ECN

Energy research Centre of the Netherlands

ANALYSIS OF OPPORTUNITIES AND SYNERGIES IN FUEL CELL AND HYDROGEN TECHNOLOGIES

Paul Lebutsch

Gerard Kraaij

Marcel Weeda

September 2009

ECN-E--09-062

EXECUTIVE SUMMARY

This report is a deliverable of the Roads2HyCom project (www.roads2hy.com , document number: R2H4007PU.2 , 13 October 2010, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project is studying technical and socio-economic issues associated with the use of fuel cells and hydrogen in a sustainable energy economy.

Within the project, several studies have been made related to the state of the art of fuel cell and hydrogen technologies. This study, Task 5 of the Work Package 4 (WT4.5) analyses 23 potential fuel cell/hydrogen applications and identifies:

- **Gaps** in the performance and costs of hydrogen technologies that need to be bridged to become a competitive alternative to conventional (or so-called reference) technologies,

- **Priorities** in the research required to bridge these gaps and

- **Opportunities** for near-term application of hydrogen technologies, including and comparing potential CO_2 emission reductions.

The results of this study should help stakeholders and communities that show commitment in developing hydrogen activities in their choice of considered applications. Light duty trucks, forklifts in 24/5 operation, sightseeing boats, outdoor utility vehicles, license-free cars and back-up systems for telecommunications as well as passenger cars have been identified as near- to mid-term market opportunities, whereas the latter show the highest potential for CO_2 emission reductions. However, research needs to deliver projected advances in cost reduction for the applications to become economically attractive.

Identified priorities could be used by communities to develop investment decisions with positive impacts on markets for fuel cell/hydrogen technologies. For the PEMFC this means increasing the power density of the fuel cell in order to reduce material needs and hence material costs, using less platinum or other materials than platinum as catalyst and increasing the durability (lifetime) of the stack and the fuel cell system as a whole.

Possible future situations for passenger cars, light duty trucks and buses were assumed and evaluated as well. Technological developments, stricter emission policies and a higher price on conventional fuels will lead to a more favourable situation for fuel cell/hydrogen technologies, but the cost of hydrogen will have critical influence on the economics whatsoever. Thus, any activity that can lead to a reduction of the price of hydrogen, including the whole pathway from production to dispensing (source-to-user) will help FC/H_2 technologies to gain ground.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
μ-CHP	Residential Combined Heat and Power
APU	Auxiliary Power Unit
BOP	Balance Of Plant
CHP	Combined Heat and Power
DMFC	Direct Methanol Fuel Cell
EOS	Economies Of Scale
FC/H_2	Fuel Cell/Hydrogen
GHG	Green House Gas
GT	Gas Turbine
HHV	Higher Heating Value
ICE	Internal Combustion Engine
kWe or kW_e	kilo Watt (electric)
LHV	Lower Heating Value
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrode Assembly
NG	Natural Gas
PEMFC	Polymer Electrolyte Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
SOTA	State-Of-The-Art
UPS	Uninterruptible Power Supply
VAT	Value Added Tax
WTW	Well-to-Wheel

1. Introduction

This document is the report on Task 5 of the Work Package 4 (WT4.5) of the EU Roads2HyCom project. WT4.5 intends to identify:

- **Gaps** in the performance and costs of hydrogen technologies that need to be bridged to become a competitive alternative to reference technologies,
- **Priorities** in the research required to bridge these gaps and
- **Opportunities** for near-term application of hydrogen technologies.

The identification of gaps, priorities and opportunities should help in developing R&D recommendations for hydrogen technologies, which is part of Work Package 6.

The identification of opportunities could also guide communities that show commitment in developing hydrogen activities in their choice of considered applications. This report therefore provides them with information on the following issues for various applications:

- Economic information on the gap between the cost of conventional technologies and fuel cell/hydrogen (FC/H_2) technologies
- Potential CO_2 reductions when using FC/H_2 technologies
- Insight into near- and mid-term opportunities for FC/H_2 applications

In order to realize these intentions, the project partners provide case studies of 23 applications.

In Chapter 2, the objectives of Work Task 4.5 in context with the goals of Work Package 4 (WP4) are described.

In Chapter 3, the methodology, which is used in this task is explained and an overview about the case studies is given. Furthermore, cost and CO_2 emission parameters used throughout this task are presented.

In Chapter 4, the results of the case studies are combined and the metrics cost and CO_2 emissions are analysed. Results from this analysis are discussed in Chapter 5.

In Chapter 6, the conclusions of this task can be found.

The Appendix A: and Appendix B: contain background information including the parameters used in the calculation and definition of fuel costs and CO_2 emissions, which were used in the case studies.

The case studies made by the partners are provided in report R2H4008PU.

2. Objectives

2.1 General Objectives of WP4

The WP4 “Development of technology pathways”, as part of the Roads2HyCom project, intends to identify topics and priorities of research agenda items necessary for making fuel cell/hydrogen technologies competitive to today’s applications. This could also help communities that want to invest in fuel cell/hydrogen technologies in their investment decisions, i.e. selection of applications and planning of future activities.

WT4.5 is the last task in WP4 and uses some of the results of WT4.1 – WT4.4 for its assumptions. The titles of the other work packages are:

WT4.1: “Scenarios for evolutionary pathways“

WT4.2: “Profiling regional and community level“

WT4.3: “Source-to-Tank: Technology pathways and carbon balance“

WT4.4: “Tank-to-User: Technology pathways and carbon balance“

2.2 Objectives of WT4.5

WT4.5 provides specifications, boundaries and a thorough description of present applications (using so-called “reference technologies” at the moment) that might be suitable for future implementation of fuel cell/hydrogen technologies. Anticipated developments in reference technologies and possible alternatives are described additionally.

This information is used to determine the economics of reference and both State of the Art (SOTA) and feasible future FC/H_2 technologies for different cases, e.g. different operation hours or number of units produced. The economics of equally performing reference and SOTA or future FC/H_2 technologies are then compared to evaluate under which circumstances this change can be achieved and hence which research items should be prioritised.

Another objective is to determine potential reductions in CO_2 emissions through usage of FC/H_2 technologies for the applications considered.

3. Methodology

3.1 General Approach

First, 23 potential FC/H_2 applications are defined based on the considerations of WT4.1 and WT4.4. Case studies provide information such as:

- Description of the applications including economics of the used reference and feasible FC/H_2 technologies such as €/km, €/hour of operation or €/kWh
- Description of the expected technological and non-technological developments (energy prices, emission and fuel policies, etc.) until 2020 with an outlook to 2030

Second, as both the hydrogen cost and the fuel cell system costs are uncertain, the current costs of the reference technologies will be used to evaluate the allowable costs of hydrogen as a function of a range of assumed fuel cell system costs for each application. These evaluations provide, for each single application, so-called “Lines of Equality” or “Windows of Opportunity” that illustrate the circumstances, under which the costs per unit service of the reference and FC/H_2 technology are equal.

Third, the costs of the applications using SOTA (state-of-the-art) or evaluated 2020 - 2025 FC/H_2 technologies are analysed to determine the economic competitiveness against current reference technologies.

Fourth, the gaps between the “Windows of Opportunity” and the SOTA or evaluated 2020 - 2025 costs of the FC/H_2 technologies are determined and analysed in order to identify reasons for different costs. The outcome of these evaluations shows the possibilities to overcome the gaps in order to make the FC/H_2 system competitive to the reference technology (e.g. technological development and/or mass production) in more detail.

3.2 Potential Areas for Applications

Based on the work of WT4.1 and WT4.4 23 potential FC/H_2 applications are considered in this task in the areas of:

- Transport applications:
  - Passenger Cars
  - Light Trucks
  - Buses
  - Outdoor Utility Vehicles
  - License-free Cars (also known as City Cars)

    - Scooter
    - Forklifts
    - Aircraft Tow Trucks
    - Sightseeing Boats
    - Airplanes
- Auxiliary Power Units (APU) for transport applications
    - Truck APU
    - Pleasure Boat APU
    - Mega Yacht APU
    - Airplane APU
- Stationary applications:
    - Back-up Power for Telecom
    - Back-up Power for Hospitals
    - Industrial CHP
    - Residential μ-CHP

3.3 Case Study Allocation

Table 1 allocates all 23 case studies to the partners contributing to this task. The case studies can be found in report R2H4008PU.

