Technical description THRIVE GHG module

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Abstract
As part of the long term research program EOS, a Dutch research project was started to investigate plausible scenarios for a roll-out of hydrogen fuel cell vehicles (FCEV) and a corresponding infrastructure: THRIVE ('Towards a Hydrogen Refuelling Infrastructure for VEhicles'). A simulation model delivers, for a number of scenarios, projections for the number of FCEV's on the Dutch market. The THRIVE greenhouse gas module quantifies the effect on the related Well-to-Wheel emissions for these THRIVE scenarios. This report describes the so-called THRIVE GHG module. As the impact on the emissions will depend on a number of assumptions, several comparisons are made against different background developments. Especially the assumptions around vehicle efficiency development towards 2050, the development of the Well-to-Wheel emissions of the involved fuels and the mix of production routes will be relevant. Finally, the relative emission reductions are presented, including the effect for the total passenger car fleet for the THRIVE scenarios.

Contents

List of tables 4

List of figures 4

Summary 5

1. Introduction and objective 7

2. Basic concept of the model 9

3. ICE and FC H_2 vehicle efficiencies 11
   - 3.1 Introduction 11
   - 3.2 Reference year 2010 11
   - 3.3 Future years 2020, 2030, 2040 and 2050 12

4. Production routes fossil fuels 14
   - 4.1 Introduction 14
   - 4.2 Reference year 2010 14
   - 4.3 Future years 2020, 2030, 2040 and 2050 14

5. Production routes biofuels 16
   - 5.1 Introduction 16
   - 5.2 Reference year 2010 16
   - 5.3 Future years 2020, 2030, 2040 and 2050 17

6. Production routes for Hydrogen 18
   - 6.1 Introduction 18
   - 6.2 Reference year 2010 18
   - 6.3 Future years 2020,2030,2040 and 2050 19

7. Results for THRIVE scenarios 20
   - 7.1 Main drivers for emission reduction and energy savings 20
   - 7.2 Relative emission reductions and energy use: ICE versus H_2 FC vehicle 22
   - 7.3 THRIVE scenarios: WTW emission reduction for passenger car fleet 24
   - 7.4 Sensitivity analysis 25
     - 7.4.1 Different mix of replaced gasoline/diesel powered ICE vehicles 25
     - 7.4.2 No energy efficiency improvement of refineries 25
     - 7.4.3 Introduction magneto caloric cooling to produce liquid hydrogen 25
     - 7.4.4 Employing biogas in the production of hydrogen 26
     - 7.4.5 Conclusions 26

References 27

Appendix A Vehicle energy consumptions per scenario and future year 28

Appendix B Production routes biofuels 29

List of tables

Table S.1 *Overview main assumptions on key driver development for 2050* 5
Table S.2 *FC vehicle share and relative well-to-wheel emission reduction in 2050 for different THRIVE scenarios for the passenger car fleet* 6

Table 3.1 *Vehicle energy consumption for new vehicles in 2010* 11
Table 3.2 *Vehicle energy consumption for the whole vehicle park in 2008* 12
Table 3.3 *Vehicle efficiencies of Toyota FC vehicles* 12
Table 3.4 *Correction Type Approval Emission versus Real World Emission* 13
Table 3.5 *Vehicle energy use in 2050* 13
Table 4.1 *Energy balance and GHG emission of fossil fuels in 2010* 14
Table 4.2 *WTT Energy balance and WTT GHG emission of fossil fuels in 2050* 15
Table 4.3 *WTT Energy balance of fossil fuels for future years* 15
Table 4.4 *WTT GHG emission of fossil fuels for future years* 15
Table 5.1 *Ethanol production routes chosen in the GHG emission module for 2010* 16
Table 5.2 *Biodiesel production routes chosen in the GHG emission module for 2010* 16
Table 5.3 *Ethanol production routes chosen in the GHG emission module for 2050* 17
Table 5.4 *Biodiesel production routes chosen in the GHG emission module for 2050* 17
Table 6.1 *Energy balance and GHG emission for hydrogen production* 18
Table 6.2 *Energy balances and GHG emission for H_2 production (SMR) based on LH2 transport* 19
Table 6.3 *Energy efficiencies and GHG emission for hydrogen production in 2050* 19
Table 7.1 *Fuel production scenarios with different carbon intensiveness* 22
Table 7.2 *Relative well-to-wheel emission reduction in 2050 for different carbon intensiveness combinations for the low vehicle efficiency development scenario* 22
Table 7.3 *Relative well-to-wheel emission reduction in 2050 for different carbon intensiveness combinations for the medium vehicle efficiency development scenario* 23
Table 7.4 *Relative well-to-wheel emission reduction in 2050 for different carbon intensiveness combinations for the high vehicle efficiency development scenario* 23
Table 7.5 *FC vehicle share and relative well-to-wheel emission reduction in 2050 for different THRIVE scenarios for the passenger car fleet.* 24
Table 7.6 *Impact on relative well-to-wheel emission reduction in 2050 in percent points* 26

Table A.1 *Vehicle energy consumption in the low technical improvement scenario* 28
Table A.2 *Vehicle energy consumption in the medium technical improvement scenario* 28
Table A.3 *Vehicle energy consumption in the maximum potential improvement scenario* 28
Table B.1 *Well to Tank energy balance for several bio fuel production routes* 29
Table B.2 *Well to Tank GHG emissions for several bio fuel production routes* 29

List of figures

Figure 1.1 *Overview of the scenarios used in the THRIVE model* 7
Figure 2.1 *Flow chart of the GHG emission model* 9
Figure 7.1 *Overview of the scenarios used in the THRIVE model* 20
Figure 7.2 *FC vehicles relative share in the kilometres driven by passengers cars for all THRIVE scenarios* 21
Figure 7.3 *Relative Well-to-Wheel emissions for medium vehicle efficiency scenario* 23
Figure 7.4 *Relative Well-to-Wheel energy use for medium vehicle efficiency scenario* 24

Summary

Currently the transport sector is almost completely dependent on vehicles with Internal Combustion Engines and fossil fuels. There are several alternative technologies that could improve the environmental impact of the transport sector. One of these alternatives, hydrogen fuel cell electric vehicles (FCEV), is the subject of the THRIVE project. The THRIVE project has identified three basic scenarios[1] for a roll-out of hydrogen FCEV's and the corresponding refueling infrastructure (Low, Medium, High). For the High scenario, an additional scenario was constructed in which consumers are willing to make a small detour for refueling.

To identify the impact of these scenarios on the Well-to-Wheel greenhouse gas emissions, an additional post-processing module has been created, which is the subject of this report. This THRIVE greenhouse gas module determines the relative emission reduction from a Well-to-Wheel basis towards 2050, based on the market penetration as indicated by the THRIVE simulation model (Lebutsch et al., 2010).

The main drivers for the relative emission reduction (g_{WTW} CO_2 per km driven) are vehicle efficiency and the "carbon intensity" and production mix of the (bio)fuels involved. Current legislation around renewable energy and energy efficiency standards, is expected to ensure that these drivers will improve over time. Towards 2050, several technological improvements can even result in improvements that exceed the current obligations, but some of these are still uncertain.

Given this uncertainty, three development paths (Low, Medium and High) have been developed for the key drivers, which are presented in the following table. Low, Medium and High are related to the relevant driver (efficiency, carbon intensity), and not to the resulting Well-to-Wheel emissions. For a number of other drivers the underlying assumptions have been based on literature or set in line with the assumptions of the overall THRIVE project. One of these assumptions is that the hydrogen is produced using Steam Methane Reforming (SMR) and liquefied before being transported to the refueling stations.

Table S.1 *Overview main assumptions on key driver development for 2050*

	Low	Medium	High
Vehicle efficiency			
- ICE (gasoline/diesel)	130 g/km norm	95 g/km norm	80 g/km norm
- FCEV (H_2)	0,9 MJ/km	0,76 MJ/km	0,63 MJ/km
Carbon intensity fuel			
- Gasoline/diesel	30% biofuel	20% biofuel	100% fossil fuel
- Hydrogen	SMR with CCS	SMR, 20% biogas	SMR, natural gas

SMR: Steam Methane Reforming
CCS: Carbon Capture and Storage

Based on our starting points hydrogen FC vehicles, in 2050, will reduce the well-to-wheel emissions per kilometre compared to ICE's substantially. The reduction varies between 10% to 40% for hydrogen produced without the application of CCS. In case CCS is applied to the SMR process, the relative emission reductions are larger, between 70% and 80%, depending on the carbon intensiveness of the displaced fuel. In both situations, the relative emission reduction is maximal in a scenario in which the vehicle efficiency is not further improved beyond the 130

[1] Three coherent sets of model assumptions describing car industry, fuel supplier and consumer behaviour have been selected for simulation of hydrogen rollout. These coherent sets are considered to reflect the effect of policy scenarios for car, fuel and infrastructure with low, medium and high ambition level.

g/km norm for 2015 (i.e. in the low efficiency scenario). For the years until 2050, the relative emission reductions show the same dynamics, but can vary around the values above.

