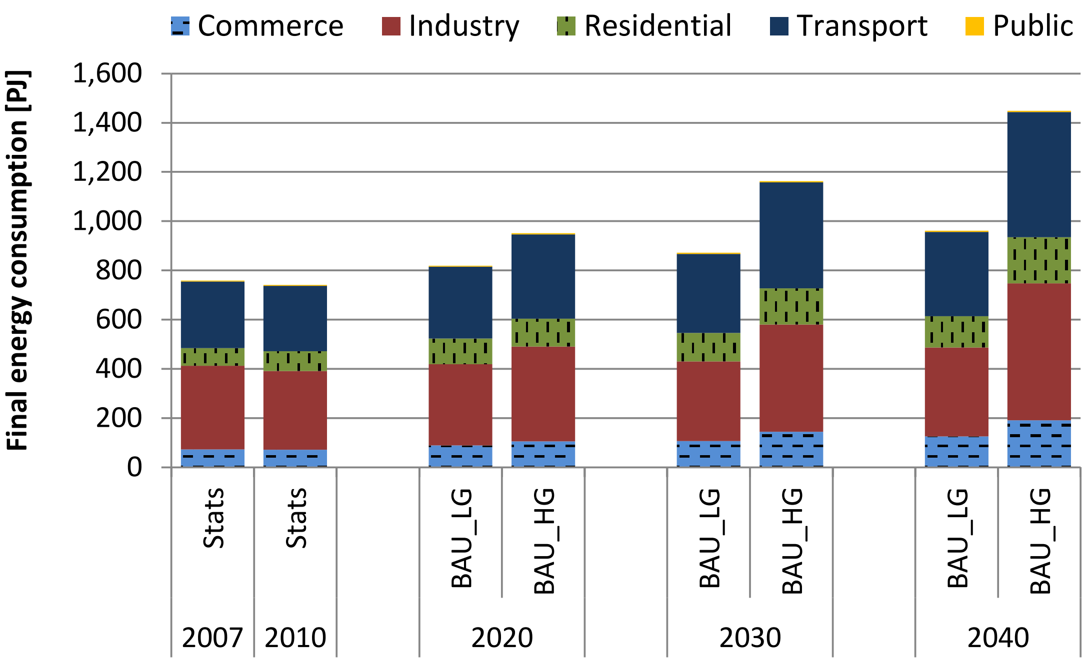


Figure 51: Total final energy consumption of Gauteng by sector under BAU scenario conditions between 2007 and 2040. Source: own calculations.

Figure 52 shows the final energy consumption of the transport sector in more detail. Given their minor energy consumption in relation to the total, the big bus, small bus and BRT modes have been aggregated into the category "buses". Freight and passenger rail including Gautrain are shown aggregated under "rail" in the figure.

Final energy consumption for motorized individual vehicles (i.e. passenger cars, SUVs and motorcycles, shown as hatched areas in the figure) is estimated to increase by 75% under high socio-economic growth conditions, from about 94 PJ in 2007 to more than 164 PJ in 2040. In the low socio-economic growth scenario, the increase is 13.6 PJ (+14%). Final energy consumption for public road transport (all buses, including minibuses), on the other hand, decreases from 24 PJ in 2007 to 20.5 PJ and 17.4 PJ in 2040 in BAU_HG and BAU_LG, respectively. The highest absolute increase is in road freight at 42.5 PJ (+50%) in the high socio-economic growth scenario for the period from 2007 to 2040.

Rail services are likely to remain insignificant under BAU scenario conditions in terms of their final energy consumption independently of socio-economic growth. In 2007, a final energy consumption of about 4.9 PJ for rail passenger, freight and the Gautrain is calculated. In 2040, this figure is 8.3 PJ for the high socio-economic growth scenario, to which the Gautrain contributes only 0.6 PJ. The corresponding final energy consumption under low socio-economic growth conditions is 6.6 PJ in 2040. However, passenger rail is seen to have a higher share in the final energy consumption in the BAU_LG scenario compared to BAU_HG, as the lower income groups (which are more reliant on rail transport) are represented more in the former scenario.

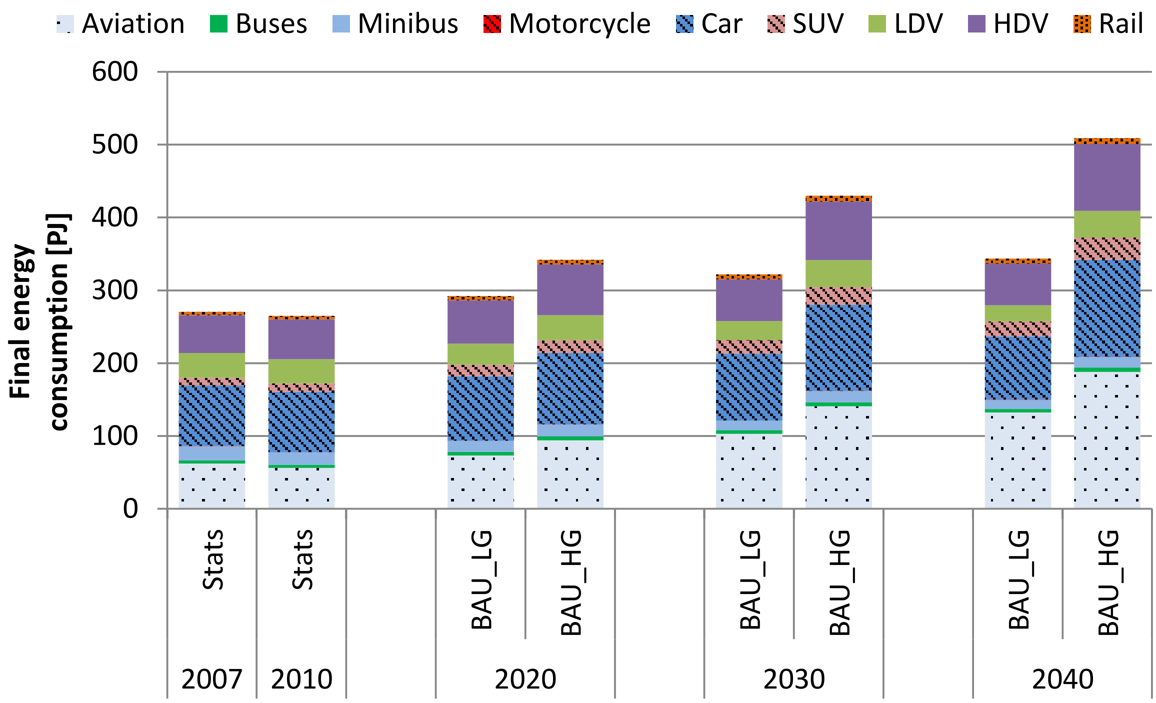


Figure 52: Final energy consumption of Gauteng by the transport sector by mode under BAU scenario conditions between 2007 and 2040. Source: own calculations.

Figure 52 illustrates the increase in final energy consumption for most transport modes, especially for SUVs (+90% and +190% for BAU_LG and BAU_HG), HDVs (+11% and +78% for BAU_LG and BAU_HG), motorcycles (+35% and +103% for BAU_LG and BAU_HG) and aviation (+113% and +203% for BAU_LG and BAU_HG) between 2007 and 2040. However, the final energy consumption for motorcycles increases significantly in relative terms; in absolute figures it remains negligible (0.2 PJ in 2007, and 0.3 PJ and 0.4 PJ in 2040 under low and high socio-economic growth conditions, respectively).

In absolute terms, the greatest increases in the BAU scenarios are for HDVs (+6 PJ / 40 PJ for BAU_LG / BAU_HG), aviation (+70 PJ / 126 PJ for BAU_LG / BAU_HG) and passenger cars (+4 PJ / 50 PJ for BAU_LG / BAU_HG). The only mode showing a notable decrease in final energy consumption in both scenarios is minibuses (–7 PJ in BAU_LG and –5 PJ in BAU_HG), which is due to declining specific fuel consumption as old vehicles are replaced and the assumption of an increasing occupancy rate as a result of the minibus taxi recapitalization programme (see section 2.2.4).

Given that the transport demand increase is higher than that in final energy consumption (see section 6.2.3), a significant decrease in specific final energy consumption can be noted as depicted in Figure 53 for road and rail transport. As shown, in the year 2007 the average energy consumption by road and rail passenger transport was about 3.9 MJ/vkm. The corresponding figure for freight transport was 7.5 MJ/vkm on average. By 2040, those figures are found to improve in both scenarios.

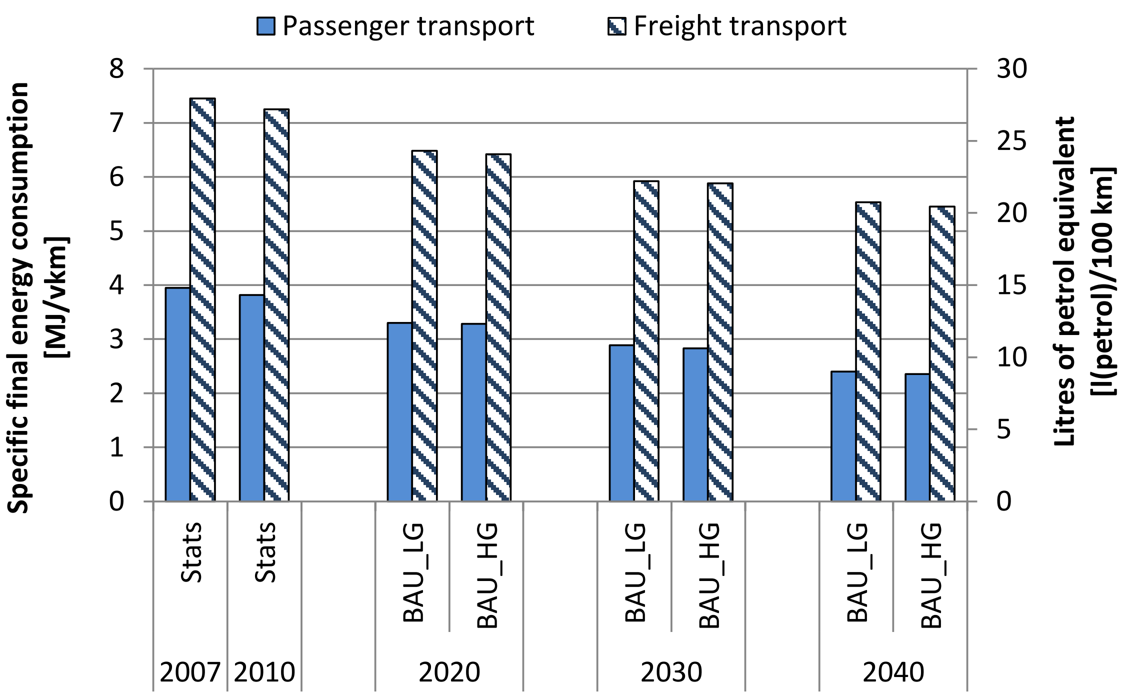


Figure 53: Specific final energy consumption by the transport sector of Gauteng under BAU scenario conditions from 2007 to 2040. Source: own calculations.

The figures are slightly different between the two reference scenarios due to the different modal split. Average energy consumption for freight transport in BAU_HG reduces to 5.4 MJ/vkm (5.5 MJ/vkm in BAU_LG), whereas that for passenger transport declines to about 2.4 MJ/pkm in both scenarios. This means that the expected improvements in the passenger sector are greater than those for freight transport as passenger transport consumes about 39–40% less energy per vkm in 2040 than in 2007 and freight transport 26–27% less per vkm, respectively. However, this is not sufficient to prevent the significant growth in final energy consumption.

If total final energy consumption in the transport sector is analysed in terms of used energy carriers, the dependence on fossil energy becomes obvious (Figure 54). The consumption of diesel from crude oil increases from 41 PJ in 2007 to 104 PJ under high socio-economic growth conditions, and to 44 PJ in the low socio-economic growth scenario. The consumption of petrol based on crude oil decreases in the low socio-economic growth scenario from 99 PJ in 2007 to 65 PJ in 2040. In the BAU_HG scenario, an increase of about 15 PJ is calculated. Kerosene consumption, which is used in aviation, grows significantly from 62 PJ in 2007, to 132 PJ and 188 PJ in 2040 for BAU_LG and BAU_HG, respectively.

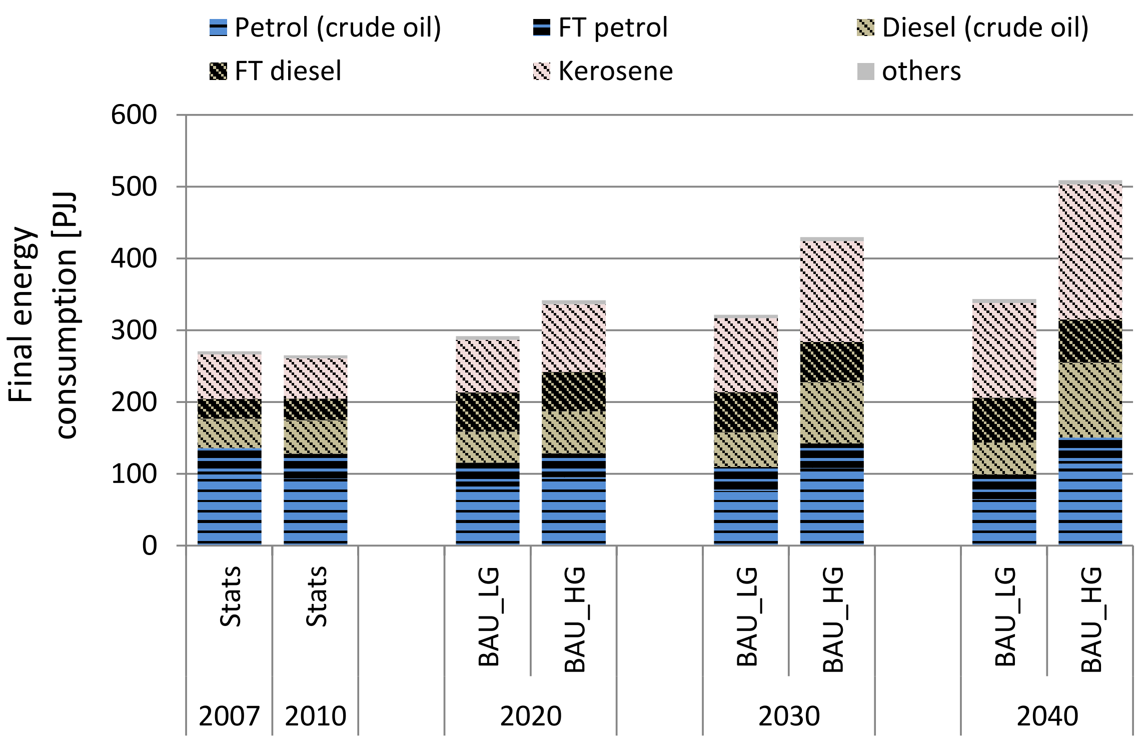


Figure 54: Final energy consumption by the transport sector of Gauteng by energy carrier under BAU scenario conditions between 2007 and 2040. “Others” comprise biodiesel and electricity. Source: own calculations.

In total about 102–103 PJ of transport fuels not based on crude oil is used in the BAU scenarios in 2040 – which is a significant increase – compared to only 69 PJ consumed in the transport sector in 2007. As the absolute contribution is almost equal under both socio-economic growth conditions, the relative share of alternative fuels is significantly higher in BAU_LG at about 30% compared to about 20% in BAU_HG. The use of transport fuels not based on crude oil under the conditions of the reference scenarios depends mainly on synthetic Fischer-Tropsch fuels, which are found to remain significant as a share of transport fuel consumption at about 97 PJ in 2040 independently from the socio-economic framework. In the BAU scenarios, the consumption of synthetic gasoline is found to remain relatively stable at about 37 PJ in 2007 and 35 PJ in BAU_LG (36 PJ in BAU_HG) in 2040. On the other hand, the use of synthetic diesel increases significantly to 61–62 PJ in 2040 (about 28 PJ in 2007). In the low socio-economic growth scenario, this corresponds to an increased share in transport's final energy consumption of 18% in 2040 compared to 10% in 2040. Gaseous fuels and LPG are not used in the transport sector under reference scenario conditions. Energy crops and ethanol from lignocellulosic biomass are not used for biofuel provision in the business-as-usual scenarios as well. However, small amounts of biodiesel from waste cooking oil are consumed, i.e. 0.2 PJ initially in 2020.

The Fischer-Tropsch synthetic fuels originate mainly from fossil sources, the foremost being coal. The sources of synthetic fuels are similar under low socio-economic growth and high socio-economic growth conditions. However, the total magnitude is lower in the BAU_LG scenario at about 97 PJ in 2040 compared to about 102 PJ in the BAU_HG scenario for the same year. In 2007 about 64 PJ of synthetic fuels were consumed. The provision of Fischer-Tropsch synthetic fuels is illustrated for the years 2007 and 2040 of the BAU_HG scenario in Figure 55.

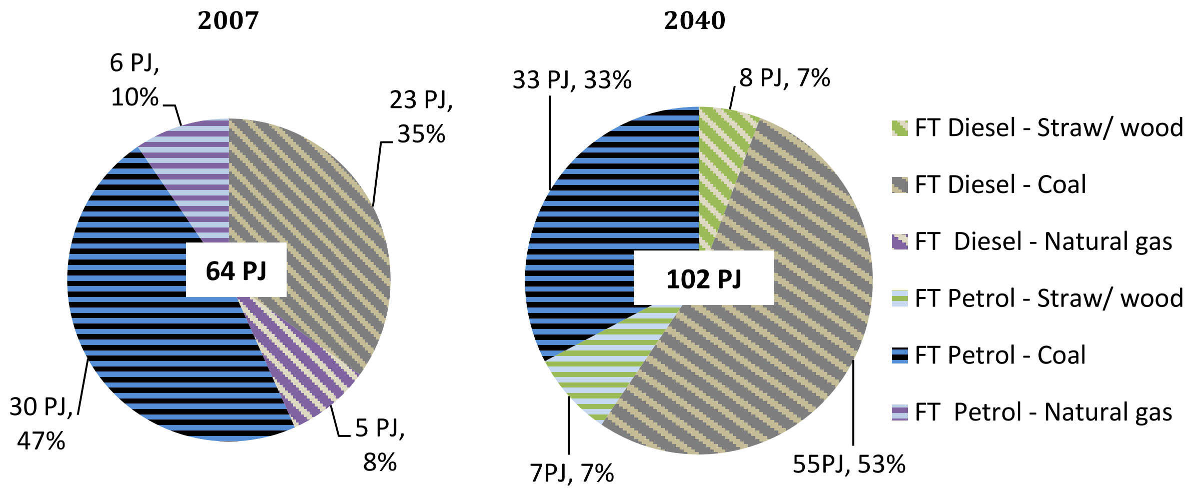


Figure 55: Final energy consumption by the transport sector of Gauteng for Fischer-Tropsch fuels between 2007 (left) and 2040 under BAU_HG scenario conditions (right). Source: own calculations.

About 88 PJ of coal-based synthetic fuels are being consumed in 2040 in both reference scenarios, which is a result of expanded synthetic fuel capacities in CTL coming onstream in 2020 by virtue of the construction of the Mafutha project (see section 5.1.2). These additional capacities are without CCS under BAU scenario conditions. From 2020 onwards, no GTL fuels are being used and the residual capacities will have reached the end of their lifetime. No additional GTL capacities are being built under least-cost conditions. In addition, smaller amounts of BTL are anticipated to be consumed in 2040. These are about 14 PJ in the BAU_HG scenario as shown in Figure 55 and about 9 PJ in the BAU_LG scenario

6.2.3 Transport vehicle powertrain use and vehicle activity

The vehicle technology used is comparable in both socio-economic growth scenarios; vehicles running on ICEs remain the dominant technology until 2040 (Figure 56). In fact, only about 9,300 vehicles using non-conventional ICE powertrains operate in 2040 under the conditions of the BAU_LG scenario and approximately 11,300 in the BAU_HG scenario. This is about 0.2% of the total fleet in both cases. Those powertrain technologies have been aggregated to "other" in the figure because of their small numbers.

The most important alternative vehicle technology considered in the reference cases is the diesel–mild hybrid CI that is used for public buses. Additionally, some vehicles are using (biodiesel) B100–ICE CI engines to accommodate the biodiesel utilized in the transport sector. This has been done for BRT buses, which offers advantages due to its comparatively great annual mileage.

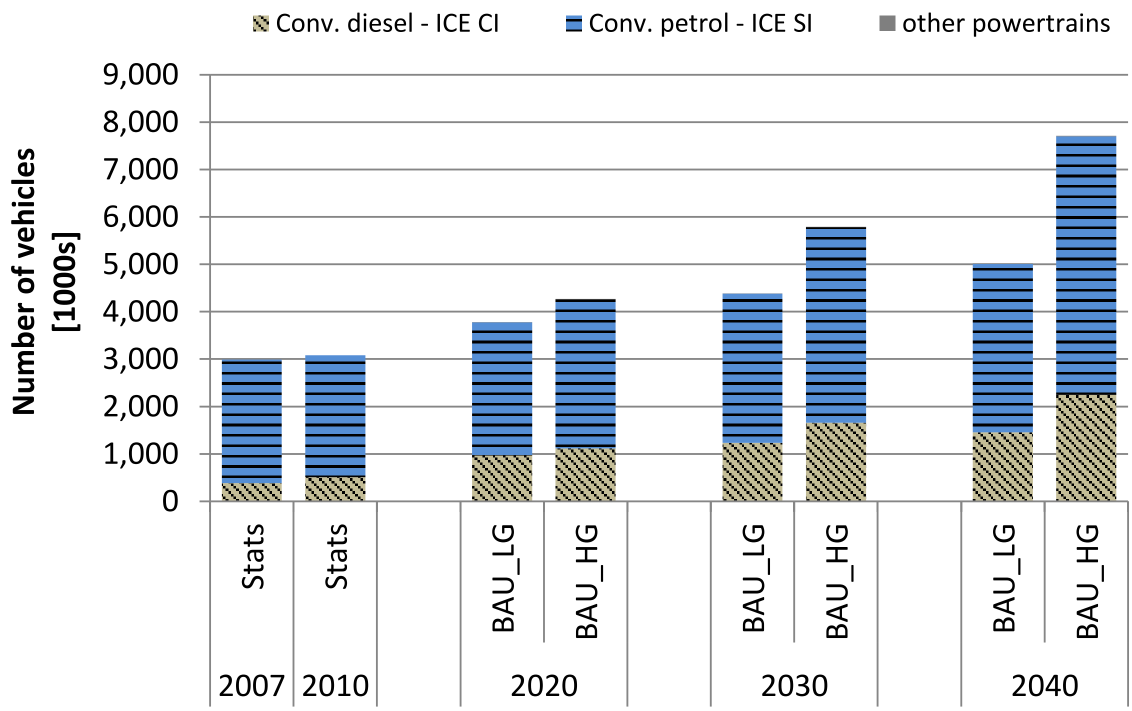


Figure 56: Vehicle fleet in Gauteng by technology in terms of number of vehicles under BAU scenario conditions from 2007 to 2040. Source: own calculations.

The highest growth in powertrains used in the vehicle fleet is that of conventional diesel–ICE vehicles, which increase from 13% of the total (about 388,000 vehicles in 2007) to about 29% of the fleet in 2040 in the BAU scenarios. This growth corresponds to more than 1.4 million and more than 2.2 million vehicles in the low and high socio-economic growth scenarios, respectively. The growth in diesel–ICE CI is determined by the assumptions about the future market penetration of such engines (see section 6.1.3). The share of conventional petrol–ICE SI vehicles, on the other hand, declines considerably from 87% in 2007 to 71% in 2040 under the conditions of the reference scenarios. Nonetheless, the absolute number of petrol-fuelled vehicles is seen to increase by 37% to about 3.5 million vehicles in 2040 under low socio-economic growth conditions and by 110% to about 5.4 million vehicles under high socio-economic growth. In total, there will be 5.0 million and 7.7 million road vehicles in 2040 in the BAU_LG and BAU_HG scenarios, respectively.

As a result, vehicle activity, in terms of vkm, increases from $42.4\cdot10^9$ vkm in 2007 to $105.0\cdot10^9$ vkm in 2040 (+147%) under the high socio-economic growth conditions of the reference case (BAU_HG, Figure 57). In BAU_LG the increase in total vkm is also significant (i.e. $68.8\cdot10^9$ vkm in 2040, +62%), although considerably lower than in the case of high socio-economic growth. In both cases, no further (explicit) expansions of the BRT in Johannesburg or in Tshwane or of the Gautrain railway system occur under least-cost conditions (see section 4.3). The conversion of existing lines to trolley-buses, which is also considered as an explicit model option, is also not taking place under the conditions of the BAU scenarios, too. In the figure small, big and BRT buses have been aggregated to the single category “buses”. The Gautrain as well as passenger and freight rail are combined in the category “rail” in Figure 57.

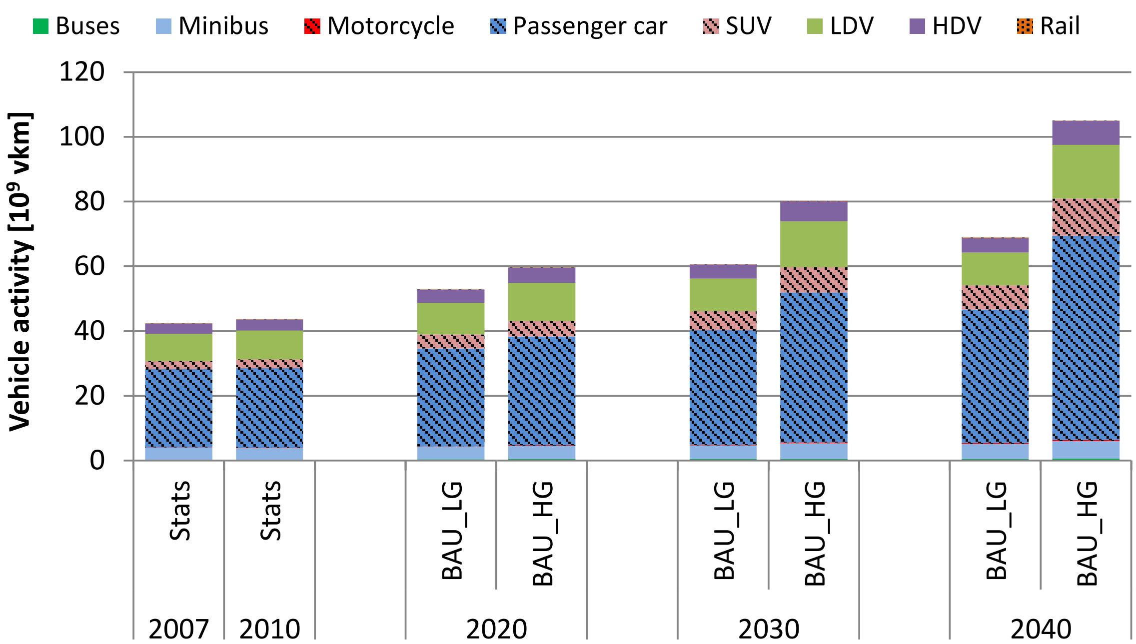


Figure 57: Vehicle activity in Gauteng in the reference scenarios by mode of transport between 2007 and 2040. Source: own calculations.

Under reference scenario conditions the major share of the growth in travel demand is in individual private transport (i.e. passenger cars, SUVs and motorcycles, which are shown as hatched areas in Figure 57). Individual transport increases its share of total vehicle activity from 63% in 2007 to 71% in BAU_LG and BAU_HG. Minibuses contributed about 9% to the vehicle activity in 2010. In the BAU scenarios the share decreases to 5% in BAU_HG and 7% in BAU_LG, due to only modest absolute growth in minibuses (+26% in BAU_LG and +46% in BAU_HG). Public buses and BRT continue to make a small contribution (less than 1%) in the reference scenarios. Significant future growth is probable for road freight transport also, which increases from about $11.7 \cdot 10^9$ vkm in 2007 to $14.7 \cdot 10^9$ vkm and $24.0 \cdot 10^9$ vkm in BAU_LG and BAU_HG, respectively.

Figure 58 disaggregates vehicle kilometres for road transport by technology for the year 2040. In this figure, vkm for buses (including both small and big buses and the BRT) have been aggregated. Due to their negligible vehicle activity, motorcycles have been excluded from the figure. In both socio-economic growth scenarios, the relative shares of vehicle technology application are similar. The greatest proportion of conventional petrol–ICE SI engines are used for passenger cars. Vehicles using conventional petrol–ICE SI engines represent about 85% of the vehicle activity for passenger cars in 2040. This corresponds to about $35.1 \cdot 10^9$ vkm and $53.6 \cdot 10^9$ vkm for the low and high socio-economic growth scenarios, respectively. For the other modes, higher shares of conventional diesel–ICE CI powertrains are probable. Conventional diesel–ICE CI engines correspond to about $24.1 \cdot 10^9$ vkm and $36.7 \cdot 10^9$ vkm in BAU_LG and BAU_HG in 2040, respectively

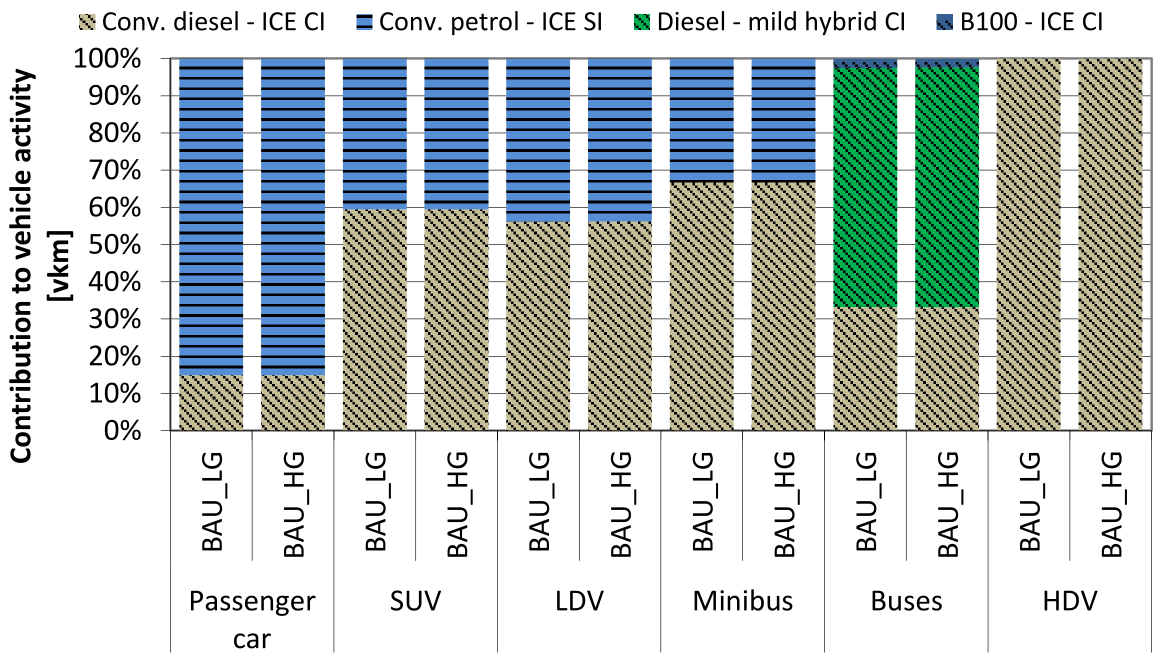


Figure 58: Contribution to vehicle kilometres of road transport in Gauteng by technology and mode for the year 2040 under BAU scenario conditions. The figure legend shows only those powertrains that are represented in results.
Source: own calculations.

Furthermore, in 2040 most buses in the reference scenarios are mild hybrid CI vehicles that use diesel. The contribution of mild hybrids to vehicle activity in respect of buses is likely to be 64% under business-as-usual conditions. However, the share in total vehicle actively remains below 1%. Additionally, B100–ICE CI powertrains are applied in the bus category (i.e. for BRT), but the total contribution to vehicle activity remains negligible.

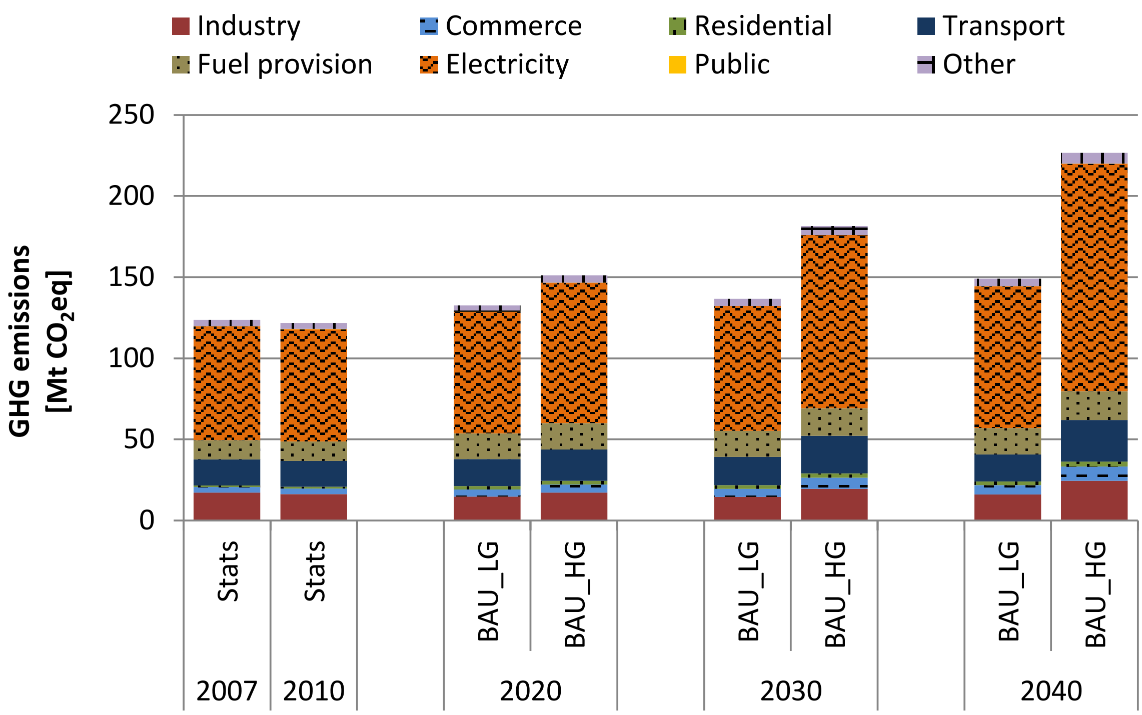
6.2.4 Emissions

The growth in energy consumption and the great dependence on fossil fuels results in an increase in GHG emissions attributable to Gauteng. Under the conditions of the BAU scenarios, GHG emissions increase from about 123 Mt CO_2eq in 2007 to about 227 Mt CO_2eq in 2040 (+84%) and to 149 Mt CO_2eq (+21%) for the high socio-economic growth and low socio-economic growth BAU scenarios, respectively (Figure 59). A major contributor to GHG emissions is the electricity sector. Its GHG emissions increase from about 70 Mt CO_2eq in 2007 to about 140 Mt CO_2eq in 2040 in the high socio-economic growth scenario and to about 87 Mt CO_2eq in BAU_LG.