Table 1: Partner allocation of case studies

(Field of) Application			Partner	
Transportation				
H_2-ICE Buses	FC Buses	Light Trucks	FEV	FEV Motorentechnik GmbH (DE)
H_2-ICE Passenger Cars	FC Passenger Cars		DC	Daimler AG (DE) (+Energy research Centre of the Netherlands (NL))
License-free Cars	Outdoor Utility Vehicles	Sightseeing Boats	ECN	Energy research Centre of the Netherlands (NL)
Forklifts			IFP	Institut Français du Pétrole (FR)
Aircraft Tow Trucks	Airplanes		AD	Airbus Deutschland GmbH (DE)
Scooter			CRF	Centro Ricerche Fiat (IT)
Transport APU				
Truck APU	Pleasure Boat APU		VTEC	Volvo Technology Corporation (SE)
Mega Yacht APU	Airplane APU		AD	Airbus Deutschland GmbH (DE)
Back-up/Remote power				
Hospitals	Telecom		JBRC	Ceske vysoke uceni technicke v Praze (CZ)
Industrial CHP				
PEMFC	MCFC (Biogas)	SOFC-GT (NG)	IEn	Instytut Energetyki, (PL)
µ-CHP (1 - 5 kW)				
PEMFC (H_2 or NG)	SOFC (NG)		GdF	Gaz de France S.A. (FR)

The WT4.5 leader provided a template for the analysis of the applications. The paragraphs in the template are:

- Description of the application
- Description of the reference technology
- Description of the market
- Description of FC/H_2 technology suitable for the application
- Economic boundary conditions for FC/H_2 technology
- CO_2 reduction potential Source-to-User
- Conclusions and recommendations
- References

3.4 Economics

In the comparison of FC/H_2 technology to reference technology, the whole drivetrain (transport applications) and components that are different (stationary applications) are taken into account. For example, if the drivetrain of the reference technology comprises the fuel tank and internal combustion engine including the cooling system, gearbox and exhaust system, the FC drivetrain comprises the hydrogen tank, fuel cell system (fuel cell stack, cooling system, power inverter), electric motor and battery. In the case of comparing a FC drivetrain to a purely electrical drivetrain, the electromotor is the same but still considered in the calculations for both technologies (for ease of using the same equations).

Parts like the body of a car are not included in the analysis.

Maintenance and applicable replacement costs are included for all technologies to ensure the same lifetimes.

Both state-of-the-art and future technologies are considered in this analysis.

3.4.1 "Line of Equality" for Comparison

The economics of a certain application using either reference or FC/H_2 technology are evaluated on an "equal cost per unit service" basis (€/km, €/hr or €/kWh). Thus, the total cost of the reference technology per unit service (both €/km and €/hr are being used) is first calculated using following equation:

$$\text{Total Cost of Ref.-Tech.}\,[\text{€/km or €/hr}] = \frac{C_{DT} \cdot P_{Ref}}{t_{Ref} \cdot U_{Ref}} + \frac{C_{Fuel} \cdot Eff_{Ref}}{1000} + C_{Ref-maint.}$$

C_{DT}	Cost of the reference drivetrain	[€/kW]
P_{Ref}	Power of the reference drivetrain	[kW]
t_{Ref}	Lifetime of the reference drivetrain	[years]
U_{Ref}	Annual use of the reference drivetrain	[km/year or hr/year]
C_{Fuel}	Fuel cost including excise duties	[€/GJ]
Eff_{Ref}	Efficiency/Energy consumption of the reference drivetrain	[MJ/km or MJ/hr]
$C_{Ref-maint.}$	Maintenance cost of the reference drivetrain	[€/km or €/hr]

Using the total cost of the reference technology per unit service as the basis, the allowable cost of hydrogen, which is dependent on certain assumed FC/H_2 drivetrain costs, is calculated (see equation below). This linear correlation of allowable hydrogen costs to assumed FC/H_2 drivetrain costs is from now on referred to as the "Line of Equality" (see Figure 1). Along this line, the total cost of ownership of the FC/H_2 technology is equal to the reference technology in the considered case.

$$\text{Allowed Cost of } H_2\ [€/GJ] = \frac{(C_{ref} - C_{H_2\text{-Sys-maint.}}) \cdot t_{H_2\text{-Sys}} \cdot U_{H_2\text{-Sys}} - C_{H_2\text{-Sys}} \cdot P_{H_2\text{-Sys}}}{t_{H_2\text{-Sys}} \cdot U_{H_2\text{-Sys}} \cdot \frac{Eff_{H_2\text{-Sys}}}{1000}}$$

C_{ref}	Total cost of reference system	[€/km or €/hr]
$C_{H2\text{-}Sys\text{-}maint.}$	Cost of Maintenance of FC/H_2 system	[€/km or €/hr]
$t_{H2\text{-}Sys}$	Lifetime of the FC/H_2 system	[years]
$U_{H2\text{-}Sys}$	Annual use of FC/H_2 system	[km/year or hr/year]
$C_{H2\text{-}Sys}$	Assumed cost of FC/H_2 system	[€/kWe]
	(Values used: 0, 200, 500, 1000, 2000, 4000)	
$P_{H2\text{-}Sys}$	Power of FC/H_2 system	[kW]
$Eff_{H2\text{-}Sys}$	Efficiency/Energy consumption of the FC/H_2 system	[MJ/km or MJ/hr]

Figure 1: "Line of Equality" – Methodology for economical comparison of applications on an equal cost per unit service basis

For the evaluation of the cost-competitiveness, the calculated, assumed and targeted costs of SOTA and future FC/H_2 drivetrains are plotted (on the x-axis) against a **projected** price of hydrogen at the filling station of either

- 51,8 €/GJ (equal to 6,2 €/kg) for hydrogen produced from natural gas via steam methane reforming (mean 2007 price of NG at 12,1 €/GJ) used for SOTA drivetrain costs or
- 68 €/GJ (equal to 8,2 €/kg) for hydrogen based on the HyWays production mix (2030) used for future drivetrain costs.

All hydrogen costs also include cost of transportation to the filling station, VAT and forecourt costs. Other duties like excise taxes are neglected. At these cost levels, the hydrogen distribution system and the filling stations are assumed to be well established.

Below the “Line of Equality” lies the “Window of Opportunity”: If the data point reflecting hydrogen cost to the FC/H_2 system cost lies within the “Window of Opportunity” (see Figure 2, situation A), the conditions for the FC/H_2 drivetrain are favourable. The vertical distance from the data point to the “Line of Equality” reflects the possibility for taxation of hydrogen as the “Line of Equality” was obtained including excise duties on conventional fuels.

If the data point reflecting hydrogen cost to FC/H_2 drivetrain cost lies above this “Line of Equality” (see Figure 2, situation B), the conditions for the hydrogen technology are unfavourable. The vertical distance to the “Line of Equality” then reflects necessary subsidies on the cost of hydrogen, if the cost of the FC/H_2 drivetrain would stay the same. If the cost of hydrogen stays the same, the horizontal distance reflects necessary FC/H_2 drivetrain cost reductions e.g. through mass production or technological development. These gaps are then analysed in more detail to research possibilities for cost reductions.