The overall expected reduction for the WTW emissions on the complete passenger fleet can be estimated if the relative reductions are combined with the fleet's share of FC vehicles, according to the THRIVE simulation model,. Although the actual results in 2050 will be dependent on future developments (including volume, efficiency developments that are also depending on economic, price and policy developments), Table S.2 shows that hydrogen fuel cell electric vehicles can result in significant WTW emission reductions for the passenger car fleet. Without the application of CCS, the High scenario of THRIVE results in about 15% to 20% WTW emission reduction. If the hydrogen is produced with CCS, the expected WTW emission reduction can be increased to about 30% to 40%. This latter scenario assumes a proactive approach from all involved actors including the consumers' willingness to make small adjustments in their refuelling behaviour.

Table S.2 *FC vehicle share and relative well-to-wheel emission reduction in 2050 for different THRIVE scenarios for the passenger car fleet*

		Low vehicle efficiency		Medium/High vehicle efficiency	
	FC vehicle share	H_2 medium/high	H_2 low	H_2 medium/high	H_2 low
Scenario Low	~ 7%	2-3%	5-6%	1-2%	5%
Scenario Medium	~ 20%	4-9%	16-17%	2-7%	15-16%
Scenario High	~ 35%	8-16%	27-29%	4-13%	26%-28%
Scenario High+	~ 50%	11-22%	39-41%	5-18%	37%-39%

Note that the ranges do not indicate the uncertainty interval, but the smallest range in which the results of all combinations of the aggregated level are included.

The sensitivity analysis shows that especially the introduction of the magneto caloric cooling to produce liquid hydrogen, and the replacement of natural gas by biogas as feedstock for the SMR process, can further improve these emission reductions.

1. Introduction and objective

THRIVE ('Towards a Hydrogen Refuelling Infrastructure for VEhicles') is a Dutch research project with the overall objective to identify plausible scenarios for roll-out of hydrogen fuel cell electric vehicles (FC) and a corresponding refuelling infrastructure. As part of the project a simulation model has been developed to explore the effect of different deployment strategies of car industry and fuel suppliers on the roll-out of the hydrogen option. The simulation takes into account the interdependency in growth of a FC vehicle fleet and the availability of a hydrogen station network, both as a function of time and geographic location. Scenarios have been developed, which consist of a coherent set of starting points for some of the main actors involved in the roll-out, i.e. consumers, fuel suppliers and car manufacturers. Different sets of assumptions are considered to reflect the effect of different policy ambition levels with regard to sustainable mobility (generic) and the hydrogen option (specific). Three main scenarios have been defined which are considered to reflect the effect of policy settings with low, medium and high ambition level. These scenarios are depicted in Figure 1.1. Further discussion of these scenarios is beyond the scope of this document and is provided in (Lebutsch et al., 2010).

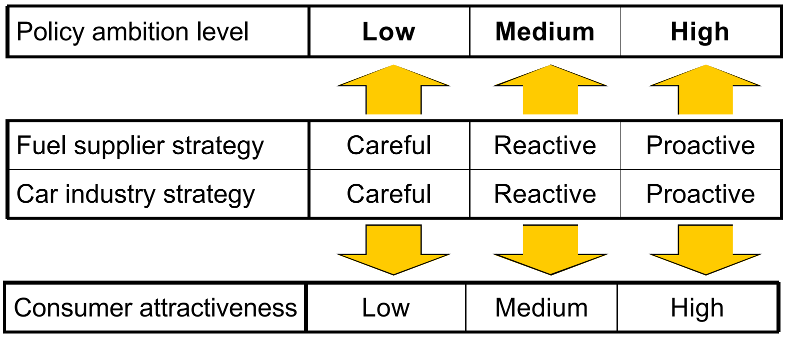

Figure 1.1 *Overview of the scenarios used in the THRIVE model*

This report presents and discusses the THRIVE greenhouse gas (GHG) emission module. The goal of the THRIVE GHG emission module is to assess the impact of the introduction of hydrogen fuel cell vehicles on car fleet GHG emissions from a well-to-wheel perspective (WTW). The greenhouse gases taken into account are CO_2, CH_4 and N_2O. In the GHG model the effect of FC vehicles replacing fossil fuel powered internal combustion engine-based vehicles (ICE) is quantified as a relative improvement versus a reference scenario with only ICE vehicles on fossil fuels. The rate of introduction of the FC vehicles as considered in the THRIVE GHG model, as well as the underlying assumed scenario for the development of the passenger car fleet, are based on the output from the THRIVE simulation model and is not described in this document, see (Lebutsch et al., 2010).

The emission effect determined using the THRIVE GHG emission module is based on a number of (adjustable) model inputs. The user can define three different production route mixes (often with different GHG WTW emissions) for fossil fuels as well as for Hydrogen. These can be used to perform a sensitivity analysis for the impact of different futures production route mixes. Also the energy consumption development of ICE and Hydrogen FC vehicles towards the future can be chosen from three different future outlooks.

Chapter 2 describes the methodology applied in the THRIVE GHG emission module. Chapter 2 to Chapter 6 provide the starting points for the comparison between the THRIVE hydrogen scenarios and the considered reference scenarios. In addition, these chapters present current and projected WTW energy use and CO_2 emission data for cars and fuel production routes in the timeframe 2010-2050. Finally, in Chapter 7 results are presented for development of the WTW emissions of an average car for different fuel production mixes in the considered timeframe. These results are combined with results of THRIVE roll-out simulations to determine potential impact of FC vehicles on car fleet GHG emissions as a percentage. Chapter 7 is concluded with a sensitivity analysis on a number of assumptions.

2. Basic concept of the model

The THRIVE GHG emission module is based on the output of the THRIVE simulation model for roll-out of a hydrogen fuelled car fleet and corresponding refueling infrastructure. The THRIVE simulation model simulates the FC vehicle penetration in every year until 2050, expressed in numbers of vehicles. The related vehicle travelled kilometres (VTKs in mln km's) of Hydrogen FC vehicles for each scenario mentioned above are calculated by assuming an annual kilometrage of 15,000 km/year. A basic starting point of the study is that if a car is replaced by a Hydrogen FC vehicle, the car owner keeps his current travel behaviour (besides small detours for refuelling), so the average annual mileage (15,000 km) and the road type mix remain similar. The Hydrogen VTKs serve as the scenario based input for the GHG module. The THRIVE simulation model has 5 different sight years: 2010, 2020, 2030, 2040 and 2050. For conclusions on other years, the model needs to be adjusted.

Figure 2.1 shows the flow chart of the THRIVE GHG emission model. The THRIVE simulation model calculates the vehicle traveled kilometers of FC vehicles for each THRIVE scenario and future year, indicated with the white box. The light blue boxes represent the calculations done by the GHG model.

The dark green boxes indicate that there are various scenarios or production routes possible. These scenarios are described in Chapter 7.