Other major contributors in 2040 are industry (16 Mt CO_2eq for BAU_LG and 241 Mt CO_2eq in BAU_HG), transport (about 17 Mt CO_2eq in BAU_LG and about 26 Mt CO_2eq in BAU_HG), and fuel provision (16 Mt CO_2eq in BAU_LG and 18 Mt CO_2eq in BAU_HG). Direct residential GHG emissions remain insignificant and stay below 3 Mt CO_2eq in 2040 in both scenarios. The GHG emissions in the commerce sector increase by about 67% and by 154% in BAU_LG and in BAU_HG, respectively. The public sector is responsible for minor GHG emissions (< 0.1 Mt CO_2eq) as it does not consume large amounts of energy, of which most is electricity (Figure 59).

As shown in Figure 59, further GHG emissions are related to the provision of primary energy, principally coal and natural gas; and to other conversions of energy carriers (e.g. coking coal). In 2040, those GHG emissions contribute about 7 Mt CO_2eq (BAU_HG) to the total GHG emissions, which is an increase of almost 3 Mt, or 80%, compared to 2007.

Sectoral contributions to total GHG emissions change under the conditions of the reference scenarios. Whereas the electricity sector contributes about 57% to total GHG emissions in 2007, the share increases to 59% in BAU_LG and to 62% in BAU_HG. The GHG emissions from fuel provision, on the other hand, are 8% (BAU_HG) and 11% (BAU_LG) of total GHG emissions in 2040, and were 10% of total emissions in 2007. The share of GHG emissions of the transport sector in total GHG emissions decreases under the conditions of the reference scenarios (i.e. from 13% in 2007 to about 11% in the BAU_HG BAU_LG scenarios in 2040), independently from the assumptions for the socio-economic framework.



Other concludes non-electricity energy conversion (e.g. coking) and primary energy provision.

Figure 59: Greenhouse gas emissions by sector attributable to Gauteng under BAU scenario conditions from 2007 to 2040. Source: own calculations.

Tank-to-wheel (TTW) GHG emissions of the transport sector, differentiated by mode, are shown in Figure 60. In the figure the modes small, big and BRT buses have been aggregated as the single category “buses”. The category “rail” incorporates the Gautrain as well as passenger and freight rail. It can be seen that TTW GHG emissions under BAU scenario conditions increase from 16.1 Mt CO_2eq in 2007 to 25.7 Mt CO_2eq (+60%) and to 16.7 Mt CO_2eq (+4%) in 2040 for BAU_HG and BAU_LG, respectively. Given the calculated increase in vehicle activity (+62% in BAU_LG and +147% in BAU_HG, see section 6.2.3), it is obvious that the improvements due to investments in new vehicles (section 5.2.7) slow the growth in TTW GHG emissions, but do not stop it.

A major contributor to GHG emissions in the transport sector is private transport (displayed as hatched areas in the figure) at 11.6 Mt CO_2eq (BAU_HG) and 7.4 Mt CO_2eq (BAU_LG) in 2040 (6.8 Mt CO_2eq in 2007). Most of these emissions are due to passenger car transport (9.5 Mt CO_2eq and 6.2 Mt CO_2eq for BAU_HG and BAU_LG, respectively, in 2040). TTW GHG emissions from road freight transport are also seen to be significant in 2040 at 9.2 Mt CO_2eq (for BAU_HG) and 5.7 Mt CO_2eq (for BAU_LG) in 2040, which equals an increase of 47% in the high socio-economic growth scenario. In BAU_LG, on the other hand, TTW GHG emissions from freight transport decrease by about 9%.

The remainder of total transport TTW GHG emissions consists mainly of aviation (3.5 Mt CO_2eq in BAU_HG and 2.5 Mt CO_2eq in BAU_LG in 2040) and minibuses (about 1 Mt CO_2eq in 2040). The highest relative growth in road GHG emissions is calculated for

SUVs and motorcycles, which increase by about 163% and 102% in the high socio-economic growth scenario. However, as for energy consumption (see section 6.2.1), absolute GHG emissions from motorcycles remain negligible at less than 0.1 Mt CO_2eq in 2040. Under business-as-usual conditions, TTW GHG emissions from minibus transport in the BAU scenarios decline from about 1.4 Mt CO_2eq in 2007 to 1.1 Mt CO_2eq (in BAU_HG) and to 0.8 Mt CO_2eq (in BAU_LG) in 2040. The BRT, which is used from 2010 onwards (see section 2.2.2), contributes less than 0.1 Mt CO_2eq in 2040 to total GHG emissions in both scenarios.

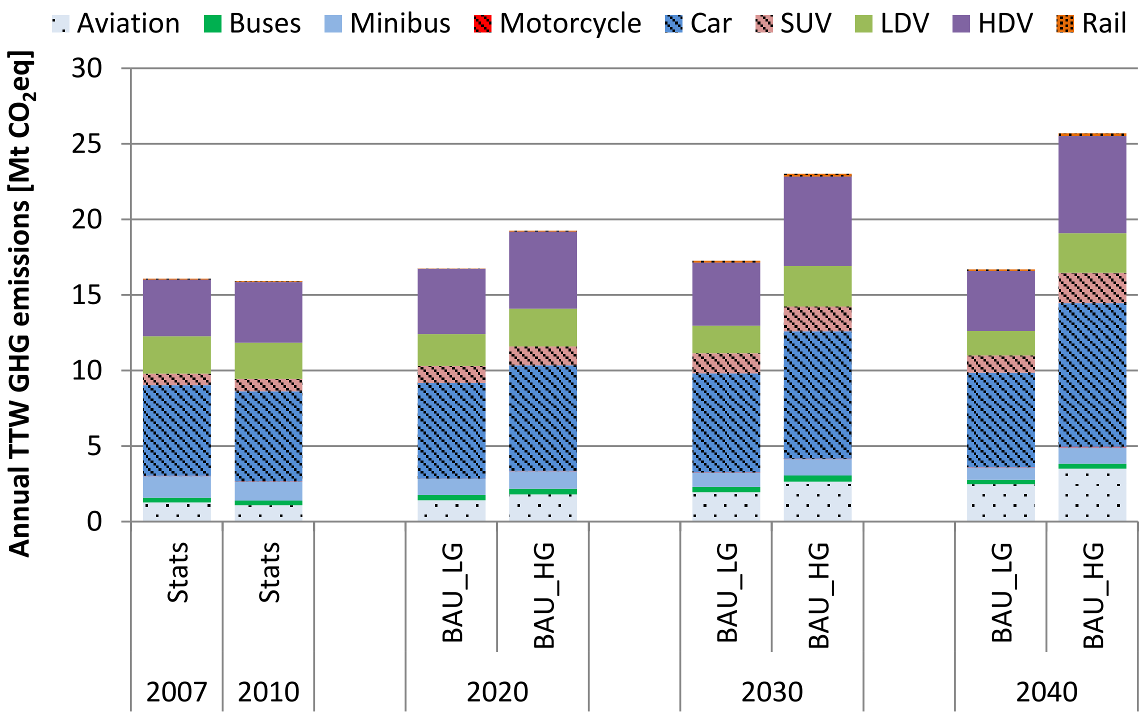


Figure 60: TTW greenhouse gas emissions generated by the transport sector of Gauteng under BAU scenario conditions between 2007 and 2040.
Source: own calculations.

Specific TTW emissions in the transport sector decline from 349.9 g CO_2eq/km for road and rail transport in 2007 to 206.8 g CO_2eq/km in BAU_LG and to 211.8 g CO_2eq/km in BAU_HG. This corresponds to a reduction in specific TTW GHG emissions of 39–41%. The decline is a result of the improvement in vehicle technologies (see section 5.2) and the renewal of the fleet, as old vehicles have to be replaced (see section 3.4). Figures for the two reference scenarios are slightly different for 2040, due to the different assumptions for socio-economic growth and changed modal split (see section 3.1.3).

Figure 61 shows the well-to-wheel (WTW) GHG emissions of the transport sector, which include those GHG emissions from energy provision that are attributable to the transport sector. In total, WTW GHG emissions are about twice as much as TTW GHG emissions. In 2007 about 32.8 Mt CO_2eq WTW GHG emissions was generated. Under the conditions of the reference scenarios, the figure increases to 38.5 Mt CO_2eq and to 51.5 Mt CO_2eq in BAU_LG and BAU_HG, respectively.

As shown in Figure 61, a significant proportion of transport WTW GHG emissions is due to the production of fossil Fischer-Tropsch fuels (between 27% and 37% over the time horizon analysed). Furthermore, GHG emissions due to electricity provision for the transport sector (i.e. for rail transport, and for auxiliary energy consumption of fuel providing technologies) account for about 11–13% of WTW GHG emissions in the reference scenario. WTW GHG emissions from crude oil refining of fuels used in the Gauteng transport sector increase from 1.6 Mt CO_2eq in 2007 to 2.0 Mt CO_2eq in the BAU_LG scenario and to 3.3 Mt CO_2eq in BAU_HG in 2040.

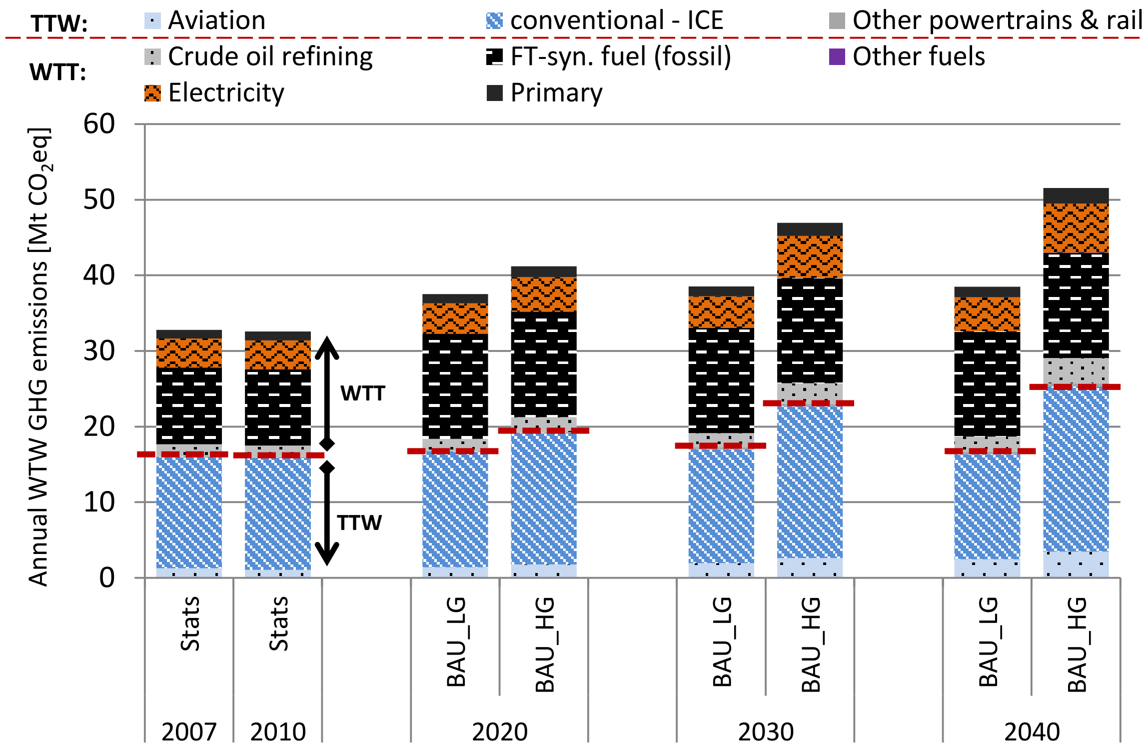


Figure 61: WTW greenhouse gas emissions attributable to the transport sector of Gauteng under BAU scenario conditions between 2007 and 2040. Other powertrains comprise B100–ICE CI and CNG–ICE SI. Source: own calculations.

Figure 62 shows non-GHG TTW emissions for the road transport sector in Gauteng for the reference scenario. A clear reduction of non-GHG emissions is evident for all pollutants analysed. This is due to the province's ageing baseline vehicle fleet with its higher shares of vehicles subject to older emission standards (see section 3.4 and section 2.1.2).

Hydrocarbon and CO emissions decline by about 94–99% in 2040 compared to the base year of 2007. NO_x emissions fall from 101 kt in 2007 to about 27 kt in BAU_LG and 44 kt in BAU_HG. The reduction of SO_2 emissions between 2007 and 2040 is about 77% in BAU_HG and 87% in BAU_LG. Particulate matter in 2040 is 0.4 kt for BAU_LG and 0.7 kt for BAU_HG. Most of these reductions are likely until the year 2030 when the baseline fleet of 2007 is replaced with new vehicles. After 2030, non-GHG emissions increase slightly again in the high socio-economic growth scenario, due to the increase in vehicle travel.

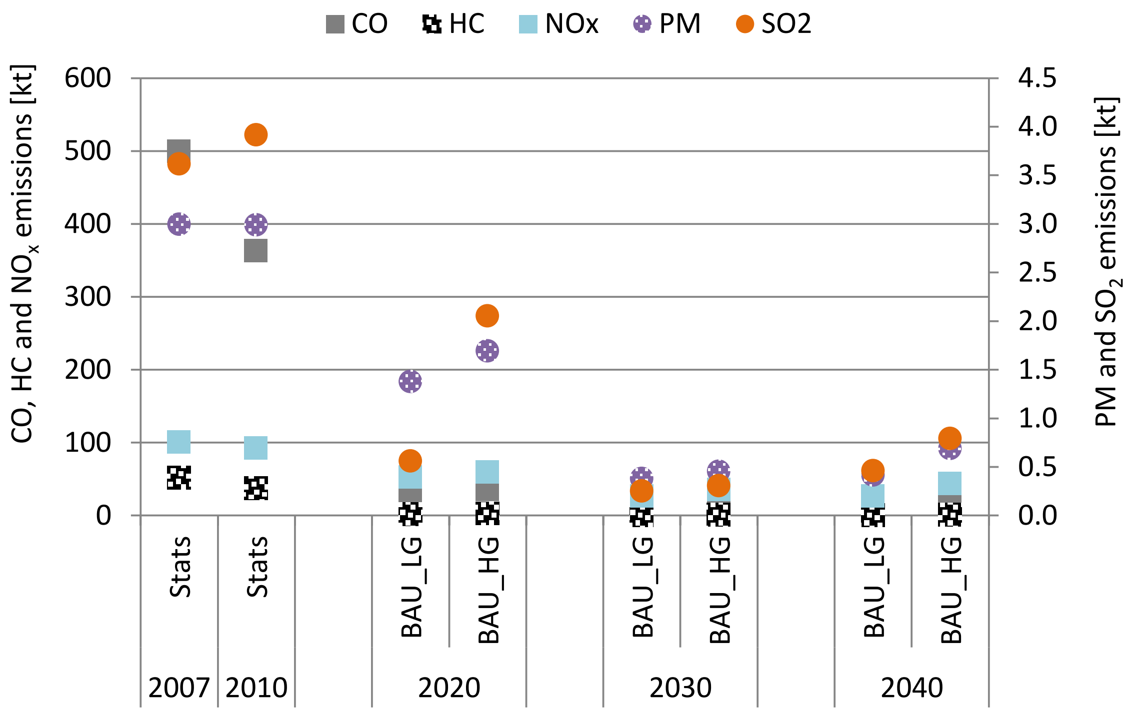


Figure 62: Non-GHG TTW emissions of road transport in Gauteng under BAU scenario conditions between 2007 and 2040. Source: own calculations.

6.3 Model results: GHG tax – The role of the transport sector in GHG mitigation

In this section, the role of the transport sector in addressing GHG reduction targets is presented by analysing how the energy provision, consumption and related GHG emissions of the transport sector change if GHG taxes are introduced as part of the energy system. Furthermore, it will be shown which GHG mitigation measures are to be implemented.

To generate MACCs for GHG emissions, 18 model runs per scenario are performed with GHG taxes from 25 ZAR_{2007}/t CO_2eq to 2,500 ZAR_{2007}/t CO_2eq. Smaller steps are chosen for the lower GHG taxes as most changes in the energy system are expected there. Taxes have been applied system-wide to CO_2, CH_4 and N_2O emissions and have been compounded to the base year at an interest rate of 8%, which is inherent to TIMES-GEECO. The GHG taxes have been introduced in the model from the year 2018 onwards.

The results are presented to show the differences from the reference cases of section 6.2. The positive values in the figures indicate the alternative technologies applied under GHG taxes, whereas the negative values show which technologies previously used in the reference scenarios are replaced. Detailed results are shown for high socio-economic growth conditions as this scenario represents higher transport energy consumption and emissions. The low socio-economic growth scenario is presented for comparison in a more aggregated form.

6.3.1 Transport final energy consumption and provision

Figure 63 presents the final energy consumption in the Gauteng transport sector in 2040 for the GHG_HG scenario. All the results shown express changes from the reference scenario (BAU_HG) in 2040 if the GHG taxes indicated are applied.

Biodiesel (i.e. 10.6 PJ) substitutes for crude oil-based diesel in the first step (i.e. 25 ZAR_{2007}/t CO_2eq). For GHG taxes of 150 ZAR_{2007}/t CO_2eq to 250 ZAR_{2007}/t CO_2eq, additional biodiesel (i.e. 5.8–6.2 PJ) is used in the system and the consumption of diesel (from crude oil refining) is slightly reduced further. However, the situation changes for a GHG tax of 300 ZAR_{2007}/t CO_2eq, when ethanol displaces some biodiesel. The energy yield per hectare is significantly higher for sugar cane (see section 5.1.6). The contribution of ethanol from sugar cane is therefore greater than for biodiesel and the equivalent of about 29 PJ is produced.

Additionally, the consumption of synthetic fuels from biomass (i.e. BTL) increases to 22 PJ from 9 PJ without GHG taxes (see section 6.2.2) at marginal abatement costs of 25 ZAR_{2007}/t CO_2eq. Beginning with GHG abatements costs of 50 ZAR_{2007}/t CO_2eq, fossil Fischer-Tropsch synthetic fuels are replaced in the GHG_HG scenario. To do so, crude oil-based fuels (i.e. petrol and diesel) and additional BTL from cellulosic biomass are used. The substitution of fossil Fischer-Tropsch synthetic fuels is completed at a GHG abatement cost of 100 ZAR_{2007}/t CO_2eq and the potential for BTL from straw and wood is exhausted.

Beginning at a marginal abatement cost of 200 ZAR_{2007}/t CO_2eq, 0.6 PJ SNG are provided via upgrading gas from landfill sites. Further amounts (i.e. additional 1.1 PJ) of SNG are provided from upgrading gas from sewage plants at a marginal abatement cost of 250 ZAR_{2007}/t CO_2eq, which is again used initially for electricity provision.

From 300 ZAR_{2007}/t CO_2eq onwards, the consumption of petrol and diesel in the Gauteng transport sector is reduced continuously. At a marginal abatement cost of 600 ZAR_{2007}/t CO_2eq, the electricity consumption for transport begins to increase.

At a marginal GHG abatement cost of 600 ZAR_{2007}/t CO_2eq, 14 PJ hydrogen is consumed in the transport sector. The amount of hydrogen used then continuously increases. For a GHG tax of 1,000 ZAR_{2007}/t CO_2eq, the consumption of diesel and petrol (from the refining of crude oil) is reduced by 39% in comparison with the BAU_HG reference scenario in 2040. Under a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, further hydrogen is provided, which replaces Fischer-Tropsch fuels from cellulosic biomass (i.e. BTL process). Hydrogen consumption increases to about 105 PJ at a marginal GHG abatement cost of 2,500 ZAR_{2007}/t CO_2eq and thus it further replaces petrol and diesel derived from crude oil. The total final energy consumption of the transport sector is reduced by about 78 PJ to about 431 PJ at a marginal GHG abatement cost of 2,500 ZAR_{2007} compared to the BAU_HG scenario at about 509 PJ in 2040.

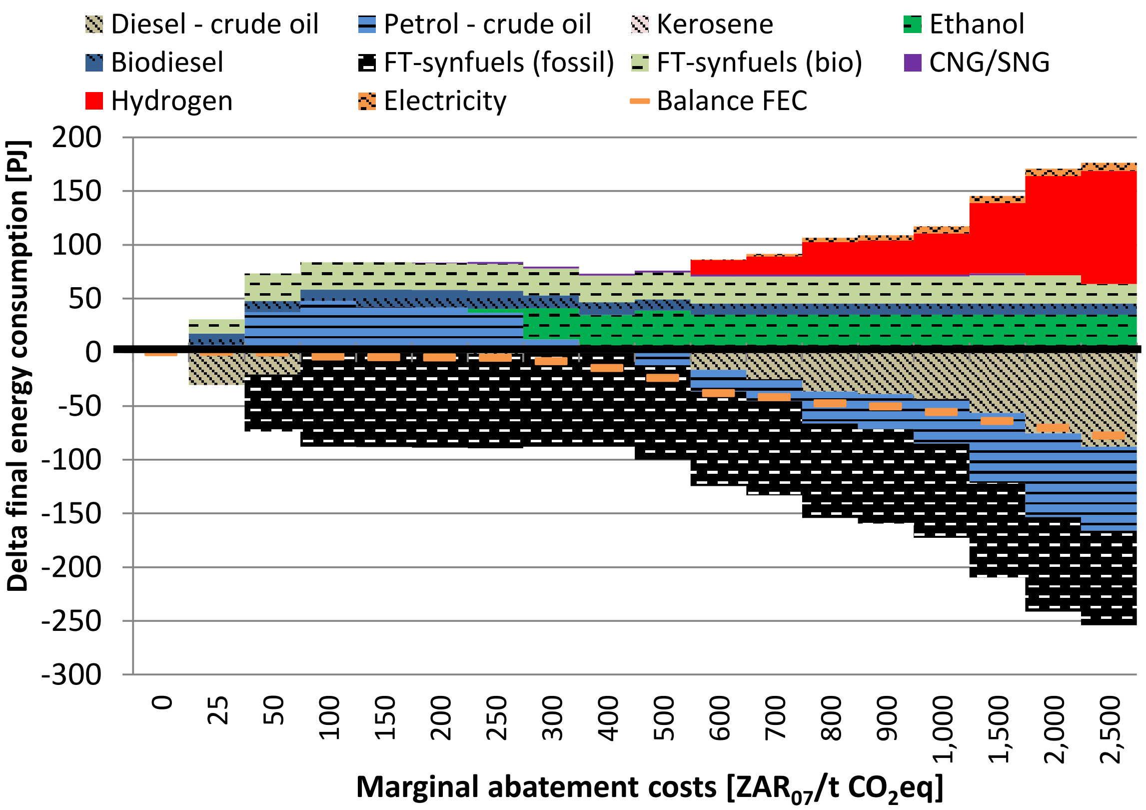


Figure 63: Final energy consumption in the transport sector of Gauteng compared to the reference scenario in 2040 (BAU_HG). Source: own calculations.

The final energy consumption of the transport sector in the GHG_LG scenario is similar to that in the GHG_HG scenario in terms of the energy carriers used, although some differences can be identified (Figure 64). As for the high socio-economic growth marginal abatement costs curve, fossil Fischer-Tropsch synthetic fuels of the reference scenario are fully replaced at marginal abatement costs of 100 ZAR_{2007}/t CO_2eq, and the final energy consumption of crude oil-based petrol and diesel as well as the consumption of synthetic fuels from biomass (i.e. BTL) is increased. However, under low socio-economic growth, additional synthetic fuels based on the CTL process are provided using carbon capture and storage (CCS) between marginal abatement cost of 100 to 600 ZAR_{2007}/t CO_2eq. The reason can be seen in the limited (annual) storage capacity for CO_2 (see section 5.1.4). In GHG_HG there is a greater need for electricity provision (e.g. in 2040 this is about 352 PJ in BAU_LG compared to 546 PJ in BAU_HG), which also uses coal with CCS and prevents CTL with CCS from coal CCS being used under high-socio-economic growth.

Consistent with the GHG_HG scenario, biodiesel consumption increases at marginal abatement costs of 25 ZAR_{2007}/t CO_2eq (to 10.8 PJ). In contrast to the GHG_HG scenario, the rises in final energy consumption of biodiesel as well as of ethanol can be identified at higher marginal abatement costs. Whereas final energy consumption of biodiesel is reduced to 12 PJ for a marginal abatement cost of 300 ZAR_{2007}/t CO_2eq in GHG_HG it remains at higher levels under low socio-economic growth till marginal abatement costs of 400 ZAR_{2007}/t CO_2eq. Ethanol is initially consumed at 300 ZAR_{2007}/t CO_2eq in GHG_LG whereas a similar final energy consumption is evident for GHG taxes of 250 ZAR_{2007}/t CO_2eq in the MACC under high socio-economic growth.

The most significant difference can be identified in the final energy consumption of hydrogen, which is already consumed at marginal abatement costs of 400 ZAR_{2007}/t CO_2eq in the GHG_LG scenario, whereas in the GHG_HG scenario no hydrogen is consumed at marginal abatement costs lower than 600 ZAR_{2007}/t CO_2eq. The hydrogen final energy consumption of the transport sector increases to 64 PJ under GHG emission taxes of 2,500 ZAR_{2007}/t CO_2eq. At this level of taxation the final energy consumption of the transport sector in 2040 is reduced by about 53 PJ compared to the GHG_LG scenario.

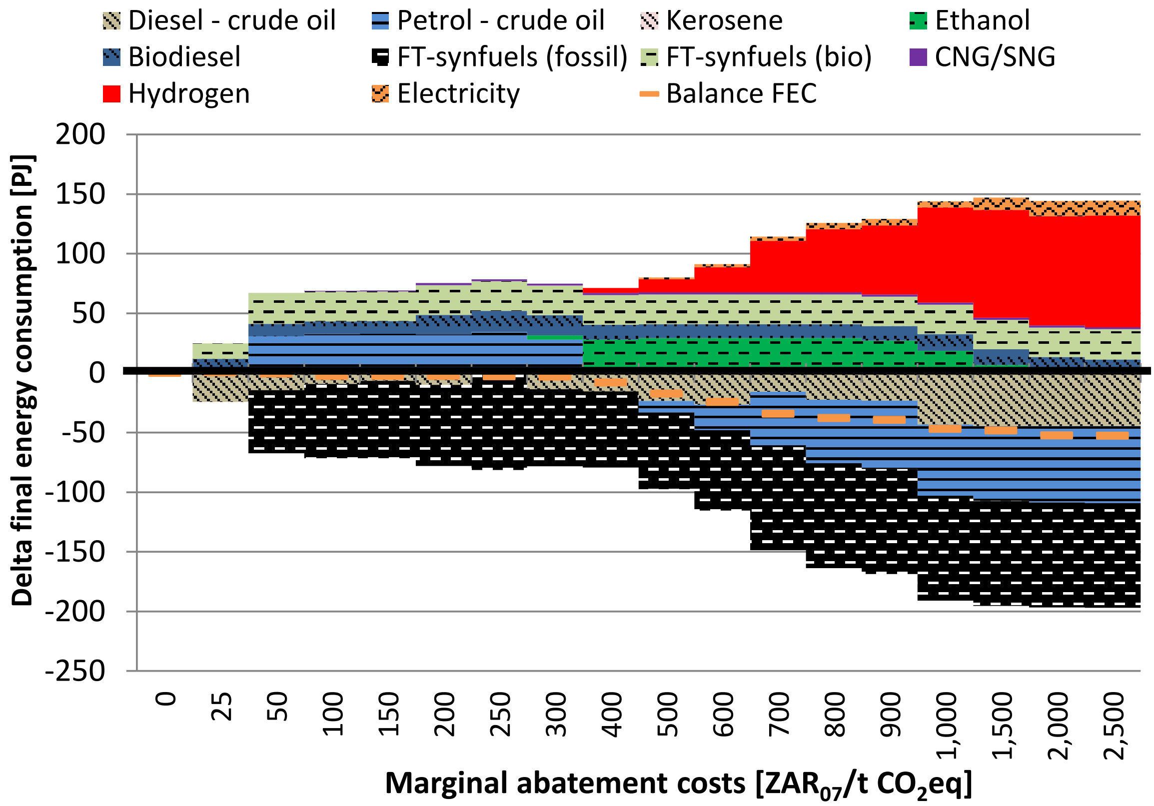


Figure 64: Final energy consumption in the transport sector of Gauteng compared to the reference scenario in 2040 (BAU_LG). Source: own calculations.

The differences in hydrogen provision between the GHG_HG and the GHG_LG scenarios are shown in Figure 65 for the year 2040 in terms of selected marginal abatement costs. Note that figures for hydrogen provision are obviously higher than for final energy consumption as losses occur in transportation and distribution (see section 5.1.9). In the GHG_HG scenario, hydrogen is initially supplied at a marginal GHG abatement cost of 600 ZAR_{2007}/t CO_2eq, via natural gas upgrading with CCS, which reaches about 96 PJ at a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq. The further increase in hydrogen provision under a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq is provided via biomass gasification and upgrading and thus replaces BTL as it competes for the same biomass potential. Hydrogen provision from biomass gasification is 11 PJ at a marginal

GHG abatement cost of 2,500 ZAR_{2007}/t CO_2eq. For this GHG tax, the total provision of hydrogen is 107 PJ under high socio-economic growth.

In the low socio-economic growth marginal abatement cost curve (GHG_LG), on the other hand, hydrogen is initially provided via coal gasification with CCS at a lower marginal abatement cost (i.e. 400 ZAR_{2007}/t CO_2eq). As for CTL with CCS, this is a result of the limited (annual) storage capacity for CO_2 that prevents hydrogen from coal with CCS being applied under high socio-economic growth. However, at a marginal abatement cost of 1,000 ZAR_{2007}/t CO_2eq the supply begins to change to natural gas reforming with CCS as in the high socio-economic growth scenario. At a marginal abatement cost of 2,000 ZAR_{2007}/t CO_2eq, hydrogen is provided only via the reforming of natural gas. In GHG_LG, biomass is not used as feedstock for hydrogen provision and thus the production of BTL does not have to be reduced for high marginal abatement costs; this explains why the consumption of first-generation ethanol declines with marginal abatement costs of 1,000 ZAR_{2007}/t CO_2eq and higher.

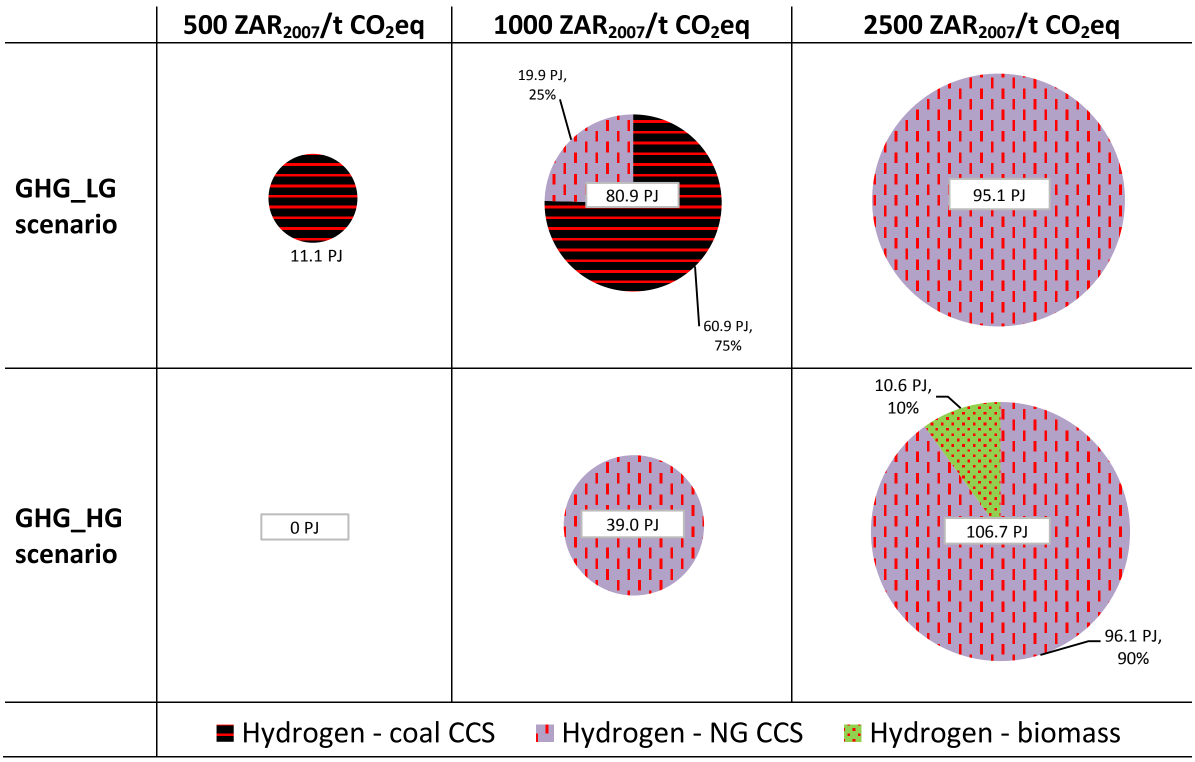


Figure 65: Hydrogen provision for the transport sector in 2040. Source: own calculations.

Electricity provision for the transport sector is depicted in Figure 66 for the GHG_HG scenario. Only the share of electricity provided to the transport sector is shown, which is about 1–3% of total electricity provision. In the reference scenario, electricity provision was mainly totally based on coal-fired power plants. However, even for very low marginal abatement costs (i.e. 25 ZAR_{2007}/t CO_2eq) this situation changes and alternative means of electricity provision are applied. At a marginal abatement cost of 600 ZAR_{2007}/t CO_2eq, the electricity provision for transport begins to increase as electricity is then also used for road transport (see section 6.3.2). Electricity provision reaches more than 14 PJ under a GHG tax of 2,500 ZAR_{2007}/t CO_2eq. In the low socio-economic growth scenario, on the other hand, electricity provision increases up to 18 PJ at a marginal abatement cost of 2,000 ZAR_{2007}/t CO_2eq, which is a result of the lower overall electricity consumption under low socio-economic growth, which allows for higher provision to the transport sector. However, the technologies to generate electricity have not changed between the GHG_LG and the GHG_HG scenarios.

The alternative technologies used for electricity provision are nuclear energy (which is already fully in the system at 50 ZAR_{2007}/t CO_2eq); coal-fired (integrated gasification combined cycle) power plants with CCS (which enters the system after the maximal new nuclear capacity is used up); and CSP combined with a parabolic trough with storage (where initial new capacities are built at 100 ZAR_{2007}/t CO_2eq). Furthermore, electricity is provided from landfill and sewage gas but reaches only 0.6 PJ.