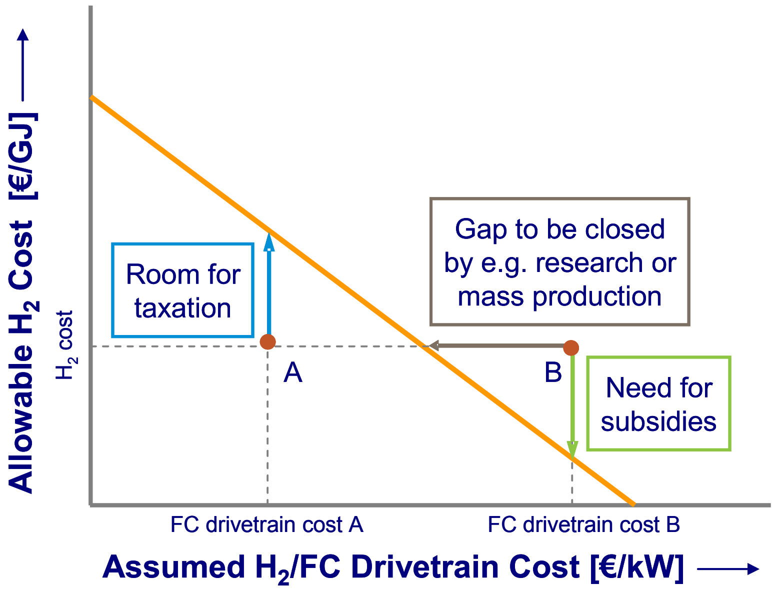


Figure 2: Plotting assumed/evaluated/targeted costs of hydrogen to FC/H_2 drivetrain costs

In this graph, necessities or possibilities of the application using FC/H_2 technology are illustrated: It is cost-competitive compared to the reference technology, if the data point lies within the Window of Opportunity, which enables for example taxation (excise duties on hydrogen). Otherwise, the costs have to decrease by, for example, means of research, mass production or subsidies

As this analysis requires a common basis for the cost of the fuel used by reference technologies in 2007 and 2030, it uses the scenario described in Appendix A::

- Price of crude oil in January 2007: oil_{2007} = 60 \$/barrel or 7,1 $€_{2000}$/GJ

  (0,7575 € = 1 \$; 159 L/barrel; 34,8 MJ/L; $€_{2000} = €_{2007}/1{,}164$)

- Price of crude oil in 2030: oil_{2030} = 14 $€_{2000}$/GJ (= 135 \$/bbl)

The resulting prices, which are used in the analysis, are listed in Table 2:

Table 2: Energy prices in €$_{2000}$ including taxes (for consumers and small industries)

	Consumer				Small industry	
	Gasoline €/GJ	**Diesel €/GJ**	**Gas €/GJ**	**Electricity €/GJ**	**Gas €/GJ**	**Electricity €/GJ**
The lowest energy price in the 25 EU countries in 2007 (Low 2007)	21,7	19,7	5,1	16,4	4,3	14,2
The average energy price in the 25 EU countries in 2007 (Mean 2007)	29,1	23,5	12,1	33,4	9,6	30,1
The estimated average energy price in the 25 EU countries in 2030 (Mean 2030)	39,0	33,4	20,6	36,9	18,2	33,6
The estimated highest energy price in the 25 EU countries in 2030 (High 2030)	47,1	43,5	35,0	65,0	23,4	52,7

This variation in energy prices enables regions or communities to estimate the effect of their present day energy price on the fuel cost of the reference technology.

3.4.2 Sensitivities

This chapter intends to explain the sensitivities of the calculations towards used parameters such as:

- Annual usage (distance or operation time)
- Cost of engine (reference technology)
- Cost of fuel
- Energy efficiency of the reference technology
- Energy efficiency of the FC/H_2 technology

Data for passenger cars equipped with an internal combustion engine or a fuel cell drivetrain is used, whereas only one of the parameters described above is changed. **It is important to notice that the shown figures do not reflect any real or even future situation!**

3.4.2.1 Annual usage

The chosen values reflect annual usages ranging from 10 000 to 40 000 km, which covers the majority of distances travelled with passenger vehicles. The total lifetime of the assumed passenger car is 15 years. This parameter affects the slope of the “Line of Equality” towards favouring the use of FC/H_2 technologies in applications with higher annual usage, i.e. driven kilometres or hours of operation.

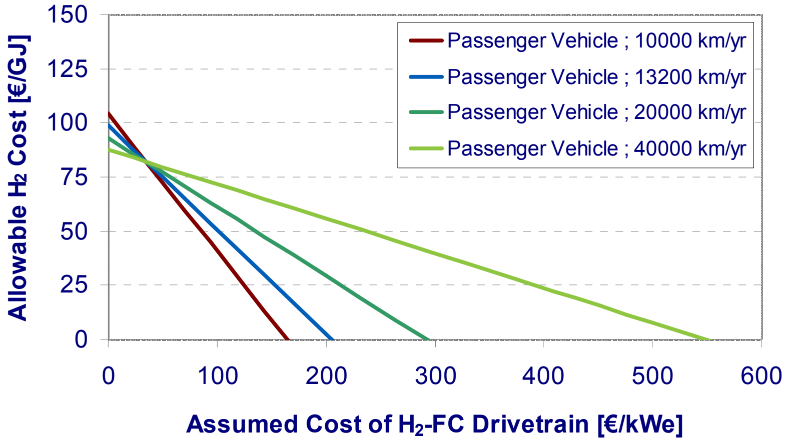


Figure 3: Sensitivity of the calculation of the Window of Opportunity towards different annual usage

3.4.2.2 Cost of Engine and Fuel, Energy Efficiency (Reference Technology)

Figure 4, Figure 5 and Figure 6 show the sensitivities towards costs of engine, the fuel price and the energy efficiency, all of which for the reference technologies.

The chosen cost of engine ranges from 30 to 60 €/kWe. It covers both small-scale SOTA ICE running on gasoline as well as future, highly-developed and very efficient low-emissions engines.

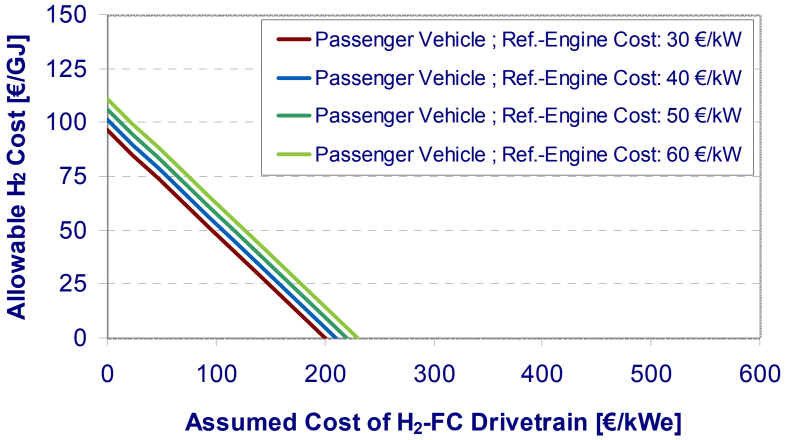


Figure 4: Sensitivity of the calculation of the Window of Opportunity towards different engine costs for reference technology

The chosen fuel prices range from 20 to 50 €/GJ. For better comparability to pump prices: This converts into a price of 0,64 to 1,60 €/L gasoline or 0,80 to 1,80 €/L diesel respectively (diesel has a higher energy density per litre).

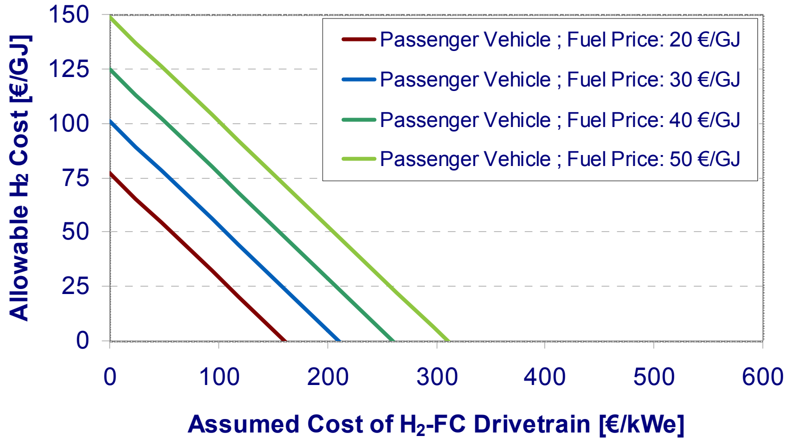


Figure 5: Sensitivity of the calculation of the Window of Opportunity towards different cost of fuel used by reference technologies

The chosen engine efficiency ranges from 1 MJ/km to 2,5 MJ/km, which is equivalent to approximately 0,28 to 0,69 kWh/km or 3,1 to 7,8 L gasoline per 100km. This covers ICE as used in small vehicles (e.g. scooter), SOTA Hybrid efficiencies and ICE used in larger vehicles such as station wagons.