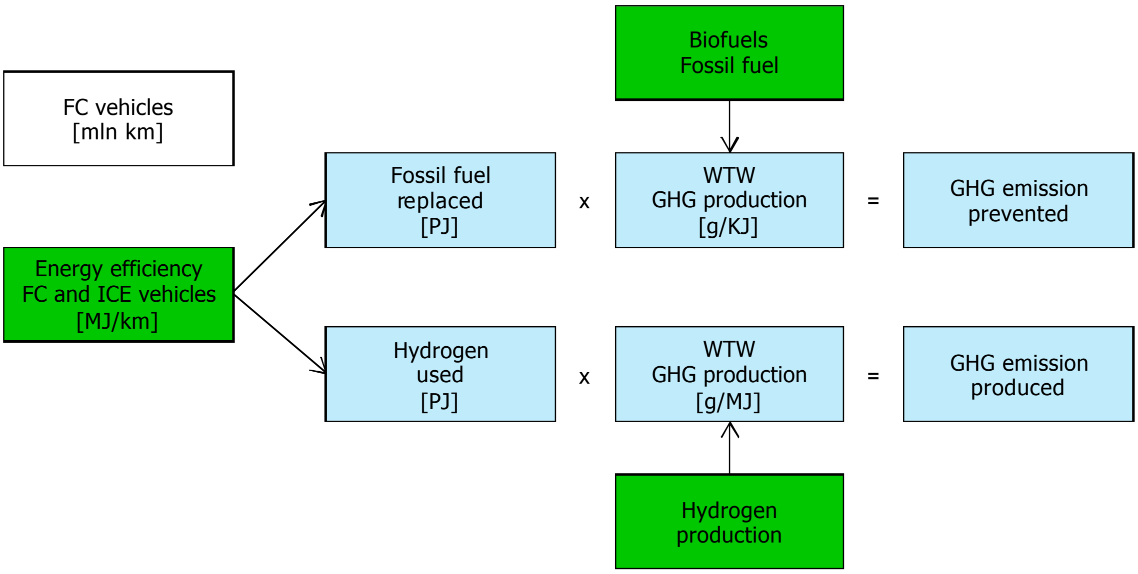

Figure 2.1 *Flow chart of the GHG emission model*

To calculate the energy consumption of the fuel cell (FC) vehicle fleet, the vehicle traveled kilometers are multiplied with the average energy consumption of the FC vehicles. Note that the THRIVE GHG emission model uses the average energy consumption and WTW GHG emissions of the whole ICE or FC vehicle fleet and not the energy consumption and GHG emissions of only the new introduced vehicles of the specified year. The FC vehicle fleet will replace a part of the vehicles powered by an ICE. The amount of fossil fuel replaced is calculated by multiplying (1) the VTKs from the THRIVE simulations with (2) the energy consumption of an average ICE vehicle. The energy consumption of both FC and ICE vehicles, including future developments, that are used in the GHG model are described in Chapter 3.

The GHG emissions prevented by replacing ICE vehicles with FC vehicles are calculated by multiplying (1) the amount of fossil fuels replaced with (2) the GHG emission produced during manufacturing and combustion of these fossil fuels (g/MJ), i.e. the GHG emissions from Well to Wheel (WTW). Biofuel usage and energy efficiency improvement of the refinery process are taken into account. The WTW GHG emissions of ICE vehicles are described in Chapter 4 for fossil fuels and in Chapter 5 for biofuels. The GHG emission model assumes that of the replaced ICE VTKs, 40% is gasoline powered and 60% is diesel powered. However, the ratio between the gasoline and diesel powered ICE vehicles can be adjusted.

The only exhaust from a FC vehicle is water and no CO_2 is emitted by the vehicle, i.e. the Tank to Wheel CO_2 emission is zero. This means that the emission of green house gases only occurs during the production of the hydrogen. Consequently, the Well to Wheel GHG emission is equal to the Well to Tank GHG emission. The WTW GHG emissions of FC vehicles are described in Chapter 6.

The measure for the GHG balance is the difference between (1) the GHG emission prevented by replacing fossil fuels and (2) the GHG emission produced during the production of hydrogen.

3. ICE and FC H_2 vehicle efficiencies

3.1 Introduction

To convert the vehicle travelled kilometres (VTKs) of FC vehicles from a THRIVE scenario into used and displaced energy consumption, the vehicle energy consumptions are needed, see Figure 2.1. This calculation is straightforward: the product of (1) the VTKs (mln km) and (2) the energy consumption (MJ/km) of the fuel cell vehicle yields the amount of energy needed in the form of hydrogen for the THRIVE scenario. The energy content of the fossil fuel replaced by hydrogen is calculated by the product of (1) the VTKs and (2) the energy use of the vehicle with an Internal Combustion Engine (ICE). This chapter describes the origin of the chosen energy efficiencies for ICE and FC vehicles.

3.2 Reference year 2010

The average energy consumption of ICE and FC vehicles in 2010 can be found in the literature. The energy efficiencies reported in (Edwards, 2008) and (Kroon, 2009) are based on new introduced ICE vehicles in 2010, see Table 3.1. The first two columns are based on (Edwards, 2008), the last two columns are based on (Kroon, 2009).

Table 3.1 *Vehicle energy consumption for new vehicles in 2010*

Vehicle type	Energy Consumption [MJ/km]	Direct CO_2 emission [g/km]	Energy Consumption [MJ/km]	Direct CO_2 emission [g/km]
Gasoline	1,90	137	1,90	137
Diesel	1,61	131	1,76	131
H2 FC	0,84		0,94	
Ratios*				
H2 FC/gasoline	44%	44%	49%	49%
H2 FC/diesel	52%	52%	53%	53%

* ratios of H2 energy use, relative to the ICE alternative.

For the GHG module we will only use the average energy consumption of the whole vehicle park. The values reported by (Gül, 2008) and (Uyterlinde, 2009) represent the average energy consumption of gasoline and diesel cars of the whole ICE vehicle fleet, see Table 3.2.

The energy use and CO_2 emission reported in these two studies are identical, so only one value is listed here. Note that these correspond to actual average efficiencies based on actual driving patterns, i.e. they represent real world efficiencies and direct CO_2 emissions (Tank-to-Wheel), and should not be compared with CO_2 legislation which often is based on specific test cycles (see below for more details).

Table 3.2 *Vehicle energy consumption for the whole vehicle park in 2008*

Vehicle type	Energy Consumption [MJ/km]	Direct CO_2 emission [g/km]
Gasoline	2,50	180
Diesel	2,20	163
H2 FC	1,20*	
Ratios**		
H2 FC/gasoline	48%	48%
H2 FC/diesel	55%	55%

* this value is based on fuel cell electric vehicles without the ability to use regenerative breaking.
** ratios of H2 FC vehicles versus the ICE alternative.

In this study we use the average energy consumption of the whole vehicle fleet as given by (Gül, 2008) and (Uyterlinde, 2009). We have used the 2008 energy consumptions of gasoline and diesel powered ICE vehicles directly for 2010. Note that the energy consumption ratio between gasoline - H_2 FC and diesel - H_2 fuel FC is similar in all studies.

The energy efficiencies for the FC vehicles reported in the studies mentioned above correspond well with the efficiencies for the FC vehicles produced by Toyota (Bruijn, 2005), see Table 3.3.

Table 3.3 *Vehicle efficiencies of Toyota FC vehicles*

Vehicle	Efficiency [%]	Energy use [MJ/km]
Toyota FCV	38	1,20
Toyota FCHV*	50	0,90
Target	60	0,76

* Fuel cell Hybrid Vehicle

The Honda Clarity has an energy use similar to the Toyota FCV. The difference between the Toyota FCV and the Toyota FCHV is that the FCHV employs regenerative breaking which will improve the efficiency of this next generation of Toyota substantially. To reach the target still other efficiency improvements are needed.

3.3 Future years 2020, 2030, 2040 and 2050

It is uncertain how technology will evolve over time, so energy usage of ICE and FC vehicles for the future years 2020, 2030, 2040 and 2050 is difficult to predict. To resolve this problem three different technological development scenarios are defined. Two are related to current EU policy ambition levels, and one to a more extreme scenario based on a maximum potential.

The emission limits published in the EC regulation No 443/2009, the so called cars and CO_2 regulation, provides for 2015 a CO_2 emission limit for new sold vehicles of 130 g CO_2/ km, and a target of 95 g CO_2/km for 2020. This target for 2020 is still pending an evaluation, and therefore uncertain. It is assumed that new legislation on the CO_2 emission limits will stimulate efficiency improvement for both the ICE vehicles and the H2 FC vehicles.

Energy consumption ICE vehicles
The maximum potential scenario is estimated at 80 g CO_2/km based on two publications:
- (Sharpe, 2009) states that a limit of 85 g CO_2 / km is technically and economically feasible.
- (Bosch, 2009) claims that 70 g CO_2 /km emission is possible for an ICE powered car with a weight of 1200 kg.

Based on this, the following three technology improvement scenarios have been defined:
- Low: ICE technology meets 130 g CO_2/km limit per 2015 and stabilises at that level.
- Medium: ICE technology meets 130 g CO_2/km (2015) and 95 g CO_2/km limit (in 2020 and afterwards).
- High: After meeting the 95 g CO_2/km limit in 2020, the technology improves towards a 80 g CO_2/km limit around 2040.

Note that these CO_2 emission limits are based on type approval values measured over a test cycle, which can differ from the real world emissions. To correct for the deviation between type approval values and the real world emissions based on fuel sales, we have corrected the 130 g/km and 95 g/km limit using the correction factors for 2010 from (Ligterink, 2009), see Table 3.4.

Table 3.4 *Correction Type Approval Emission versus Real World Emission*

Fuel type	Type approval value [g/km]	Real World value [g/km]	Correction factor [%]
Gasoline	160	160	0
Diesel	165	180	9

Energy consumption hydrogen fuel cell electric vehicle

The energy use of the FC vehicle for the reference year 2010 is taken from the studies by (Gül, 2008) and (Uyterlinde, 2009). Note that this number corresponds with the energy use of the Toyota FCV and the Honda Clarity, both vehicles do not employ regenerative breaking.