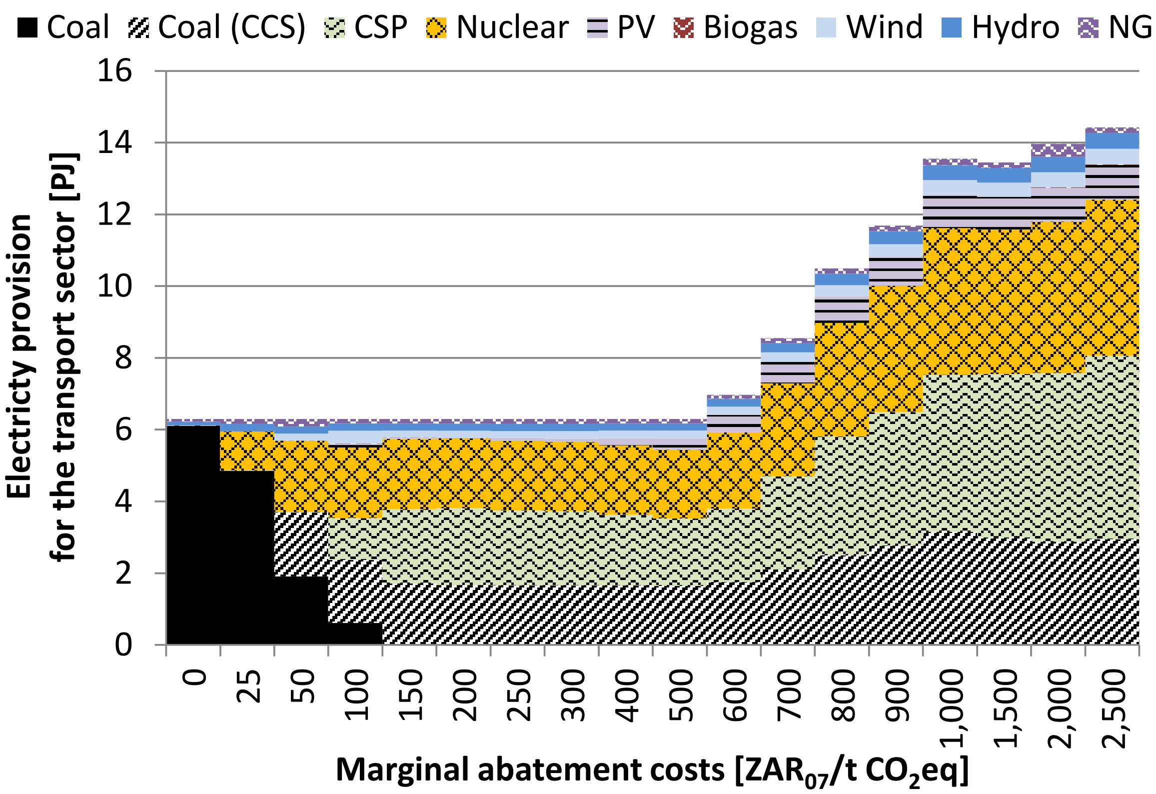


Figure 66: Electricity provision for the transport sector in the GHG_HG scenario in 2040. Source: own calculations.

The provision of first-generation biofuels (i.e. produced from energy crops or from waste cooking oil) is shown in detail in Figure 67 for the GHG_HG scenario in 2040. The initial provision of biodiesel (i.e. 0.2 PJ under reference scenario conditions) is based on waste cooking oil (produced within Gauteng) and is also used at all higher marginal abatement costs. Between GHG taxes of 150 ZAR_{2007}/t CO_2eq and 250 ZAR_{2007}/t CO_2eq, biodiesel is provided from rapeseeds (i.e. 5–6 PJ). However, the situation starts to change for a GHG tax of 250 ZAR_{2007}/t CO_2eq, when ethanol is produced from sugar cane. Both fuels are produced outside the province. As the available land area for cultivation of energy crops is limited for both South Africa and Gauteng (based on the assumption that a maximum of 20% of the arable land may be used for energy crops /Telsnig et al. 2013a/, /Tomaschek et al. 2013/, /IER 2012/, see section 6.1.4), ethanol from sugar cane displaces biodiesel from rapeseeds, which is no longer produced at a marginal abatement cost of 300 ZAR_{2007}/t CO_2eq. The energy yield per hectare is significantly higher for sugar cane (see section 5.1.6), so that the contribution of ethanol from sugar cane is greater than for biodiesel and the equivalent of about 29 PJ is produced.

Small amounts of biodiesel from sunflower seeds (i.e. about 1.2 PJ) are produced in Gauteng, beginning at a marginal tax of 250 ZAR_{2007}/t CO_2eq. As previously identified for biofuel production from energy crops in South Africa, the fuel produced switches to ethanol at even higher marginal abatement costs (in this case to ethanol from sugar beet at a GHG tax of 500 ZAR_{2007}/t CO_2eq and above).

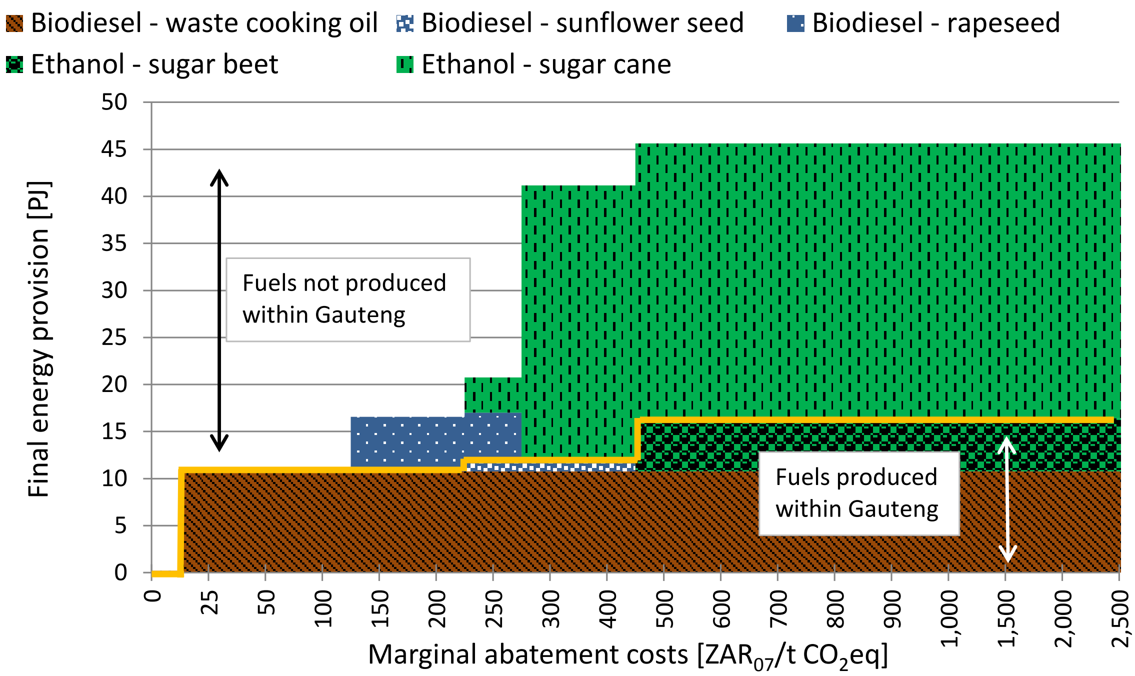


Figure 67: Biofuel provision from energy crops and waste cooking oil for the transport sector in the GHG_HG scenario in 2040. Source: own calculations.

In the GHG_LG scenario, the means of providing first-generation biofuels are as for the GHG_HG scenario. However, as identified previously biodiesel from energy crops is initially produced at a marginal abatement cost of 200 ZAR_{2007}/t CO_2eq (i.e. 150 ZAR_{2007}/t CO_2eq in GHG_HG) and ethanol at a marginal abatement cost of 300 ZAR_{2007}/t CO_2eq (i.e. 250 ZAR_{2007}/t CO_2eq in GHG_HG) in the GHG_LG scenario. Differences between the two scenarios indicate that no ethanol based on sugar beet is produced in Gauteng according to the marginal abatement cost curve for the low socio-economic growth scenario. Moreover, in the GHG_LG scenario the provision of ethanol decreases for a marginal abatement cost of 1,000 ZAR_{2007}/t CO_2eq and higher because the final energy consumption of the transport sector is based on other fuels (such as hydrogen) and electricity, as previously pointed out.

6.3.2 Transport vehicle powertrain use and vehicle activity

Although the possibility of changing the modal split by investing in additional public transport facilities for the BRT in Tshwane and Johannesburg, as well as for the Gautrain, has been explicitly investigated in the TIMES-GEECO model (see section 4.3), additional investments are not part of the scenario results.

However, this result is reasonable: on the one hand, previous phases of the BRT mainly substituted for minibus transport (61%) and did not attract many drivers of private passenger cars (10%) /Bubeck 2012/. In the scenarios analysed, this situation is not assumed to change significantly in future /Bubeck 2012/. Moreover, additional phases of the Gautrain project which have been analysed are very costly compared to the additional passenger volume expected /Bubeck 2012/.

On the other hand, from an energy and GHG emissions point of view, minibus taxis are very efficient: the comparatively high occupancy rates and the sponsorship of fleet renewal (through the TRP, see section 2.2.1) result in low specific energy consumption and low specific GHG emissions. As a consequence, further investments in the BRT and Gautrain infrastructure are not reasonable for the model as the effect on GHG mitigation is low and costs are high. However, there are further implications of expanding the BRT and Gautrain facilities such as safety, accessibility and convenience, which are not considered in this analysis.

In the following section, the powertrains technologies applied under GHG taxes are illustrated. The positive parts of the figures show the alternative technologies applied under GHG taxes, whereas the negative values show the technologies previously used in the business as usual scenarios, which are replaced.

In Figure 68 the changes in vehicle technology use are depicted for passenger cars under GHG mitigation costs compared with the reference scenarios (section 6.3.1). Powertrains for passenger cars of the BAU_HG reference scenario are changed at abatement costs of 300 ZAR_{2007}/t CO_2eq, where conventional petrol–ICE SI passenger cars are replaced with E85–ICE SI. At 400 ZAR_{2007}/t CO_2eq, petrol-driven mild hybrid vehicles are adopted; this contribution is increased up to 900 ZAR_{2007}/t CO_2eq and conventional petrol–ICE SI passenger cars are fully replaced. Additionally, small quantities of CNG–ICE SI vehicles are used at 400 ZAR_{2007}/t CO_2eq using SNG from landfill and sewage gas upgrading (section 6.3.1). At a marginal abatement cost of 600 ZAR_{2007}/t CO_2eq, diesel mild hybrids are initially used as alternatives for conventional diesel–ICE CI engines.

At a higher mitigation cost of 1,000 ZAR_{2007}/t CO_2eq, the MACC for passenger cars shows fuel cell hybrid electric vehicles (FCHEV) which are introduced instead of mild hybrid vehicles as an alternative for conventional ICEs. The share of hydrogen vehicles further increases at a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq and reaches 49% of the total vehicle activity of passenger cars.

With even higher marginal abatement costs, full hybrids are used instead of mild hybrids as alternatives for conventional ICEs. As for mild hybrids, petrol SI engines are replaced initially. Full hybrid diesel CI is applied at 1,500 ZAR_{2007}/t CO_2eq and all conventional diesel–ICE CI vehicles have been replaced with alternative powertrains at this marginal abatement cost.

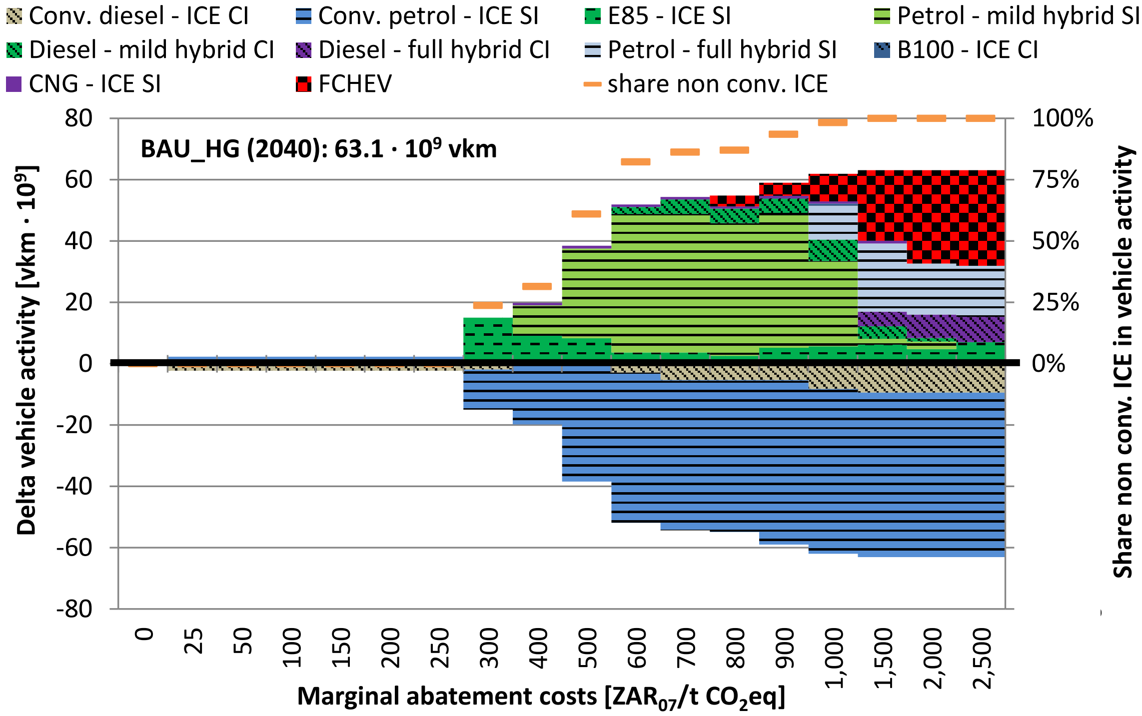


Figure 68: Changes in vehicle activity of passenger cars in Gauteng compared to the reference scenario in 2040 (BAU_HG). The figure legend shows only those powertrains that are part of the scenario results. Source: own calculations.

Figure 69 shows the changes in vehicle technology used for SUVs if GHG taxes are applied. In comparison with passenger cars, alternative powertrains are adopted at lower marginal abatement costs. At marginal abatements costs ≥ 250 ZAR_{2007}/t CO_2eq small proportions of conventional diesel–ICE CI powertrains are replaced with B100–ICE CI vehicles. The contribution of this powertrain technology changes as the quantity of biodiesel provision changes (see section 6.3.1); and for some marginal abatement costs the total amount of biodiesel cannot be blended.

For marginal abatement costs ≥ 250 ZAR_{2007}/t CO_2eq an increasing share of E85–ICE SI vehicles can be identified, substituting for conventional petrol–ICEs. Their contribution increases continuously and all conventional petrol-driven SUVs are replaced at a marginal abatement cost of 800 ZAR_{2007}/t CO_2eq. Mild hybrids are initially used as the propulsion technology for SUVs at a marginal GHG tax of 600 ZAR_{2007}/t CO_2eq. In contrast to passenger cars, no petrol-driven mild hybrids are used for SUVs. The contribution of mild hybrids to SUV vehicle activity increases continuously until

1,500 ZAR_{2007}/t CO_2eq, when conventional diesel–ICE CI powertrains are no longer used. Lastly, for a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, diesel-driven full hybrid vehicles contribute about 18% to SUV vehicle activity.

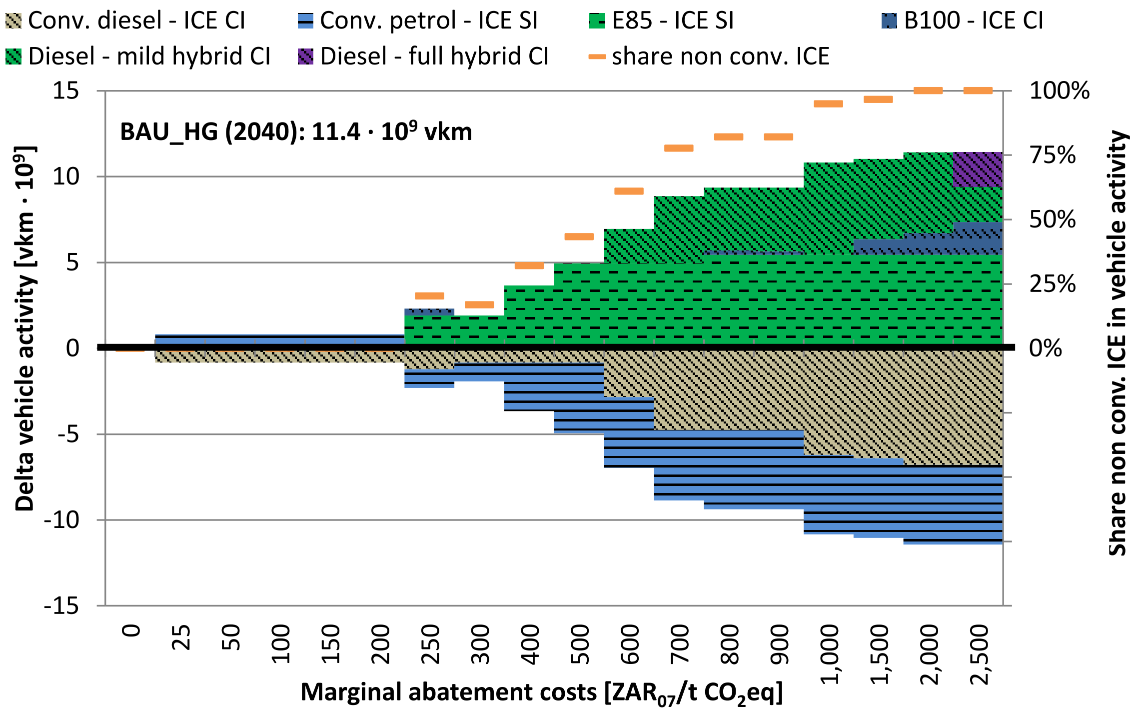


Figure 69: Changes in vehicle activity of SUVs in Gauteng compared to the BAU_HG reference scenario in 2040. The figure legend shows only those powertrains that are part of the scenario results. Source: own calculations.

The MACC showing changes in the activity of LDV vehicles is presented in Figure 70. The results are comparable to those for passenger cars and SUVs as far as the application of E85 powertrains is concerned, which are the initial alternative powertrains applied. This substitution starts at a marginal abatement cost of 300 ZAR_{2007}/t CO_2eq. With a marginal GHG tax of 600 ZAR_{2007}/t CO_2eq, about 45% of the activity of LDVs is based on E85–ICE SI powertrains. Furthermore, as for passenger cars and SUVs, the technology next used as an alternative is mild hybrids, which can be identified for LDVs at a marginal abatement cost of 500 ZAR_{2007}/t CO_2eq. Only smaller proportions of vehicle activity of LDVs are attributed to petrol SI mild hybrids. However, diesel mild hybrids replace for 55% of the activity of conventional CI engines in the BAU_HG reference scenario at a marginal abatement cost of 800 ZAR_{2007}/t CO_2eq. Full hybrids are used as alternative powertrains, instead of mild hybrids, for a marginal abatement cost of 2,000 ZAR_{2007}/t CO_2eq and higher and no conventional ICEs are used further for SUV propulsion.

Significant differences from the previously analysed modes can be seen at marginal GHG mitigation costs of 800 ZAR_{2007}/t CO_2eq and higher. Due to the greater annual mileage of LDVs (about 15,000 km/a compared to about 12,600 km/a for passenger cars and SUVs), plug-in hybrid electric vehicles (PHEV) become competitive and displace the mild hybrids as an alternative to conventional ICE powertrains. Only diesel plug-in hybrid electric vehicles are used and E85–ICE SI remains dominant for the modelled share of non-CI engines for LDVs (see section 6.1.3). At a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq about 35% of the total vehicle activity of LDVs is attributed to plug-in hybrid electric vehicles and about 28% to full hybrid vehicles.

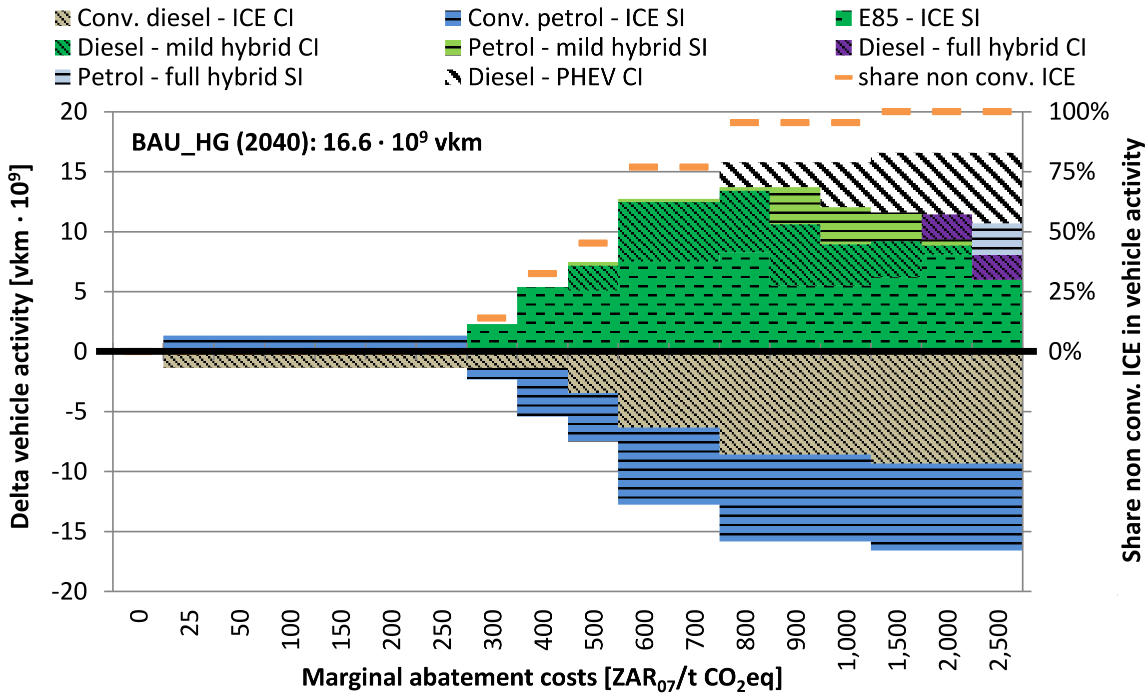


Figure 70: Changes in vehicle activity of LDVs in Gauteng compared to the BAU_HG reference scenario in 2040. The figure legend shows only those powertrains that are part of the scenario results. Source: own calculations.

Figure 71 shows the changes in vehicle activity for minibuses in relation to the high socio-economic growth scenario for 2040. Technologies for minibuses change more rapidly than for the previously analysed modes as a consequence of the large annual mileage (about 35,000 km/a) of minibuses and their high occupancy rates. At a low marginal GHG mitigation cost of 25 ZAR_{2007}/t CO_2eq, alternative powertrains are initially adopted for minibus travel. At this marginal abatement cost, petrol mild hybrid vehicles are used instead of conventional petrol ICEs, which corresponds to about 23% of the total vehicle activity of minibuses. Conventional diesel CI engines are replaced by mild hybrids at a marginal abatement cost of 100 ZAR_{2007}/t CO_2eq, and only about 4% of the vehicle activity is still attributed to conventional ICE powertrains.

Between GHG taxes of 200 ZAR_{2007}/t CO_2eq and 300 ZAR_{2007}/t CO_2eq a small proportion of CNG–ICE SI engines are used for minibus propulsion. As previously noted, methane gas is used for passenger cars at higher marginal abatement costs. At 600 ZAR_{2007}/t CO_2eq, full hybrid minibuses are used instead of mild hybrids. As for mild hybrids, initial substitution focuses on petrol vehicles; however, diesel full hybrids are also used. Furthermore, fuel cell hybrid electric are initially applied. For a GHG tax of

700 ZAR_{2007}/t CO_2eq, plug-in hybrid electric vehicles are used instead of mild hybrids as alternative powertrain. Plug-in and fuel cell hybrid electric powertrains continuously increase their contribution to minibus travel until a marginal abatement cost of 1,000 ZAR_{2007}/t CO_2eq. At even higher marginal abatement costs, an increasing contribution of full hybrids in powertrain application can be identified.

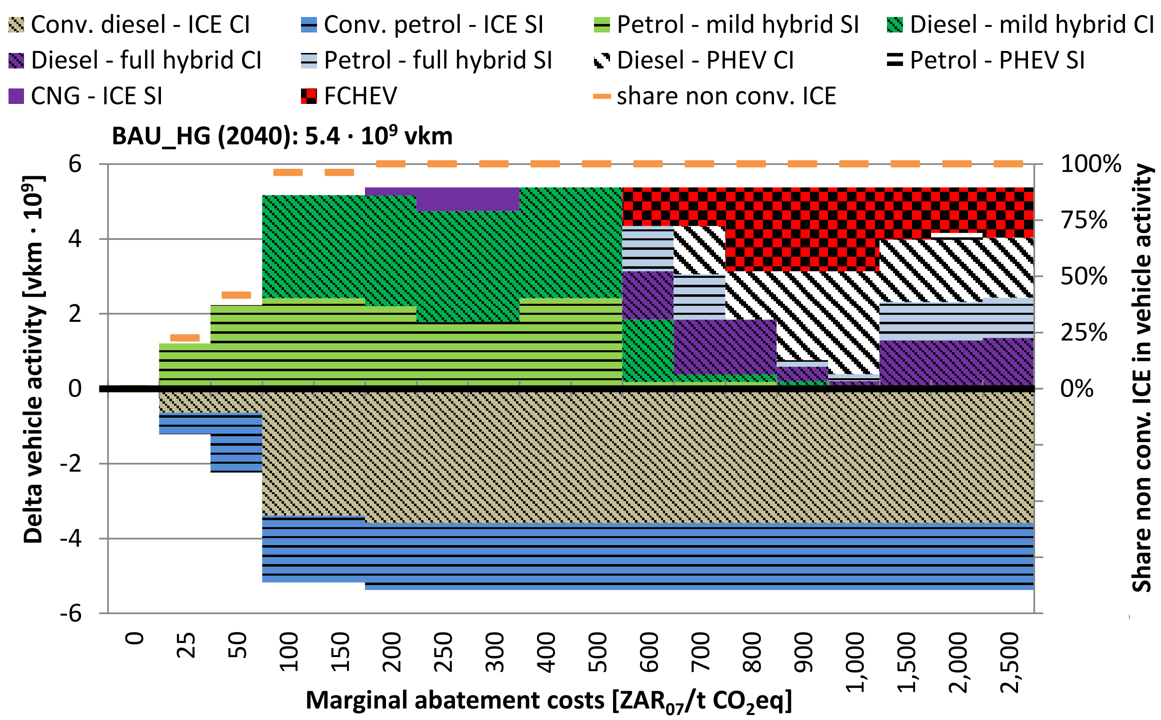


Figure 71: Changes in vehicle activity of minibuses in Gauteng compared to the BAU_HG reference scenario in 2040. The figure legend shows only those powertrains that are part of the scenario results. Source: own calculations.

The result of introducing a high proportion of hybrid vehicles at comparatively low marginal mitigation costs is reasonable considering the dominant role of urban travel of minibuses (on average about 73%) in the model. In addition, high annual mileage and occupancy rates favour early hybridization. For the same reason, all reference scenario technologies are already replaced at 200 ZAR_{2007}/t CO_2eq.

The combined vehicle activity of buses is shown in Figure 72, aggregated for small, big and BRT buses. The remaining vehicle activity, which is not already represented by B100–ICE CI powertrains and diesel mild hybrids under reference conditions (see section 6.2.3), is replaced by mild hybrids at the first mitigation step analysed (i.e. 25 ZAR_{2007}/t CO_2eq). At this marginal abatement cost, 100% of the vehicle activity is performed with non-conventional ICE powertrains. The first full hybrids are used as alternatives for the reference scenario vehicles – including mild hybrids, which are already in use in the base case – at a marginal GHG mitigation cost of 250 ZAR_{2007}/t CO_2eq. As for minibuses, the implementation of hybrids at lower marginal mitigation costs (in comparison with, for example, passenger cars) is reasonable as the proportion of urban travel is high (on average 73.5%) and so are annual mileages (about 36,000 km/a for scheduled buses) as well as the lifetime of the vehicles (14 years).

At 500 ZAR_{2007}/t CO_2eq, most reference technologies have been replaced with full hybrid diesel CI vehicles, which then provide 98% of the vehicle activity for buses. Beginning at a marginal abatement cost of 600 ZAR_{2007}/t CO_2eq, fuel cell hybrid electric vehicles are introduced for buses in Gauteng. The proportion of those powertrains in bus vehicle travel increases at 800 ZAR_{2007}/t CO_2eq and further until a marginal abatement cost of 1,500 ZAR_{2007}/t CO_2eq, at which stage fuel cell hybrid electric vehicles are used for all small, big and BRT buses, and represent 100% of the vehicle activity. At higher marginal abatement costs, some full hybrid engines are being applied.

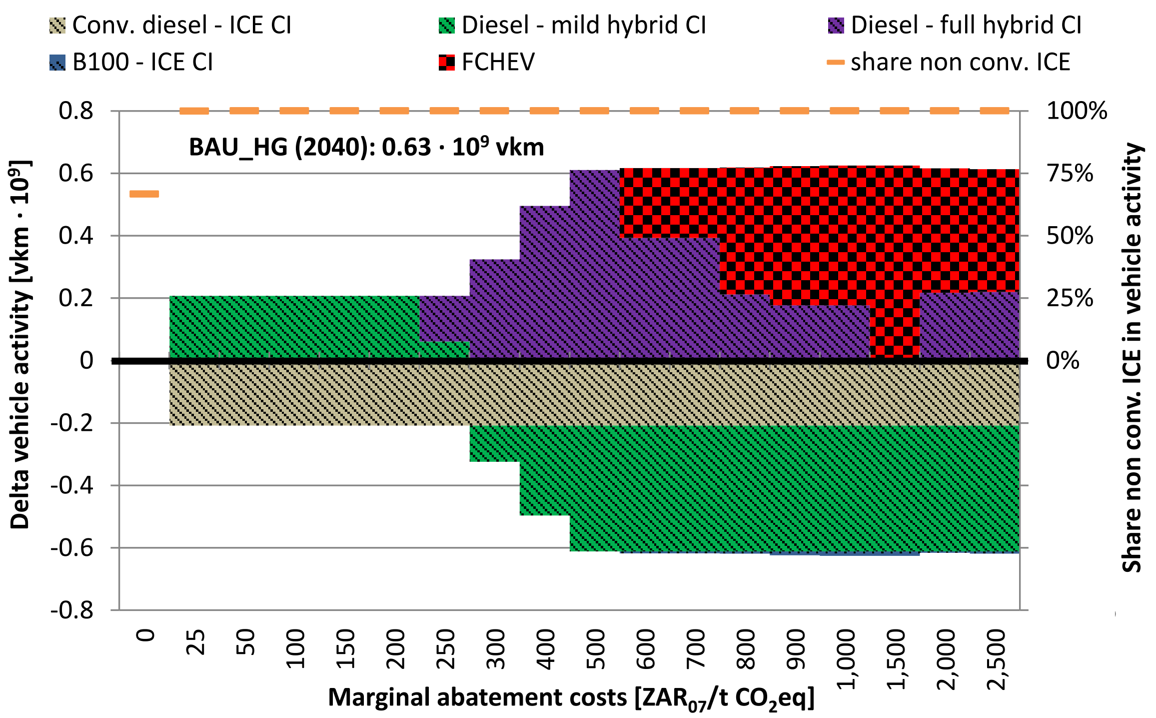


Figure 72: Changes in vehicle activity of buses in Gauteng compared to the BAU_HG reference scenario in 2040. The figure legend shows only those powertrains that are part of the scenario results. Source: own calculations.

Figure 73 shows vehicle activity for HDVs compared to the high socio-economic growth reference scenario (BAU_HG) in 2040. Initially, at a marginal abatement cost of 100 ZAR_{2007}/t CO_2eq, about 30% of the vehicle activity for HDVs changes from conventional diesel ICE CI to mild hybrid (diesel). The contribution of mild hybrids increases gradually with increasing marginal abatements cost until 400 ZAR_{2007}/t CO_2eq, at which stage about 72% of vehicle activity is based on mild hybrid diesel ICEs. Full hybrids are used for HDV propulsion at marginal abatement costs of 500 ZAR_{2007}/t CO_2eq

However, the share of full hybrid ICEs does not increase significantly with higher marginal abatement costs. Instead, fuel cell hybrid electric vehicles are used as alternatives to the conventional diesel ICE CI HDVs of the BAU_HG reference case at 600 ZAR_{2007}/t CO_2eq and higher, and all of the HDV vehicle activity is performed with alternative technologies. At a GHG tax of 2,000 ZAR_{2007}/t CO_2eq, mild hybrids are no longer used as alternatives for the reference fleet in the GHG_HG scenario; only full hybrids and fuel cell hybrid electric vehicles are used instead. The contribution of fuel cell hybrid electric vehicles to HDV vehicle travel increases for higher marginal abatement costs and reaches 82% at 2,500 ZAR_{2007}/t CO_2eq.

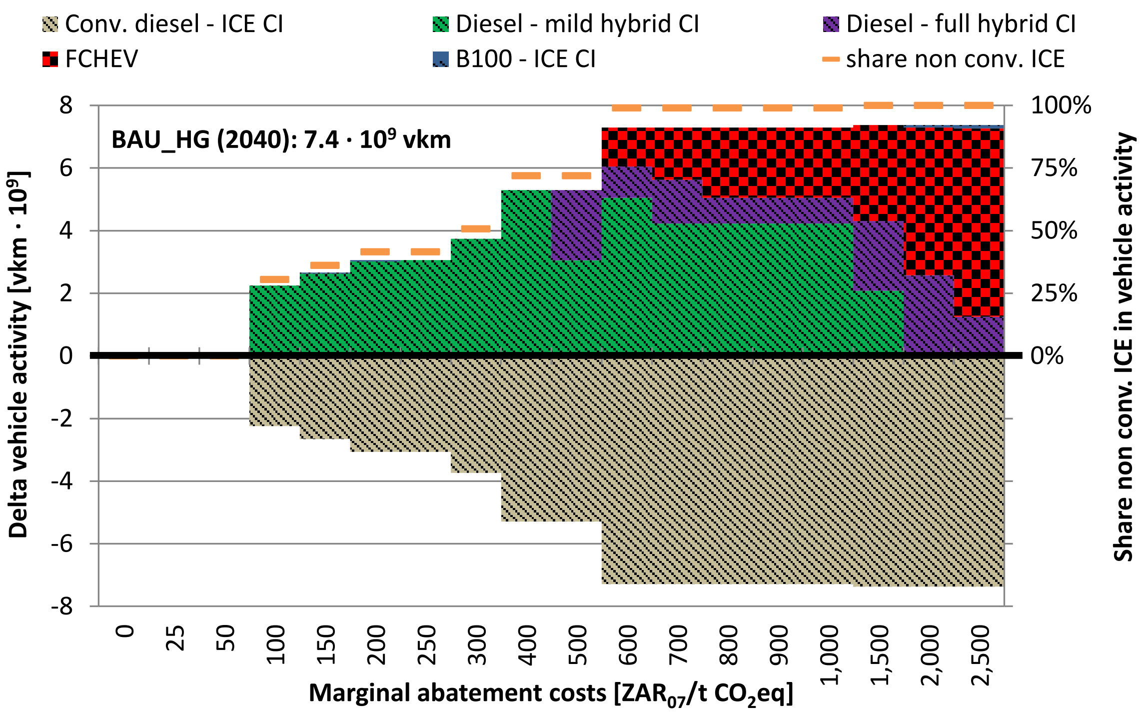


Figure 73: Changes in vehicle activity of HDVs in Gauteng compared to the BAU_HG reference scenario in 2040. The figure legend shows only those powertrains that are part of the scenario results. Source: own calculations.