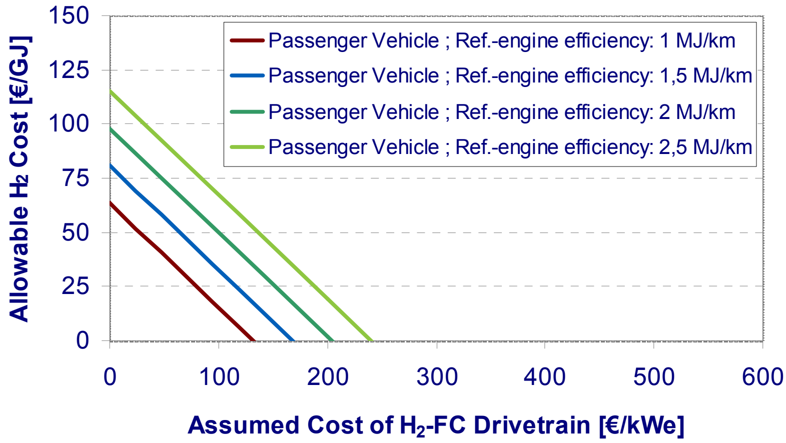


Figure 6: Sensitivity of the calculation of the Window of Opportunity towards different engine efficiencies of the reference technology

All three parameters do not affect the slope of the "Line of Equality" as they are only used linearly. However, it can be seen that the higher the cost for the reference system or the fuel it uses and the lower its efficiency, the bigger the "Window of Opportunity" becomes for the FC/H_2 technology.

3.4.2.3 Energy Efficiency of the FC/H_2 technology

The chosen values reflecting different energy efficiencies of the FC/H_2 technology range from 0,5 to 2 MJ/km. HyWays [3] estimates a fuel cell efficiency for passenger cars at approximately 0,84 MJ/km, whereas ICE running on hydrogen are assumed to have only half of this efficiency, i.e. 1,68 MJ/km. For a specific comparison see Chapter 4.3.1.1.

As the fuel cell technology is expected to become more efficient in the future, lower values are included in Figure 7 as well.

This parameter affects the slope of the "Line of Equality" only in regard to allowable cost of hydrogen.

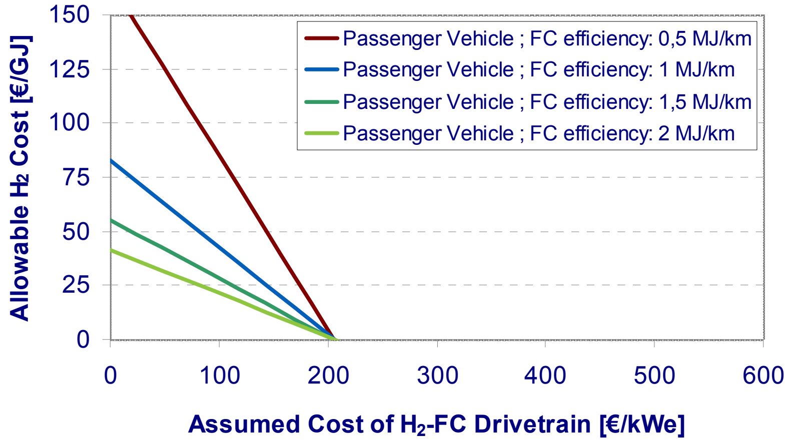


Figure 7: Sensitivity of the calculation of the Window of Opportunity towards different FC/H_2 system efficiencies

3.4.3 Hydrogen Fuel Cell Drivetrain Cost Evaluations

The FC drivetrain cost for the considered application is evaluated for different combinations of parameters and plotted against the evaluated/targeted cost of hydrogen. The cases considered include different reference technologies, annual usage, emission policies (leading to CO_2 taxation) and estimations for future technology. Fuel cell system costs for all drivetrain components

- Fuel cell system
- Hydrogen storage
- Electromotor
- Batteries

are taken from both TIAX [10] and HyWays [3] studies and used as input C_0. The total cost of the FC system C_x in €/kW_e is the sum of the calculated costs of all its parts divided by the application's power. Furthermore, a series of coefficients reflecting economies-of-scale, possible fuel cell degradation, influence of the system power and future cost reductions due to progress is multiplied with the component's costs as appropriate (explained in the chapters below):

$$C_x = C_0 \cdot c_{EOS} \cdot c_{LT} \cdot c_{SP} \cdot c_P \cdot \frac{1}{P_{DT}}$$

C_x	…	Cost of the considered drivetrain component	[€/kW$_e$]
C_0	…	Reference Cost of the considered drivetrain component (input)	[€]
c_{EOS}	…	Economies-of-scale coefficient	
c_{LT}	…	Lifetime coefficient	
c_{SP}	…	System power coefficient	
c_P	…	progress coefficient reflecting future situation	
P_{DT}	…	Power of the system/drivetrain	[kW$_e$]

3.4.3.1 Basic Input for Calculations

The cost of mass production of state-of-the-art fuel cell systems for 500 000 units of 100 kW for passenger cars is taken from the studies conducted by TIAX [10] and IFP for the WT4.4 [8] and amounts to 100 €$_{2000}$/kW$_e$ for an adjusted platinum cost of 2000 $/troy oz (≈46 000 €/kg) as experienced in the first half of 2008.

The minimum cost of mass produced state-of-the-art hydrogen storage systems for 500 000 units/year is estimated by TIAX [11] as 10 $/kWh for 5,6 kg H_2, which converts to 1350 €$_{2000}$ per storage system.

For the electromotor as well as for the batteries the starting point is the HyWays cost projection for the electromotor and batteries in 2013 at 1863 cumulative vehicles sold. They amount to 8187 € for the electromotor and 6331 € for the batteries. The fuel cell system produces a net maximum output of 80 kW in the HyWays study.

Table 3 lists all parameters used in the calculations, whereas progress, EOS (economies-of-scale) and power indices and their use are explained further below

Table 3: Basic input for calculations: Main input parameters are written in bold

	H_2-FC System	H_2 Storage	Electromotor	Battery
Power of reference system P_{Ref}	100 kW	100 kW	80 kW	80 kW
C_0	**1000 €$_{2000}$**	**1350 €$_{2000}$**	**8187 €$_{2000}$**	**6331 €$_{2000}$**
Progress index λ_P	0,32	0,24	0,15	0,15
Progress ratio L_P	**0,80**	**0,85**	**0,90**	**0,90**
EOS index λ_{EOS}	**0,19**	**0,19**	**n/a**	**n/a**
EOS Rate L_{EOS}	0,81	0,81	n/a	n/a
Power index λ_{SP} [1]	**0,71**	**0,25**	**0,6**	**0,71**

[1] See Chapter 3.4.3.4 for further explanation

3.4.3.2 Economies-of-Scale (EOS) Effects

As the input values for the fuel cell system and the hydrogen storage are given at annual production capacities of 500 000 units, they are, for both SOTA and 2020–2025 projections, adjusted for economies-of-scale appropriate to current (estimated) annual fuel cell system manufacturing capacities first to have a reasonable starting point. These numbers are 40 annually produced units for all cases except light duty trucks and passenger cars, where an annual production capacity of 250 is assumed.

In order to include EOS effects in the calculations of estimated drivetrain costs, the following coefficient has to be multiplied with the input costs of the fuel cell system and hydrogen storage respectively:

$$c_{EOS} = \left(\frac{PC_{Ref}}{PC_{assumed}} \right)^{\lambda_{EOS}}$$

c_{EOS}	…	Economies-of-scale coefficient
$PC_{assumed}$	…	Assumed annual production capacity of fuel cell drivetrains for the considered application
PC_{Ref}	…	Annual production capacity of fuel cell drivetrains (for the considered application) underlying the reference cost value
$\lambda_{EOS} = 1 - L_{EOS}$	…	Economies of scale index reflecting the EOS rate L_{EOS}

The scale function follows a power law. Its exponent λ is derived from data provided by the DOE [13] and is found to be 0,19 (i.e. a progress rate of 81%) for fuel cell systems. We assume that the economies of scale effects for hydrogen storage will be similar and therefore use the same scale exponent.

Figure 8 illustrates economies-of-scale effects on the cost of fuel cell systems (storage, motor and battery not included) per kW_e as well as different levels of system powers (explained further below) and how this affects the cost. The fuel cell system cost provided by NREL for 2006 [10] at an annual production capacity of 500 000 units was used as basis and is also reflected in the graph.