In the low technology improvement scenario only the implementation of regenerative breaking is taken into account, this leads to an energy use of about 0,9 MJ/km corresponding with the energy use of the Toyota FCHV.

In the medium technology improvement scenario we have used the target efficiency published by (Bruijn, 2005), see Table 3.5.

The energy use in the high technology improvement scenario for the FC vehicle in 2050 is based on improvements of the roll resistance and the mass reduction potential of the vehicle taken from (Passier, 2008).

Table 3.5 *Vehicle energy use in 2050*

Vehicle	2010 [MJ/km]	Low 2050 130 g/km [MJ/km]	Medium 2050 95 g/km [MJ/km]	High 2050 80 g/km [MJ/km]
ICE gasoline	2,50	1,81	1,32	1,11
ICE diesel	2,20	1,91	1,39	1,17
H2 FC	1,20	0,90	0,76	0,63

At this moment, the THRIVE GHG emission model does not allow for scenarios in which the ICE technology develops according to one scenario and the fuel cell vehicles develops according to another scenario (e.g. ICE conform low and H_2 conform medium or high). This assumption is based on expectation that several efficiency improvements will be shared by FC and ICE (e.g. aerodynamics, weight reduction, rolling resistance). However, different technological developments for FC and ICE vehicles would lead to different results. Note that the THRIVE simulation model has assumed a stable vehicle efficiency, see (Lebutsch et al., 2010).

The explicit energy consumptions per future year are given in Appendix A.

4. Production routes fossil fuels

4.1 Introduction

In the previous chapter we have established the energy usage of both ICE and FC vehicles. The next step in the calculation is to multiply the fossil fuel/biofuel that is replaced by hydrogen, with the corresponding Well To Wheel (WTW) GHG emission. A similar step is done for the hydrogen used, see Figure 2.1. The Well-to-Wheels emissions of all fuels involved will depend on the origin and production/distribution methods chosen.

For the different stages of a fuel production route, the Concawe report (Edwards, 2008) gives: (1) the energy balance, i.e. the ratio of the energy expended for production and the energy content of the final fuel and (2) the GHG emission (grams/energy content of the final fuel).
The different stages of a fuel production route are:

- Extraction of primary fuel or cultivation of feedstock.
- Transport of primary fuel or feedstock.
- Production of fuel: Refining or processing.
- Distribution and dispensing of fuel.

The sum of these three contributions represents the Well-to-Tank (WTT) part for the energy balance and the GHG emission. Only when the production route is not specifically listed in the Concawe report (Edwards, 2008), the separate contributions are given which were used in the calculation.

4.2 Reference year 2010

The energy balance and GHG emission for gasoline and diesel are taken from the Concawe report (Edwards, 2008). The energy numbers are expressed as net energy (MJ) expended per MJ energy content of the final fuel. The GHG emission, including CO_2, CH_4 and N_2O, are expressed as grams per MJ energy content of the final fuel. The energy balance and GHG emissions associated with tar sand production routes and the production routes diesel from Coal To Liquid and Gas To Liquid are taken from (Kroon, 2009). Currently only the GHG emissions of gasoline and diesel from relatively light crude oils are used in the GHG emission model; see Table 4.1. The GHG emissions listed in this table for gasoline and diesel are used for the reference year 2010.

Table 4.1 *Energy balance and GHG emission of fossil fuels in 2010*

	Energy balance [MJ/MJ_f]	WTT GHG emission [g/MJ_f]	WTW GHG Emission [g/MJf]
Gasoline	0,14	12,5	84,5
Diesel	0,16	14,2	88,4
Gasoline from tar sand	0,31	29,5	101,5
Diesel from tar sand	0,33	31,1	105,3
CTL diesel	0,89	108,4	182,6
GTL diesel (from CNG)	0,69	22,0	96,2

4.3 Future years 2020, 2030, 2040 and 2050

The Well-To-Tank (WTT) GHG emission of fossil fuels can change in the future. Technological improvement of refineries, especially the distillation and vacuum distillation parts of the refinery can be improved substantially. Retrofitting more efficient distillation columns can improve the efficiency of the refinery by 13%. However, an entirely new refinery, a so called green field refinery, will have a 30% better energy efficiency than current refineries (Wilde, 2010). However, due to restrictions on air polluting emissions by international shipping, residual fuels usage, the heaviest fraction of the crude oil, will be banned from 2020 on. In response, gradually more residual fuels will be converted in gasoline and diesel by the so called deep conversion process (cracking and hydrogenation). This deep conversion process will increase the CO_2 emission for the production of gasoline and diesel. When all refineries will convert all the residual fuels the total CO_2 emission will increase by about 30% (Wilde,2009). To estimate the energy balances and GHG emission of gasoline and diesel for 2050 the following assumptions are made:

- No contribution of heavy oil is expected in Europe for future years (Kroon, 2010).
- The energy efficiency of a refinery increases by 30% in 2050[2].
- There is no contribution of deep conversion to the gasoline and diesel production.

Correcting for the 30% refinery efficiency increase over the production chain leads to the energy balance and GHG emission for 2050 listed in Table 4.2. The last two columns represent the Well-To-Tank (WTT) energy consumption and GHG emission index with respect to 2010.

Table 4.2 *WTT Energy balance and WTT GHG emission of fossil fuels in 2050*

	Energy [MJ/MJ_f]	GHG [g/MJ_f]	Energy Index [%]	GHG index [%]
Gasoline	0,12	10,40	82,9	83,2
Diesel	0,13	11,62	81,3	81,8

The WTT energy consumption indexes for all future years are listed in Table 4.3. The last column represents the absolute energy balance factor used for 2050 in the model.

Table 4.3 *WTT Energy balance of fossil fuels for future years*

Energy	2010 [MJ/MJ]	2020 [%]	2030 [%]	2040 [%]	2050 [%]	2050 [MJ/MJ]
Gasoline	0,14	95	91	87	83	0,12
Diesel	0,16	95	91	86	81	0,13

The WTT GHG emissions for all future years are listed in Table 4.4. The last column represents the absolute GHG emission factor used for 2050 in the model.

Table 4.4 *WTT GHG emission of fossil fuels for future years*

GHG emission	2010 [g/MJ]	2020 [%]	2030 [%]	2040 [%]	2050 [%]	2050 [g/MJ]
Gasoline	12,5	96	92	87	83	10,4
Diesel	14,2	95	91	86	82	11,6

2 Note that the energy efficiency improvement of the refinery can be adjusted in the model. As a part of the sensitivity analysis this value will be altered.

5. Production routes biofuels

5.1 Introduction

The energy and GHG balances are taken from the Well to Wheel analysis of the future automotive fuels study by Concawe (Edwards, 2008). The energy balances and GHG emissions for the different bio fuel production routes are calculated by considering different stages in the production pathways. These stages include:

- Production and conditioning at the source.
- Transportation (to the EU).
- Conditioning, transformation and distribution in the EU.

There is a variety of biofuels and underlying feed stocks available for substituting fossil diesel and gasoline, See Annex B for details. To assure substantial CO_2 emission reductions once biofuels are used, the EU implemented the Fuel Quality Directive (Directive 2009/30/EC,2009). This directive states (article 7b, paragraph 2) that the greenhouse gas saving resulting from the use of biofuels must be at least 35%, compared to the Well- To-Wheel greenhouse gas emission of the corresponding fossil fuel. Starting the 1th of January 2017, the greenhouse gas emission saving from the use of biofuels has to be at least 50%. From 1th of January 2018 the greenhouse gas emission saving has to be at least 60% for biofuels produced in installations that came into production has started on or after 1 January 2018. The CO_2 emission reduction originating from biofuels in 2050 is assumed to be ~60% in this study.

5.2 Reference year 2010

In the GHG emission model we have chosen a combination of production routes from Annex B that meets the GHG emission reduction requirements of the fuel quality directive. As a result we obtain the WTW GHG emissions for biodiesel and ethanol, that are shown below.

Table 5.1 *Ethanol production routes chosen in the GHG emission module for 2010*

Production route	Share [%]	GHG emission [g/MJ]
Ethanol from grain	100	51

Table 5.2 *Biodiesel production routes chosen in the GHG emission module for 2010*

Production route	Share [%]	GHG emission [g/MJ]
Biodiesel HVO	100	50

HVO stands for Hydrogenated Vegetable Oil, a 1st generation biodiesel that has a good fuel quality and can be used up to at least 30% mixed in fossil diesel without the need for specially adapted vehicles. In contrast, the conventional 1st generation biodiesel, FAME (Fatty Acid Methyl Esters) can only be used up to 7% mixed in fossil diesel.

Note that the by-product in the case of FAME production is glycerol and that the by-product in the case of HVO production is propane.