The results of a MACC for the road transport sector have been aggregated in Figure 74. In the figure CNG–ICE SI, B100–ICE CI and rail have been combined as a single category because to their small contributions to total vehicle activity. The initial technology modifications involve the substitution of conventional ICEs with (diesel) ICE CI mild hybrids for vehicles with large annual mileages and a big share of urban travel (i.e. minibuses and buses), which continuously increases with higher mitigation costs. However, the effect of the initial substitution of vehicle powertrains for buses is only small and the first significant changes can be identified at a marginal GHG mitigation cost of 100 ZAR_{2007}/t CO_2eq when this technology is adopted also for HDVs. At 300 ZAR_{2007}/t CO_2eq the increase in E85–ICE SI vehicle activity for passenger cars, SUVs and LDVs becomes visible. At this marginal abatement cost, about 18% of the total vehicle traffic in road and rail transport is based on E85–ICE SI engines.

At 400 ZAR_{2007}/t CO_2eq, about 38% of vehicle travel is performed by non-conventional vehicle powertrain technologies and larger shares of mild and full hybrid propulsion systems can be identified. At his stage, petrol-driven mild hybrid ICE SI engines are used initially for passenger cars. At even higher marginal abatement costs, the substitution of reference technologies in the transport sector continuously increases.

Fuel cell hybrid electric vehicles show up early on the vehicle activity curve (i.e. at 600 ZAR_{2007}/t CO_2eq for buses, heavy-duty vehicles and minibuses). This finding is based on the large annual mileages for those modes and the high urban shares in the vehicle driving cycles for buses and minibuses. However, the total contribution to transport vehicle activity remains small. At this mitigation cost and above, the contribution of fuel cell hybrid electric vehicles to total transport vehicle activity increases steadily.

Higher proportions of total vehicle activity change to full hybrids at a marginal abatement cost of 1,000 ZAR_{2007}/t CO_2eq, when this technology is initially applied to passenger cars. Thus, mild hybrid engines are used to a lesser extent as alternative for conventional engines than for lower marginal abatement costs. Minibuses are the first to use plug-in hybrid electric vehicles in the transport system, which is at a marginal abatement cost of 700 ZAR_{2007}/t CO_2eq. The activity of plug-in hybrid electric vehicles increases further at 800 ZAR_{2007}/t CO_2eq and above, when this technology is also used for LDVs.

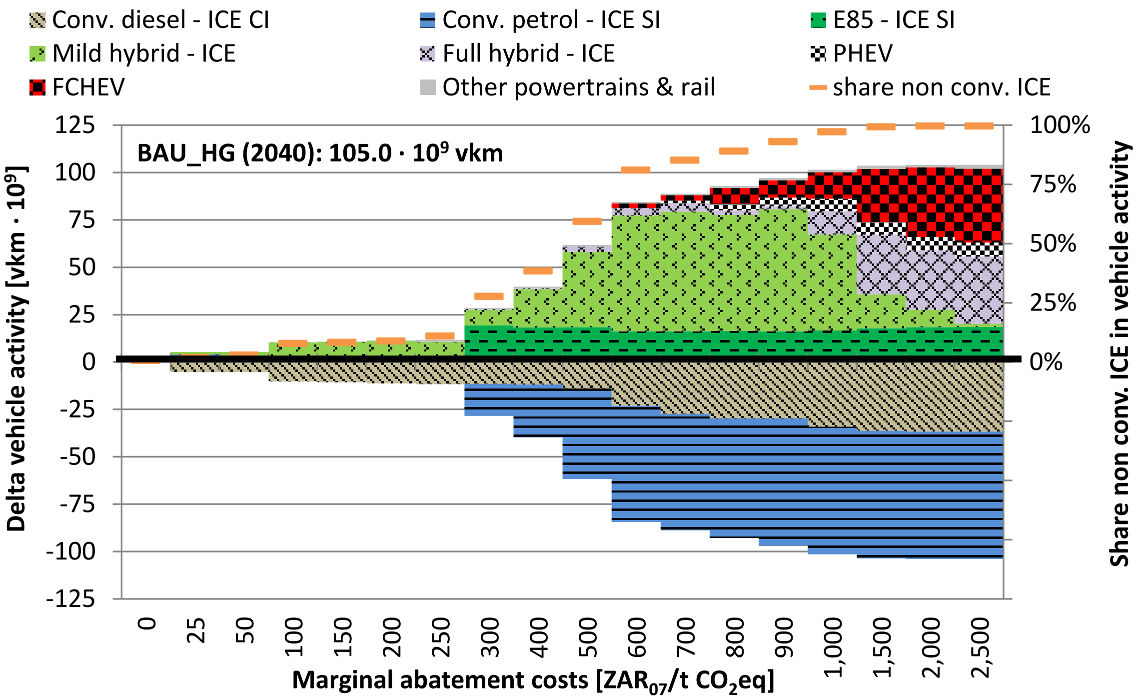


Figure 74: Changes in vehicle activity in the Gauteng transport sector compared to the BAU_HG reference scenario in 2040. "Other powertrains" comprise B100–ICE CI and CNG–ICE SI engines. Source: own calculations.

For a marginal abatement cost of 2,000 ZAR_{2007}/t CO_2eq, no conventional ICEs remain in the system for the GHG_HG scenario (except for motorcycles) and all other reference vehicles have been replaced with alternative technologies. At the highest GHG tax analysed (i.e. 2,500 ZAR_{2007}/t CO_2eq), fuel cell hybrid electric vehicles contribute about 37% of the total vehicle activity. The second largest share of total vehicle activity is provided by full hybrid vehicles, which contribute about 34% to total vehicle kilometres at this cost. However, E85–ICE SI is also a significant technology at this marginal abatement cost, corresponding to about 18% of the total vehicle activity.

Compared to previously analysed MACC for the high socio-economic growth scenario, Figure 75 presents the changes in vehicle activity for low socio-economic growth conditions (GHG_LG). In the figure CNG–ICE SI, B100–ICE CI and rail have been combined as a single category for consistency with the previous figure. The year for this analysis is again 2040. In the GHG_LG scenario, the choice of vehicle powertrains is comparable to the high socio-economic growth scenario as far as the ranking of alternative technologies is concerned; in both high and low growth scenarios the favoured modes for those alternative powertrains are similar. Thus, changes for passenger cars, LDVs and SUVs initially are to E85–ICE SI as identified in the high socio-economic growth MACC. Likewise, hybrid vehicles are initially used as alternatives for conventional ICEs for buses and HDVs, as seen before.

Noteworthy differences can be identified in the magnitude of plug-in hybrid electric vehicles and fuel cell hybrid electric vehicle activity in both marginal abatement cost curves, as the contribution of plug-in hybrid electric and hydrogen-fuelled vehicles is significantly greater in GHG_LG. This is a result of the limited potential for low-carbon electricity (e.g. based on nuclear energy or renewables) and also of the limited storage capacity of CCS. The smaller energy consumption under low socio-economic growth results in higher quantities low-carbon electricity to be used in the transport sector.

Additionally, some vehicles that use hydrogen are based on ICEs, which are cheaper than fuel cell hybrid electric vehicles but offer lower energy efficiency (see sections 5.2.3 and 5.2.5). The reason is found by looking at the time of investment of the technology in use in 2040: the first investments in hydrogen ICE SI technology were made before those in fuel cell hybrid electric vehicles. Because of the higher cost of fuel cell hybrid electric vehicles in earlier investment years, ICE SI vehicles are used instead.

Given the fixed potentials for biomass and alternative energy sources (see section 6.1.4); differences arise in the relative contributions of alternative powertrains. For example, the relative contribution of E85–ICE SI vehicles to the total vehicle activity in 2040 is greater on the GHG_LG mitigation cost curve than on the MACC in GHG_HG. However, the total activity with this technology is comparable in both cases, i.e. up to $16.4 \cdot 10^9$ vkm and $19.2 \cdot 10^9$ vkm in the low and high socio-economic growth MACC, respectively. On the other hand, B100–ICE CI vehicles contribute more to vehicle travel in GHG_LG. This can be explained by the adoption of the $10\%_{vol}$ blending restriction (see sections 2.2.4 and 4.3). As the magnitude of total vehicle activity is considerably less in GHG_LG than in GHG_HG, the whole amount of biodiesel in the system cannot be blended. This becomes even more relevant when higher shares of plug-in hybrid electric vehicles and fuel cell hybrid electric vehicles are used for transport and biodiesel needs to be used in B100–ICE CI vehicles.

In both the high and the low socio-economic growth scenarios, with marginal GHG abatement costs of 1,500 ZAR_{2007}/t CO_2eq, no conventional ICEs (i.e. either petrol or diesel) remain with the exception of motorcycles.

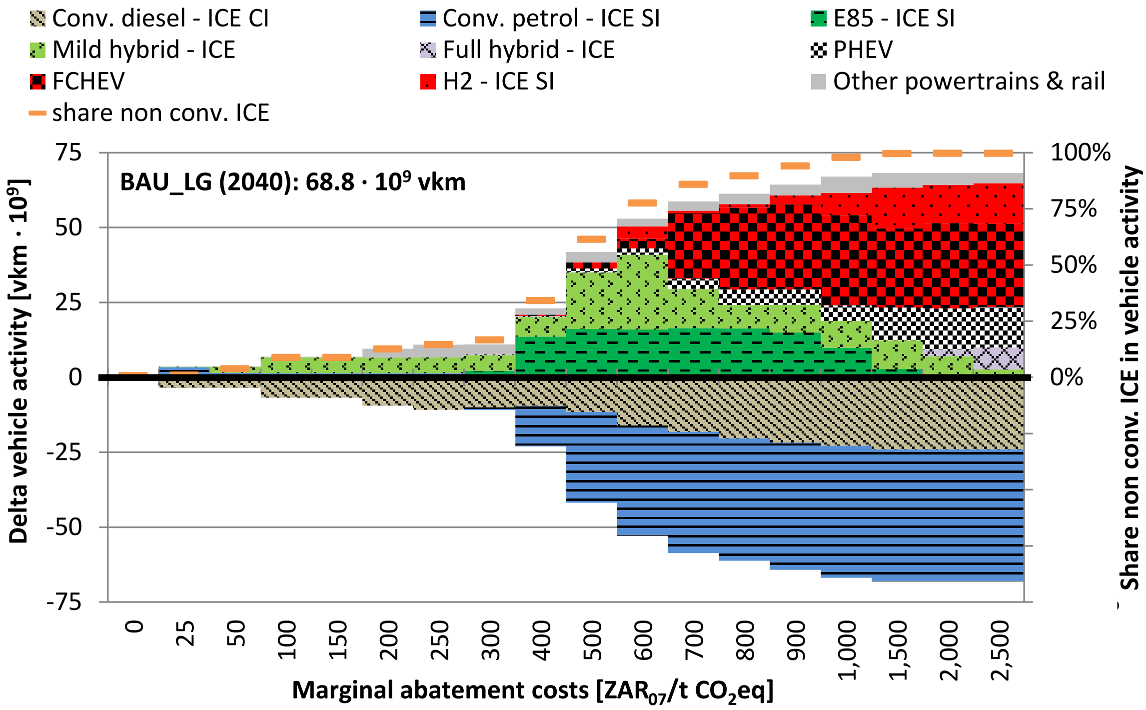


Figure 75: Changes in vehicle activity in the transport sector of Gauteng compared to the BAU_LG reference scenario in 2040. "Other powertrains" comprise B100–ICE CI and CNG–ICE SI engines. Source: own calculations.

6.3.3 Transport-related GHG emissions

This section compares transport-related GHG emissions to the reference scenario for 2040 and presents the effects of the changes in total transport energy consumption (section 6.3.1) and powertrain use (section 6.3.2). The high socio-economic growth scenario is again emphasized. For consistency with previous analyses, additional emissions as a result of alternative technologies are shown as positive values whereas negative values indicate mitigated emissions of reference scenario technologies. The net reduction in GHG emissions is indicated to show the overall impact of the changes in the transport sector.

Figure 76 depicts tank-to-wheel (TTW) GHG emissions of the transport sector in comparison with the BAU_HG scenario, in which about 25.7 Mt CO_2eq TTW emissions were emitted in 2040 (see section 6.2.4). Beginning with a GHG tax of 25 ZAR_{2007}/t CO_2eq, TTW emissions from conventional ICEs continuously decrease as these are replaced by alternative vehicle powertrain technologies. Furthermore, the additional GHG emissions of the alternative vehicles are found to be less than those of the reference scenario technologies. As carbon emissions from the combustion of biogenic sources are balanced as zero (based on the assumption that the carbon is accumulated in preceding biomass cultivation), the contribution of E85–ICE SI vehicles to TTW emissions is obviously less than their contribution to total vehicle activity, and the GHG emissions of B100 vehicles are almost zero.

At a marginal GHG abatement cost of 600–700 ZAR_{2007}/t CO_2eq, TTW GHG emissions from alternative technologies are at their peak at 10.3 Mt CO_2eq and only low TTW GHG emissions of conventional powertrains remain (i.e. at less than 3 Mt CO_2eq in comparison to about 21.8 Mt CO_2eq in BAU_HG in 2040). Total TTW GHG emissions then reduce to 16.7 Mt CO_2eq (–34%). With higher GHG taxes, TTW GHG emissions of alternative powertrains are lower, based on further electrification of the transport sector and the use of hydrogen (see section 6.3.1). At 1,500 ZAR_{2007}/t CO_2eq only about 10.6 Mt CO_2eq TTW GHG emissions remain in the transport sector, of which about 7.1 Mt CO_2eq corresponds to road transport. At a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, transport TTW GHG emissions decline further to 7.3 Mt CO_2eq, which corresponds to a reduction of 72% compared to the reference scenario in 2040.

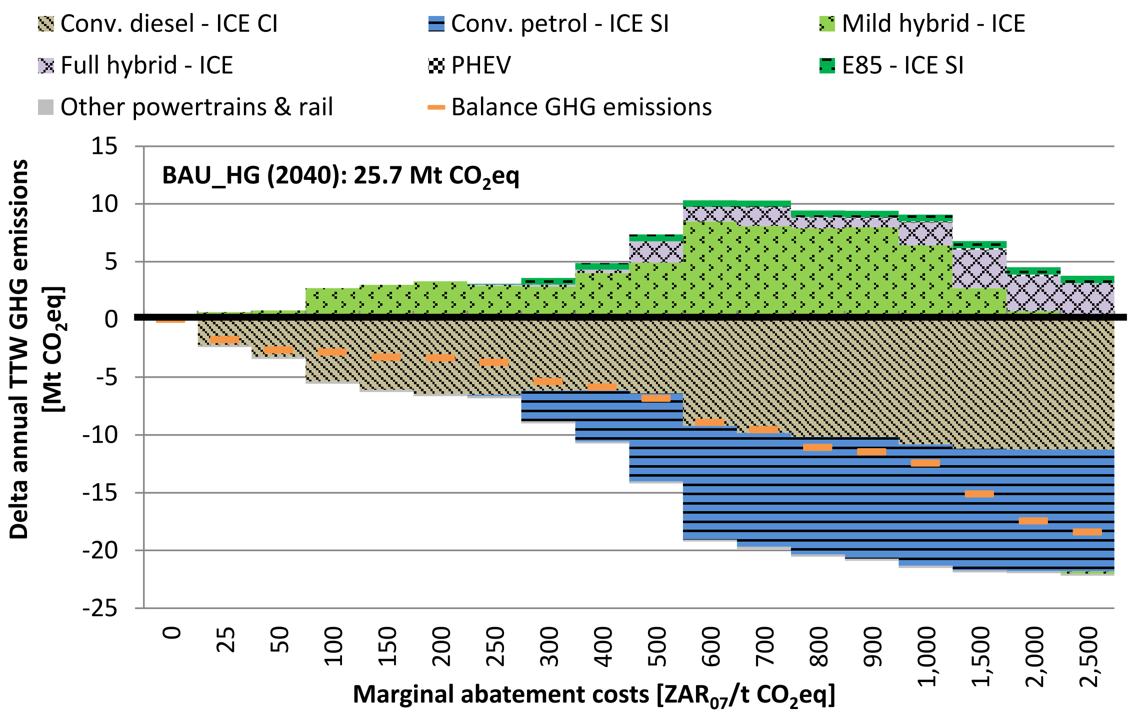


Figure 76: Changes in annual TTW emissions in the transport sector of Gauteng compared to the BAU_HG reference scenario in 2040. "Other powertrains" comprise B100–ICE CI and CNG–ICE SI engines. Source: own calculations.

Figure 77 places these reductions in TTW GHG emissions in the transport sector in the context of the entire energy system. It can be seen that the transport sector is clearly not the first sector to be addressed for GHG mitigation. For marginal abatement costs of ≤ 250 ZAR_{2007}/t CO_2eq, the share of GHG emission reductions in the transport sector in relation to the total mitigation of these emissions is only about 2%. For higher mitigation targets the significance of the transport sector for GHG mitigation increases.

However, Figure 77 shows that substantial GHG mitigation can be realised for a relatively low marginal abatement cost of 100 ZAR_{2007}/t CO_2eq. This corresponds to about

66% of the total GHG emissions compared to the BAU_HG reference scenario in 2040 (where total GHGs are about 227 Mt CO_2eq). The reductions can be realized primarily by alternative means of electricity supply and changes in fuel provision but also as a consequence of further measures in the other demand sectors of the energy system. In the following section the reductions of in the energy supply sectors, which are attributable to the transport sector activity, are analysed.

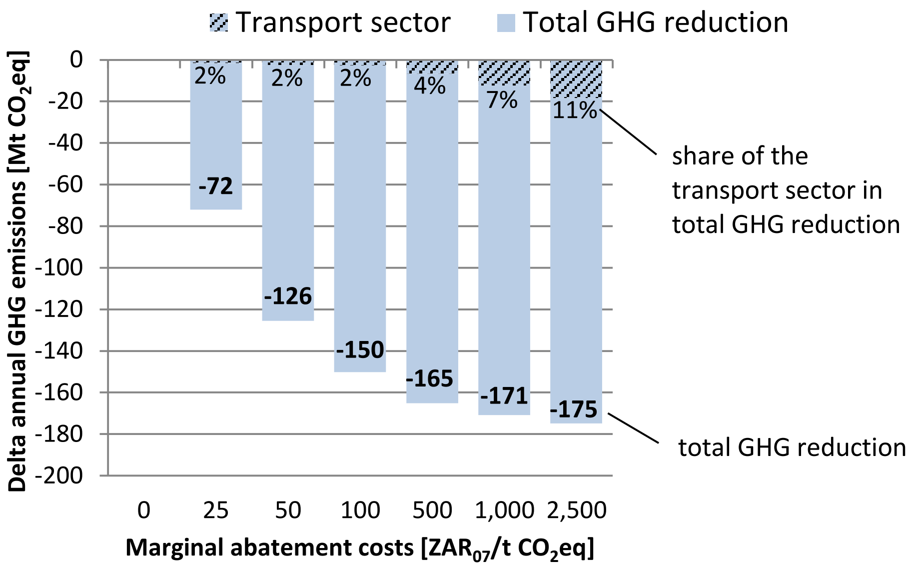


Figure 77: Contribution of the transport sector to total TTW GHG emission reduction compared to the BAU_HG reference scenario in 2040.
Source: own calculations.

Figure 78 shows the change in annual well-to-tank (WTT) GHG emissions compared to the high socio-economic growth reference scenario in 2040. Only the shares attributable to the activity of transport sector are shown in the figure including auxiliary energy consumption for transport fuel provision as well as GHG emissions due to primary energy provision.

Significant reductions in transport WTT GHG emissions can be achieved from the decarbonization of transport energy supply at low marginal abatement costs. Initially, WTT GHG reduction due to the decarbonization of electricity provision can be identified at a marginal GHG abatement cost of 25 ZAR_{2007}/t CO_2eq (Figure 78). At this GHG tax, no plug-in electric vehicles are being applied and transport related electricity provision is determined by the electricity consumption of rail transport as well as by the consumption of auxiliary energy for transport fuel provision and associated primary energy provision. However, at a marginal abatement cost of 50 ZAR_{2007}/t CO_2eq, WTT GHG emissions are reduced significantly due to the substitution of Fischer-Tropsch synthetic fuels. At 100 ZAR_{2007}/t CO_2eq, the total amount of Fischer-Tropsch synthetic fuel is replaced and about 19.4 Mt CO_2eq is mitigated in total. At higher marginal mitigation costs, significant additional WTT GHG emissions occur due to the alternative fuel technologies used. This is for example due to the use of ethanol (i.e. involving biomass transport, crop cultivation and conversion emissions; see section 5.1.6) beginning at 250 ZAR_{2007}/t CO_2eq. The emissions due to the provision of ethanol increase to about 1.3 Mt CO_2eq at marginal abatement costs of 500 ZAR_{2007}/t CO_2eq and higher, as the final energy consumption of ethanol as a transport fuel is greatest at this level of taxation.

Beginning with the marginal abatement cost of 600 ZAR_{2007}/t CO_2eq, the GHG emissions from hydrogen provision via natural gas reformation with CCS are visible, because the total amount of CO_2 generated cannot be captured and sequestered (see section 5.1.4) and furthermore due to hydrogen distribution. The increasing provision of alternative fuels results in lower WTT GHG emission reduction, seen at GHG taxes of ≥ 600 ZAR_{2007}/t CO_2eq in comparison to GHG taxes of 25–500 ZAR_{2007}/t CO_2eq. At 2,500 ZAR_{2007}/t CO_2eq, about 7.3 Mt CO_2eq remains for transport WTT GHG emissions, mainly due to crude oil refining, and the provision of biofuel and hydrogen.

The total reduction in transport WTT GHG emissions at a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq is 18.5 Mt CO_2eq (–72%) relative to the reference scenario BAU_HG in 2040 (see section 6.2.4). The reduction in WTW GHG emissions is comparable to the reduction of TTW emissions, for which GHG emissions are reduced by 18.4 Mt CO_2eq (–72%) compared to the BAU_HG scenario in 2040.

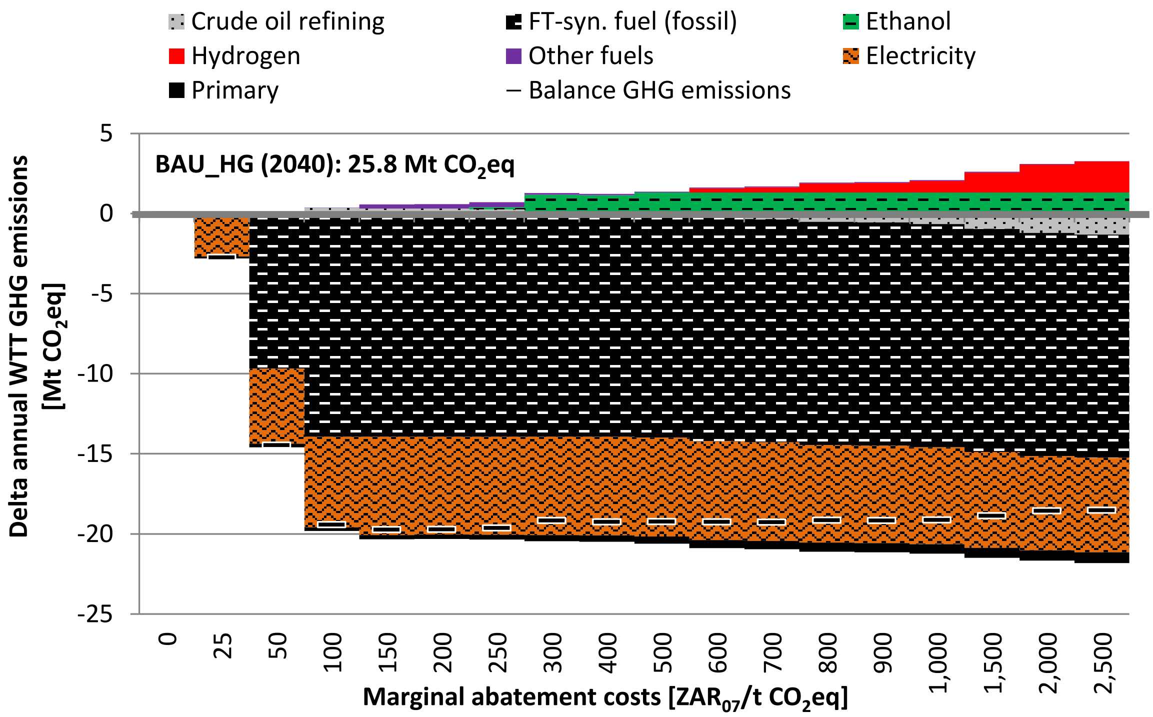


Figure 78: Changes in annual WTT emissions attributable to the transport sector of Gauteng compared to the BAU_HG reference scenario in 2040. “Other fuels” comprise biodiesel, BTL and CNG/SNG. Source: own calculations.

Total transport well-to-wheel (WTW) GHG emissions, are shown for the high and the low socio-economic growth scenarios in Figure 79. Again, the main difference between these scenarios is the magnitude of WTW emissions. The increase in transport WTW GHG emissions due to the application of alternative vehicles and fuels is clearly compensated for by replacing reference scenario technologies. Initially, high WTW GHG emission reduction is achieved by the substitution of Fischer-Tropsch synthetic fuels. However, the substitution of conventional ICE vehicles increases continuously at higher marginal GHG mitigation costs. Obviously, additional WTW GHG emissions arise because of alternative vehicle powertrain technologies and fuels applied. Those additional emissions are highest at a marginal GHG abatement cost of 600–700 ZAR_{2007}/t CO_2eq with 11.9 Mt CO_2eq in GHG_HG and 5.5 Mt CO_2eq under low socio-economic growth. At higher GHG taxes, additional WTW GHG are lower in both scenarios and further reductions are achieved.

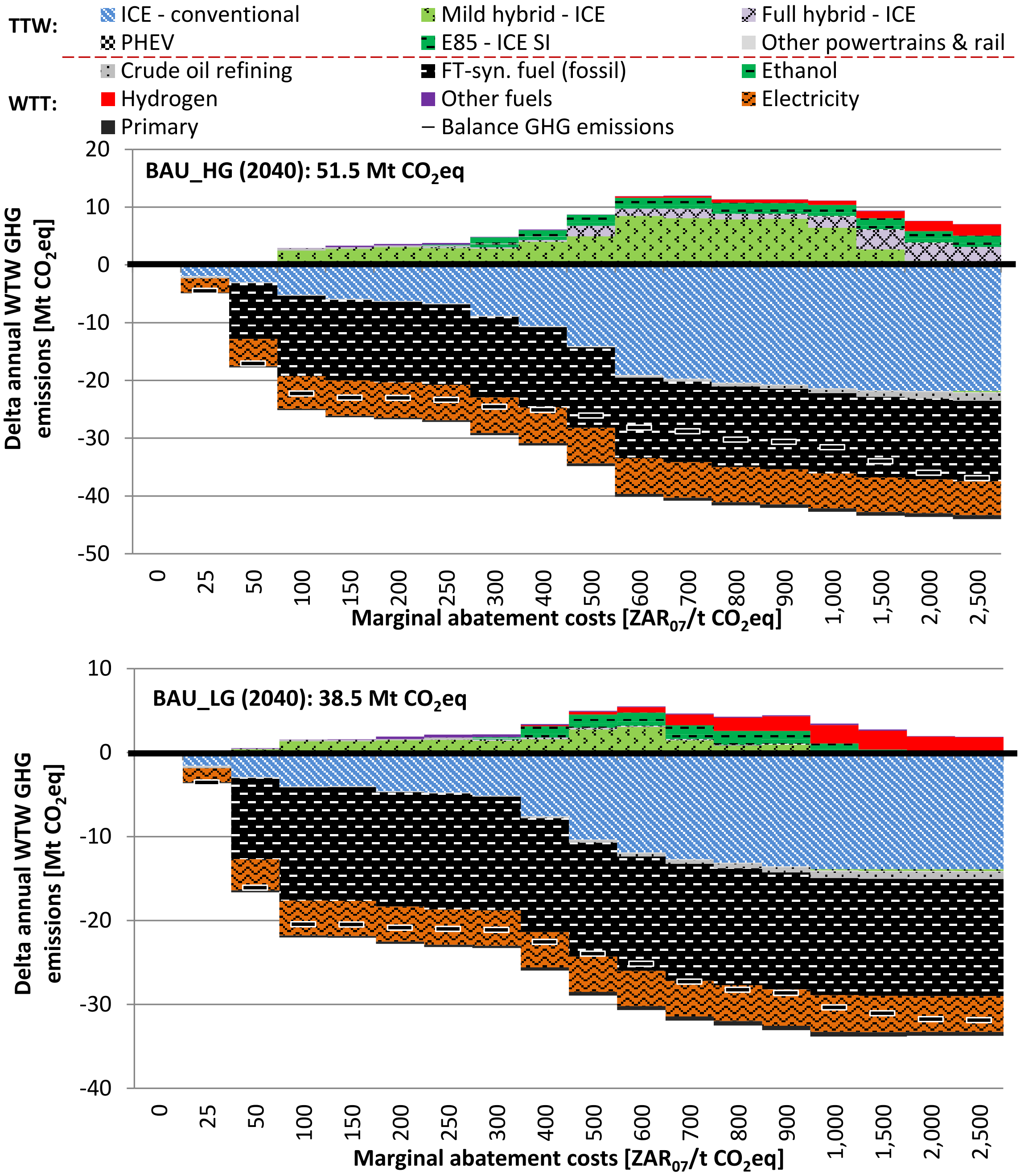


Figure 79: Changes in annual WTW emissions attributable to the Gauteng transport sector compared to the BAU_HG reference scenario (upper figure) and to the BAU_LG reference scenario (lower figure) in 2040. “Other powertrains” comprise B100–ICE CI, CNG–ICE SI and H_2–ICE SI engines. “Other fuels” comprise biodiesel, BTL and CNG/SNG. Source: own calculations.

The low socio-economic growth scenario shows a greater contribution of WTW GHG emissions due to hydrogen provision via coal gasification (see section 6.3.1) but significantly lower TTW emissions for most GHG taxes due to higher hydrogen and electricity consumption in the transport sector (see section 6.3.1). This result is also reflected in the smaller contribution of full hybrid vehicles in this scenario. For a GHG tax of 2,000 ZAR_{2007}/t CO_2eq and above, relatively few additional WTW GHG emissions can be seen in the GHG_LG scenario (i.e. ≤ 1.8 Mt CO_2eq). At this marginal abatement cost, the WTW GHG emissions of the transport sector are about 6.7 Mt CO_2eq in the low socio-economic growth scenario and 15.5 Mt CO_2eq in the high growth case. This corresponds to a reduction in WTW GHG emissions of 83% and of 70% compared to the BAU_LG and BAU_HG scenarios, respectively, in 2040.

Obviously, the reduction in WTW GHG emissions through the application of alternative powertrains and fuels is associated with increased mobility costs (Figure 80). Under the conditions of the reference scenarios (i.e. BAU_HG and BAU_LG), the costs of road transport in Gauteng are about 2.0 ZAR_{07}/km in 2040.

With GHG taxes imposed, these increase up to 8.7 ZAR_{07}/km for the GHG_HG scenario and to 5.6 ZAR_{07}/km in the GHG_LG scenario for GHG taxes of 2,500 ZAR_{2007}/t CO_2eq. The increase in mobility costs under low socio-economic growth is lower because of lower commodity prices in the scenario, but it is still substantial with 278%. However, the significant reductions of WTW GHG emissions which can be achieved for relatively low marginal abatement costs of 100 ZAR_{2007}/t CO_2eq do not result in a marked increase in mobility costs (i.e. only about 2.2 ZAR_{07}/km in both scenarios).

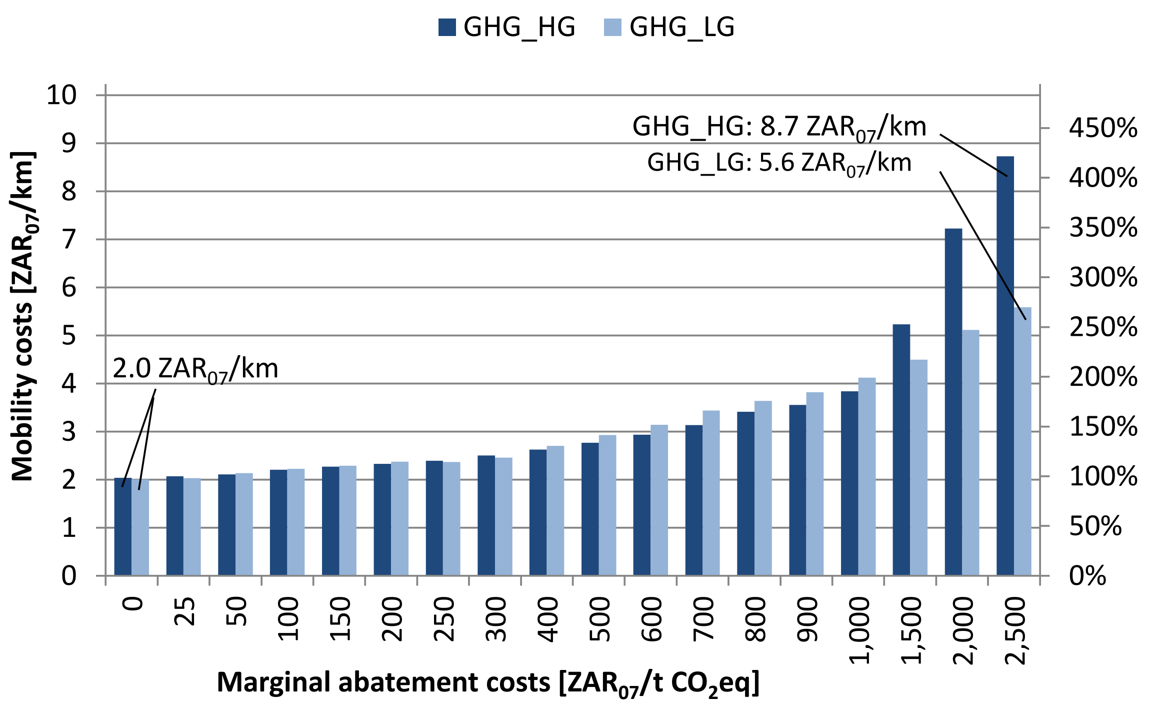


Figure 80: Mobility costs of road transport in Gauteng for the GHG_HG and GHG_LG scenarios. Source: own calculations.