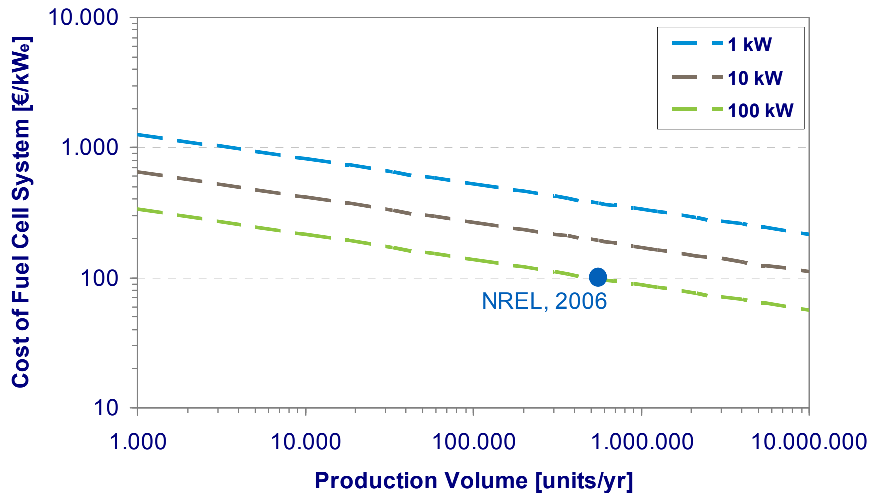


Figure 8: Economies of scale effects on drivetrain costs

3.4.3.3 *Lifetime of Fuel Cells System*

As there isn't any (available) long-term experience on fuel cell system behaviour, replacement of the whole fuel cell system or stack before the end of the lifetime of the application might be necessary due to degradation. Depending on the considered situation, an additional coefficient needs to be multiplied with the input cost value for the fuel cell system (only!):

- Lifetime of the FC System is equal to or higher than the lifetime of the application:

$$c_{LT} = 1$$

- Lifetime of the FC System is a fraction of the applications' lifetime; the whole system needs replacement:

$$c_{LT} = \frac{t_{App}}{t_{App} \cdot f_{FC}}$$

- Lifetime of the FC System is a fraction of the applications' lifetime; only stack needs replacement:

$$c_{LT} = \frac{t_{App}}{t_{App} \cdot f_{FC}} \cdot f_{stack} + (1 - f_{stack})$$

c_{LT}	…	Lifetime-coefficient	[€/kWe]
t_{App}	…	Lifetime of the application	[years]
f_{FC}	…	FC system's lifetime as fraction of the application's lifetime	
f_{stack}	…	Cost of the FC stack as fraction of total FC system cost	[years]

3.4.3.4 *Influence of System Power*

This coefficient follows the same scheme for all components and reflects that the component's costs do not scale linearly with the system power:

$$c_{SP} = \left(\frac{P_{DT}}{P_{Ref}} \right)^{\lambda_{SP}}$$

c_{SP}	…	System power coefficient	
P_{DT}	…	Power of the fuel cell drivetrain of the considered application	[kW]
P_{Ref}	…	Power of the fuel cell drivetrain (of the considered application) underlying the reference cost value	[kW]
λ_{SP}	…	System power index reflecting cost changes for hydrogen storage, the electromotor or the battery at different FC system capacities.	

The system power index λ_{SP} for the battery is chosen to be the same value as for the FC system (0,71 – see TIAX study [10], which was also used for WT4.4) since this is also an electrochemical process. For the electromotor it is chosen to be 0,6. In case of the hydrogen storage the value is small since 2 effects are combined; the storage volume for transportation systems with small fuel cell sizes like the license-free car does not scale with the fuel cell size due to the much higher load factor for this fuel cell compared to passenger cars. For a similar driving time between refuelling, the size of the hydrogen storage tank for the license-free car is about one third the size of the tank for the passenger car, whereas the fuel cell is a factor 20 smaller. Together with a size factor for the tank of 0,67 this combines to an exponent of 0,25 when the cost of the hydrogen storage is related to the fuel cell system power.

3.4.3.5 Progress (Future) Effects

In case of comparing future (2020-2025) reference technology to future fuel cell technology, the drivetrain costs are further reduced due to progress. Progress includes all effects that occur when the technology is being developed, for example learning curve effects such as learning by searching (i.e. research activities) and learning by doing as well as cost reductions due to scale-up of production.

Assumptions of **future reference technologies** involved have already been adjusted before using them as input. For example: The investment costs for internal combustion engines running on conventional fuels, which are used as input to calculate the “Windows of Opportunities” have been adjusted (regarding an assumed future situation) previously to any calculation.

In the case of estimating the cost of **future fuel cell technology**, the following coefficient is multiplied with the evaluated SOTA costs of the drivetrain parts:

$$c_P = \left(\frac{CP_{DT}}{CP_{Ref}} \right)^{-\lambda_P}$$

c_P	…	progress coefficient reflecting future situation
CP_{DT}	…	Cumulative production of fuel cell drivetrains for the considered application
CP_{Ref}	…	Assumed cumulative production of fuel cell drivetrains (for the considered application) underlying the reference cost (starting point)
$\lambda_P = -\frac{\ln(L_P)}{\ln(2)}$	…	Progress index reflecting the progress ratio $L_P = 2^{-\lambda_P}$

The progress ratios for all components are derived from the HyWays roadmap [11] (ratios reflect fast learning, initial phase) and are summarised in Table 3. By definition, progress ratios reflect the fraction to which the manufacturing cost of one unit is reduced when the cumulative number of units produced doubles.

To calculate cumulative production of H_2-FC drivetrains for the considered application (CP_{DT}), first annual manufacturing capacities equal to 1% and 10% of the total annual sales of new applications is assumed. This is also called market share, market penetration or sales penetration of the H_2-FC technology in a certain field of application (e.g. passenger cars). It should not be confused with fleet penetrations!

All H_2-FC units being produced are assumed to be sold.

For each assumed annual production capacity, the cumulative number of units produced (CP_{DT}) is derived by applying the HyWays “high policy support, fast learning" penetration scheme for passenger cars [3] to all considered fields of applications (see Table 4). The size of the European fleet for each application is estimated to the number of units sold per year times the lifetime of the vehicle. This is used to calculate the size of the fuel cell vehicle fleet for each application for each year, i.e. applying the percentaged HyWays penetration curve. By accounting for exchange of vehicles at the end of their lifetime, the cumulative number of units produced is calculated for each year. Hence, the annual production capacity necessary to reach this cumulative number can be simply calculated by subtracting the cumulative number in Year x-1 from the cumulative number in Year x. The annual production capacity is plotted against the cumulative number to exclude direct time-dependency and a polynomial function fitted for interpolation.

The cumulative number CP_{Ref} of fuel cell systems and hydrogen storage underlying the reference cost values C_0 is estimated to approximately 300 for light duty trucks, 700 for passenger cars and 40 units for all other applications. In the case of Aircraft Tow Trucks, only the "10%" value is meaningful, whereas for sightseeing boats, no future projections can be made. In both cases the small market sizes are responsible.

The cumulative number CP_{Ref} of electromotors and batteries underlying the reference cost values C_0 taken from HyWays is approximately 2 000. For all FC drivetrain components, if the estimated cumulative number CP_{DT} is smaller than CP_{Ref}, the progress coefficient would become bigger than 1, thus reflecting negative progress, which is irrational for future situations. Consequently, SOTA cost values were taken for the affected components and cases.

Table 4: Annual production capacities and corresponding cumulative production – all values are just approximations

	Annual Production Capacity (% of annual sales)	Cumulative number of units produced
Urban (city) buses	100 (1%)	150 - 200
	1 000 (10%)	3 500 - 4500
Passenger Cars	150 000 (1%)	220 000 – 230 000
	1 500 000 (10%)	5 000 000 – 5 200 000
Light Duty Trucks	20 000 (1%)	30 000 – 35 000
	200 000 (10%)	650 000 – 700 000
License-Free Cars	350 (1%)	600 – 700
	3 500 (10%)	13 000 – 14 000
Outdoor Utility Vehicle	200 (1%)	300 – 400
	2 000 (10%)	7 500 – 8 000
Scooter	14 000 (1%)	17 000 – 18 000
	140 000 (10%)	700 000 – 750 000
Forklifts	1 600 (1%)	2 000 – 2 500
	16 000 (10%)	80 000 – 85 000
Aircraft Tow Trucks	8 (10%)	40 - 50

3.5 CO_2 emissions

For environmental comparison of different applications a common basis for the CO_2 emissions for the fuel use of the reference technology as well as for the hydrogen use for different pathways is established and described in Appendix B:. The basis for the emission factors are the Concawe study [2], the HyWays results [3] and the information on the CO_2 emission factors for the electricity network in different countries [4] [5].