5.3 Future years 2020, 2030, 2040 and 2050

The combination of production routes chosen in 2050 leads to a GHG emission reduction of 61% for both ethanol and biodiesel. Of course effective improvement of the individual biofuel production pathways could influence the final mix that is needed to meet the Fuel Quality Directive targets. However, the final mix of pathways needs to give a 60% emission reduction.

Annex B also gives estimates of potential improvement for some of the biofuel production routes towards 2050. However, these potential improvements are not used in the model as we use the requirements from the Fuel Quality Directive as a starting point.

Table 5.3 lists the production routes chosen for the ethanol production. The share of the production routes is chosen in such a way that the GHG reduction is in accordance with the fuel quality directive, see Appendix B.

Table 5.3 *Ethanol production routes chosen in the GHG emission module for 2050*

Production route	Share [%]	GHG emission [g/MJ]
Ethanol from sugar cane	35	
Ethanol from farmed wood*	30	
Ethanol from grain	35	
Ethanol aggregate		33

* note that ethanol from wood is a 2nd generation biofuel

Table 5.4 lists the production routes chosen for the biodiesel production. The share of the production routes is chosen in such a way that the GHG reduction is in accordance with the fuel quality directive.

Table 5.4 *Biodiesel production routes chosen in the GHG emission module for 2050*

Production route	Share [%]	GHG emission [g/MJ]
Biodiesel HVO*	65	
FT diesel from farmed wood	35	
Biodiesel aggregate		34

* Note that HVO is a 1st generation biofuel.

6. Production routes for Hydrogen

6.1 Introduction

The energy balances and WTT GHG emissions for several hydrogen production routes are derived from (Edwards , 2008). The GHG emission of the production routes listed in the Concawe report are based on the following assumptions:

- Central production of hydrogen.
- Transport of liquid hydrogen from the production site to the fuelling station.
- Storage of liquid hydrogen at the refuelling station
- Evaporation of the liquid hydrogen at the fuelling site yielding CGH2 upon refuelling.
- CGH2 (pressurized hydrogen, ~800 bar) is used in the fuel cell vehicles.

In this report we have adapted the production routes for transportation of liquefied hydrogen.

Remarks:

- A pressure of about 875 bar is required to fast fill the fuel cell car to an ultimate pressure of about 700 bar.
- In the model it is assumed that a cryo-pump based concept is used to pressurize starting in 2010, so no additional compressor is needed[3].
- Note that the direct GHG emission of the FC vehicle is zero, which means that the WTT GHG emission is equivalent to the WTW GHG emission.

Although we have not included hydrogen production by electrolysis in the current report we have looked at the energy balances and GHG emission for different electricity production routes as well.

6.2 Reference year 2010

Several hydrogen production pathways given in the Concawe report involve the transport of gaseous hydrogen via pipelines. The energy balances and GHG emissions of these production pathways are corrected for liquid hydrogen transport, leading to the following results (see Table 6.1).

Table 6.1 *Energy balance and GHG emission for hydrogen production*

Technique	[MJ_{WTT}/MJ_{Final}]	GHG [g_{WTT}/MJ_{Final}]
LH2 liquefaction	0,62	33,8
LH2 transport + evaporation	0,04	1,8

Note that the energy balance and GHG emission stated at the LH2 transport and evaporation is based on a scheme involving pressurization of hydrogen using a cryopump, and based on production routes using Steam Methane Reforming (starting point for THRIVE project).

The energy balance and GHG emission for various hydrogen production routes with LH2 transport derived from (Edwards, 2008) used in the GHG emission model are listed below, see Table 6.2.

3 A cryopump pumps liquid hydrogen which subsequently evaporates in a confined volume yielding pressurized gaseous hydrogen. This process is more energy efficient than the alternative method which first evaporates the liquid hydrogen to a low pressure gaseous hydrogen and next uses a compressor to reach the desired pressure level.

Table 6.2 *Energy balances and GHG emission for H_2 production (SMR) based on LH2 transport*

Production route	Energy balance [MJ_{WTT}/MJ_{Final}]	GHG emission [g_{WTT}/MJ_{Final}]
SMR gas (4000 km)	1,15	127,8
SMR Biogas	1,21	38,8
SMR gas (4000 km) with CCS	2,79	55,9

SMR: Steam Methane Reforming
CCS: Carbon Capture and Storage

6.3 Future years 2020,2030,2040 and 2050

To estimate the energy balances and GHG emissions of the hydrogen production routes listed in Table 6.2 for future years, several technical improvements could be considered:
- Magneto caloric cooling to produce liquid hydrogen.
- ECN HYSEP membrane technology for SMR.

Magneto caloric cooling
The energy efficiency of the conventional technique to liquefy hydrogen can be improved from 0,62 MJ/MJ to about 0,52 MJ/MJ. Possibly in the near future a new technique, magneto caloric cooling, will become available to liquefy hydrogen. Employing magneto caloric cooling the energy consumption for hydrogen liquefaction can drop from 0,62 MJ/MJ to 0,25 MJ/MJ (Weeda, 2010). This corresponds with an improvement of about 60%. Depending on the year when magneto caloric cooling will become available on the market, a certain part of the installed liquefiers will be conventional and will stay operational in the near future. The effect of this, still uncertain, potential efficiency improvement is presented as a sensitivity analysis in Paragraph 7.4.3. For the main comparison only the expected efficiency improvement of conventional cooling is used to determine the improved energy efficiency for the liquefaction.

HYSEP membrane technology
The overall efficiency of the SMR process is about 70%. Using the ECN HYSEP membrane process the efficiency of the SMR can increase from 70% to 80%, this is an efficiency improvement of ~9% over the whole transport and production chain. In the model we assume a linear decrease of the energy balance towards 2050. This linear decrease in energy consumption must reflect the gradual introduction of membrane technology at the hydrogen production site.

Table 6.3 lists the energy efficiencies and the GHG emission for the hydrogen production routes involving SMR, employing the HYSEP membrane technology and some efficiency improvements in conventional cooling (excluding Magneto caloric cooling).

Table 6.3 *Energy efficiencies and GHG emission for hydrogen production in 2050*

Production route	Energy balance [MJ/MJ_f]	GHG emission [g/MJ_f]	Energy index [%]	GHG index [%]
SMR	1,00	112,8	79	84
SMR + biogas	2,65	50,0	91	81
SMR + CCS	1,06	35,0	79	78

The last two columns show the indexes of the energy and GHG emission for the indicated production process compared to 2010 for the considered production routes based on SMR.

7. Results for THRIVE scenarios

In the THRIVE GHG module the greenhouse gas emissions and the energy use of the THRIVE scenarios are compared to a business-as-usual scenario in which only ICE vehicles are employed, both on a well-to-wheel basis. Currently the growth in the number of vehicles in THRIVE is based on a particular scenario. Based on this vehicle fleet development and different starting points for the main actors involved in the roll-out of a hydrogen FC vehicle fleet and corresponding refuelling infrastructure, three main THRIVE scenarios have been simulated. These scenarios for the introduction of hydrogen as a transport fuel are defined in the THRIVE model and are depicted in Figure 7.1 (for details, see THRIVE final report (Lebutsch et al., 2010)).

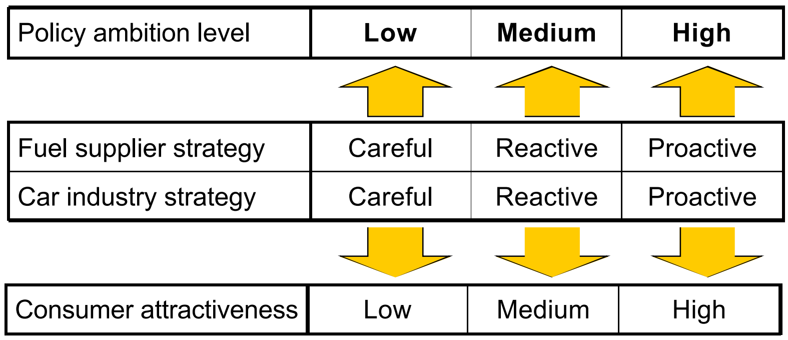

Figure 7.1 *Overview of the scenarios used in the THRIVE model*

7.1 Main drivers for emission reduction and energy savings

The actual emission reduction[4] for these scenarios until 2050 will depend mainly on:

1. The relative share of kilometres driven by FC vehicles (instead of ICE vehicles).
2. Vehicle efficiency development of ICE and FC vehicles.
3. Development of carbon-intensiveness of involved fuels, including share of renewable energy.

For the THRIVE project, a number of possible scenarios have been developed for the main drivers, which will be explained next. Although the scenarios aim to provide an objective evaluation for the context of a sustainable future with (low-carbon) hydrogen, they do not intend to provide an exhaustive set that includes all other alternative assumptions.