Scenario analysis shows that there are several options to reduce the well-to-wheel (WTW) GHG emissions of Gauteng's transport sector. The lowest marginal mitigation costs (≤ 100 ZAR_{2007}/t CO_2eq) have been identified for biodiesel produced from waste cooking oil and for the substitution of fossil-based synthetic fuels derived via Fischer-Tropsch synthesis even if crude oil-based fuels are used as replacement. Synthetic fuels from cellulosic biomass can furthermore reduce transport-related GHG emissions, partly based on the assumption that the tank-to-wheel CO_2 emissions of biomass balanced as zero.

The application of alternative vehicle powertrains seems reasonable for those vehicles that cover relatively great annual distances such as buses, trucks and minibuses. Thus, at marginal mitigation costs of about 100 ZAR_{2007}/t CO_2eq, more than 20 Mt CO_2eq of transport WTW GHG emissions can be mitigated independently from the assumptions on future socio-economic growth. However, the analysis also shows that the transport sector is not the first sector to be addressed to cost-optimally mitigate large amounts of GHG emissions. Significant reduction potential lies, for example, in the decarbonization of electricity supply. Carbon capture and storage (CCS) was one option identified for CO_2 mitigation in electricity provision at a relatively low marginal abatement cost of 50 ZAR_{2007}/t CO_2eq. Furthermore, CCS is used in the supply of hydrogen for the transport sector at relatively high GHG taxes (≥ 400 ZAR_{2007}/t CO_2eq). Battery electric vehicles were not identified as a cost-optimal option for transport GHG mitigation but plug-in electric vehicles were so identified in the case of higher marginal mitigation costs.

6.4 Model results: Scenario variation – GHG tax (high socio-economic growth) with medium primary energy prices

In order to analyse the sensitivity of the results to the primary energy carrier prices, this section presents the consequences for the GHG_HG scenario (section 6.3) if primary energy carrier prices (which have been correlated with the crude oil price) reach a lower level. The anticipated crude oil prices used in the scenarios are about 97 USD_{2010}/bbl in 2040 under medium prices and 123 USD_{2010}/bbl for the higher price scenario. This corresponds to about 257 USD_{2040}/bbl and 326 USD_{2040}/bbl, respectively, assuming an annual inflation rate of 3.3% /IEA 2011c/, /BLS 2012/.

Figure 81 shows the changes in total vehicle activity for medium crude oil and primary energy carrier prices (GHG_HG–MP) compared to the GHG_HG marginal abatement cost curve in 2040. When alternative vehicle powertrains are adopted, the substitution of conventional vehicle powertrains is shifted to higher marginal GHG abatement costs. Whilst a significant contribution of $7.6 \cdot 10^9$ vkm for ICE mild hybrids corresponds to a GHG tax of 100 ZAR_{2007}/t CO_2eq under high oil prices (GHG_HG), comparable activity can be seen at 150 ZAR_{2007}/t CO_2eq for medium-level oil prices. This shift results in only 4% of the total vehicle activity being performed with non-conventional

ICE powertrains in comparison to about 8% in the GHG_HG scenario. In addition, the increase in E85–ICE SI vehicles due to the provision of ethanol from sugar cane is seen later. When the primary energy carrier price is relatively high, this stage can be found at 250 ZAR_{2007}/t CO_2eq, whereas for medium prices it is at 400 ZAR_{2007}/t CO_2eq. In consequence, the proportion of non-conventional ICE powertrains in total vehicle activity is only 9% under medium primary energy carrier prices compared to 28% in the GHG_HG scenario for a marginal abatement cost of 300 ZAR_{2007}/t CO_2eq. In addition, the further hybridization of the transport sector is recognized at a higher marginal abatement cost. For example, the vehicle activity of fuel cell hybrid electric vehicles amounts to $8.4 \cdot 10^9$ vkm under a GHG tax of 800 ZAR_{2007}/t CO_2eq in the high price scenario and under 900 ZAR_{2007}/t CO_2eq for medium energy carrier prices.

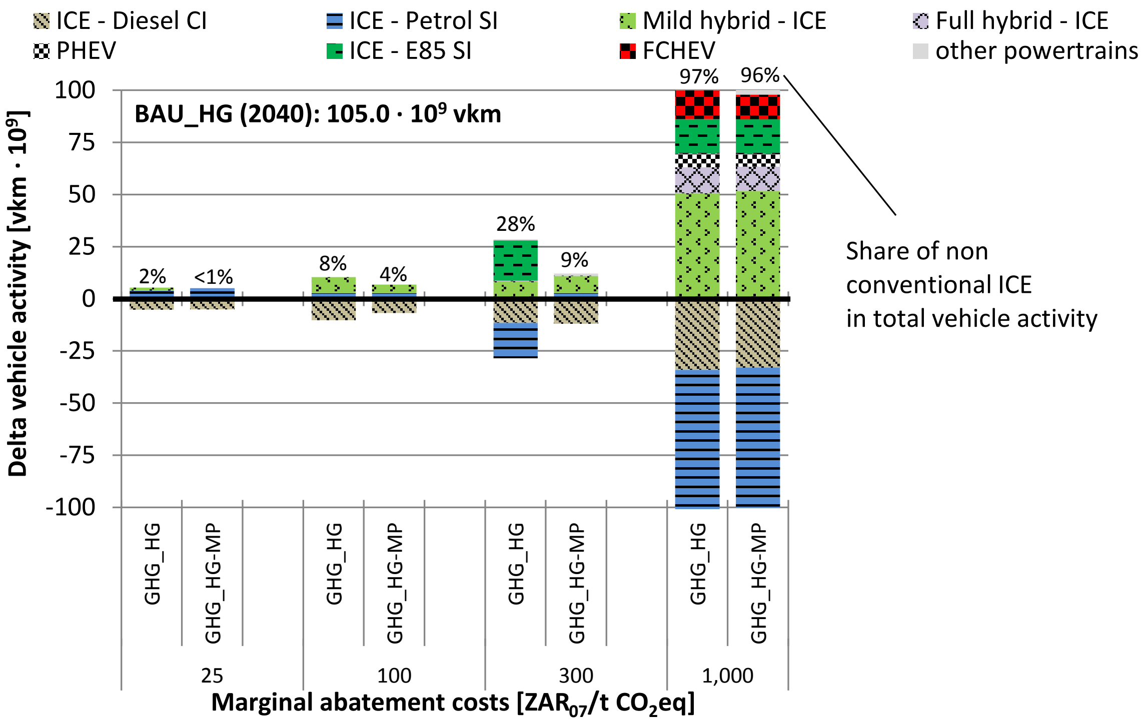


Figure 81: Changes in vehicle activity in the Gauteng transport sector under medium primary energy prices compared to the BAU_HG scenario in 2040.
Source: own calculations.

Comparing both scenarios GHG_HG and GHG_HG–MP, shows that the same vehicle powertrain technologies are used for the substitution of the conventional reference ICEs for all modes of transport analysed. Under a marginal abatement cost of 900 ZAR_{2007}/t CO_2eq and higher, the activity of non-conventional vehicles is comparable in both scenarios. On the other hand, at a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, the contribution of fuel cell hybrid electric vehicles in GHG_HG-MP is less than in the higher price scenario (about $0.8 \cdot 10^9$ vkm) and corresponds to greater activity of full and plug-in hybrid electric vehicles.

Similar findings can be drawn for WTW GHG emissions under medium crude oil prices (Figure 82) as the entire GHG cost curve is slightly shifted to higher marginal GHG abatement costs compared to the GHG_HG scenario (section 6.3.3). Whereas in the high price scenario, substitution of Fischer-Tropsch synthetic fuels occurs initially at 25 ZAR_{2007}/t CO_2eq, it begins at a GHG tax of 50 ZAR_{2007}/t CO_2eq under lower cost of primary energy. In both scenario coal-to-liquid fuels are not used at 100 ZAR_{2007}/t CO_2eq anymore. This results in smaller total reductions of transport WTW GHG emissions in GHG_HG-MP, especially for lower marginal mitigation costs.

Furthermore, a comparable contribution of alternative vehicle powertrain technologies to additional WTW GHG emissions is seen for higher marginal GHG abatement costs. For example, the WTW emissions of E85–ICE SI are comparable for 300 ZAR_{2007}/t CO_2eq for high prices and 400 ZAR_{2007}/t CO_2eq under medium prices (i.e. about 0.6 Mt CO_2eq). For marginal abatement costs of 1,000 ZAR_{2007}/t CO_2eq and higher the reductions in transport WTW GHG emissions compared to the BAU_HG scenario are similar under high and under medium primary energy carrier prices and the effects of a high proportion of hydrogen-fuelled vehicles can be identified.

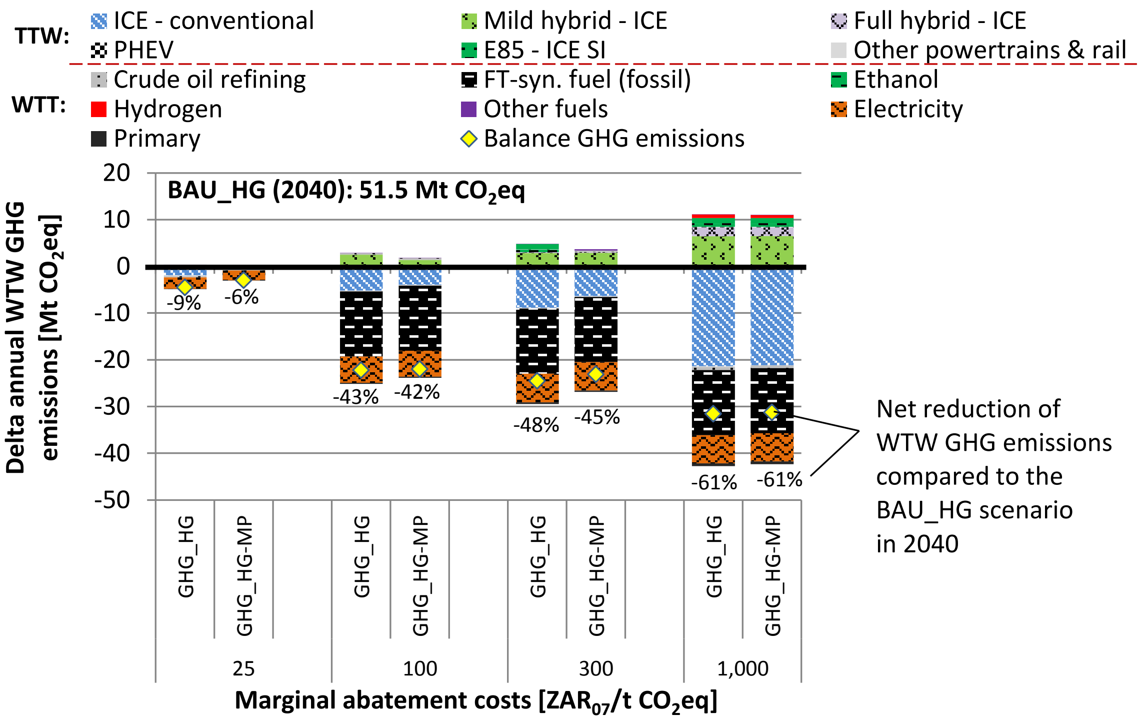


Figure 82: Changes in annual WTW emissions attributable to the Gauteng transport sector under medium primary energy prices compared to the BAU_HG scenario in 2040. Source: own calculations.

It can be concluded that the identified alternative transport fuels and vehicle powertrains identified as cost-optimal options for mitigating GHG emissions under GHG taxes are not sensitive to the variation in primary energy carrier prices considered here. However, the marginal abatement costs for GHG mitigation options clearly increase with lower primary energy carrier prices because reduced energy consumption results in lower cost savings.

6.5 Model results: Scenario variation – GHG tax (high socio-economic growth) without CCS

CCS is part of the previous scenario results involving many technologies – for example, the decarbonization of the electricity supply depends on coal-based integrated gasification combined-cycle (IGCC) power plants combined with CCS, which are relied upon after the restrictions on building nuclear power plants are reached. More relevant to the transport sector – as electricity consumption by the sector is comparatively small – is the application of CCS for hydrogen generation via coal gasification and upgrading (in GHG_LG) and via the reforming of natural gas (see sections 6.3 and 6.4). To demonstrate the role of CCS in GHG mitigation in Gauteng, this section presents a variant of the high socio-economic growth GHG mitigation costs curve under high crude oil prices, in which CCS is not used.

Figure 83 shows the final energy consumption by the Gauteng transport sector in the absence of CCS. It is found that many conclusions derived from scenarios considered above are also valid for this scenario. Initially (at 25 ZAR_{2007}/t CO_2eq), higher shares of biodiesel (from waste cooking oil) and BTL replace crude oil fuels. Under a higher marginal abatement cost ($\geq$ 200 ZAR_{2007}/t CO_2eq), the additional provision of crude oil-based fuels is lower. In both scenarios, ethanol from sugar cane is part of the scenario results at 250 ZAR_{2007}/t CO_2eq and its full potential is used at 300 ZAR_{2007}/t CO_2eq. Similar results can be identified for ethanol supplied from sugar beet, which is produced in Gauteng at a marginal abatement cost of 500 ZAR_{2007}/t CO_2eq independently of CCS restrictions. For lower marginal abatement costs, arable land is used to supply biodiesel.

Moreover, major differences between the high and low growth scenarios can be seen for a GHG tax of 600 ZAR_{2007}/t CO_2eq and more. In the scenario with CCS, hydrogen use in the transport sector increases continuously under high growth conditions; however, it is not used in the no-CCS scenario at this marginal mitigation cost. Electricity consumption in the transport sector is lower in the scenario without CCS and increases to 6.2 PJ under a GHG tax of 2,500 ZAR_{2007}/t CO_2eq (compared to 13.3 PJ in the GHG_HG scenario) as the provision of low-carbon electricity is more expensive.

Hydrogen then becomes part of the no-CSS scenario at 1,500 ZAR_{2007}/t CO_2eq. Biomass gasification is used to supply hydrogen, which is at lower marginal abatement costs than the GHG_HG reference, where biomass gasification is initially used for hydrogen generation at a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq. As biomass potential was used mainly to provide BTL in the GHG_HG scenario (see section 6.3.1), the contribution of Fischer-Tropsch fuels from cellulosic biomass is lower, with 27 PJ in the no-CCS scenario at a marginal abatement cost of 1,500 ZAR_{2007}/t CO_2eq, compared to 35 PJ with CCS. However, with highest marginal abatement costs analysed this difference diminishes. In the Gauteng transport sector in 2040 without CCS, under a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, about 143 PJ of mainly fossil-based final energy provision is replaced by about 92 PJ of alternatives. This is clearly less than in the

GHG_HG scenario; whose corresponding figures are 262 PJ and 182 PJ, respectively (see section 6.3.1).

Further differences between the GHG_HG scenario and the no-CSS variant can be identified in regard to electricity provision. In the GHG_HG scenario gas from landfill sites and sewage plants is used for SNG supply at marginal abatement costs ≥ 200 ZAR_{2007}/t CO_2eq (starting with landfill sites), yet no SNG is produced in the no-CCS scenario and biogas is used to supply electricity. Instead, some CNG is used in the transport sector in the no-CCS scenario.

The decarbonization of electricity provision benefits from nuclear energy, as in the previous scenarios, but reflects higher shares of solar energy instead of that from coal-based IGCC power plants with CCS. As for the scenario with CCS, concentrated solar power (based on parabolic trough with storage) is initially used at 100 ZAR_{2007}/t CO_2eq. However, solar energy electricity production is greater in the no-CCS scenario for that GHG tax.

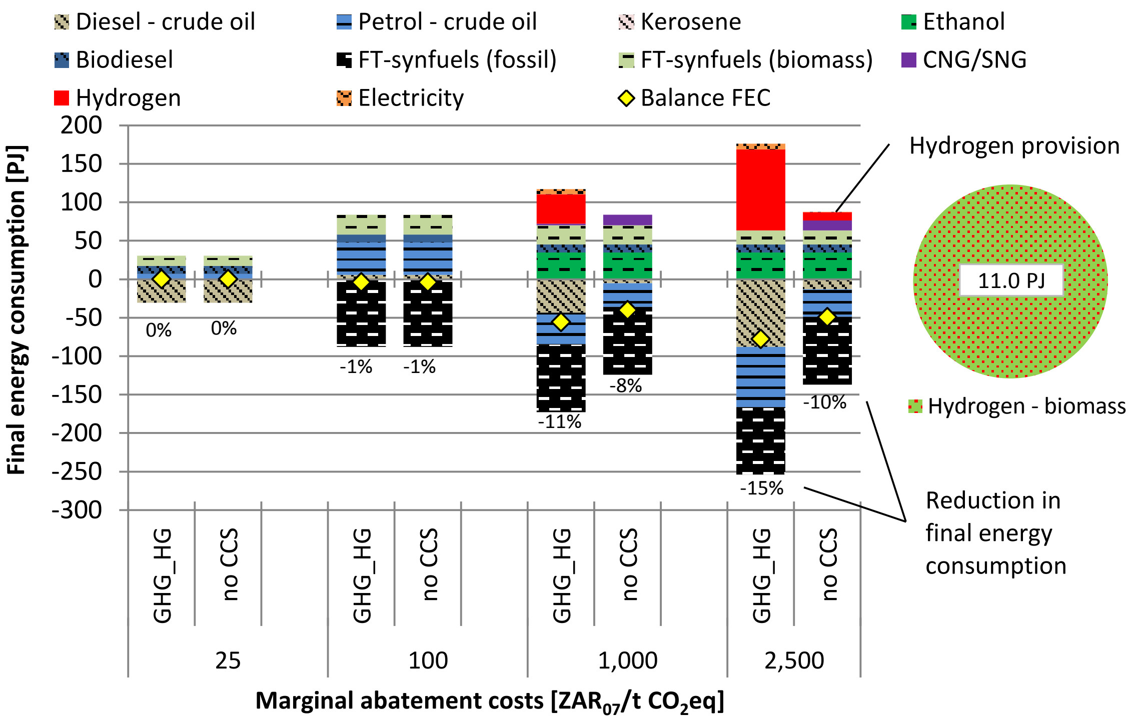


Figure 83: Changes in final energy consumption in the transport sector of Gauteng without CCS compared to the BAU_HG scenario in 2040.
Source: own calculations.

Figure 84 illustrates vehicle activity of the Gauteng transport sector in the GHG_HG no-CCS scenario compared to the BAU_HG reference scenario in 2040. The relative shares of alternative vehicle powertrains in vehicle activity are shown in comparison with the GHG_HG scenario (Figure 74). Changes in vehicle powertrains are comparable for the two scenarios at marginal abatement costs < 600 ZAR_{2007}/t CO_2eq. Small differences arise at those marginal abatement costs when first-generation biofuels are initially produced, as a result of slight differences in total final energy consumption.

However, for the next higher marginal abatement costs analysed, vehicle activity for dedicated biofuel vehicles is similar for the no-CCS and the GHG_HG scenarios.

In accordance with the GHG_HG scenario, in the GHG_HG no-CCS scenario conventional ICEs are continuously replaced with mild hybrids, starting with diesel ICE CI mild hybrids for buses (on scheduled services and the BRT) and petrol ICE SI mild hybrids for minibuses at 25–50 ZAR_{2007}/t CO_2eq at low vehicle activity. Conventional ICEs for smaller vehicles are replaced at higher marginal abatement costs – initially at 400 ZAR_{2007}/t CO_2eq for passenger cars.

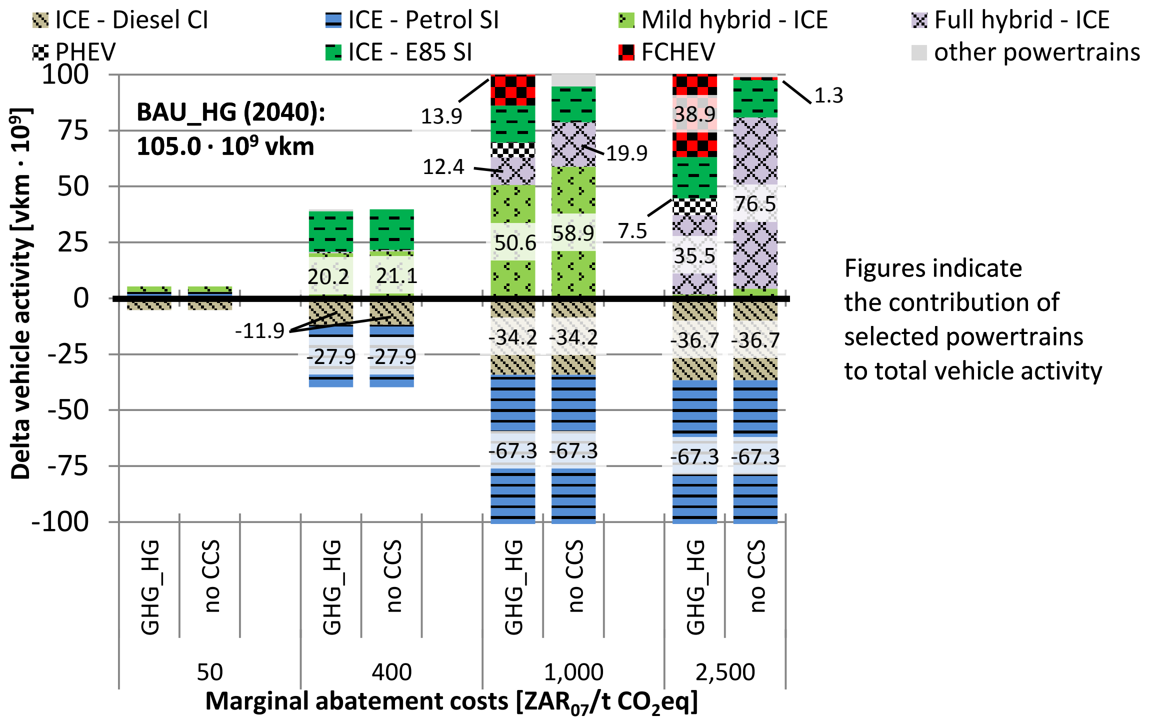


Figure 84: Changes in vehicle activity in the Gauteng transport sector without CCS compared to the BAU_HG scenario in 2040. Source: own calculations.

Conversely, major differences can be identified for marginal abatement costs of ≥ 600 ZAR_{2007}/t CO_2eq when fuel cell hybrid electric vehicles are part of the GHG_HG scenario but initially at 1,500 ZAR_{2007}/t CO_2eq under CCS restrictions. The reason is that hydrogen in the GHG_HG scenario is supplied by reforming natural gas with CCS (see section 6.3.1), at those marginal abatement costs and thus no fuel cell hybrid electric vehicles are used at this GHG taxes under CCS restriction. The difference increases as the final energy consumption of hydrogen rises in the GHG_HG scenario. For a marginal abatement cost of 1,000 ZAR_{2007}/t CO_2eq, the activity of fuel cell hybrid electric vehicles is $13.9 \cdot 10^9$ vkm in the GHG_HG scenario, whereas in the no-CCS scenario no fuel cell hybrid electric vehicles are used. Plug-in hybrid electric vehicles, which are used at a marginal abatement cost of ≥ 700 ZAR_{2007}/t CO_2eq for minibuses in the GHG_HG scenario, are not used in the no-CCS scenario. The reason can be found in the supply of electricity, as low-carbon electricity cannot be provided by coal with CCS. Instead, full hybrid vehicles replace the conventional ICEs of the BAU_HG reference scenario in 2040. Thus, the total activity of non-conventional vehicles is similar in both scenarios, although different alternative vehicle technologies are used. In addition, some contributions of CNG–ICE SI vehicles can be identified for a marginal abatement cost of 900 ZAR_{2007}/t CO_2eq and above.

As a consequence, the activity of full hybrid vehicles is about 19.9·10^9 vkm at a marginal abatement cost of 1,000 ZAR_{2007}/t CO_2eq, which is about 60% higher in the GHG_HG no-CCS scenario than in the GHG_HG scenario. This difference increases for even higher marginal abatement costs. At a marginal abatement cost of ≥ 1,500 ZAR_{2007}/t CO_2eq, when hydrogen is initially provided, it is used for the BRT, scheduled buses and for HDVs as in the MACC of the high socio-economic growth scenario. However, this use can already be identified for a marginal abatement cost of 600 ZAR_{2007}/t CO_2eq in the GHG_HG scenario. No vehicle activity is attributed to fuel cell hybrid electric vehicles for LDVs, minibuses and passenger cars, as insufficient hydrogen is provided.

The impact of the changes in the use of transport vehicle powertrain technology and final energy consumption on transport-related WTW GHG emissions is shown in Figure 85. The results reflect the previously identified differences between the GHG_HG scenario and the scenario with CCS restrictions.

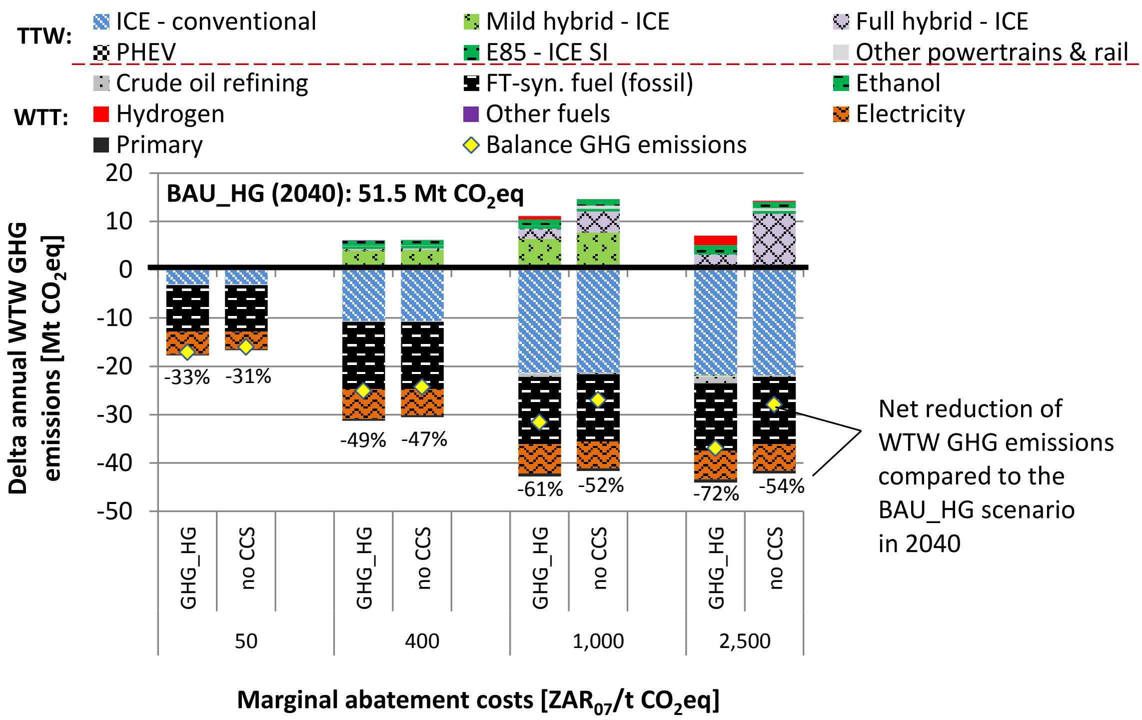


Figure 85: Changes in annual WTW emissions attributable to the Gauteng transport sector without CCS compared to the BAU_HG scenario in 2040.
Source: own calculations.

When fuel cell hybrid electric vehicles become part of the model solution of the GHG_HG scenario (at 600 ZAR_{2007}/t CO_2eq and higher), the GHG_HG no-CCS scenario indicates greater GHG emissions clearly visible as a result of the substantial contribution of full hybrid vehicles to additional WTW GHG emissions. For example, at 900 ZAR_{2007}/t CO_2eq the WTT GHG emissions of mild and full hybrid vehicles are about 11.8 Mt CO_2eq, whereas with CCS this figure is 9.0 Mt CO_2eq. The difference increases with higher contributions of hydrogen in the GHG_HG scenario, as the full hybrid ICEs that are used in the no-CCS scenario instead of fuel cell hybrid electric vehicles obviously generate more GHG emissions. This results in the WTW GHG emissions being reduced by 52% in the GHG_HG no-CSS scenario at a GHG tax of 1,000 ZAR_{2007}/t CO_2eq compared to the BAU_HG scenario in 2040, whereas in this scenario the reduction with CCS is 61%.

It can therefore be stated that CCS can play an important role in GHG mitigation, which can be seen at a lower marginal abatement cost for electricity provision and at higher marginal abatement costs for the transport sector and its energy supply. Absolute WTW GHG emissions of the transport sector in 2040 under CCS restriction correspond to 23.6 Mt CO_2eq at a marginal GHG abatement cost of 2,500 ZAR_{2007}/t CO_2eq. This value is significantly higher than the 14.6 Mt CO_2eq in the GHG_HG scenario, for the same year and abatement cost. WTW GHG emissions can be disaggregated into 6.9 Mt CO_2eq WTT GHG emissions (7.3 Mt CO_2eq under GHG_HG) and 16.7 Mt CO_2eq TTW GHG emissions (7.3 Mt CO_2eq under GHG_HG).

6.6 Model results: Scenario variation – GHG tax (high socio-economic growth) with cost variation

In the above analysis (see sections 6.3, 6.4 and 6.5), besides biodiesel from waste cooking oil and the substitution of fossil Fischer-Tropsch synthetic fuels; synthetic fuels from cellulosic biomass (i.e. BTL) and hybrid electric vehicles have been identified as particularly promising options for de-carbonizing the transport sector. However, uncertainties about future battery costs were identified (section 5.2.4) as well as in the cost of supplying cellulosic biomass (section 6.1.4). Thus, in the following two variations have been considered (see section 6.1): an increase in the cost of supplying cellulosic biomass by 50% (GHG_HG-CV, a), and a reduction in specific battery costs of 50% (GHG_HG-CV, b).

With increased cost of biomass provision, the final energy consumption of BTL declines by 69% to about 3 PJ if no GHG taxes are imposed in comparison with the BAU_HG scenario in 2040 (Figure 86). The increasing supply of BTL fuels, which was identified in the GHG_HG scenario (see section 6.3.1), now occurs at higher marginal abatement costs. Consequently, the final energy consumption of crude oil-based fuels is enlarged. Whereas the full potential of cellulosic biomass is used to provide BTL at 50 ZAR_{2007}/t CO_2eq in the GHG_HG scenario, this can be identified at 150 ZAR_{2007}/t CO_2eq if the costs of providing cellulosic biomass are increased by 50%. At a marginal abatement cost of 150 ZAR_{2007}/t CO_2eq and above, the final energy consumption of Fischer-Tropsch synthetic fuel from biomass is almost identical to that in the GHG_HG scenario.

Further findings are similar for both scenarios and the negligible differences between them do not greatly affect the transport sector – for example, there is slightly greater electricity consumption from wind power at a low marginal abatement cost. As in the GHG_HG scenario, biomass is used to supply hydrogen at a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, so that the final energy consumption of BTL fuels is then reduced. However, the total hydrogen provision is somewhat lower (Figure 86). All relevant results (e.g. the initial provision of biodiesel from waste cooking oil or the substitution of fossil Fischer-Tropsch fuels with crude oil products) are similar for the GHG_HG scenario and for the variation in which the cost of biomass is increased.

Moreover, higher costs of supplying biomass do not result in significant changes in the MACCs for vehicle activity compared to the GHG_HG scenario (section 6.3.1). This result is reasonable as Fischer-Tropsch synthetic fuels do not require vehicle technology to be adapted and thus a lower final energy consumption of BTL fuels is not reflected in differences in the application of alternative powertrains.

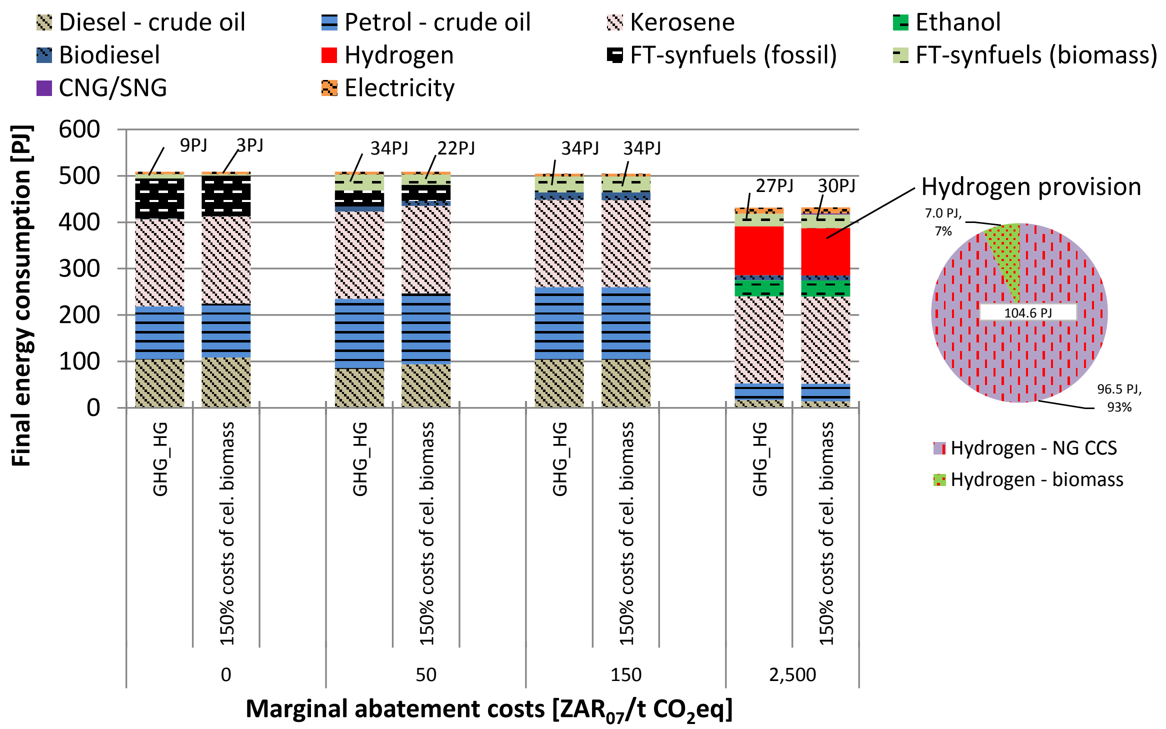


Figure 86: Final energy consumption in the transport sector of Gauteng with 150% cost of lignocellulosic biomass provision compared to the BAU_HG scenario in 2040. Source: own calculations.