Table 5 provides the source-to-user emission factors for conventional fuels and H_2 from different sources, all used in the analysis. Furthermore, it provides a mean of taxing CO_2 emissions based on an assumed CO_2 tax of 50 €/ton CO_2 emitted.

Table 5: Source-to-user emission factors for conventional fuels and H_2

Conventional fuel	Mean [kg CO_2/GJ]	CO_2 tax [€/GJ]
Diesel	87	4,35
Gasoline	85	4,25
Natural gas	63	3,15
Electricity EU-25	119	5,95
Source for gaseous H_2		
Onsite steam methane reforming	110	5,5
Waste wood gasification	13	0,65
Offshore wind electricity+ electrolysis	11	0,55
Coal gasification + CCS	45	2,25
Electricity EU-25 + electrolysis	156	7,8

As the **projected** price of hydrogen at the filling station of 68 €/GJ (Figure 9) is based on the HyWays production mix (large scale), which includes various sources with different CO_2 emission factors (see Figure 26), Table 5 does in this case not provide the means for CO_2 taxation. The HyWays production mix includes a CO_2 emissions factor of 56 g CO_2/MJ, which means that, based on a CO_2 tax of 50€/ton, 2,8 €/GJ have to be added to reflect CO_2 taxation. To illustrate a taxation of 100€/ton CO_2 emitted, 5,6 €/GJ have to be added.

4. Results

This study includes many uncertainties about details such as input values and progress ratios. Therefore it should be considered as first-order analysis only. Results shown are not intended to make a positive business case or bring a full stop to one, but rather aim to give an indication about the potential of fuel cell/hydrogen technologies to be used in different applications. Highly potential applications deserve a much more in-depth evaluation of their full economic and environmental possibilities. This report is meant to guide in choosing applications and the right starting points for further research.

First, some general remarks on the different case studies are made in order to characterise these applications.

Second, the cost of hydrogen produced via different pathways are given and commented.

Third, different cases for transport and stationary applications are shown and evaluated.

The last sub-chapter on results investigates effects on CO_2 emissions by replacing reference with FC/H_2 technology.

4.1 General

In this chapter, Table 6, Table 7 and Table 8 provide an overview of input parameters used for all applications in the analysis, either taken from the case studies or adapted from literature.

Table 6: Specifications of reference applications; energy uses of 2020 passenger car, bus and light truck have been adapted by applying data from [14]

Field of Application (Engine/Fuel)	Power Reference Technology	Energy use	Operational use	Lifetime
	kW	MJ/unit	unit/yr	yr
Passenger Car (SOTA ICE-Diesel)	80	1,95 MJ/km	20 000 - 40 000 km/yr	15
Passenger Car (SOTA ICE-Gasoline)		2,02 MJ/km	10 000 - 20 000 km/yr	
Passenger Car (2020 ICE-Diesel)		1,56 MJ/km	20 000 - 40 000 km/yr	
Passenger Car (2020 ICE-Gasoline)		1,67 MJ/km	10 000 - 20 000 km/yr	
Bus (SOTA ICE-Diesel)	220	12,20 MJ/km	50 000 - 60 000 km/yr	15
Bus (SOTA Diesel Hybrid)		10,70 MJ/km		
Bus (2020 ICE-Diesel)		9,76 MJ/km	50 000 - 60 000 km/yr	15
Bus (2020 Diesel Hybrid)		8,99 MJ/km		
Light Truck (SOTA ICE-Diesel)	95	2,05 MJ/km	50 000 - 75 000 km/yr	15
Light Truck (SOTA Diesel Hybrid)		1,80 MJ/km		
Light Truck (2020 ICE-Diesel)		1,64 MJ/km	50 000 - 75 000 km/yr	15
Light Truck (2020 Diesel Hybrid)		1,51 MJ/km		
Licence-free Vehicle	4	1,06 MJ/km	5000 - 15 000 km/yr	15
Outdoor Utility Vehicle (ICE-Diesel)	4	1,24 MJ/km	5000 - 10 000 km/yr	15
Outdoor Utility Vehicle (Electric)		0,31 MJ/km		
Scooter (ICE-Gasoline)	7	0,81 MJ/km	5000 - 10 000 km/yr	10
Scooter (Electric)		0,2 MJ/km		
Forklift (ICE-Diesel)	45	13 MJ/km	10 000 km/yr	10
Forklift (ICE-LPG)	39	13 MJ/km		
Forklift (Electric 8/5)	20	2 MJ/km		
Forklift (Electric 24/5)		2 MJ/km	30 000 km/yr	
Aircraft Tow Truck (ICE-Diesel)	75	80 MJ/hr	1400 - 2800 hr/yr	10
Aircraft Tow Truck (Electric)		10 MJ/hr		
Sightseeing Boat (ICE-Diesel)	67	61 MJ/hr	959 - 1900 hr/yr	10
Sightseeing Boat (Electric)	16	14,9 MJ/hr		
Truck APU (ICE-Diesel)	200	149,4 MJ/hr	500 hr/yr	10
Pleasure Boat APU (ICE-Diesel)	2	2,25 MJ/hr	720 hr/yr	
Mega-Yacht APU (ICE-Diesel)	500	4885 MJ/hr	3000 hr/yr	12
Back-up Telecom (Electric)	1,1	4 MJ/kWh	56 hr/yr	10
Back-up Hospitals (ICE-Diesel)	200	10,5 MJ/kWh	56 hr/yr	15
Industrial CHP (Natural Gas)	250	9 MJ/kWh	8760 hr/yr	5
Residential CHP (Boiler)		n.a.	n a	15

Table 7: Specifications of reference applications; engine investment costs for 2020 passenger car, bus and light truck have been adapted by applying data from [14]

Field of Application (Engine/Fuel)	Number of Units in total	Market Size in units sold per year	Engine Investment cost	Maintenance cost
			€/kW	€/unit
Passenger Car (SOTA ICE-Diesel)	231 000 000	15 040 000	45,6	0,03 €/km
Passenger Car (SOTA ICE-Gasoline)			35,0	0,02 €/km
Passenger Car (2020 ICE-Diesel)			52,5	0,03 €/km
Passenger Car (2020 ICE-Gasoline)			51,9	0,02 €/km
Bus (SOTA ICE-Diesel)	600 000	40 000	45,6	0,07 €/km
Bus (SOTA Diesel Hybrid)			66,0	0,09 €/km
Bus (2020 ICE-Diesel)	600 000	40 000	52,5	0,07 €/km
Bus (2020 Diesel Hybrid)			63,1	0,09 €/km
Light Truck (SOTA ICE-Diesel)	30 000 000	2 000 000	45,6	0,07 €/km
Light Truck (SOTA Diesel Hybrid)			66,0	0,09 €/km
Light Truck (2020 ICE-Diesel)	30 000 000	2 000 000	52,5	0,07 €/km
Light Truck (2020 Diesel Hybrid)			63,1	0,09 €/km
Licence-free Vehicle	525 000	35 000	500	0,07 €/km
Outdoor Utility Vehicle (ICE-Diesel)	300 000	20 000	500	0,07 €/km
Outdoor Utility Vehicle (Electric)			2250	
Scooter (ICE-Gasoline)	14 000 000	1 400 000	70	0,02 €/km
Scooter (Electric)			400	0,01 €/km
Forklift (ICE-Diesel)	1 620 000	164 000	80	0,12 €/km
Forklift (ICE-LPG)			85	
Forklift (Electric 8/5)	2 430 000		600	0,7 €/km
Forklift (Electric 24/5)			1000	
Aircraft Tow Truck (ICE-Diesel)	1250	80	100 - 200	0,71 - 2,14 €/hr
Aircraft Tow Truck (Electric)			190,7	
Sightseeing Boat (ICE-Diesel)	500	30	257	1,79 - 2,56 €/hr
Sightseeing Boat (Electric)			1500	1,64 - 1,74 €/hr
Truck APU (ICE-Diesel)	100 000			0,08 €/hr
Pleasure Boat APU (ICE-Diesel)	50 000		500	0,50 €/hr
Mega-Yacht APU (ICE-Diesel)	50		400	2,44 €/hr
Back-up Telecom (Electric)	417 000		1837	476 €/yr
Back-up Hospitals (ICE-Diesel)	14 900		278	475 €/yr
Industrial CHP (Natural Gas)	440 000		633	0,0055 €/kWh
Residential CHP (Boiler)	90 000 000		n.a.	