Ad 1) The relative share of kilometres driven by FC vehicles

In each THRIVE scenario different amounts of vehicles with Internal Combustion Engines (ICE) are replaced by hydrogen Fuel Cell vehicles, based on the simulated market penetration. The average amount of annual kilometres driven will vary per person, however for this analysis we assume an average usage of 15.000 km per year and that, on average, “average-size” cars will be replaced (i.e. FC vehicles not limited to big or small vehicles). These assumptions will introduce an uncertainty around the final emission reduction, but still allow for a comparison between the scenarios. This uncertainty is considered relatively small compared to the overall uncertainty in the THRIVE scenarios and the background scenario. Figure 7.2 shows the share of hydrogen FC vehicles in the passenger car segment for the different THRIVE scenarios. The dotted line concerns the most ambitious THRIVE scenario (“high”: infra and car industry both

[4] Based on the same drivers and the information in Chapter 4, Chapter 5 and Chapter 6, also the impact of the energy use over the chain can be determined. For simplicity, this paragraph focuses on emission reduction. Next paragraphs will present the resulting impacts on emissions and energy use.

pro-active) in combination with consumers that are willing to drive further than their currently preferred filling station, or are willing to make a small detour to refuel their car (changed refuelling behaviour). In this scenario, about half of all kilometres driven in 2050 by passenger cars are driven in a FC vehicle.

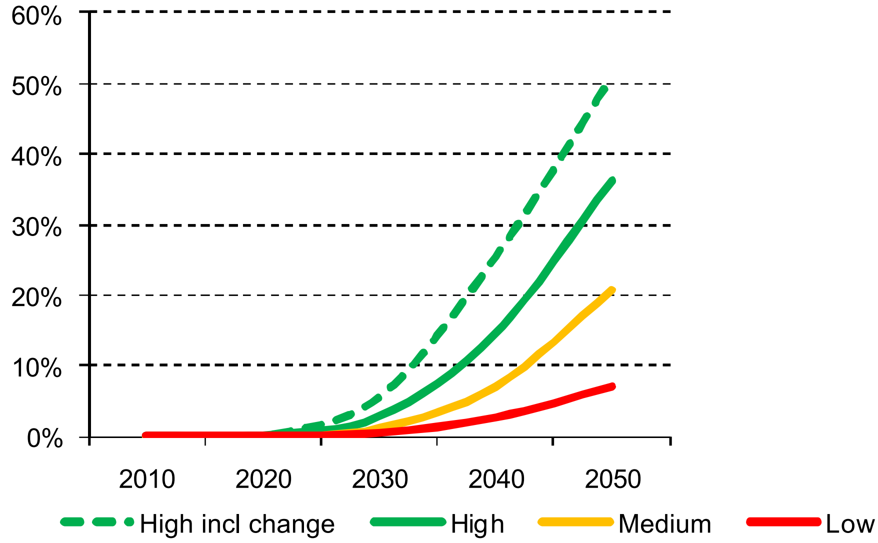

Figure 7.2 *FC vehicles relative share in the kilometres driven by passengers cars for all THRIVE scenarios*

Ad 2) Vehicle efficiency development of ICE and FC vehicles

For our evaluation of the environmental impact we have assumed three potential background scenarios for vehicle efficiency (low, medium, high), see Chapter 3 for details. The efficiency development of ICE towards a more efficient vehicle (low, medium, high), is assumed to be in line with a similar low, medium or high improvement of the FC vehicle's efficiency. So this dimension provides only three different outcomes[5].

Ad 3) Carbon-intensiveness of the production mix for the involved fuels

For all energy carriers involved (Diesel, Gasoline and Hydrogen), three carbon-intensity scenarios (low, medium, high) have been developed based on assumed production route mixes that could include biofuels and other renewable routes. The carbon-intensity of the different production routes have been described in Chapter 4 (fossil fuels), Chapter 5 (biofuels) and Chapter 6 (hydrogen), and generally are expected to improve towards 2050.

The fuel production scenarios assumed for gasoline, diesel and hydrogen are listed in Table 7.1. The percentages listed in this table are a measure for the amount of fossil fuel versus biofuel used in the scenario, varying from 0% to 30%. For hydrogen the table presents the share of the different variations of SMR production route in the different carbon intensiveness scenarios.

[5] In theory, one could also compare the worst case efficiency development for ICE with a best case efficiency for FCEV and other "mixed combinations" to obtain 9 different comparisons, but this is not considered likely, as a number of the energy efficiency improvements will be relevant to both ICE and FCEV (weight reduction, aerodynamic improvements, Low rolling resistance tyres, efficient airco).

Table 7.1 *Fuel production scenarios with different carbon intensiveness*

Carbon intensiveness	Scenario	Low [%]	Medium [%]	High [%]
Gasoline (ICE)	gasoline	70	80	100
	ethanol	30	20	0
Diesel (ICE)	diesel	70	80	100
	Biodiesel	30	20	0
H_2 - (FC)	SMR	0	80	100
	SMR with CCS	100	0	0
	SMR with biogas	0	20	0

The scenarios for carbon intensiveness can be compared in a number of ways, based on the relevant expectations one has for the future. The high carbon intensiveness scenario for ICE of 0% biofuel displacement will lead to a larger emission reduction, and should only be applied in case the displaced biofuel used by the displaced ICE vehicles, is expected to be fully relocated to the transportsector. This could for example be realised as result of an increased share of biofuels in the remaining vehicles or by an increased volume of high-blend vehicles (e.g. flex fuel).

However, in case one expects that the biomass is needed for the chosen hydrogen production mix (e.g. medium scenario with biogas), it seems more appropriate to compare this hydrogen scenario to a comparable carbon intensity for ICE where also biofuels will really be displaced (limiting the emission reduction.

7.2 Relative emission reductions and energy use: ICE versus H_2 FC vehicle

In this paragraph the relative well-to-wheel emissions (GHG_{WTW} per km) will be presented for several combinations of vehicle efficiency development and carbon intensiveness scenarios. By multiplying this information with the kilometres driven by the hydrogen vehicles in a specific THRIVE scenario, the total emission reduction will be determined and presented in Paragraph 7.3.

For a specific vehicle efficiency improvement scenario, the relative well-to-wheel emission reduction depends on the assumed carbon intensiveness of the ICE and the H_2 FC vehicle. Table 7.2, Table 7.3 and Table 7.4 present the results per vehicle efficiency improvement scenario for the 9 possible combinations of carbon intensiveness scenarios for 2050. Note that these figures also depend on a number of other assumptions described in this report, for example the share of displaced gasoline and diesel vehicles. Also note that the mentioned emissions per kilometre are based on Well-to-wheel emissions, and should not be confused with the Tank-to-wheel efficiencies that are used for EU legislation on car efficiency (e.g. 130, 139 and 158 g/km (all well-to-wheel) for ICE - High in Table 7.2 correspond all to low vehicle efficiency, with 130 g/km "vehicle efficiency" (tank-to-wheel).

Table 7.2 *Relative well-to-wheel emission reduction in 2050 for different carbon intensiveness combinations for the low vehicle efficiency development scenario*

		H_2 - Low (31 g/km)	H_2 - Medium (90 g/km)	H_2 - High (102 g/km)
ICE - Low	(130 g/km)	76%	30%	22%
ICE - Medium	(139 g/km)	77%	35%	27%
ICE - High	(158 g/km)	80%	43%	36%

Table 7.3 *Relative well-to-wheel emission reduction in 2050 for different carbon intensiveness combinations for the medium vehicle efficiency development scenario*

		H_2 - Low (26 g/km)	H_2 - Medium (76 g/km)	H_2 - High (85 g/km)
ICE - Low	(95 g/km)	72%	20%	10%
ICE - Medium	(102 g/km)	74%	25%	16%
ICE - High	(115 g/km)	77%	34%	26%

Table 7.4 *Relative well-to-wheel emission reduction in 2050 for different carbon intensiveness combinations for the high vehicle efficiency development scenario*

		H_2 - Low (22 g/km)	H_2 - Medium (63 g/km)	H_2 - High (71 g/km)
ICE - Low	(80 g/km)	72%	21%	11%
ICE - Medium	(86 g/km)	74%	26%	17%
ICE - High	(97 g/km)	77%	35%	27%

These results show that, in 2050, based on our starting points hydrogen FC vehicles reduce the well-to-wheel emissions per kilometre compared to ICE's substantially. The reduction varies between 10% to 40% for hydrogen produced without the application of CCS. In case CCS is applied to the SMR process, the relative emission reductions are larger, between 70% and 80%, depending on the carbon intensiveness of the displaced fuel. In both situations, the relative emission reduction is maximal in a future in which the vehicle efficiency is not further improved beyond the 130 g/km norm for 2015 (i.e. in the low efficiency scenario).