In Figure 87, vehicle activity is shown for battery prices reduced by 50% (GHG_HG-CV, b). For a better comparison with the GHG_HG scenario, the contribution of selected powertrains to total vehicle activity in the transport sector is indicated for both scenario options. The reduction in specific battery investment costs obviously encourages the uptake of vehicles using batteries for energy storage. At a marginal abatement cost of

50 ZAR_{2007}/t CO_2eq, vehicle activity of mild hybrids is increased by about $6.0 \cdot 10^9$ vkm compared to the GHG_HG scenario. Full hybrids are used for buses beginning at a marginal abatement cost of 150 ZAR_{2007}/t CO_2eq (compared to 250 ZAR_{2007}/t CO_2eq in GHG_HG). At 400 ZAR_{2007}/t CO_2eq, the delta activity for mild hybrids reaches its climax at $16.1 \cdot 10^9$ vkm. After that, the substitution tends to favour full hybrid electric vehicles. At a marginal abatement cost of 900 ZAR_{2007}/t CO_2eq, the activity of full hybrid electric vehicles is about $36.0 \cdot 10^9$ vkm higher for reduced battery cost compared with the GHG_HG scenario.

Furthermore, a clear increase in activity by plug-in hybrid electric vehicles is evident, which are initially applied at 300 ZAR_{2007}/t CO_2eq in GHG_HG, compared to 700 ZAR_{2007}/t CO_2eq in GHG_HG. When battery investment costs decline to 150 €$_{2007}$/kWh, plug-in hybrid electric vehicle activity reaches levels of $16.1 \cdot 10^9$ vkm at 1,500 ZAR_{2007}/t CO_2eq, whereas for the GHG_HG scenario with standard battery investment costs the activity is $6.6 \cdot 10^9$ vkm at this marginal abatement cost. As a result, the contribution of fuel cell hybrid electric vehicles is less at marginal abatement costs of 600 ZAR_{2007}/t CO_2eq and above. The application of further alternative technologies is comparable in both scenarios. However, even with battery prices reduced by 50%, battery electric vehicles (BEV) are not used in the scenario.

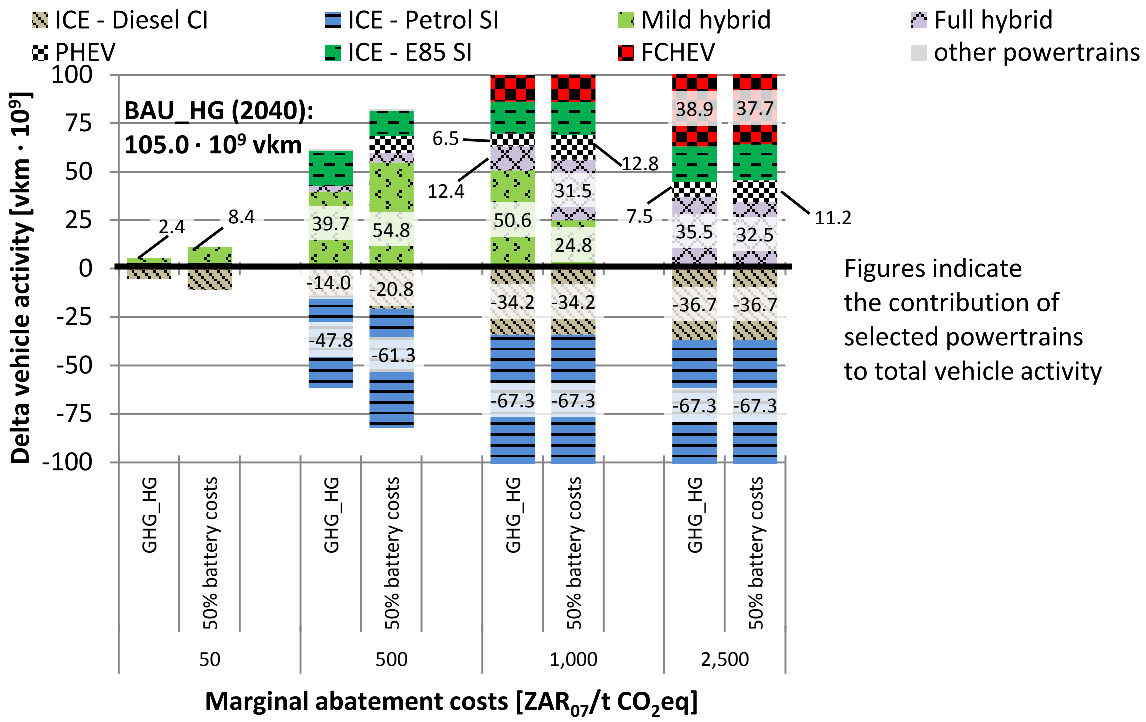


Figure 87: Changes in vehicle activity in the transport sector of Gauteng with lower battery costs compared to the reference scenario BAU_HG in 2040.
Source: own calculations.

6.7 Concluding evaluation of scenario results

The scenario analysis has shown that the expected future socio-economic growth of Gauteng may cause a significant increase in energy consumption and GHG emissions. Under "business as usual" politics, it is likely that the province's future energy system will still be greatly dependent on the use of coal (for process energy, electricity generation and fuel provision). Thus, more than 70% of primary energy consumption in 2040 in both reference scenarios is based on coal. Consequently, the energy-related GHG emissions attributable to Gauteng may nearly double by 2040, reaching almost 230 Mt CO_2eq in that year under high socio-economic growth. Under lower growth conditions, the increase in GHG emissions is less but still significant at more than 25 Mt CO_2eq (+21%).

Similar results can be stated for the future transport sector of Gauteng under business-as-usual conditions. A significant increase in transport activity was identified as possibly resulting from the province's socio-economic growth. It is found that with business-as-usual politics, a large proportion of this activity is likely to be road based. Moreover, high contributions of individual transport seem probable. Although energy efficiency is found to increase significantly in the Gauteng transport sector (due mainly to fleet renewal), scenario analysis shows that final energy consumption attributed to transport probably increases. Depending on future economic and population growth, and also on income distribution, this increase is likely to be between 27% and 88%. As a result, the increase in transport-related GHG emissions is also likely to be significant.

The role of the transport sector as part of the energy system to reduce GHG emissions at minimum cost has been analysed using GHG tax curves, or marginal abatement costs curves. This method allows the identification of the measures that should be addressed first – namely, those with the lowest marginal GHG mitigation costs. Moreover, it is possible to identify quantitatively those measures corresponding to a specific GHG reduction target. To account for uncertainties – for example, in the future price of crude oil – and to reflect sensitivities in the results, additional scenario variations have been investigated.

The analysis, conducted for both low and high socio-economic growth conditions, revealed that there are several options for GHG mitigation for the transport sector and its energy supply in Gauteng and in South Africa, but with different mitigation costs. The technology options identified for fuel provision include the decarbonization of fuel supply as a result of the substitution of fossil Fischer-Tropsch synthetic fuels as well as higher shares of biofuels in the final energy mix. The main biofuels used are biodiesel from waste cooking oil and synthetic fuels from cellulosic biomass (i.e. BTL process). In addition, biodiesel from sunflower seeds and rapeseed, and ethanol from sugar cane or sugar beet are also used for biofuels for higher reduction targets, where the crop used depends on the GHG mitigation target. Furthermore, the use of upgraded landfill and sewage gas as transport fuel can lead to reduced GHG emissions but the potential may be limited and it competes with gas use for electricity provision. The greater use of more efficient powertrains (such as mild, full and plug-in hybrid electric vehicles) is for lower marginal abatement costs focused on vehicles with high annual mileages and higher shares of urban travel (i.e. buses). Hydrogen might lead to even further reductions of transport-related GHG emissions for high marginal GHG mitigation costs. However, it was also found that initial changes in the energy system for cost-efficient GHG mitigation should not take place in the transport sector but for electricity generation. Promising options identified include nuclear energy and coal-based integrated gasification combined cycle power plants with carbon capture and storage as well as solar energy use (i.e. concentrated solar power with parabolic troughs). Higher shares of plug-in hybrid electric vehicles and fuel cell hybrid electric vehicles were identified in the low economic growth scenario for high marginal abatement cost in comparison to the high growth scenario under GHG taxes. Furthermore, hydrogen from coal gasification and upgrading with carbon capture and storage are adopted under low socio-economic growth conditions but not in the GHG_HG scenario. The reason was found in the limited potential for renewable electricity provision and carbon storage. These are primarily bound to providing low-carbon electricity to the non-transport sectors in the GHG_HG scenario, whereas under low economic growth conditions these are available for application in transport energy provision.

These results of the integrated analysis are consistent with the initial findings for well-to-wheel GHG abatement costs of passenger cars in section 5.3 – for example, the substitution of fossil Fischer-Tropsch fuels with crude oil products and biodiesel from waste cooking oil showed the lowest marginal abatement costs. However, the abatement costs calculated are different as the assumptions of the reference fuel mix and technology in section 5.3 are not necessarily the same as the scenario results in the energy system model. Moreover, marginal abatement costs in the marginal abatement costs curve have been compounded with an interest rate of 8% to the model base year 2007.

The integrated analysis with the TIMES-GEECO model revealed that expansion of the public transport infrastructure for bus rapid transit and for the Gautrain are not part of a least-cost GHG mitigation strategy under the conditions of the scenarios. However, this result is also based on the extrapolation of the historic shift of minibus passengers to the new systems, which was observed as previous systems were introduced (see section 4.3). As minibuses show comparable low specific energy consumption per passenger kilometre, their substitution with larger buses does not result in significant reductions of GHG emissions. Trolley buses for least-cost GHG mitigation were result of any of the scenarios.

To account for uncertainties in the future prices of crude oil and primary energy carriers, in the costs of cellulosic biomass provision, in the future specific investment costs of Li-ion batteries and in the political acceptance of carbon capture and storage, additional scenarios have been analysed. It is found that most of the options identified for GHG mitigation are not sensitive to these variations or to changes in the crude oil price, except those technologies using carbon capture and storage, such as hydrogen from coal gasification and upgrading. Ignoring carbon capture and storage technology discourages the uptake of hydrogen (which is otherwise produced from natural gas upgrading and via coal gasification, both incorporating carbon capture and storage, at a medium marginal GHG abatement cost). Furthermore, not using carbon capture and storage limits the use of electricity in the transport sector, as the provision of low-carbon electricity is more expensive. Total well-to-wheel emissions are greater, especially at higher marginal abatement cost when not using carbon capture and storage.

Changing battery costs as well as altering the costs of providing cellulosic biomass results mainly in smaller shifts in the mitigation cost curves but does not change the optimal technologies identified for GHG mitigation. A lower increase in the future crude oil price will obviously reduce the substitution of crude oil fuels, although this effect diminishes for higher abatement costs. As the costs of biomass provision increase, the uptake of BTL is slowed down, but it can still be seen as a feasible option for GHG mitigation. Cheaper batteries encourage hybrid electric vehicles. In any case, the substitution of conventional internal combustion engines with different forms of hybrid electric engines can significantly reduce the specific energy consumption in the transport sector (i.e. depending on the degree of hybridization and the share of urban travel, more than 20% reduction in specific energy consumption is achievable; see section 5.2.5). Consequently, higher proportions of hybrid electric vehicles reduce transport-related GHG emissions, especially in an urban environment like Gauteng. Initial substitutions are reasonable for vehicles with high annual mileages and relatively large shares of urban travel (i.e. buses). However, pure battery electric vehicles are not part of the model solution in any scenario.

Finally, Figure 88 compares the annual transport-related well-to-wheel emissions for all scenarios for the year 2040. In all scenarios, significant reductions in well-to-wheel GHG emissions are possible at low marginal abatement costs (due to the substitution of fossil Fischer-Tropsch synthetic fuels). Well-to-wheel GHG emissions are comparable for all high socio-economic growth conditions with the exception of the no-CCS scenario. However, well-to-wheel GHG emissions for the GHG_LG scenario are considerably lower.

Lower crude oil prices in the GHG_HG-MP scenario are responsible for comparably higher annual well-to-wheel GHG emissions for most marginal abatement costs as they impede the substitution of conventional fuels and powertrains. On average, the well-to-wheel GHG emissions are about 0.5 Mt CO_2eq higher than in the GHG_HG scenario. The greatest deviation can be identified for a marginal abatement cost of 25 ZAR_{2007}/t CO_2eq (1.5 Mt CO_2eq) due to the substitution of Fischer-Tropsch fuels at these costs.

The reduction of specific battery costs obviously reduces annual well-to-wheel GHG emissions, whereas an increase of cellulosic biomass provision costs by 50% results in an intensification of well-to-wheel GHG emissions. However, the differences are of little account and for marginal abatement costs of 150 ZAR_{2007}/t CO_2eq and above, the annual well-to-wheel GHG emissions in the GHG_HG and GHG_HG-CV a) and b) scenarios are similar and reach a level of 14.6 Mt CO_2eq at 2,500 ZAR_{2007}/t CO_2eq.

In GHG_LG about 31.9 Mt CO_2eq can be mitigated at such costs (–83%) compared to the BAU_LG scenario in 2040.

Conversely, annual well-to-wheel emissions of the transport sector under high socio-economic growth without carbon capture and storage (GHG_HG – no CCS) are clearly higher than in the other high socio-economic growth marginal abatement cost curves. The difference reaches more than 1.0 Mt CO_2eq at marginal abatement costs above 600 ZAR_{2007}/t CO_2eq. At a marginal abatement cost of 2,500 ZAR_{2007}/t CO_2eq, transport-related well-to-wheel GHG emissions are 23.6 Mt CO_2eq for the GHG_HG – no CCS scenario. In the GHG_HG scenario the corresponding figure is 14.6 Mt CO_2eq, which corresponds to a reduction of GHG emissions relative to the BAU_HG reference scenario in 2040 of 72% or 36.9 Mt CO_2eq.

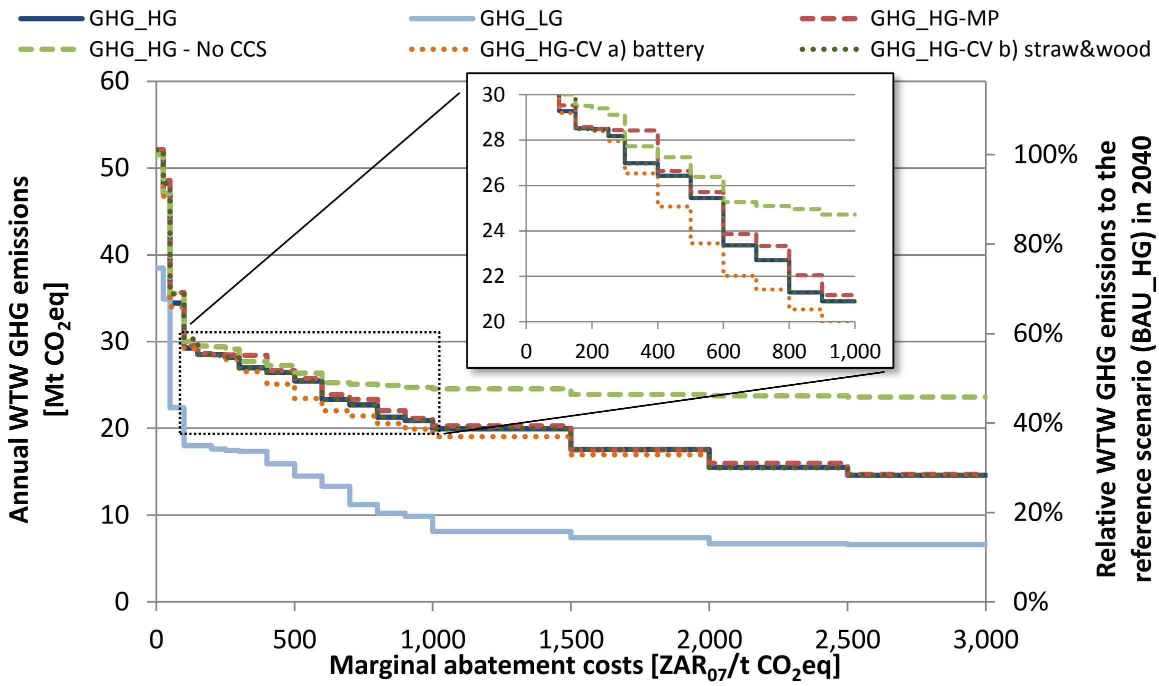


Figure 88: Comparison of annual transport WTW GHG in relation to marginal abatement cost for all scenarios investigated. Source: own calculations.

7 Summary and conclusions

Gauteng province has been identified as being of major importance to South Africa and for the African continent as a whole in terms of its population and its economic prospects. However, it also has to – and wants to – play a leading role in the country's climate change prevention and GHG mitigation efforts. The transport sector has been identified as a major field of action as it provides several levers to reduce energy consumption and GHG emissions, such as changes in fuel supply, vehicle powertrain technologies and modal shift.

There is a lack of data relevant to transport in South Africa and specifically for Gauteng. Few investigations have focused on alternative transport technologies and fuels as GHG mitigation options for Gauteng, which highlights the need for analysing abatement costs of alternative fuels and powertrains.

The analysis presented in this thesis has shown that Gauteng's transport sector has evolved by focusing on infrastructure for individual motorized transport within a sprawled urban form. Consistent with a relatively old vehicle fleet and the high proportion of synthetic fuels from coal and natural gas in the fuel mix, vehicle travel is responsible for high GHG emissions over the whole fuel chain (well-to-wheel). Well-to-wheel GHG emissions attributable to transport activity in Gauteng accounted for 33 Mt CO_2eq in 2007, which is about 27% of the total GHG emissions that can be allocated to the province. However, Gauteng recently focused on expanding its public transport network with the construction of bus rapid transit lines and a suburban rail train system, the Gautrain. Moreover, Gauteng and South Africa are encouraging the use of alternative fuels and powertrains by building test vehicle fleets (e.g. for compressed natural gas and liquefied petroleum gas use) and considering the prospects for biofuel blending targets.

Analysis of transport fuel chains and vehicle propulsion technologies

In this thesis, a comprehensive analysis of alternative fuels and vehicle powertrain technologies for the transport sector of Gauteng was conducted. Initially, a huge variety of vehicle propulsion technologies and fuels were analysed by considering local provincial conditions and South Africa as a whole. Fuel production and delivery costs have therefore been calculated as well as vehicle investment costs and fuel consumption. It has been shown that there are many possibilities of reducing GHG emissions and/or increasing energy efficiency in the transport sector. These include options such as biofuels from waste cooking oil, whose fuel provision costs are calculated at about 163 ZAR_{2007}/GJ in 2010 and 205 ZAR_{2007}/GJ in 2040 compared to 126 ZAR_{2007}/GJ in 2010 and 185 ZAR_{2007}/GJ in 2040 for diesel from crude oil. As there are only minor engine adaption costs for pure biodiesel usage, well-to-wheel GHG abatement costs were found to be below 400 ZAR_{2007}/t CO_2eq for application in passenger cars in 2010. Ethanol from lignocellulosic biomass showed promising fuel costs in 2040 (about 204–246 ZAR_{2007}/GJ) as well as biomass to liquid Fischer-Tropsch fuels (about 183–237 ZAR_{2007}/GJ for synthetic petrol and diesel).

Additional fuel options have been analysed, including synthetic fuels from coal and natural gas (with and without carbon capture and storage); biofuels from energy crops (i.e. sugar cane and sugar beet as a source of ethanol; rapeseeds, sunflower seeds and soybeans for biodiesel provision); the substitution of natural gas by biomass gasification or upgrading gas from landfill and sewage sites; and hydrogen provision from various sources. The lowest well-to-wheel GHG emissions were calculated for Fischer-Tropsch synthetic diesel from biomass and for ethanol from lignocellulosic biomass, which are less than 3 g CO_2eq/MJ. The GHG mitigation potential of these fuels is significant compared to petrol from the refining of crude oil, which corresponds to well-to-wheel GHG emissions of about 101 g CO_2eq/MJ in 2010 and 92 g CO_2eq/MJ in 2040, and to crude diesel with about 105.2 g CO_2eq/MJ in 2010 and 96.4 g CO_2eq/MJ in 2040. Furthermore, biodiesel from waste cooking oil can reduce well-to-wheel GHG emissions significantly. These were found to be about 6.0 g CO_2eq/MJ in 2010 and 4.2 g CO_2eq/MJ in 2040.

Alternative vehicle propulsion technologies like hybrid vehicles were found to offer reduced specific energy consumption, e.g. up to 60% for passenger cars as plug-in hybrid electric vehicles. Additional investment costs were calculated to decline from about 207,500 ZAR_{2007} in 2010 to about 82,400 ZAR_{2007} in 2040, taking the example of a petrol-fuelled (spark-ignition) plug-in hybrid passenger car. However, even in 2010 significant reductions in specific energy consumption can be achieved with mild hybrid vehicles at comparatively low additional costs (i.e. about 35,200 ZAR_{2007} for a mild hybrid petrol passenger car, which reduces fuel consumption by about 16%). Moreover, the prospects of establishing a hydrogen economy were analysed, which showed comparatively low production costs if generated from fossil sources (i.e. about 71.0 ZAR_{2007} for hydrogen from coal with carbon capture and storage in 2010). However, significant costs arise due to fuel transport and distribution, which contribute an additional 295 ZAR_{2007} in this example. Moreover, under the 2010 electricity mix, well-to-wheel GHG emissions can be up to 523 g CO_2eq/MJ for hydrogen produced in a decentralized way via electrolysis. Alternative options for using low-carbon or carbon-free electricity have also been analysed.

An analysis of well-to-wheel GHG emission abatement costs and GHG mitigation potential was conducted for passenger cars. It was shown that biomass to liquid fuels and ethanol from lignocellulosic biomass as well as biodiesel from waste cooking oil provide high mitigation potential (> 5 t CO_2eq/a) at comparatively low mitigation costs (≤ 1,000 ZAR_{2007}/t CO_2eq). However, these technologies are not available on a commercial scale today. The mitigation option with the lowest costs identified (i.e. < 400 ZAR_{2007}/t CO_2eq in 2010) is the substitution of the current fuel mix with crude oil-based fuels, but the mitigation potential (on a single vehicle) is less than for previous options. Many options for mitigating passenger car GHG emissions were identified but show only a modest annual abatement potential (1–5 t CO_2eq/a) at mitigation costs between 1,000 and 2,500 ZAR_{2007}/t CO_2eq. These include hybrid electric vehicles, first-generation biofuels as well as methane gas and liquefied petroleum gas use in the transport sector. The application of hydrogen-fuelled vehicles and plug-in hybrid electric vehicles for passenger cars showed medium annual GHG mitigation potential of more than 2 t CO_2eq/a at comparatively high cost of more than 400 ZAR_{2007}/t CO_2eq if sourcing the hydrogen from natural gas, biomass or from coal using carbon capture and storage.

Integrated analysis of the transport sector of Gauteng using an energy system model

The analysis has also shown that the effects and prospects of many options are aligned to each other and that there are interlinkages in the energy system. The set of mitigation options furthermore depends on the desired GHG mitigation target. This study is the first application of a cost-optimization and energy system model for Gauteng to address these issues. The advantages of using energy system models have been identified by the inclusion of interlinkages and interdependencies as well as in the avoidance of setting mutually exclusive targets or strategies. For this purpose, the TIMES energy system model-generator has been adapted to Gauteng conditions in the TIMES-GEECO model.

This new model application includes the characteristics of a developing society such as Gauteng as it includes all relevant modes, vehicle technologies, fuel options as well as explicit future expansion of the public transport infrastructure. It has been based on a comprehensive analysis of Gauteng's mobility patterns and possible future development, which enables a realistic view of the prospects for implementing new technologies in Gauteng. In addition, application of the TIMES-GEECO model comprises methodical extensions of the modelling approach used in other studies as it includes the possibilities for transport infrastructure extension, vehicle-to-grid energy storage and the consideration of road types. Income inequality and socio-economic development were considered in a travel demand model based on homogeneous groups of behaviour and fed into the TIMES-GEECO model. The role of Gauteng as part of the overall energy system of South Africa was reflected as all relevant energy supply capacities in the country have been implemented in the modelling efforts. Moreover, mitigation options outside the provincial boundaries have also been considered, which ensures the allocation of emissions for which Gauteng is responsible, on the one hand, but also takes account of mitigating emissions where it can be done at least cost on the other hand.

A scenario analysis was conducted for Gauteng to show the possible development of the province and to identify promising least-cost options for GHG mitigation in the field of transport. In the analysis, it was shown that under current policies a significant growth in both energy consumption and GHG emissions could be expected in the province.

To identify least-cost measures to mitigate GHG emissions for the transport sector and to demonstrate the sensitivity of the results, mitigation cost curves have been derived for different prices of GHG emissions. Using model-based marginal abatement costs curves, a technology-ranking was drawn up for cost-optimal GHG mitigation. In the scenario analysis, variations have been made for uncertain factors, such as future socio-economic growth, crude oil price, costs for cellulosic biomass provision, specific investment costs for vehicle battery storages and, moreover, for the exclusion of carbon capture and storage. In summary, the results for the year 2040 have been categorised in four classes of annual mitigation costs.

Low marginal GHG mitigation costs: < 100 ZAR_{2007}/t CO_2eq:

- Biofuels from waste cooking oil and from cellulosic biomass (i.e. BTL) can result in significant reductions in GHG emission for comparatively low mitigation costs (i.e. 25 ZAR_{2007}/t CO_2eq). However, the mitigation potential of biodiesel from waste cooking oil is limited and second-generation biofuels from lignocellulosic biomass are currently not available on a commercial scale. Dedicated biofuel vehicles might be necessary to achieve high biofuel penetration and would also increase transport energy efficiency (e.g. by the introduction of flexible-fuel vehicles such as ICE–E85).
- A powerful lever to reduce transport well-to-wheel GHG emissions at comparatively low mitigation costs, is the substitution of synthetic fuels from coal and natural gas. These fuels are currently used in South Africa and are likely to be a dominant part of the energy system in the future. In the scenario analysis, fossil Fischer-Tropsch synthetic fuels were fully changed at marginal abatement costs of 100 ZAR_{2007}/t CO_2eq independently of sensitivity to the future crude oil price. Even if crude oil-based fuels are used for this substitution, a significant reduction in well-to-wheel GHG emissions is achievable (e.g. in high socio-economic growth conditions, well-to-wheel emissions in 2040 reduce by about 13.5 Mt CO_2eq through this substitution). However, synthetic fuels are currently a significant contributor to South African fuel supply and fuel refining capacity, which makes it necessary to include the security of supply in any consideration of replacing fossil Fischer-Tropsch plants.
- Hybrid vehicles (mild and full) offer prospects for increasing energy efficiency and reducing GHG emissions at comparatively low marginal abatement costs in the case of vehicles with high annual mileages and carrying a high share of urban travel such as scheduled buses and minibuses. Moreover, for those vehicle classes the abatement costs can even be negative as seen in scenario analysis (i.e. about 64% of the vehicle activity of buses already represents mild hybrids in the reference case).
- Electricity provision from nuclear energy and coal-fired power plants with carbon capture and storage (if considered), as well as wind energy converters in windy areas, can result in a significant reduction of total GHG emissions in the energy system. However, the effects on the transport sector are small.

Medium marginal GHG mitigation costs: < 500 ZAR_{2007}/t CO_2eq:

- First-generation biofuels can be applied for medium marginal abatement costs. The most promising biofuels for use in Gauteng are biodiesel from sunflower seeds and ethanol from sugar beet. Providing biodiesel from rapeseeds or ethanol from sugar cane, which can be cultivated outside the province, is even cheaper. While biodiesel showed lower marginal abatement costs (e.g. 150–200 ZAR_{2007}/t CO_2eq for biodiesel from rapeseeds), ethanol fuels have a higher mitigation potential. Restriction on the land area available for biofuel provision might cause competition for those fuels. Water availability might be an additional limiting constraint.
- Substitute natural gas (SNG) can contribute to GHG mitigation in the transport sector at marginal abatement costs of 100–250 ZAR_{2007}/t CO_2eq and for 200–400 ZAR_{2007}/t CO_2eq for upgraded gas from landfill sites and from sewage treatment plants, respectively. However, in this study, GHG mitigation costs are lower and can even be negative if the gas is converted to electricity and not upgraded to SNG. This decision of using landfill and sewage gas for either electricity provision or for upgrading to SNG as transport fuels furthermore depends on the scale of the application and the technology applied as well as on the economic environment (in this study no taxes where considered). Moreover, in the scenario results, the restriction of carbon capture and storage prevents the application of SNG from waste sources, as alternative sources for low-carbon electricity might be limited and landfill and sewage gas is thus only used for electricity provision. As for biodiesel from waste cooking oil, the potential for energy provision from organic waste is limited.
- For medium marginal GHG mitigation costs, mild hybrid electric vehicles should not only be used for buses and minibuses but also for heavy-duty vehicles. Buses might even be using full hybrid powertrains at this marginal abatement cost. The scale of application of hybrids for small vehicles such as passenger cars and light duty vehicles depends on the battery price and on the future crude oil price.
- Further potential to mitigate GHG emissions of electricity provision was identified for concentrated solar power plants. In the scenario solutions, especially those parabolic trough configurations with (molten salt) storage were applied. However, the impact on the transport sector at medium marginal abatement costs is low.

High marginal GHG mitigation costs: < 1,000 ZAR_{2007}/t CO_2eq:

- Mild hybrid vehicles are applied even for small vehicles such as passenger cars at high marginal abatement costs. Full hybrids are dominant for all transport modes subject to large annual mileages (i.e. minibuses, scheduled buses and heavy duty vehicles).

- Hydrogen might be a feasible option for further reductions of well-to-wheel emissions for high marginal abatement costs if carbon capture and storage is an option. The marginal abatement cost for hydrogen from coal gasification is 400 ZAR_{2007}/t CO_2eq if sufficient CO_2-storage potential is available. Otherwise, natural gas upgrading with carbon capture and storage causes fewer GHG emissions but at a higher marginal abatement cost of 600 ZAR_{2007}/t CO_2eq.
- Fuel cell hybrid electric vehicles are a dominant vehicle technology for hydrogen use in the transport sector in 2040 under high GHG taxes. However, an earlier implementation of a hydrogen economy might also require vehicles using internal combustion engine for hydrogen use, as they are still considerably cheaper but offer lower energy efficiency.
- The first transport modes where fuel cell hybrid electric vehicles are used are heavy-duty vehicles and bus rapid transit buses. However, the share of vehicle activity for the bus rapid transit system in the total transport network is small.
- Plug-in hybrid electric vehicles are a further GHG mitigation option at high marginal abatement costs. However, the level of application depends on the future development of specific battery costs and primary energy carrier prices, as well as on the availability of low-carbon electricity for the transport sector – which might be subject to socio-economic growth and the availability of carbon capture and storage.

Very high marginal GHG mitigation costs: > 1,000 ZAR_{2007}/t CO_2eq:

- Hydrogen can be provided via biomass gasification at marginal abatement costs of ≥ 1,500 ZAR_{2007}/t CO_2eq. However, it competes with available resources for the supply of biomass to liquid fuels. If sufficient carbon capture and storage capacity is available, fossil energy carriers are the main source of hydrogen in 2040. However, at a marginal abatement cost of 2,000 ZAR_{2007}/t CO_2eq and higher, hydrogen will not be sourced from coal in any case.
- Fuel cell hybrid electric vehicles and plug-in hybrid electric vehicles can be a dominant technology in the transport sector for very high marginal abatement costs. However, their applicability depends on the availability of low-carbon electricity and carbon capture and storage (see above). Plug-in hybrid electric vehicles are favoured for smaller vehicles used for long-distance urban travel and large annual mileages (e.g. minibuses and light duty vehicles).

The sensitivity analysis showed that relatively low battery costs can reduce marginal abatement costs for hybrid electric vehicles even further, whereas an increase in the future price of cellulosic biomass increases the abatement costs. However, differences in the scenarios considered are small and vehicle substitutions are only slightly shifted in the marginal abatement costs curve. Furthermore, it was noted that even battery costs at

150 €/kWh did not result in using pure battery electric vehicles to mitigate GHG emissions at minimum cost and plug-in hybrid electric vehicles were not used as electricity storage (V2G) even though this option has been implemented for explicit application in the TIMES-GEECO model.

The expansion of the public transport system, of the bus rapid transit and Gautrain were not found to promote GHG mitigation and energy efficiency for Gauteng cost-effectively. This result seems to be logical in view of the comparatively low specific energy consumption of the minibuses (due to their high occupancy rates); they were replaced mainly by such public transport systems in the past, a trend that is assumed to continue in this study. However, consequences besides climate impacts, such as convenience and safety, should also be considered when analysing such actions as expanding the public transport system. Still, the minibus transport system is identified as being very energy efficient and thus can provide the province with an effective option for providing public transport services and reducing GHG emissions by regulating it, making it easier to access and by integrating it into the whole public transport system. Greening the minibus fleet might be a good possibility for a further reduction of GHG emissions and for creating awareness for new technologies.

Policy recommendations

This analysis has shown that, under current political dispensations, the GHG emissions and energy consumption of Gauteng are likely to increase significantly. Policy-makers should therefore intervene at an early stage to influence or dictate desirable developments. It has been concluded that initial changes in the energy system should involve the provision of electricity by switching from conventional coal-fired power plants to alternatives such as nuclear, solar energy (e.g. large-scale concentrated solar power collectors using parabolic troughs, but also roof-mounted photovoltaics units on buildings), or coal in conjunction with carbon capture and storage. The substitution of fossil Fischer-Tropsch synthetic fuels is relatively easily achievable as even crude oil-based fuels are responsible for significantly lower well-to-wheel emissions. However, further issues, such as those of supply security, should be taken into account as coal to liquid fuels currently provide a significant share of transport fuels.

On the other hand, the opportunities for Gauteng's government to initiate such changes might be limited. One option is to tender for the provision of "green" electricity, which might be imported to Gauteng. National government could intervene directly with measures like GHG taxes for fuels and electricity. At least from a GHG mitigation point of view, no additional coal to liquid capacity – such as the construction of the Mafutha plant – should be built without using carbon capture and storage or at least without being CCS-ready.

In the Gauteng transport sector, local government can actively reduce the province's climate impact by encouraging the use of hybrid electric vehicles, especially for those modes which cover substantial distances, i.e. buses. As most of the bus services are state owned, policy-makers can directly affect the adoption of hybrid vehicles for that mode. Moreover, the minibus taxi recapitalization programme offers the possibility of addressing the minibus sector, by subsidising hybrid vehicles. This analysis has shown that minibus transport is the backbone of the public transport system of the province. The government should address this fact, by integrating the minibus sector into the transport system instead of discouraging minibus transport. An option might be to regulate the minibus sector and its integration into a combined public transport system.

The bus rapid transit and Gautrain systems were not extended in this study in order to reduce GHG emissions in an economical way. However, this result does not necessarily imply that an expanded service should not be undertaken at some stage. One has to keep in mind that these results are based on the assumption that future systems are mainly substitutes for minibuses (as in the past). Future systems should thus focus on substituting for individual passenger transport. Moreover, the wider implications of the bus rapid transit and Gautrain – involving such as road safety, possible reduction of congestion, and travel convenience – have not been analysed in this study.