Table 8: Specifications of the considered fuel cell/hydrogen systems

(Field) of Application	FC/H2 Technology	Power FC/H2 Technology	H_2 use or fuel	Maintenance cost
		kW	MJ/unit	€/unit
Passenger Car	PEMFC	80	0,84 MJ/km	0,01 €/km
	H2-ICE	80	1,68 MJ/km	0,02 €/km
Bus	PEMFC	220	5,86 MJ/km	0,02 €/km
	H2-ICE	220	12,2 MJ/km	0,04 €/km
Light Truck	PEMFC	95	1 MJ/km	0,02 €/km
Licence-free Vehicle	PEMFC	4	0,6 MJ/km	0,04 - 0,05 €/km
Outdoor Utility Vehicle	PEMFC	4	0,6 MJ/km	0,06 €/km
Scooter	PEMFC	5	0,4 MJ/km	0,01 €/km
Forklift	PEMFC	20 - 45	4 - 7 MJ/km	0,05 - 0,06 €/km
Aircraft Towing Vehicle	PEMFC	75	18,5 MJ/hr	0,71 - 1,43 €/hr
Sightseeing Boat	PEMFC	16	30 MJ/hr	1,03 - 1,74 €/hr
Truck APU	PEMFC	5	10 MJ/km	0,04 €/hr
Pleasure Boat APU	DMFC	0,063	Methanol	
Mega-Yacht APU	reforming + PEMFC	500	Methanol	2,00 €/hr
Back-up Telecom	PEMFC	1,100	9 MJ/kWh	476 €/yr
Back-up Hospitals	PEMFC	200	7,2 MJ/kWh	475 €/yr
Industrial CHP	reforming + PEMFC	200	Natural Gas	0,0055 €/kWh
	MCFC			
	SOFC + GT			
Residential CHP	SOFC	1	Natural Gas	250 €/kWh

Maintenance costs for FC/H_2 drivetrains in buses and light trucks have been adjusted: The ratio between maintenance costs for passenger cars equipped with an ICE running on diesel (0,03 €/km) and maintenance costs for passenger cars equipped with H_2-FC/H_2-ICE (0,01 and 0,018 €/km) drivetrains is applied to the m aintenance costs for a bus or light truck with an ICE running on diesel (0,07 €/km). All used maintenance costs were taken from the case studies

4.2 Hydrogen Cost

The costs of hydrogen for different large-scale production pathways as shown in Figure 9 are mainly based on the results of the WT4.3 study [7]. The costs for by-product hydrogen and hydrogen produced by solar high temperature processes is assumed at 20 €/GJ and 50 €/GJ respectively. Furthermore, the HyWays study estimated the contribution of different hydrogen production processes to the total production for different years (see Table 9), which is used to calculate the projected average hydrogen cost for the EU at 68 €/GJ (about 8,2 €/kg) in 2030 used in analyses in this report.

In order to evaluate the "pump price" of hydrogen at the refuelling station, distribution costs of 6,7 €/GJ from central production facilities (see WT4.3 [7]), forecourt costs of 10 €/GJ (based on a study by Shell [12]) and VAT of 19% (EU average) are added to the production costs.

Hydrogen production via electrolysis with grid or wind electricity is only performed on-site, which means that no distribution costs are added. In the case of hydrogen production via SMR of NG, 25% on-site production is assumed, leading to a 25% reduction in distribution costs. All other processes are performed centrally.

Table 9: H_2 production mix from the member state input in the HyWays project

HyWays	2020	2030	2040	2050
By-product	28%	4%	2%	1%
Coal and CCS	3%	25%	16%	13%
Natural Gas	34%	26%	31%	26%
Nuclear Heat	0%	4%	15%	31%
Grid Electricity	3%	7%	5%	3%
Wind Electricity	10%	9%	8%	8%
Biomass	21%	18%	16%	13%
Solar Heat	0%	7%	7%	5%
Total	**100%**	**100%**	**100%**	**100%**

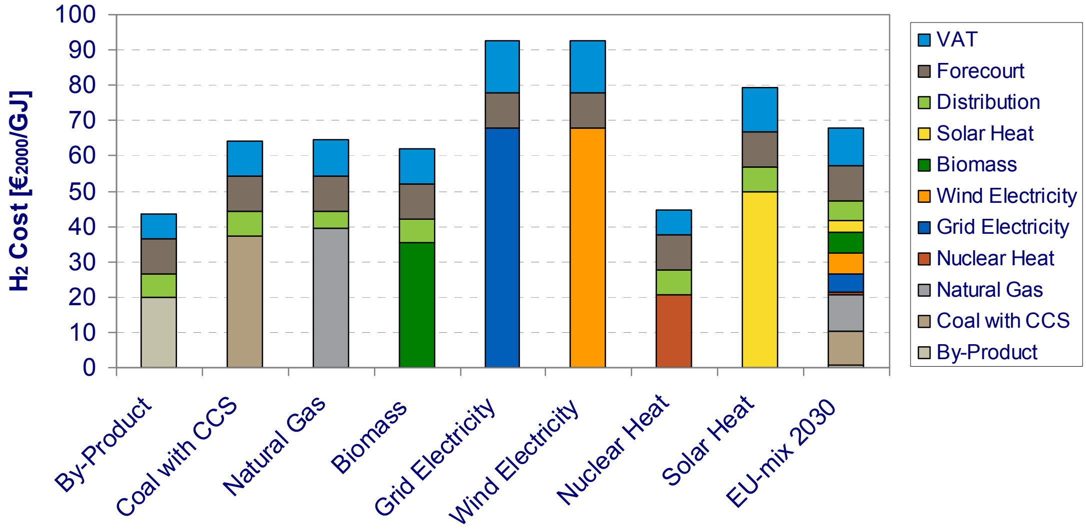


Figure 9: Cost of hydrogen (€$_{2000}$/GJ) from different sources using WT4.3 and HyWays production mix for 2030 from member state review

Based on the cost projections shown in Figure 9, by-product hydrogen will probably meet a big part of the initially hydrogen demand as it is comparably cheap. As demand grows, by-product hydrogen has to be replaced by other means of hydrogen production. From the cost figures it can be expected that SMR of NG and coal gasification with CCS technology will play a major role.

For comparison: According to the used assumptions and today's prices of NG and electricity (mean 2007) of 12,1 and 30.1 €/GJ respectively, the cost of hydrogen produced via SMR is 51,8 €/GJ.

Due to its low GHG emissions and competitive production costs at approximately 35 €/GJ, hydrogen from biomass gasification may become an important option too. Nuclear and solar heat, although much lower in cost or environmental impact respectively, are only a long-term option due to their early technological stage of development.

4.3 Cost of Applications

The first part of WT4.5 – the case studies provided in report R2H4008PU – give information about selected FC/H_2 applications including the Windows of Opportunities and corresponding specifications. This information can be used to:

- Analyse the position of FC/H_2 drivetrain costs (known or targeted) relative to the cost of the reference technology at discrete hydrogen cost,

- Evaluate differences in cost per unit service of FC/H_2 systems to reference technologies at discrete hydrogen costs in order to identify priorities for further developments,

- Identify the allowable hydrogen cost at SOTA/targeted costs of FC/H_2 technologies that would lead to a positive business case (purely based on cost-competitiveness).

The next sub-chapters will evaluate the opportunities of FC/H_2 technology in certain applications for different combinations of parameters and provide comparisons and conclusions.

4.3.1 Transport Applications

4.3.1.1 Hydrogen Internal Combustion Engines vs. Hydrogen Fuel Cells

Using passenger cars at different annual mileages, the Windows of Opportunities for cars using an internal combustion engine running on hydrogen or hydrogen fuel cells are shown in Figure 10 and Figure 11. It can be observed that in case of the H_2-ICE the Windows of Opportunity are much smaller. This is caused by the lower efficiency (see Chapter 3.4.2.3) of the H_2-ICE drivetrain compared to the H_2-FC and thus leads to lower allowable hydrogen costs.

In urban operation, it is expected that the efficiency of H_2-ICE drivetrains will stay significantly below that of the H_2-FC drivetrains, due to higher losses in direct conversion of chemically bound energy into mechanical work (especially in transient operation). Although an interesting technology for some applications, H_2-ICE technology is not further considered in the cost analysis.