For the years until 2050, the relative emission reductions show the same dynamics, but can vary around the values above. For the medium vehicle efficiency scenario, Figure 7.3 the overall development in average well-to-wheel emissions per kilometre is shown between 2010 and 2050. The substantial efficiency improvement of the vehicles, reduces the absolute reduction of hydrogen FC vehicles but the relative distance remains more or less similar. The bars correspond to the minimum and maximum carbon intensiveness scenarios of the involved fuels (diesel/gasoline mix and hydrogen). The medium scenario are indicated by a line within the bars.

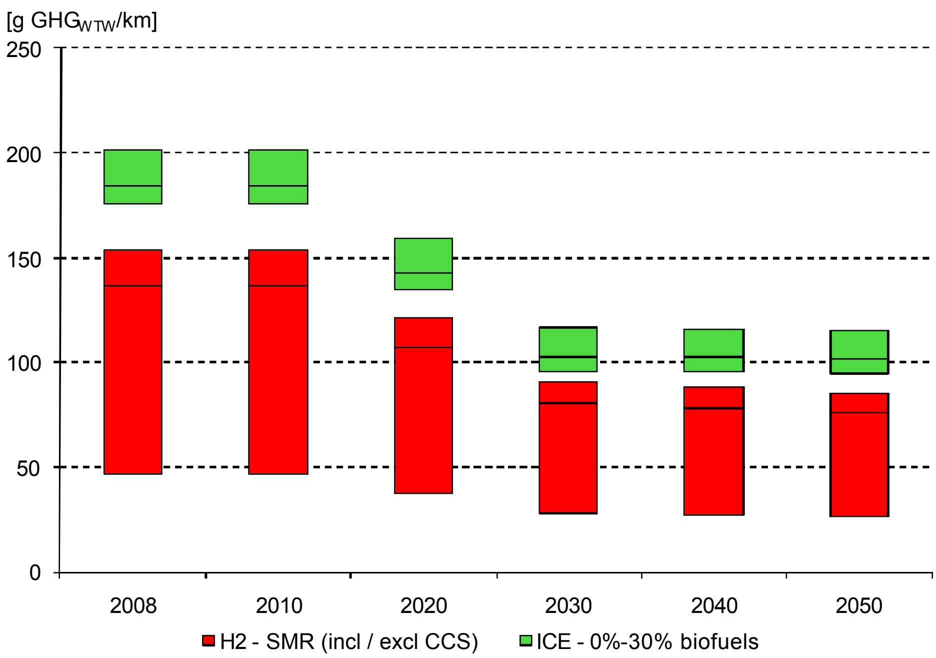

Figure 7.3 *Relative Well-to-Wheel emissions for medium vehicle efficiency scenario*

Figure 7.4 shows that the development of the well-to-wheel energy use over time is a clear driver for the substantial reduction of the well-to-wheel emissions per kilometre.

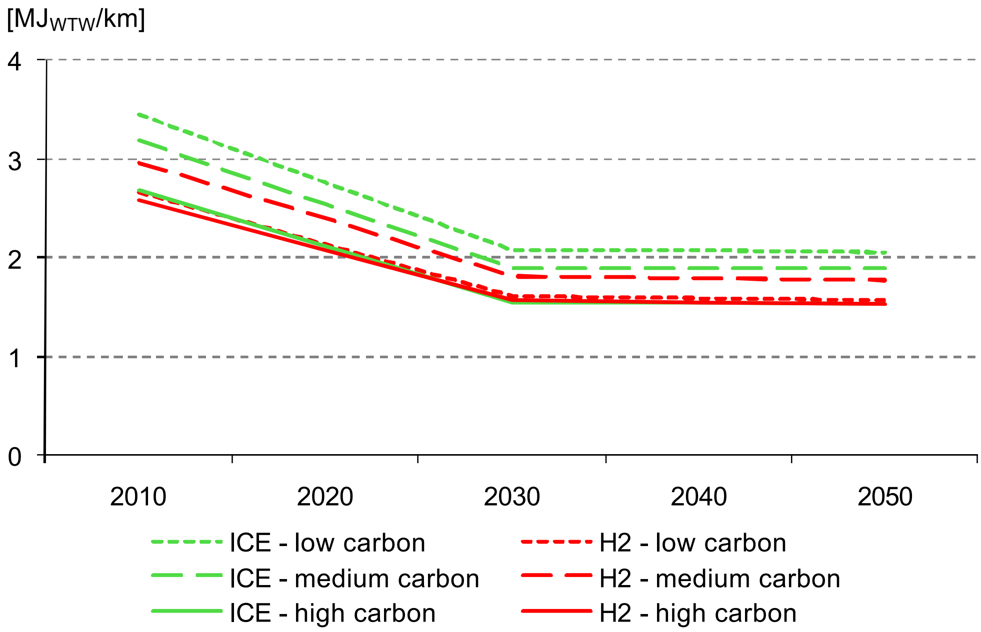

Figure 7.4 *Relative Well-to-Wheel energy use for medium vehicle efficiency scenario*

The development of the well-to-wheel energy use follows the same trend for both ICE and H_2 FC vehicles. The relative energy use is dependent on which production route is used for the fuel. Hydrogen from SMR (on natural gas without CCS) results in the lowest well-to-wheel energy use per kilometre, closely followed by hydrogen from SMR with CCS, and conventional gasoline and diesel (without biofuels). All other fuel production routes that have been investigated, have about 20% to 50% more energy use.

7.3 THRIVE scenarios: WTW emission reduction for passenger car fleet

If the relative emission reductions as presented in Paragraph 7.2 are combined with the relative share of FC vehicles for the THRIVE scenarios, the relative emission reduction for the passenger vehicle fleet can be determined in 2050. The following table provides these results on a more aggregate level. The ranges do not indicate the uncertainty interval, but the smallest range in which the results of all combinations of the aggregated level are included. Note that this only is correct if the diesel and gasoline shares in VTK's remain constant around 60% and 40%.

Table 7.5 *FC vehicle share and relative well-to-wheel emission reduction in 2050 for different THRIVE scenarios for the passenger car fleet.*

		Low vehicle efficiency		Medium/High vehicle efficiency	
	FC vehicle share	H_2 medium/high	H_2 low	H_2 medium/high	H_2 low
Scenario Low	~ 7%	2-3%	5-6%	1-2%	5%
Scenario Medium	~ 20%	4-9%	16-17%	2-7%	15-16%
Scenario High	~ 35%	8-16%	27-29%	4-13%	26%-28%
Scenario High+	~ 50%	11-22%	39-41%	5-18%	37%-39%

7.4 Sensitivity analysis

In this paragraph the sensitivity of the results of the final WTW GHG emission will be analyzed for a number of assumptions:

1. Ratio between gasoline/diesel powered ICE vehicles which are replaced by H2 FC electric vehicles.
2. The energy efficiency improvement of the refineries.
3. Employing magneto caloric cooling to produce liquid hydrogen in the future.
4. Employing biogas in the production of hydrogen.

For all analysis, the absolute change versus the original reduction ranges will be given for the year 2050. The original (base case) reduction varied between 10% to 40% for hydrogen produced without CCS (and between 70% and 80% in case CCS was applied), depending on the carbon intensiveness of the displaced fuel. Note that all sensitivities are expressed related to these ranges, and are not related to the overall WTW emission reduction for the specific Thrive scenarios (i.e. including the market penetration).

7.4.1 Different mix of replaced gasoline/diesel powered ICE vehicles

In the simulated results shown in Paragraph 7.2 and Paragraph 7.3, the ICE vehicles which are replaced by fuel cell are assumed to consist for 40% of gasoline powered vehicles and 60% of diesel powered vehicles. In case these assumptions are changed to the extreme assumptions that the composition of the replaced ICE vehicle park is assumed to consist of either 100% gasoline or 100% diesel powered cars, the results remain within the same order of magnitude. The emission reduction ranges will only shift at most 6%-point downward (in case of 100% gasoline replacement) or 3%-point upward (in case of 100% diesel replacement). This impact is only minor given the assumption that the efficiency difference between gasoline and diesel powered vehicles will decrease towards the future. However, the GHG emission associated with the production of diesel will remain higher than the GHG emission associated with the production of gasoline.

7.4.2 No energy efficiency improvement of refineries

Refineries have several options to reduce their energy consumption and hence their GHG emissions associated with the fuel production. In a so called “green field” refinery with improved heat management and integrated distillation techniques can lower the GHG emission by as much as 30%, which was the assumed efficiency improvement in the base case. As indicated before, new regulations regarding the sulfur content of fuel and the increase in capacity of the deep conversion process of bunker fuels, can offset the entire WTW emission reduction of 30%. In case the efficiency of refineries (for gasoline and diesel) in 2050 is similar to current efficiency (i.e. no 30% efficiency gain), only a marginal effect is found on the overall WTW emission reduction. The emission reduction of the introduction of Hydrogen increases by 1%-point to 2%-point, as the WTW emissions for the reference technology (ICE) deteriorates.