The effect of fleet renewal on specific energy consumption in the transport sector can be significant. Policy-makers can accelerate the introduction of vehicles with lower fuel consumption and better emission levels by stricter emission legislation. National support can help to implement such policies, for example, with minimum requirements for imported or new registered vehicles. Once again, local government could play a guiding role by using vehicles with better standards for their own fleet and for public vehicles in the province.

Furthermore, certain biofuels offer the potential of "greening" the transport sector at comparatively low costs. Initial measures could include the use of biodiesel from waste cooking oil and ethanol from sugar cane. Biodiesel from waste cooking oil can be produced within the province. The government could support its adoption by preventing the waste cooking oil being used as animal food and giving tax reductions for such biofuels. Furthermore, research that considers the quality of the fuel produced should be supported. Additionally, the provincial government can fund the upgrading of gas from landfill sites and sewage plants as incentives may be required to support the use of such energy carriers on a commercial scale. However, to achieve significant reduction potentials, the gas of most big plants would have to be used, which could be achieved by appropriate legislation. Landfill and sewage gas for electricity provision competes with its upgrading to a substitute for natural gas (SNG). The choice of either option is obviously dependent on many factors, such as the economies of scale, the distance of the site to the grid or distribution station, the biogenic share in the waste and the cost of gas upgrading. Moreover, taxes and the reference price of electricity and fuels apparently affect the optimal choice for commercial producers. In this thesis, taxes were not considered as part of a macro-economic view.

Significant GHG reduction potential can be seen in second-generation biofuels, which might be produced outside the boundaries of Gauteng. In the scenario analysis, biomass to liquid was the preferred option. On the other hand, ethanol from lignocellulosic biomass showed comparably low well-to-wheel GHG emissions and fuel costs in the long term, which indicates that this option should not be neglected. However, the necessary production technologies for second-generation biofuels are currently not commercially available and so their future feasibility is uncertain. The provincial and national governments should therefore encourage research in all fields of second-generation biofuel production and sponsor demonstration projects.

Outlook on future research

This study involves a comprehensive analysis of possible developments and potential alternative pathways for GHG reduction for the transport sector and the first application of a cost-optimizing energy system model for Gauteng. Future analysis might also include a more detailed view of non-GHG emissions by including externalities and social costs, which might prove to be important, especially in an urban environment like Gauteng. In this research, such an analysis could not be performed, as non-GHG emission factors have not been applied currently to all sectors of the TIMES-GEECO model (e.g. in the industry or residential sectors) and there is limited research on the external costs of pollutant emissions in South Africa and Gauteng. Furthermore, aviation has been identified as one of the major drivers of future energy consumption in the province. In this thesis, however, the prospects of alternative aviation fuels in Gauteng have not been analysed as only a small fraction of aviation emissions has been attributed to Gauteng and thus the corresponding GHG mitigation potential is modest. Critics argue that, due to the high quality and safety requirements of aviation fuels, the application of biofuels should initially be focused on road transport /ETAG 2007/. However, recently several tests showed the technical feasibility of biofuel use for aviation; the first commercial flight using a 50% blend of bio-kerosene based on waste cooking oil was conducted in Europe in October 2011 /EBTP 2013/. Thus, future analysis might emphasize air transport more strongly for Gauteng.

The industry sector of the province has been identified as a major consumer of energy that causes a significant impact on climate. Future research is needed to identify least-cost options in this sector. For example, similar to the transport sector, fossil fuel based Fischer-Tropsch synthesis in basic chemical production could partially be replaced by alternative processes, which would be an enhancement of current energy system models. In the residential sector, the characterization of the population by income group will allow the analysis of the effects of economic transformation and enable the finding of applicable and feasible measures to mitigate GHG emissions in that sector. Public buildings have so far not been analysed in detail in the TIMES-GEECO model. Even though the public sector accounts for only a small (< 1%) fraction of total energy consumption and GHG emissions, government buildings can become a role model to demonstrate the implementation of GHG mitigation measures.

Using an energy system model to identify least-cost options for the transport sector of Gauteng was found to be of value as interlinkages and interdependencies in the energy system are thereby taken into account. However, energy system models require certain simplifying assumptions; for example, only average or characteristic technologies are analysed. By considering several categories of passenger cars and buses of different engine sizes, an attempt was made to minimize this aspect. However, certain assumptions, like limits to the proportion of compressed ignition (i.e. diesel) engines in the model, are still necessary to allow for reasonable model results. The consideration of personal behaviour (such as car availability) for mode choice and calculation of travel demand as performed in this study can be seen to improve model inputs, but does not include personal preferences in the model decisions. This aspect has to be considered explicitly when analysing the residential sectors and their corresponding GHG mitigation options.

The TIMES-GEECO model presented here can also be used to analyse further research questions such as aspects of supply security and the country's or the province's dependence on imports. Additionally, using the model it is possible to quantify targets for renewable energy quotas or subsidies. To do this for South Africa, the approach presented here can be expanded to the whole country. However, it seems reasonable to maintain a regional modelling basis – based on provinces and municipalities – to account for the availability of local resources.

The lack of available data was found to be a major difficulty when performing this analysis. A huge effort has been put into establishing a consistent transport database for Gauteng, which can be useful for further analysis. However, the data set and assumptions – regarding, for example, occupancy levels and load figures, technology costs and travel demand in general – obviously underlie uncertainties. In this research, this aspect is addressed by calculating multiple marginal abatement costs curves for different scenarios. However, even though results can be quantified, energy system modelling aims "to provide insight and not numbers" /Huntington et al. 1982/ and thus, the results presented here can be the basis for policy development. However, the provincial and national governments as well as statistical entities and research institutions should support further research by making basic statistics available. These should include databases on vehicle fleets by engine type and fuel sales by province. Moreover, surveys should be conducted in all provinces to clarify the local transport sectors' characteristics such as driving distances, speeds and load factors.

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Appendix A: Conversion factors, exchange rates, calorific values

Table A 1: Long-term exchange rate of euro to South African rand.

Year	ZAR/EUR
2011	10.093
2010	9.698
2009	11.674
2008	12.059
2007	9.660
2006	8.531
2005	7.918
2004	8.009
2003	8.532
2002	9.907
2001	7.687
2000	6.390
1999	6.519

Source: /Bundesbank 2012/.

Table A 2: Long-term exchange rate of US dollar to South African rand.

Year	ZAR/USD
2011	7.251
2010	7.316
2009	8.412
2008	8.257
2007	7.054
2006	6.783
2005	6.370
2004	6.449
2003	7.569
2002	10.522
2001	8.583
2000	6.939
1999	6.115

Source: /FED 2012/.

Table A 3: Consumer Price Index, South Africa (2007 =100).

	Index
1990	29.6
1991	34.1
1992	38.9
1993	42.6
1994	46.4
1995	50.5
1996	54.2
1997	58.8
1998	62.9
1999	66.2
2000	69.7
2001	73.7
2002	80.4
2003	85.1
2004	86.3
2005	89.2
2006	93.4
2007	100.0
2008	111.5
2009	119.5
2010	124.6
2011	130.8
2012	138.3
2013	145.7

Sources: /StatsSA 2012a/, /IMF 2012/, own calculations.

Table A 4: Calorific values (lower) of energy carriers for South Africa.

Energy Carrier	**Calorific value**	**Unit**	**Density (kg/l)**
Natural gas	41.0	MJ/m³	
LPG	49.4	MJ/kg	0.541
Petrol	32.5	MJ/l	0.74
Diesel	35.9	MJ/l	0.83
Biodiesel	32.7	MJ/l	0.88
Ethanol	21.1	MJ/l	0.79
Syndiesel	36.1	MJ/l	
Illuminating Paraffin	37.0	MJ/l	0.788
Jet Fuel / kerosene	34.3	MJ/l	0.793
Coal (Eskom, average 1994)	20.1	MJ/kg	
Coal (general purpose)	24.3	MJ/kg	
Coal (coking)	30.1	MJ/kg	

Sources: /DOE 2009a/, /Edwards et al. 2011a/, /Edwards et al. 2011b/, /FNR 2010/

Appendix B: Vehicle costs, emission factors and fuel efficiency

This section shows in detail the calculated vehicle prices based on components costs and the assumed minimum range to calculate the dimension of energy storages (e.g. batteries or fuel tanks). All sources for the calculation are stated in section 5.2. Reference vehicles are assumed to be as follows: passenger car = VW Golf 1.4 litres (63 kW); SUV = Mitsubishi Pajero (184 kW); LDV = Toyota Hilux (118 kW); minibus = Mercedes Sprinter (110 kW); bus = Scania Marcopolo (210 kW and 315 kW for a small and a big bus, respectively); HDV = Mercedes-Benz Actros (320 kW).

The driving range for ranges LPG ICE SI, CNG ICE SI, H_2 ICE SI and BEV are considered as 200 km for passenger cars, 250 km for SUVs and LDVs, 300 km for minibuses, 500 km for buses and 400 km for HDVs, based on /Özdemir 2012/ and own assumptions. The range of PHEVs is taken as 65 km for small and 125 km for large vehicles, based on /Özdemir & Hartmann 2012/, /Özdemir 2012/, /Bruchof 2013/ and /Blesl et al. 2009/. Total battery costs of electric vehicles include battery replacement costs and have been calculated as expressed in section 5.2.4. Furthermore, a 10% retail margin is applied. The "rest of vehicle" comprises vehicle body, interiors, wiring, etc. and is calculated as relative to the vehicle price based on the components considered and the retail price stated by the manufacturers.

It was anticipated that, after 2012, all new small vehicles (passenger cars, SUVs, LDVs and minibuses) will be at least of Euro 4 standard. For large vehicles (buses and heavy-duty trucks), this assumption was made for the year 2015. After 2030, vehicles are expected to be at least of Euro 6 standard and in 2035, 60% of the new vehicles are assumed to be post-Euro 6. Figure B 1 shows the assumed composition of new small vehicles registered in Gauteng. Emission factors from the vehicle emission inventory /TÜV 2012a/, are weighted according to these assumptions.

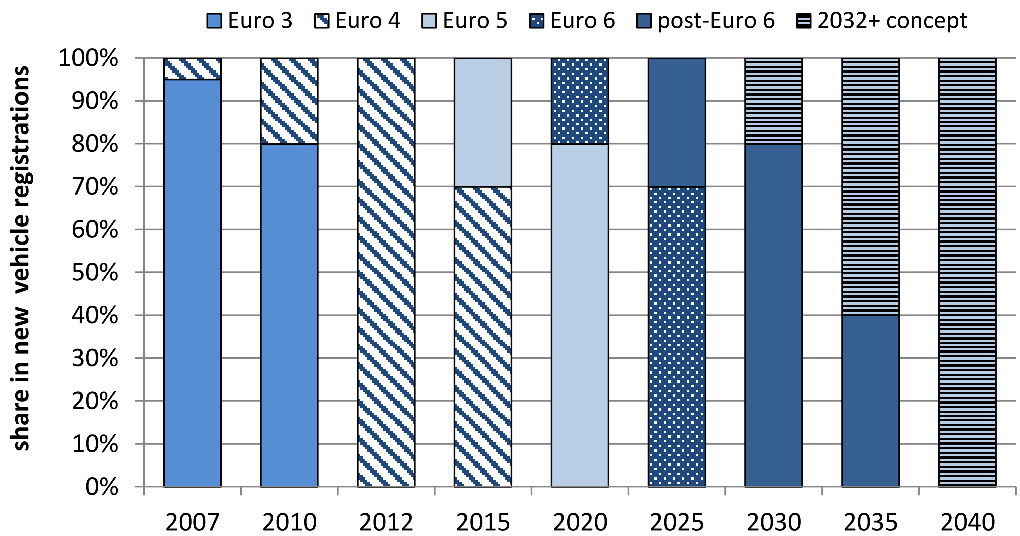


Figure B 1: Assumed emission standards of new small vehicles (passenger cars, SUVs, LDVs and minibuses) registered in Gauteng.

Passenger car

Table B 1: Costs for new passenger cars in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	EUR_{07}
Petrol - ICE SI	19,895	0	0	1,316	0	0	126,319	**147,530**	**15,417**
Diesel - ICE CI	35,130	0	0	1,316	0	0	126,319	**162,765**	**17,009**
Petrol - mild hybrid SI	19,895	2,454	0	1,316	7,298	25,418	126,319	**182,699**	**19,092**
Diesel - mild hybrid CI	35,130	2,454	0	1,316	7,298	25,418	126,319	**197,934**	**20,684**
Petrol - full hybrid SI	19,895	8,179	0	1,316	12,163	25,418	126,319	**193,290**	**20,198**
Diesel - full hybrid CI	35,130	8,179	0	1,316	12,163	25,418	126,319	**208,525**	**21,790**
Petrol - PHEV SI	11,937	12,269	0	1,316	158,115	44,993	126,319	**354,949**	**37,091**
Diesel - PHEV CI	22,094	12,269	0	1,316	158,115	44,993	126,319	**365,105**	**38,153**
BEV	0	12,269	0	0	486,508	44,993	126,319	**670,089**	**70,023**
E85 - ICE SI	19,895	0	0	9,737	0	0	126,319	**155,951**	**16,297**
B100 - ICE CI	35,130	0	0	6,579	0	0	126,319	**168,028**	**17,559**
CNG - ICE SI	19,895	0	0	31,208	0	0	126,319	**177,422**	**18,540**
LPG - ICE SI	19,895	0	0	19,505	0	0	126,319	**165,719**	**17,317**
FCHEV	0	12,269	245,374	23,011	10,948	25,418	126,319	**443,338**	**46,328**
H_2 - ICE SI	19,895	0	0	35,972	0	0	126,319	**182,186**	**19,038**

Table B 2: Costs for new passenger cars in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	EUR_{07}
Petrol - ICE SI	28,163	0	0	1,316	0	0	126,319	**155,798**	**16,281**
Diesel - ICE CI	42,502	0	0	1,316	0	0	126,319	**170,137**	**17,779**
Petrol - mild hybrid SI	28,163	1,592	0	1,316	2,737	13,051	126,319	**173,177**	**18,097**
Diesel - mild hybrid CI	42,502	1,592	0	1,316	2,737	13,051	126,319	**187,516**	**19,595**
Petrol - full hybrid SI	28,163	5,305	0	1,316	4,561	13,051	126,319	**178,715**	**18,675**
Diesel - full hybrid CI	42,502	5,305	0	1,316	4,561	13,051	126,319	**193,054**	**20,174**
Petrol - PHEV SI	16,898	7,958	0	1,316	59,293	26,130	126,319	**237,914**	**24,861**
Diesel - PHEV CI	26,457	7,958	0	1,316	59,293	26,130	126,319	**247,473**	**25,860**
BEV	0	7,958	0	0	182,441	26,130	126,319	**342,848**	**35,827**
E85 - ICE SI	28,163	0	0	4,474	0	0	126,319	**158,956**	**16,611**
B100 - ICE CI	42,502	0	0	3,947	0	0	126,319	**172,768**	**18,054**
CNG - ICE SI	28,163	0	0	27,307	0	0	126,319	**181,789**	**18,997**
LPG - ICE SI	28,163	0	0	15,604	0	0	126,319	**170,086**	**17,774**
FCHEV	0	7,958	33,159	21,573	4,105	13,051	126,319	**206,164**	**21,544**
H_2 - ICE SI	25,580	0	0	0	0	0	126,319	**151,898**	**15,873**

Table B 3: Fuel consumption and emission factors for new passenger cars in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	3.25	231.8	0.001	0.002	0.600	0.015	0.064	0.002	0.027
Diesel - ICE CI	2.31	169.9	0.001	0.006	0.087	0.024	0.729	0.022	0.001
Petrol - mild hybrid SI	2.67	190.3	0.001	0.002	0.492	0.013	0.053	0.002	0.022
Diesel - mild hybrid CI	1.96	144.5	0.000	0.005	0.074	0.020	0.620	0.019	0.001
Petrol - full hybrid SI	2.57	183.4	0.001	0.002	0.474	0.012	0.051	0.002	0.021
Diesel - full hybrid CI	1.89	139.4	0.000	0.005	0.071	0.020	0.598	0.018	0.001
Petrol - PHEV SI	1.35	19.2	0.000	0.000	0.050	0.001	0.005	0.000	0.002
Diesel - PHEV CI	1.21	17.8	0.000	0.001	0.009	0.003	0.076	0.002	0.000
BEV	1.04	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	3.06	46.7	0.001	0.001	0.480	0.014	0.052	0.001	0.001
B100 - ICE CI	2.30	0.0	0.000	0.006	0.044	0.008	0.802	0.011	0.001
CNG - ICE SI	3.25	190.8	0.027	0.001	0.168	0.322	0.075	0.004	0.004
LPG - ICE SI	2.98	182.5	0.001	0.002	0.360	0.015	0.058	0.001	0.000
FCHEV	1.77	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	2.77	0.0	0.000	0.001	0.009	0.100	0.525	0.000	0.000

Table B 4: Fuel consumption and emission factors for new passenger cars in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	2.00	142.8	0.000	0.002	0.212	0.004	0.037	0.001	0.017
Diesel - ICE CI	1.77	130.2	0.000	0.005	0.039	0.010	0.450	0.001	0.001
Petrol - mild hybrid SI	1.64	117.2	0.000	0.001	0.174	0.003	0.030	0.001	0.014
Diesel - mild hybrid CI	1.50	110.7	0.000	0.004	0.033	0.009	0.383	0.001	0.001
Petrol - full hybrid SI	1.58	112.9	0.000	0.001	0.167	0.003	0.029	0.001	0.013
Diesel - full hybrid CI	1.45	106.8	0.000	0.004	0.032	0.008	0.369	0.001	0.001
Petrol - PHEV SI	0.98	14.0	0.000	0.000	0.021	0.000	0.004	0.000	0.002
Diesel - PHEV CI	0.96	14.1	0.000	0.001	0.004	0.001	0.049	0.000	0.000
BEV	0.83	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	1.88	28.7	0.000	0.001	0.169	0.004	0.030	0.000	0.000
B100 - ICE CI	1.76	0.0	0.000	0.005	0.019	0.004	0.495	0.001	0.001
CNG - ICE SI	2.00	117.5	0.007	0.001	0.059	0.085	0.043	0.001	0.002
LPG - ICE SI	1.84	112.4	0.000	0.002	0.127	0.004	0.033	0.000	0.000
FCHEV	1.33	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	1.71	0.0	0.000	0.001	0.003	0.026	0.302	0.000	0.000

SUV

Table B 5: Costs for new SUVs in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	58,107	0	0	1,316	0	0	421,062	**480,485**	**50,210**
Diesel - ICE CI	102,603	0	0	1,316	0	0	421,062	**524,981**	**54,859**
Petrol - mild hybrid SI	58,107	7,166	0	1,316	21,314	25,418	421,062	**534,383**	**55,842**
Diesel - mild hybrid CI	102,603	7,166	0	1,316	21,314	25,418	421,062	**578,879**	**60,491**
Petrol - full hybrid SI	58,107	23,888	0	1,316	35,523	25,418	421,062	**565,314**	**59,074**
Diesel - full hybrid CI	102,603	23,888	0	1,316	35,523	25,418	421,062	**609,810**	**63,724**
Petrol - PHEV SI	34,864	35,832	0	1,316	241,310	44,993	421,062	**779,377**	**81,443**
Diesel - PHEV CI	64,528	35,832	0	1,316	241,310	44,993	421,062	**809,042**	**84,543**
BEV	0	35,832	0	0	928,114	44,993	421,062	**1,430,002**	**149,432**
E85 - ICE SI	58,107	0	0	9,737	0	0	421,062	**488,906**	**51,090**
B100 - ICE CI	102,603	0	0	6,579	0	0	421,062	**530,244**	**55,409**
CNG - ICE SI	58,107	0	0	51,968	0	0	421,062	**531,137**	**55,503**
LPG - ICE SI	58,107	0	0	32,480	0	0	421,062	**511,649**	**53,466**
FCHEV	0	35,832	716,648	40,521	31,974	25,418	421,062	**1,271,457**	**132,864**
H_2 - ICE SI	58,107	0	0	63,637	0	0	421,062	**542,806**	**56,722**

Table B 6: Costs for new SUVs in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	82,255	0	0	1,316	0	0	421,062	**504,633**	**52,733**
Diesel - ICE CI	124,133	0	0	1,316	0	0	421,062	**546,512**	**57,109**
Petrol - mild hybrid SI	82,255	4,649	0	1,316	7,993	13,051	421,062	**530,325**	**55,418**
Diesel - mild hybrid CI	124,133	4,649	0	1,316	7,993	13,051	421,062	**572,204**	**59,794**
Petrol - full hybrid SI	82,255	15,495	0	1,316	13,321	13,051	421,062	**546,500**	**57,108**
Diesel - full hybrid CI	124,133	15,495	0	1,316	13,321	13,051	421,062	**588,379**	**61,484**
Petrol - PHEV SI	49,353	23,243	0	1,316	90,491	26,130	421,062	**611,595**	**63,910**
Diesel - PHEV CI	77,272	23,243	0	1,316	90,491	26,130	421,062	**639,514**	**66,828**
BEV	0	23,243	0	0	348,043	26,130	421,062	**818,478**	**85,529**
E85 - ICE SI	82,255	0	0	4,474	0	0	421,062	**507,791**	**53,063**
B100 - ICE CI	124,133	0	0	3,947	0	0	421,062	**549,143**	**57,384**
CNG - ICE SI	82,255	0	0	45,472	0	0	421,062	**548,789**	**57,347**
LPG - ICE SI	82,255	0	0	25,984	0	0	421,062	**529,301**	**55,311**
FCHEV	0	23,243	96,844	37,989	11,990	13,051	421,062	**604,179**	**63,135**
H_2 - ICE SI	74,709	0	0	0	0	0	421,062	**495,771**	**51,807**

Table B 7: Fuel consumption and emission factors for new SUVs in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	4.32	308.8	0.001	0.002	0.603	0.015	0.065	0.002	0.036
Diesel - ICE CI	3.35	246.3	0.001	0.006	0.087	0.024	0.728	0.039	0.087
Petrol - mild hybrid SI	3.55	253.3	0.001	0.002	0.494	0.013	0.053	0.002	0.029
Diesel - mild hybrid CI	2.85	209.4	0.000	0.005	0.074	0.020	0.619	0.033	0.074
Petrol - full hybrid SI	3.42	244.0	0.001	0.002	0.476	0.012	0.051	0.002	0.028
Diesel - full hybrid CI	2.74	202.0	0.000	0.005	0.071	0.020	0.597	0.032	0.071
Petrol - PHEV SI	1.95	27.9	0.000	0.000	0.054	0.001	0.006	0.000	0.003
Diesel - PHEV CI	1.82	26.8	0.000	0.001	0.009	0.003	0.079	0.004	0.009
BEV	1.59	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	4.07	62.2	0.001	0.001	0.482	0.014	0.053	0.001	0.001
B100 - ICE CI	3.33	0.0	0.000	0.006	0.043	0.008	0.801	0.019	0.090
CNG - ICE SI	4.33	254.2	0.027	0.001	0.169	0.322	0.076	0.004	0.005
LPG - ICE SI	3.98	243.1	0.001	0.002	0.362	0.015	0.059	0.001	0.000
FCHEV	2.50	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	3.92	0.0	0.000	0.001	0.013	0.141	0.739	0.000	0.000

Table B 8: Fuel consumption and emission factors for new SUVs in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	2.66	190.2	0.000	0.002	0.213	0.004	0.037	0.001	0.022
Diesel - ICE CI	2.51	184.4	0.000	0.005	0.039	0.010	0.450	0.032	0.046
Petrol - mild hybrid SI	2.18	156.0	0.000	0.001	0.175	0.003	0.031	0.001	0.018
Diesel - mild hybrid CI	2.13	156.7	0.000	0.004	0.033	0.009	0.383	0.027	0.039
Petrol - full hybrid SI	2.10	150.3	0.000	0.001	0.168	0.003	0.030	0.001	0.017
Diesel - full hybrid CI	2.05	151.2	0.000	0.004	0.032	0.008	0.369	0.026	0.038
Petrol - PHEV SI	1.44	20.5	0.000	0.000	0.023	0.000	0.004	0.000	0.002
Diesel - PHEV CI	1.43	21.0	0.000	0.001	0.004	0.001	0.051	0.004	0.005
BEV	1.27	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	2.51	38.3	0.000	0.001	0.170	0.004	0.030	0.000	0.001
B100 - ICE CI	2.50	0.0	0.000	0.005	0.019	0.004	0.495	0.016	0.048
CNG - ICE SI	2.66	156.5	0.007	0.001	0.060	0.085	0.044	0.001	0.003
LPG - ICE SI	2.45	149.7	0.000	0.002	0.128	0.004	0.034	0.000	0.000
FCHEV	1.87	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	2.41	0.0	0.000	0.001	0.005	0.037	0.424	0.000	0.000

LDV

Table B 9: Costs for new LDVs in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	37,264	0	0	1,316	0	0	210,531	**249,111**	**26,032**
Diesel - ICE CI	65,800	0	0	1,316	0	0	210,531	**277,647**	**29,013**
Petrol - mild hybrid SI	37,264	4,596	0	1,316	14,902	25,418	210,531	**294,027**	**30,725**
Diesel - mild hybrid CI	65,800	4,596	0	1,316	14,902	25,418	210,531	**322,562**	**33,707**
Petrol - full hybrid SI	37,264	15,320	0	1,316	24,836	25,418	210,531	**314,685**	**32,884**
Diesel - full hybrid CI	65,800	15,320	0	1,316	24,836	25,418	210,531	**343,220**	**35,866**
Petrol - PHEV SI	22,358	22,979	0	1,316	199,907	44,993	210,531	**502,085**	**52,467**
Diesel - PHEV CI	41,382	22,979	0	1,316	199,907	44,993	210,531	**521,109**	**54,455**
BEV	0	22,979	0	0	768,874	44,993	210,531	**1,047,377**	**109,448**
E85 - ICE SI	37,264	0	0	9,737	0	0	210,531	**257,532**	**26,912**
B100 - ICE CI	65,800	0	0	6,579	0	0	210,531	**282,910**	**29,563**
CNG - ICE SI	37,264	0	0	38,949	0	0	210,531	**286,744**	**29,964**
LPG - ICE SI	37,264	0	0	24,343	0	0	210,531	**272,138**	**28,438**
FCHEV	0	22,979	459,590	30,791	22,355	25,418	210,531	**771,665**	**80,637**
H_2 - ICE SI	37,264	0	0	47,580	0	0	210,531	**295,375**	**30,866**

Table B 10: Costs for new LDVs in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	52,750	0	0	1,316	0	0	210,531	**264,597**	**27,650**
Diesel - ICE CI	79,607	0	0	1,316	0	0	210,531	**291,454**	**30,456**
Petrol - mild hybrid SI	52,750	2,981	0	1,316	5,588	13,051	210,531	**286,217**	**29,909**
Diesel - mild hybrid CI	79,607	2,981	0	1,316	5,588	13,051	210,531	**313,074**	**32,715**
Petrol - full hybrid SI	52,750	9,937	0	1,316	9,313	13,051	210,531	**296,899**	**31,025**
Diesel - full hybrid CI	79,607	9,937	0	1,316	9,313	13,051	210,531	**323,756**	**33,832**
Petrol - PHEV SI	31,650	14,906	0	1,316	74,965	26,130	210,531	**359,498**	**37,567**
Diesel - PHEV CI	49,555	14,906	0	1,316	74,965	26,130	210,531	**377,403**	**39,438**
BEV	0	14,906	0	0	288,328	26,130	210,531	**539,895**	**56,418**
E85 - ICE SI	52,750	0	0	4,474	0	0	210,531	**267,755**	**27,980**
B100 - ICE CI	79,607	0	0	3,947	0	0	210,531	**294,086**	**30,731**
CNG - ICE SI	52,750	0	0	34,080	0	0	210,531	**297,362**	**31,074**
LPG - ICE SI	52,750	0	0	19,475	0	0	210,531	**282,756**	**29,547**
FCHEV	0	14,906	62,107	28,867	8,383	13,051	210,531	**337,844**	**35,304**
H_2 - ICE SI	47,911	0	0	0	0	0	210,531	**258,442**	**27,007**

Table B 11: Fuel consumption and emission factors for new LDVs in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	3.24	231.4	0.001	0.006	0.871	0.014	0.091	0.003	0.007
Diesel - ICE CI	2.80	205.7	0.000	0.006	0.044	0.011	0.844	0.049	0.026
Petrol - mild hybrid SI	2.66	189.8	0.001	0.005	0.714	0.012	0.075	0.003	0.006
Diesel - mild hybrid CI	2.38	175.5	0.000	0.005	0.037	0.009	0.720	0.042	0.022
Petrol - full hybrid SI	2.56	182.8	0.001	0.005	0.688	0.011	0.072	0.003	0.005
Diesel - full hybrid CI	2.30	169.3	0.000	0.005	0.036	0.009	0.694	0.040	0.021
Petrol - PHEV SI	1.48	21.1	0.000	0.001	0.079	0.001	0.008	0.000	0.001
Diesel - PHEV CI	1.42	21.0	0.000	0.001	0.004	0.001	0.086	0.005	0.003
BEV	1.21	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	3.05	46.6	0.001	0.004	0.696	0.013	0.074	0.002	0.000
B100 - ICE CI	2.78	0.0	0.000	0.006	0.022	0.004	0.928	0.024	0.027
CNG - ICE SI	3.24	190.5	0.025	0.002	0.244	0.300	0.107	0.006	0.001
LPG - ICE SI	2.98	182.2	0.001	0.006	0.522	0.014	0.082	0.001	0.000
FCHEV	1.90	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	2.93	0.0	0.000	0.017	0.008	0.096	1.239	0.000	0.000

Table B 12: Fuel consumption and emission factors for new LDVs in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	2.02	144.5	0.000	0.000	0.509	0.006	0.033	0.002	0.001
Diesel - ICE CI	2.10	154.6	0.000	0.005	0.008	0.008	0.516	0.039	0.001
Petrol - mild hybrid SI	1.66	118.5	0.000	0.000	0.417	0.005	0.027	0.001	0.001
Diesel - mild hybrid CI	1.79	131.9	0.000	0.004	0.007	0.007	0.441	0.033	0.001
Petrol - full hybrid SI	1.60	114.2	0.000	0.000	0.402	0.005	0.026	0.001	0.001
Diesel - full hybrid CI	1.73	127.2	0.000	0.004	0.006	0.007	0.425	0.032	0.001
Petrol - PHEV SI	1.09	15.6	0.000	0.000	0.055	0.001	0.004	0.000	0.000
Diesel - PHEV CI	1.12	16.4	0.000	0.000	0.001	0.001	0.055	0.004	0.000
BEV	0.96	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	1.90	29.1	0.001	0.000	0.407	0.005	0.026	0.001	0.000
B100 - ICE CI	2.09	0.0	0.000	0.005	0.004	0.003	0.568	0.019	0.001
CNG - ICE SI	2.02	118.9	0.010	0.000	0.142	0.121	0.038	0.003	0.000
LPG - ICE SI	1.86	113.8	0.000	0.000	0.305	0.006	0.029	0.000	0.000
FCHEV	1.42	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	1.83	0.0	0.000	0.001	0.005	0.038	0.443	0.000	0.000

Minibus

Table B 13: Costs for minibuses in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	34,738	0	0	1,316	0	0	273,691	**309,744**	**32,368**
Diesel - ICE CI	61,339	0	0	1,316	0	0	273,691	**336,345**	**35,147**
Petrol - mild hybrid SI	34,738	4,284	0	1,316	20,080	25,418	273,691	**359,526**	**37,570**
Diesel - mild hybrid CI	61,339	4,284	0	1,316	20,080	25,418	273,691	**386,127**	**40,349**
Petrol - full hybrid SI	34,738	14,281	0	1,316	33,466	25,418	273,691	**382,909**	**40,013**
Diesel - full hybrid CI	61,339	14,281	0	1,316	33,466	25,418	273,691	**409,510**	**42,793**
Petrol - PHEV SI	20,843	21,422	0	1,316	375,051	44,993	273,691	**737,315**	**77,048**
Diesel - PHEV CI	38,577	21,422	0	1,316	375,051	44,993	273,691	**755,049**	**78,901**
BEV	0	21,422	0	0	1,731,007	44,993	273,691	**2,071,112**	**216,426**
E85 - ICE SI	34,738	0	0	9,737	0	0	273,691	**318,165**	**33,248**
B100 - ICE CI	61,339	0	0	6,579	0	0	273,691	**341,608**	**35,697**
CNG - ICE SI	34,738	0	0	64,218	0	0	273,691	**372,646**	**38,941**
LPG - ICE SI	34,738	0	0	40,136	0	0	273,691	**348,564**	**36,424**
FCHEV	0	21,422	428,431	47,524	30,123	25,418	273,691	**826,608**	**86,379**
H_2 - ICE SI	34,738	0	0	78,664	0	0	273,691	**387,093**	**40,450**

Table B 14: Costs for minibuses in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	49,174	0	0	1,316	0	0	273,691	**324,180**	**33,876**
Diesel - ICE CI	74,210	0	0	1,316	0	0	273,691	**349,217**	**36,492**
Petrol - mild hybrid SI	49,174	2,779	0	1,316	7,530	13,051	273,691	**347,540**	**36,317**
Diesel - mild hybrid CI	74,210	2,779	0	1,316	7,530	13,051	273,691	**372,576**	**38,933**
Petrol - full hybrid SI	49,174	9,263	0	1,316	12,550	13,051	273,691	**359,044**	**37,519**
Diesel - full hybrid CI	74,210	9,263	0	1,316	12,550	13,051	273,691	**384,080**	**40,135**
Petrol - PHEV SI	29,504	13,895	0	1,316	140,644	26,130	273,691	**485,180**	**50,700**
Diesel - PHEV CI	46,195	13,895	0	1,316	140,644	26,130	273,691	**501,871**	**52,444**
BEV	0	13,895	0	0	649,128	26,130	273,691	**962,843**	**100,615**
E85 - ICE SI	49,174	0	0	4,474	0	0	273,691	**327,338**	**34,206**
B100 - ICE CI	74,210	0	0	3,947	0	0	273,691	**351,848**	**36,767**
CNG - ICE SI	49,174	0	0	56,190	0	0	273,691	**379,055**	**39,610**
LPG - ICE SI	49,174	0	0	32,109	0	0	273,691	**354,973**	**37,094**
FCHEV	0	13,895	57,896	44,554	11,296	13,051	273,691	**414,382**	**43,302**
H_2 - ICE SI	44,663	0	0	0	0	0	273,691	**318,353**	**33,267**