7.4.3 Introduction magneto caloric cooling to produce liquid hydrogen

The production of liquid hydrogen is energy intensive and costs about 0,62 MJ per MJ hydrogen. Liquefaction contributes about 33,8 gram of GHG per MJ of hydrogen, which accounts for almost 25% of the total WTW GHG emission.

The experimental technique of Magneto Caloric Cooling (MCC) can lower the energy costs for liquefaction to about 0,25 MJ/MJ, which is a substantial improvement if compared to the expected future energy costs for improved conventional cooling techniques (0,52 MJ/MJ). Full employment of magneto caloric cooling in 2050 to liquefy hydrogen can lower the WTW GHG emission of hydrogen fuel cell vehicles by about 12%, compared to the current assumption in the GHG module. The emission reduction ranges will improve by 8%-point to 12%-point (upward) dependent on the assumptions around vehicle efficiency and carbon intensiveness of ICE-related fuels and Hydrogen.

7.4.4 Employing biogas in the production of hydrogen

The GHG emission for the hydrogen production assumes central production using Steam Methane Reforming (SMR). Three carbon intensity scenarios have been presented in Table 7.1 of which the Medium scenario assumes that 20% of the SMR is based on biogas instead of natural gas. In case only biogas (i.e. 100% SMR with biogas) is used, the relative WTW emission reduction will improve from about 30% to 40% (with 20% biogas) by 30%-points to 60% and 70%. Although substantially improved, the reduction is about 10%-point lower than achievable by the scenario where the hydrogen is produced on natural gas with application of CCS. If CCS is applied on SMR process with biogas as input even further reductions are possible. As the world-wide potential of biomass and biogas is limited, it is uncertain whether such high shares are attainable as soon as the market for hydrogen grows substantial.

7.4.5 Conclusions

In this chapter the effects of adjusting some of the main assumptions have been investigated. The following table summarizes the results of the sensitivity analysis. Especially the introduction of magneto caloric cooling and a higher share of biogas, can still improve the expected WTW emission reduction substantially by 10%-points or more. Varying the other investigated assumptions only result in changes of a few percent-points.

Table 7.6 *Impact on relative well-to-wheel emission reduction in 2050 in percent points*

	H_2 - Low (CCS) (Reduction: 70%-80%)	H_2 - Medium/High (no CCS) (Reduction: 10%-40%)
Replacement mix: 100% gasoline	Minor (~ -1%)	Minor (~ -6%)
Replacement mix: 100% diesel	Minor (~ +1%)	Minor (~ +3%)
No efficiency improvement refineries	Minor (~ +1%)	Minor (~ +2%)
Introduction magneto caloric cooling	Relevant (~ +10%)	Relevant (~ +10%)
100% share of biogas (Medium scenario only)	Not quantified	Relevant (~ +30%)

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Appendix A Vehicle energy consumptions per scenario and future year

This annex lists the assumed vehicle energy consumptions for the three technological improvement scenarios.

In the low technological improvement scenario, the first vehicles with a CO_2 emission of 130 g/km will be introduced in 2015, due to vehicle park dynamics all ICE vehicles will be replaced by an ICE vehicle with a 130 g/km emission around 2030. After 2030 there will be no additional technological improvement anymore, as the new vehicles all remain at the energy consumption level of 130 g/km (note that this might also be a result of fleet dynamics: shift to more powerful or larger cars).

Table A.1 *Vehicle energy consumption in the low technical improvement scenario*

Vehicle [MJ/km]	2010	2020	2030	2040	2050
ICE gasoline	2,50	2,15	1,81	1,81	1,81
ICE diesel	2,20	2,05	1,91	1,91	1,91
H2 FC	1,20	1,05	0,90	0,90	0,90

The vehicle energy consumption in the scenario with medium technical improvement are given in Table A.2. The medium technological improvement scenario follows the low scenario until 2015. As of 2015 until 2020, the vehicle consumption will improve until an emission of 95 g/km will be reached in 2020. Due to vehicle park dynamics all ICE vehicles will be replaced by an ICE vehicle with a 95 g/km emission around 2030. After 2030 there will be no additional technological improvement anymore.

Table A.2 *Vehicle energy consumption in the medium technical improvement scenario*

Vehicle [MJ/km]	2010	2020	2030	2040	2050
ICE gasoline	2,50	1,91	1,32	1,32	1,32
ICE diesel	2,20	1,80	1,39	1,39	1,39
H2 FC	1,20	0,98	0,76	0,76	0,76

The vehicle energy consumptions in the scenario with maximum potential improvement are given in Table A.3. The high technological improvement scenario corresponds to the medium scenario until 2030. After 2030 the energy consumption will gradually improve to the maximum potential around 2050.

Table A.3 *Vehicle energy consumption in the maximum potential improvement scenario*

Vehicle [MJ/km]	2010	2020	2030	2040	2050
ICE gasoline	2,50	1,91	1,32	1,22	1,11
ICE diesel	2,20	1,80	1,39	1,28	1,17
H2 FC	1,20	0,98	0,76	0,69	0,63

Appendix B Production routes biofuels

The figures listed in Table B.1 are used to calculate the energy balance for the specified production routes of ethanol and biodiesel.

Table B.1 *Well to Tank energy balance for several bio fuel production routes*

WTT efficiency [MJ_{WTT}/MJ_{Final}]	Extraction/ cultivation	Transport	Refining/ processing	Total
ethanol sugarcane	0,06	0,12	1,63	1,81
ethanol wheat straw	0,04	0,04	1,24	1,32
ethanol farmed wood	0,11	0,04	1,81	1,96
ethanol waste wood	0,08	0,07	1,81	1,96
ethanol sugar beet	0,11	0,05	0,26	0,42
ethanol grain	0,27	0,06	0,92	1,25
biodiesel FAME	0,19	0,04	0,74	0,97
biodiesel HVO	0,10	0,11	1,05	1,26
FT diesel farmed wood	0,09	0,03	1,08	1,20
FT diesel waste wood	0,06	0,06	1,08	1,20
biodiesel rapeseed	0,29	0,04	0,75	1,08

The figures listed in Table B.2 are used to calculate the GHG emissions for the specified production routes of ethanol and biodiesel.

Table B.2 *Well to Tank GHG emissions for several bio fuel production routes*

WTT GHG emission [g_{WTT}/MJ_{Final}]	Extraction/ cultivation	Transport	Refining/ processing	Total
ethanol sugarcane	14,5	9,0	0,7	24,2
ethanol wheat straw	3,1	2,2	3,4	8,7
ethanol farmed wood	6,3	2,4	13,3	22,0
ethanol waste wood	1,0	4,7	13,3	19,0
ethanol sugar beet	16,2	2,7	19,2	38,1
ethanol grain	39,4	2,2	9,5	51,1
biodiesel FAME	28,0	1,6	1,4	31,0
biodiesel HVO	15,5	5,7	28,4	49,6
FT diesel farmed wood	5,0	1,9	0,0	6,9
FT diesel waste wood	0,8	4,1	0,0	4,9
biodiesel rapeseed	49,4	1,6	-9,4	41,6

Technological improvement of the bio fuel production routes
The reduction percentages stated in this chapter are not used in the THRIVE GHG emission model.

Ethanol from sugar cane
Table B.1 and Table B.2 show that the energy needed to produce ethanol from sugar cane is 1,81 times more than the energy content of the produced ethanol. However, the GHG emission is relatively low compared to the other 1st generation ethanol i.e. from sugar beet and grain.

The GHG emission from the processing of sugar cane is relatively low because the by-product of the sugar cane fermentation, bagasse, is burned in a Combined Heat and Power (CHP) device to produce enough heat to make the ethanol water free. The burning of bagasse in the CHP creates a surplus of electricity, which lowers the GHG emission. The production process of ethanol from sugar cane can be optimized through:

- Co-fermentation of the cellulose part of the sugar cane plant, reducing the land use by almost 50% (Tavora,2008). This is called 2nd generation bio ethanol.
- Currently the fermentation of sugar cane leads to 6 – 10 w% ethanol.
- Employing the membrane technology Hybsi developed by ECN or employing a Heat Integrated Distillation Column (HIDiC) to separate the ethanol from the water. Both techniques can reduce the energy consumption of the water removal process by about 30%.
- Transition from water free ethanol to water containing ethanol (4% water) as a transport fuel.

A detailed study of the potential improvement is outside the scope of this study.