Table B 15: Fuel consumption and emission factors for new minibuses in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	4.45	318.0	0.001	0.006	0.972	0.016	0.100	0.003	0.009
Diesel - ICE CI	3.46	254.5	0.000	0.006	0.062	0.013	1.103	0.058	0.032
Petrol - mild hybrid SI	3.58	255.7	0.001	0.005	0.781	0.013	0.080	0.003	0.007
Diesel - mild hybrid CI	2.89	212.8	0.000	0.005	0.052	0.011	0.922	0.049	0.027
Petrol - full hybrid SI	3.45	246.2	0.001	0.005	0.752	0.012	0.077	0.003	0.007
Diesel - full hybrid CI	2.79	205.2	0.000	0.005	0.050	0.011	0.889	0.047	0.026
Petrol - PHEV SI	1.94	27.7	0.000	0.001	0.085	0.001	0.009	0.000	0.001
Diesel - PHEV CI	1.81	26.6	0.000	0.001	0.006	0.001	0.115	0.006	0.003
BEV	1.57	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	4.19	64.0	0.002	0.004	0.777	0.015	0.081	0.002	0.000
B100 - ICE CI	3.45	0.0	0.000	0.006	0.031	0.005	1.213	0.029	0.034
CNG - ICE SI	4.45	261.8	0.028	0.002	0.272	0.337	0.117	0.006	0.001
LPG - ICE SI	4.09	250.3	0.001	0.006	0.583	0.016	0.090	0.001	0.000
FCHEV	2.44	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	4.04	0.0	0.000	0.017	0.008	0.086	0.935	0.000	0.000

Table B 16: Fuel consumption and emission factors for new minibuses in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	2.76	197.1	0.001	0.000	0.597	0.008	0.050	0.002	0.001
Diesel - ICE CI	2.64	194.3	0.000	0.005	0.020	0.008	0.608	0.045	0.001
Petrol - mild hybrid SI	2.22	158.5	0.001	0.000	0.480	0.006	0.040	0.001	0.001
Diesel - mild hybrid CI	2.21	162.5	0.000	0.004	0.016	0.007	0.509	0.037	0.001
Petrol - full hybrid SI	2.14	152.5	0.000	0.000	0.462	0.006	0.039	0.001	0.001
Diesel - full hybrid CI	2.13	156.6	0.000	0.004	0.016	0.007	0.490	0.036	0.001
Petrol - PHEV SI	1.43	20.4	0.000	0.000	0.062	0.001	0.005	0.000	0.000
Diesel - PHEV CI	1.43	21.0	0.000	0.001	0.002	0.001	0.066	0.005	0.000
BEV	1.25	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	2.60	39.7	0.001	0.000	0.478	0.007	0.040	0.001	0.000
B100 - ICE CI	2.63	0.0	0.000	0.005	0.010	0.003	0.669	0.022	0.001
CNG - ICE SI	2.76	162.2	0.013	0.000	0.167	0.160	0.058	0.003	0.000
LPG - ICE SI	2.54	155.1	0.001	0.000	0.358	0.008	0.045	0.000	0.000
FCHEV	1.83	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	2.50	0.0	0.000	0.001	0.005	0.041	0.468	0.000	0.000

Small bus

Table B 17: Costs for new small busses in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	EUR_{07}
Petrol - ICE SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - ICE CI	117,101	0	0	1,316	0	0	1,368,453	**1,486,869**	**155,374**
Petrol - mild hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - mild hybrid CI	117,101	8,179	0	1,316	49,636	25,418	1,368,453	**1,570,103**	**164,072**
Petrol - full hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - full hybrid CI	117,101	27,264	0	1,316	82,727	25,418	1,368,453	**1,622,279**	**169,524**
Petrol - PHEV SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - PHEV CI	73,646	40,896	0	1,316	2,159,454	44,993	1,368,453	**3,688,758**	**385,466**
BEV	0	40,896	0	0	8,637,818	44,993	1,368,453	**10,092,159**	**1,054,606**
E85 - ICE SI	-	-	-	-	-	-	-	**-**	**-**
B100 - ICE CI	117,101	0	0	21,843	0	0	1,368,453	**1,507,396**	**157,519**
CNG - ICE SI	66,317	0	0	318,506	0	0	1,368,453	**1,753,276**	**183,213**
LPG - ICE SI	66,317	0	0	195,441	0	0	1,368,453	**1,630,211**	**170,353**
FCHEV	0	40,896	817,914	240,296	74,463	25,418	1,368,453	**2,567,439**	**268,291**
H_2 - ICE SI	66,317	0	0	424,116	0	0	1,368,453	**1,858,886**	**194,249**

Table B 18: Costs for new small busses in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	EUR_{07}
Petrol - ICE SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - ICE CI	141,674	0	0	1,316	0	0	1,368,453	**1,511,443**	**157,942**
Petrol - mild hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - mild hybrid CI	141,674	5,305	0	1,316	18,614	13,051	1,368,453	**1,548,412**	**161,805**
Petrol - full hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - full hybrid CI	141,674	17,685	0	1,316	31,023	13,051	1,368,453	**1,573,201**	**164,396**
Petrol - PHEV SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - PHEV CI	88,191	26,527	0	1,316	809,795	26,130	1,368,453	**2,320,412**	**242,477**
BEV	0	26,527	0	0	3,239,182	26,130	1,368,453	**4,660,292**	**486,989**
E85 - ICE SI	-	-	-	-	-	-	-	**-**	**-**
B100 - ICE CI	141,674	0	0	9,211	0	0	1,368,453	**1,519,338**	**158,767**
CNG - ICE SI	93,878	0	0	278,693	0	0	1,368,453	**1,741,024**	**181,933**
LPG - ICE SI	93,878	0	0	156,353	0	0	1,368,453	**1,618,683**	**169,148**
FCHEV	0	26,527	110,529	225,278	27,924	13,051	1,368,453	**1,771,760**	**185,145**
H_2 - ICE SI	85,265	0	0	0	0	0	1,368,453	**1,453,718**	**151,910**

Table B 19: Fuel consumption and emission factors for new small busses in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	10.60	780.3	0.003	0.008	0.572	0.107	7.675	0.032	0.119
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	8.85	651.1	0.002	0.007	0.478	0.090	6.404	0.027	0.099
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	8.53	627.7	0.002	0.006	0.460	0.086	6.174	0.026	0.095
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	4.60	67.7	0.000	0.001	0.050	0.009	0.666	0.003	0.010
BEV	3.62	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	10.56	0.0	0.001	0.008	0.286	0.038	8.442	0.016	0.123
CNG - ICE SI	13.26	778.9	0.042	0.009	0.209	1.770	2.590	0.003	0.083
LPG - ICE SI	11.96	731.4	0.003	0.010	0.490	0.049	1.595	0.003	0.000
FCHEV	7.40	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	13.07	0.0	0.000	0.002	0.034	15.690	2.223	0.000	0.000

Table B 20: Fuel consumption and emission factors for new small busses in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	7.63	561.3	0.000	0.011	0.293	0.001	5.400	0.001	0.003
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	6.36	468.4	0.000	0.009	0.245	0.001	4.506	0.001	0.002
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	6.14	451.5	0.000	0.009	0.236	0.001	4.344	0.001	0.002
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	3.54	52.2	0.000	0.001	0.027	0.000	0.502	0.000	0.000
BEV	2.90	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	7.60	0.0	0.000	0.011	0.147	0.000	5.940	0.001	0.003
CNG - ICE SI	9.54	560.3	0.000	0.012	0.107	0.015	1.822	0.000	0.002
LPG - ICE SI	8.61	526.2	0.000	0.014	0.251	0.000	1.123	0.000	0.000
FCHEV	5.55	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	9.40	0.0	0.000	0.003	0.017	0.136	1.564	0.000	0.000

Big bus & BRT

Table B 21: Costs for big busses and BRT busses in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	EUR_{07}
Petrol - ICE SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - ICE CI	175,651	0	0	1,316	0	0	2,315,843	**2,492,810**	**260,493**
Petrol - mild hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - mild hybrid CI	175,651	12,269	0	1,316	74,455	25,418	2,315,843	**2,604,952**	**272,211**
Petrol - full hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - full hybrid CI	175,651	40,896	0	1,316	124,091	25,418	2,315,843	**2,683,215**	**280,390**
Petrol - PHEV SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - PHEV CI	110,469	61,344	0	1,316	3,703,590	44,993	2,315,843	**6,237,555**	**651,809**
Trolley	0	61,344	0	0	0	44,993	4,380,722	**4,487,059**	**468,887**
E85 - ICE SI	-	-	-	-	-	-	-	**-**	**-**
B100 - ICE CI	175,651	0	0	21,843	0	0	2,315,843	**2,513,337**	**262,638**
CNG - ICE SI	99,476	0	0	527,622	0	0	2,315,843	**2,942,941**	**307,530**
LPG - ICE SI	99,476	0	0	323,758	0	0	2,315,843	**2,739,077**	**286,227**
FCHEV	0	61,344	1,226,871	412,122	111,694	25,418	2,315,843	**4,153,292**	**434,009**
H_2 - ICE SI	99,476	0	0	695,665	0	0	2,315,843	**3,110,984**	**325,090**

Table B 22: Costs for big busses and BRT busses in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	ZAR_{07}	EUR_{07}
Petrol - ICE SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - ICE CI	212,511	0	0	1,316	0	0	2,315,843	**2,529,670**	**264,344**
Petrol - mild hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - mild hybrid CI	212,511	7,958	0	1,316	27,921	13,051	2,315,843	**2,578,599**	**269,457**
Petrol - full hybrid SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - full hybrid CI	212,511	26,527	0	1,316	46,534	13,051	2,315,843	**2,615,782**	**273,343**
Petrol - PHEV SI	-	-	-	-	-	-	-	**-**	**-**
Diesel - PHEV CI	132,286	39,790	0	1,316	1,388,846	26,130	2,315,843	**3,904,212**	**407,981**
Trolley	0	39,790	0	0	0	26,130	2,969,683	**3,035,604**	**317,213**
E85 - ICE SI	-	-	-	-	-	-	-	**-**	**-**
B100 - ICE CI	212,511	0	0	9,211	0	0	2,315,843	**2,537,565**	**265,169**
CNG - ICE SI	140,817	0	0	461,669	0	0	2,315,843	**2,918,329**	**304,958**
LPG - ICE SI	140,817	0	0	259,006	0	0	2,315,843	**2,715,666**	**283,781**
FCHEV	0	39,790	165,793	386,364	41,885	13,051	2,315,843	**2,962,727**	**309,598**
H_2 - ICE SI	127,898	0	0	0	0	0	2,315,843	**2,443,741**	**255,365**

Table B 23: Fuel consumption and emission factors for new big busses and BRT busses in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	17.56	1,292.5	0.004	0.008	1.009	0.149	11.911	0.051	0.196
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	14.65	1,077.9	0.003	0.007	0.842	0.125	9.933	0.043	0.164
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	14.12	1,039.1	0.003	0.006	0.811	0.120	9.575	0.041	0.158
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	7.79	114.6	0.000	0.001	0.090	0.013	1.057	0.005	0.017
Trolley	6.21	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	17.50	0.0	0.001	0.008	0.505	0.052	13.102	0.026	0.204
CNG - ICE SI	21.96	1,290.3	0.059	0.009	0.369	2.464	4.019	0.004	0.138
LPG - ICE SI	19.82	1,211.6	0.004	0.010	0.864	0.068	2.476	0.004	0.000
FCHEV	12.70	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	21.43	0.0	0.000	0.004	0.060	23.095	4.416	0.000	0.000

Table B 24: Fuel consumption and emission factors for new big busses and BRT busses in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	13.08	962.6	0.000	0.011	0.490	0.001	7.140	0.002	0.005
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	10.91	802.8	0.000	0.009	0.409	0.001	5.954	0.002	0.004
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	10.52	773.9	0.000	0.009	0.394	0.001	5.740	0.002	0.004
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	6.08	89.4	0.000	0.001	0.046	0.000	0.663	0.000	0.000
Trolley	4.97	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	13.03	0.0	0.000	0.011	0.245	0.001	7.854	0.001	0.005
CNG - ICE SI	16.35	961.0	0.001	0.012	0.179	0.025	2.409	0.000	0.003
LPG - ICE SI	14.76	902.4	0.000	0.014	0.419	0.001	1.484	0.000	0.000
FCHEV	9.52	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	15.96	0.0	0.000	0.006	0.029	0.230	2.647	0.000	0.000

HDV

Table B 25: Costs for new HDV in 2010.

2010	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	178,439	0	0	1,316	0	0	1,210,554	**1,390,310**	**145,284**
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	178,439	12,463	0	1,316	112,773	25,418	1,210,554	**1,540,964**	**161,027**
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	178,439	41,545	0	1,316	187,955	25,418	1,210,554	**1,645,227**	**171,922**
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	112,223	62,317	0	1,316	5,611,286	44,993	1,210,554	**7,042,689**	**735,944**
BEV	-	-	-	-	-	-	-	-	-
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	178,439	0	0	21,843	0	0	1,210,554	**1,410,836**	**147,429**
CNG - ICE SI	101,055	0	0	216,232	0	0	1,210,554	**1,527,841**	**159,656**
LPG - ICE SI	101,055	0	0	478,832	0	0	1,210,554	**1,790,441**	**187,097**
FCHEV	101,055	0	0	352,389	0	0	1,210,554	**1,663,998**	**173,884**
H_2 - ICE SI	0	62,317	1,246,345	295,252	0	25,418	1,210,554	**2,839,886**	**296,761**

Table B 26: Costs for new HDV in 2040.

2040	ICE	Electric Engine	Fuel cell	Fuel tank (and adaption)	Battery (Li-Ion)	Converter & controller	rest of vehicle	Total	
Unit	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**ZAR_{07}**	**EUR_{07}**
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	215,884	0	0	1,316	0	0	1,210,554	**1,427,754**	**149,197**
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	215,884	8,084	0	1,316	42,290	13,051	1,210,554	**1,491,179**	**155,825**
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	215,884	26,948	0	1,316	70,483	13,051	1,210,554	**1,538,236**	**160,742**
Petrol - PHEV SI	85,831	40,422	0	1,316	2,104,232	26,130	1,210,554	**3,468,486**	**362,448**
Diesel - PHEV CI	134,386	40,422	0	1,316	2,104,232	26,130	1,210,554	**3,517,041**	**367,522**
BEV	-	-	-	-	-	-	-	-	-
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	215,884	0	0	9,211	0	0	1,210,554	**1,435,649**	**150,022**
CNG - ICE SI	143,052	0	0	172,985	0	0	1,210,554	**1,526,592**	**159,525**
LPG - ICE SI	129,928	0	0	0	0	0	1,210,554	**1,340,482**	**140,077**
FCHEV	143,052	0	0	308,340	0	0	1,210,554	**1,661,946**	**173,669**
H_2 - ICE SI	0	40,422	168,425	276,799	0	13,051	1,210,554	**1,709,251**	**178,613**

Table B 27: Fuel consumption and emission factors for new HDV in 2010.

2010 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	14.66	1,079.1	0.011	0.010	2.691	0.465	9.350	0.208	0.164
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	12.59	926.4	0.010	0.009	2.310	0.399	8.027	0.179	0.141
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	12.15	894.1	0.009	0.008	2.229	0.385	7.747	0.172	0.136
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	7.48	110.0	0.001	0.001	0.274	0.047	0.953	0.021	0.017
BEV	-	-	-	-	-	-	-	-	-
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	14.61	0.0	0.003	0.010	1.345	0.163	10.285	0.104	0.171
CNG - ICE SI	18.33	1,077.2	0.184	0.011	0.984	7.673	3.155	0.018	0.115
LPG - ICE SI	16.55	1,011.5	0.014	0.012	2.303	0.210	1.944	0.018	0.000
FCHEV	11.00	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	18.44	0.0	0.000	0.003	0.035	2.838	3.293	0.000	0.000

Table B 28: Fuel consumption and emission factors for new HDV in 2040.

2040 Unit	Fuel MJ/km	CO_2 g/km	CH_4 g/km	N_2O g/km	CO g/km	HC g/km	NO_x g/km	PM g/km	SO_2 g/km
Petrol - ICE SI	-	-	-	-	-	-	-	-	-
Diesel - ICE CI	10.96	806.3	0.001	0.015	1.934	0.028	6.530	0.046	0.004
Petrol - mild hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - mild hybrid CI	9.41	692.2	0.001	0.013	1.660	0.024	5.607	0.040	0.003
Petrol - full hybrid SI	-	-	-	-	-	-	-	-	-
Diesel - full hybrid CI	9.08	668.0	0.001	0.013	1.602	0.023	5.411	0.038	0.003
Petrol - PHEV SI	-	-	-	-	-	-	-	-	-
Diesel - PHEV CI	5.85	86.1	0.000	0.002	0.207	0.003	0.698	0.005	0.000
BEV	-	-	-	-	-	-	-	-	-
E85 - ICE SI	-	-	-	-	-	-	-	-	-
B100 - ICE CI	10.91	0.0	0.000	0.015	0.967	0.010	7.184	0.023	0.004
CNG - ICE SI	13.70	804.8	0.011	0.017	0.707	0.463	2.204	0.004	0.003
LPG - ICE SI	12.36	755.8	0.001	0.019	1.655	0.013	1.358	0.004	0.000
FCHEV	8.25	0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H_2 - ICE SI	13.78	0.0	0.000	0.005	0.026	0.171	2.300	0.000	0.000

Appendix C: Techno-economic and environmental characteristics of power plants

Investment costs and efficiencies of fossil-fuelled power plants for the base year are calculated on the basis of South African studies /DOE 2011/, /Marquard et al. 2008/, /Winkler 2006/ and /Winkler 2007/. These are combined with the predictions given in /IEA & NEA 2010/ for future cost trajectories. Emission factors are taken from /Schulz 2003/. Techno-economic descriptions of electricity generation from renewables (such as CSP, open-field PV and wind power) are according to /Telsnig et al. 2012/.

Table C 1: Techno-economic and environmental characteristics of coal pulverized fuel (PF) dry cooled power plants with flue gas desulphurisation (FGD).

Process	PF dry cooled with FGD		
Input	Coal		
Output	Electricity		
		2010	2040
Capacity	MW	642	
	PJ/a	20.2	
AFA	h	7,709	
Construction time	a	4	
Lifetime	a	35	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.35	0.35
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	369,287	341,040
	EUR_{07}/kW	1,471	1,358
FOM	ZAR_{07}/TJ_{cap}	4,658	4,658
	$EUR_{07}/kW_{cap}/a$	19	19
VOM	ZAR_{07}/TJ_{out}	2,448	
	EUR_{07}/MWh_{out}	1.1	
Direct GHG emissions	g CO_2eq/MJ_{out}	265.5	265.5

Table C 2: Techno-economic and environmental characteristics of coal fluidized bed combustion (FBC) power plants with flue gas desulphurisation (FGD).

Process	FBC with FGD		
Input	Coal		
Output	Electricity		
		2010	2040
Capacity	MW	233	
	PJ/a	7.3	
AFA	h	7,709	
Construction time	a	4	
Lifetime	a	35	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.37	0.37
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	387,404	359,157
	EUR_{07}/kW	1,543	1,430
FOM	ZAR_{07}/TJ_{cap}	7,144	7,144
	$EUR_{07}/kW_{cap}/a$	28	28
VOM	ZAR_{07}/TJ_{out}	4,416	
	EUR_{07}/MWh_{out}	2.0	
Direct GHG emissions	g CO_2eq/MJ_{out}	250.4	250.4

Table C 3: Techno-economic and environmental characteristics of advanced coal power plants.

Process	Advanced coal		
Input	Coal		
Output	Electricity		
		2010	2040
Capacity	MW	642	
	PJ/a	20.2	
AFA	h	7,709	
Construction time	a	4	
Lifetime	a	35	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.40	0.45
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	397,142	368,894
	EUR_{07}/kW	1,582	1,469
FOM	ZAR_{07}/TJ_{cap}	8,083	8,083
	$EUR_{07}/kW_{cap}/a$	32	32
VOM	ZAR_{07}/TJ_{out}	5,286	
	EUR_{07}/MWh_{out}	2.4	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	229.7	204.2

Table C 4: Techno-economic and environmental characteristics of integrated gasification combined cycle (IGCC) coal power plants.

Process	IGCC		
Input	Coal		
Output	Electricity		
		2010	2040
Capacity	MW	550	
	PJ/a	17.3	
AFA	h	7,709	
Construction time	a	5	
Lifetime	a	30	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.42	0.51
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	418,650	418,650
	EUR_{07}/kW	1,667	1,667
FOM	ZAR_{07}/TJ_{cap}	13,403	13,403
	$EUR_{07}/kW_{cap}/a$	53	53
VOM	ZAR_{07}/TJ_{out}	5,943	
	EUR_{07}/MWh_{out}	2.7	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	218.8	180.2

Table C 5: Techno-economic and environmental characteristics of integrated gasification combined cycle (IGCC) coal power plants with CCS.

Process	IGCC+CCS		
Input	Coal		
Output	Electricity		
		2010	2040
Capacity	MW	550	
	PJ/a	17.3	
AFA	h	7,709	
Construction time	a	5	
Lifetime	a	30	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.35	0.44
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	596,334	583,655
	EUR_{07}/kW	2,375	2,325
FOM	ZAR_{07}/TJ_{cap}	14,563	14,563
	$EUR_{07}/kW_{cap}/a$	58	58
VOM	ZAR_{07}/TJ_{out}	14,018	
	EUR_{07}/MWh_{out}	6.4	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	35.2	28.0

Table C 6: Techno-economic and environmental characteristics of natural gas combined cycle gas turbine (CCGT) power plants.

Process	CCGT		
Input	Natural Gas		
Output	Electricity		
		2010	2040
Capacity	MW	500	
	PJ/a	15.8	
AFA	h	7,446	
Construction time	a	3	
Lifetime	a	30	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.56	0.60
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	188,316	188,316
	EUR_{07}/kW	750	750
FOM	ZAR_{07}/TJ_{cap}	5,665	5,665
	$EUR_{07}/kW_{cap}/a$	23	23
VOM	ZAR_{07}/TJ_{out}	4,399	
	EUR_{07}/MWh_{out}	2.0	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	94.6	88.9

Table C 7: Techno-economic and environmental characteristics of natural gas open cycle gas turbine (OCGT) power plants.

Process	OCGT – Natural gas		
Input	Natural Gas		
Output	Electricity		
		2010	2040
Capacity	MW	150	
	PJ/a	4.7	
AFA	h	7,446	
Construction time	a	2	
Lifetime	a	30	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.36	0.38
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	110,191	102,658
	EUR_{07}/kW	439	409
FOM	ZAR_{07}/TJ_{cap}	2,935	2,935
	$EUR_{07}/kW_{cap}/a$	12	12
VOM	ZAR_{07}/TJ_{out}	4,575	
	EUR_{07}/MWh_{out}	2.1	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	148.2	140.4

Table C 8: Techno-economic and environmental characteristics of diesel open cycle gas turbine (OCGT) power plants.

Process	OCGT - oil		
Input	Diesel, kerosene		
Output	Electricity		
		2010	2040
Capacity	MW	120	
	PJ/a	3.8	
AFA	h	7,446	
Construction time	a	2	
Lifetime	a	25	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.33	0.33
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	110,191	102,658
	EUR_{07}/kW	439	409
FOM	ZAR_{07}/TJ_{cap}	2,935	2,935
	$EUR_{07}/kW_{cap}/a$	12	12
VOM	ZAR_{07}/TJ_{out}	5,214	
	EUR_{07}/MWh_{out}	2.4	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	219.8	219.8

Table C 9: Techno-economic and environmental characteristics of hydro power plants (2MW).

Process	Hydro power (small)		
Input	Water		
Output	Electricity		
		2010	2040
Capacity	MW	2	
	PJ/a	0.1	
AFA	h	8,410	
Construction time	a	2	
Lifetime	a	40	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	1.00	1.00
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	404,736	404,736
	EUR_{07}/kW	1,612	1,612
FOM	ZAR_{07}/TJ_{cap}	7,475	7,475
	$EUR_{07}/kW_{cap}/a$	30	30
VOM	ZAR_{07}/TJ_{out}	0	
	EUR_{07}/MWh_{out}	0.0	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	0.0	0.0

Table C 10: Techno-economic and environmental characteristics of pumped storages.

Process	Pumped storage		
Input	Electricity		
Output	Electricity		
		2010	2040
Capacity	MW	333	
	PJ/a	10.5	
AFA	h	8,410	
Construction time	a	7	
Lifetime	a	40	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.76	0.76
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	201,245	201,245
	EUR_{07}/kW	801	801
FOM	ZAR_{07}/TJ_{cap}	3,742	3,742
	$EUR_{07}/kW_{cap}/a$	15	15
VOM	ZAR_{07}/TJ_{out}	2,998	
	EUR_{07}/MWh_{out}	1.4	
Direct GHG emissions	$g\ CO_2eq/MJ_{out}$	0.0	0.0

Table C 11: Techno-economic and environmental characteristics of nuclear pressure water reactors.

Process	**Nuclear PWR**		
Input	Uranium		
Output	Electricity		
		2010	2040
Capacity	MW	874	
	PJ/a	27.6	
AFA	h	7,096	
Construction time	a	4	
Lifetime	a	40	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.32	0.32
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	753,263	627,719
	EUR_{07}/kW	3,000	2,500
FOM	ZAR_{07}/TJ_{cap}	18,714	18,714
	$EUR_{07}/kW_{cap}/a$	75	75
VOM	ZAR_{07}/TJ_{out}	1,100	
	EUR_{07}/MWh_{out}	0.5	
Direct GHG Emissions	$g\ CO_2eq/MJ_{out}$	0.0	0.0

Table C 12: Techno-economic and environmental characteristics of electricity production from sewage gas.

Process	**Electricity production from sewage gas**		
Input	Biogas (sewage)		
Output	Electricity		
		2010	2040
Capacity	MW	0.17	1.12
	PJ/a	0.01	0.04
AFA	h	8,000	
Construction time	a	3	
Lifetime	a	15	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.35	0.35
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	361,613	227,792
	EUR_{07}/kW	1,440	907
FOM	ZAR_{07}/TJ_{cap}	62,348	29,856
	$EUR_{07}/kW_{cap}/a$	248	119
VOM	ZAR_{07}/TJ_{out}	25,000	
	EUR_{07}/MWh_{out}	11.4	
Direct GHG Emissions	$g\ CO_2eq/MJ_{out}$	164.6	

Table C 13: Techno-economic and environmental characteristics of electricity production from landfill gas.

Process	Electricity production from landfill gas		
Input	Biogas (landfill)		
Output	Electricity		
		2010	2040
Capacity	MW	0.50	1.72
	PJ/a	0.02	0.05
AFA	h	8,000	
Construction time	a	3	
Lifetime	a	15	
Efficiency	$MJ_{electricity}/MJ_{feedstock}$	0.35	0.35
Specific investment costs	$ZAR_{07}/(TJ/a)_{cap}$	298,382	249,421
	EUR_{07}/kW	1,188	993
FOM	ZAR_{07}/TJ_{cap}	28,785	15,927
	$EUR_{07}/kW_{cap}/a$	115	63
VOM	ZAR_{07}/TJ_{out}	25,000	
	EUR_{07}/MWh_{out}	11.4	
Direct GHG Emissions	$g\ CO_2eq/MJ_{out}$	164.6	

Appendix D: Battery capacity available for V2G energy storage in Gauteng

For several reasons the whole battery capacity cannot be used for V2G energy storage as some capacity, such as daily driving capability, should not be affected and technical limitations occur. The available storage capacity c_s [kWh] of a vehicle can be calculated as expressed in Equation 19,

$$\boldsymbol{c_{s,i} = (c_{b,i} - c_{d,i} - c_{r,i}) \cdot a_t \cdot a_p} \qquad \text{Equation 19}$$

where c_b is the total battery storage capacity [kWh] of a vehicle of type i, c_d is the capacity needed for average daily driving [kWh] based on the energy consumption and the average daily driving distance (see chapter 3 and section 5.2.4), c_r is the capacity reserve [kWh] (i.e. the minimum reserve to prevent deep de-charging), which is defined as 20% of the total capacity /Hartmann et al. 2012/, a_t is the temporal availability of a vehicle (i.e. the proportion of vehicles which is not being driven) and a_p is the V2G acceptance factor (i.e. the proportion of people who chose to adopt V2G, which is taken as 20% /Hartmann et al. 2012/.

Only passenger cars (i.e. passenger cars and SUVs) are considered as suitable vehicle types for V2G energy storage, because only those are expected to have sufficient standing times /Özdemir & Hartmann 2012/. The temporal availability of passenger vehicles (a_t) is calculated based on /DOT 2003/ and /Goyns 2006/. To do so, the distribution of daily passenger trips with passenger vehicles from /Goyns 2006/ is allocated to the distribution of trip length from /DOT 2003/. It was found that not more than 10% of all passenger vehicles in Gauteng are being driven at the same time, which corresponds to a study undertaken for Germany /Özdemir & Hartmann 2012/.

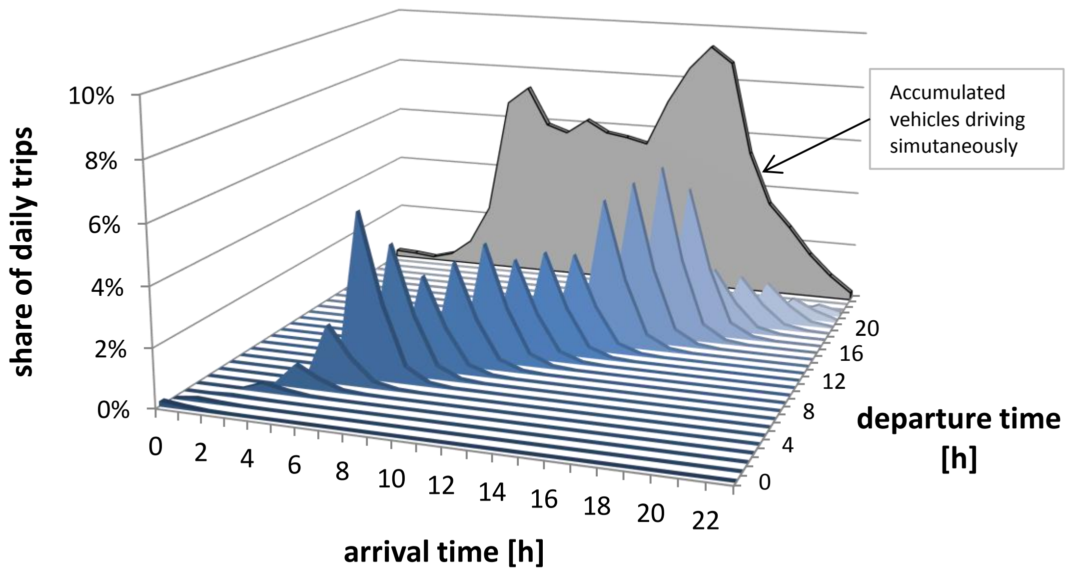
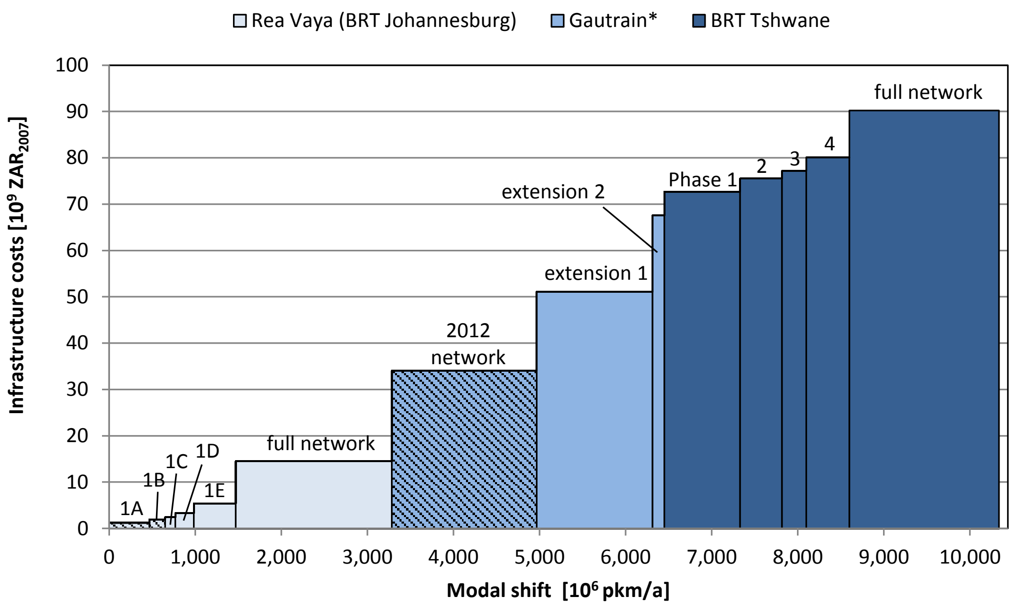


Figure D 1: Temporal distribution of vehicle trips in Gauteng. Source: own figure based on /DOT 2003/ and /Goyns 2006/.

Appendix E: Costs and potentials of public transport expansion for BRT systems and the Gautrain

The data source for the investments costs of expanding the public transport system and possible changes in the modal shift used in this study is the master's thesis of Bubeck /Bubeck 2012/. In his study he analysed the effects of extensions (planned and hypothetical) of the Johannesburg Rea Vaya transport system in terms of their likely transport demand as well as of their investment costs /Bubeck 2012/. Moreover, the introduction of a BRT system in Tshwane (see section 2.2.2) as well as possible extensions of the Gautrain (see section 2.2.3) have been analysed /Bubeck 2012/. In the study it was shown that, the performance of public transport in Gauteng can be increased significantly as a result of the expansion of the system, which goes in hand with an increased attractiveness of existing services /Bubeck 2012/. However, the contributions, in terms of vkm, of the Gautrain and BRT in the overall transport sector is likely to remain small, even if the systems are extended /Bubeck 2012/. Obviously, the performance of such systems depends on the socio-economic framework (e.g. future population development) and on several assumptions such as modal shift behaviour.

Figure E 1 shows the modal-shift potential of different expansions of the public transport system in Gauteng calculated for the year 2040. The expansions, which have already been finalised in 2012, are shown hatched in the figure. All the other extensions are currently not under construction, but are possible new investments /Bubeck 2012/. The modal-shift potential is calculated in terms of the number of people living in a certain area around the systems /Bubeck 2012/.



*includes rail and feeder bus.

Figure E 1: Modal-shift potential of public transport expansion for BRT systems in Johannesburg and Tshwane and the Gautrain for the year 2040. Source: own calculations based on /Bubeck 2012/ and /Wehnert et al. 2011/.

The potential shown in the figure is based on the population development forecast by the Institute for Future Studies and Technology Assessment (IZT), which estimated a population growth to 19.1 million in 2040 /Wehnert et al. 2011/. About 10.3 billion pkm/a in 2040 can be attributed to the BRT and Gautrain in the year 2040, which is about 4% of the total travel demand in that year. Assuming lower socio-economic growth (i.e. a population of 14.4 million in 2040, see Table 39) the performance calculated for the assumed full network is 9.3 billion pkm/a. The full network is calculated to cost about 90 billion ZAR_{2007}.

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