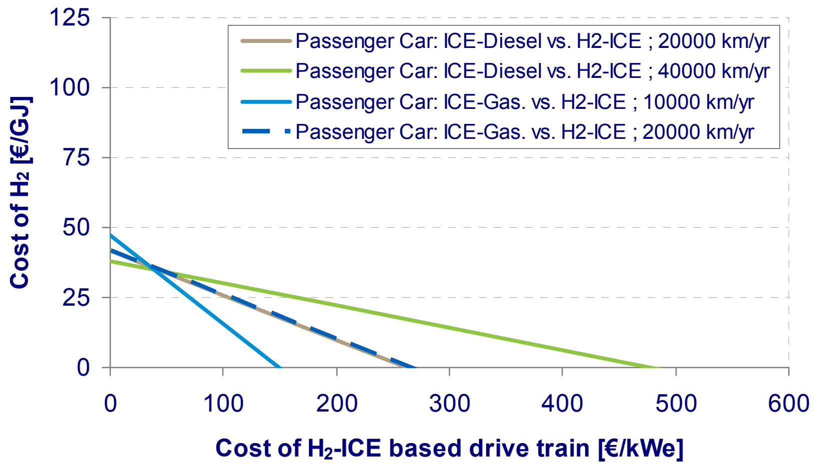


Figure 10: Windows of Opportunity for passenger cars using a H2-ICE based drive train.

Considered reference technologies are internal combustion engines running on either diesel or gasoline for different annual mileage (km)

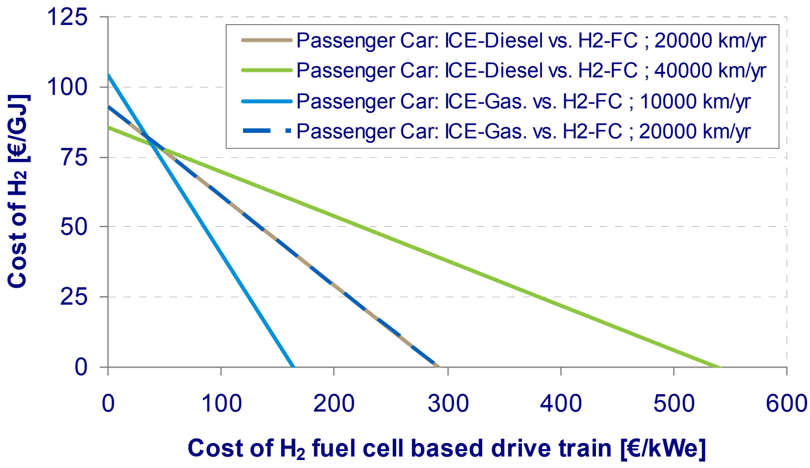


Figure 11: Windows of Opportunity for passenger cars using a H2-FC based drive train.

Considered reference technologies are internal combustion engines running on either diesel or gasoline for different annual mileage (km)

4.3.1.2 H_2-FC Passenger Cars

The analysis of different cases for passenger cars gives insights into the complexity of projections and its manifold influencing factors. This sub-chapter is intended to illustrate the development of state-of-the-art into future technologies taking stricter policies and increasing fuel prices into account. All specifications of the considered reference and fuel cell technologies, if not stated differently in the explanations below, are provided in Chapter 2 of the Case Studies Report (R2H4008PU).

To compare different cases, both the Windows of Opportunity and data points illustrating specific situations are evaluated and plotted against each other. The data points reflect costs of SOTA (economies of scale adjusted) or future (different cumulative production levels) H_2-FC drivetrains.

To calculate the cumulative number of vehicles sold, the total number of passenger cars annually sold in Europe has been estimated to approximately 15 million units (see Chapter 2 in report R2H4008PU).

Except where a taxation of CO_2 or SOTA SMR production is assumed, the price of hydrogen is **projected** at 68 €/GJ (see Chapter 4.2) for large scale production for all cases. It should be noted that the price for hydrogen might also decrease with increasing demand due to higher utilisation of the infrastructure, which is not taken into account in these projections.

Figure 12 compares SOTA reference technologies to SOTA fuel cell technology. The used specifications can be found in Table 6, Table 7 and Table 8. Both 50% and 100% lifetime (yet to be proven) have been assumed for the fuel cell system. If the lifetime is only 50% the lifetime of the application, additional stack costs lead to an increase in the total drivetrain cost of approximately 40%.

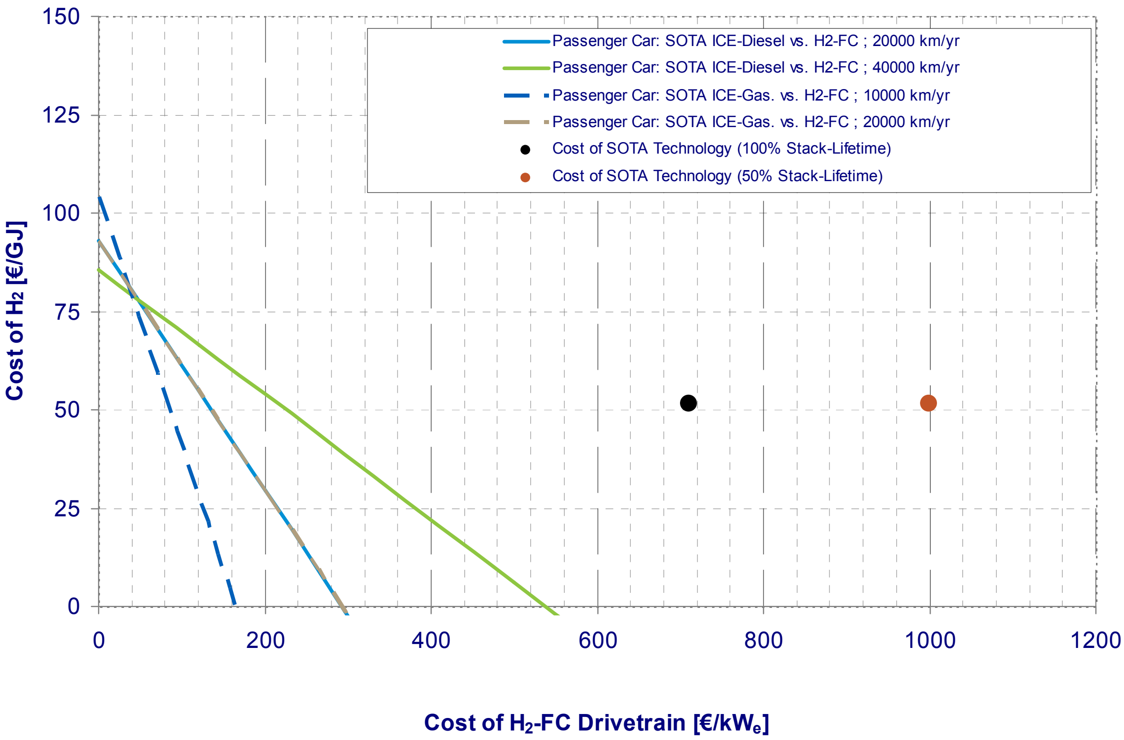


Figure 12: Windows of Opportunity for passenger cars based on SOTA technologies and 2007 prices and policies

The data points reflect the cost of SOTA H2-FC drivetrains for both 50% and 100% stack-lifetime. The cost of hydrogen reflects production from NG (mean 2007 cost) via SMR.

Figure 13 shows that the target, i.e. the Windows of Opportunity, is moving over time as stricter emission policies lead to higher efficiencies of the reference technologies but at the same time disproportionately higher engine costs for e.g. advanced filters (see Table 6 and Table 7). The change is also caused by higher costs of fossil fuels (see Appendix A:). In the case of passenger cars this leads to higher cost-competitiveness for fuel cell technologies.

The current cost value for SOTA FC technology (100% stack-lifetime) is again shown in the plot. To complete the picture we estimate the cost of future (2020-2025) H_2-FC technology at production capacities of 1% and 10% of the total annual sales of passenger cars. These values are plotted against the hydrogen cost reflecting the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030.

Already at a production capacity of 1% of annual passenger car sales (i.e. ~150 000 cars), fuel cell passenger cars could be cost-competitive to passenger cars running on diesel at an annual mileage of 40 000 km. At a production capacity of 10% of the total annual passenger car sales, FC passenger cars could cost less per unit service than all shown reference cases.

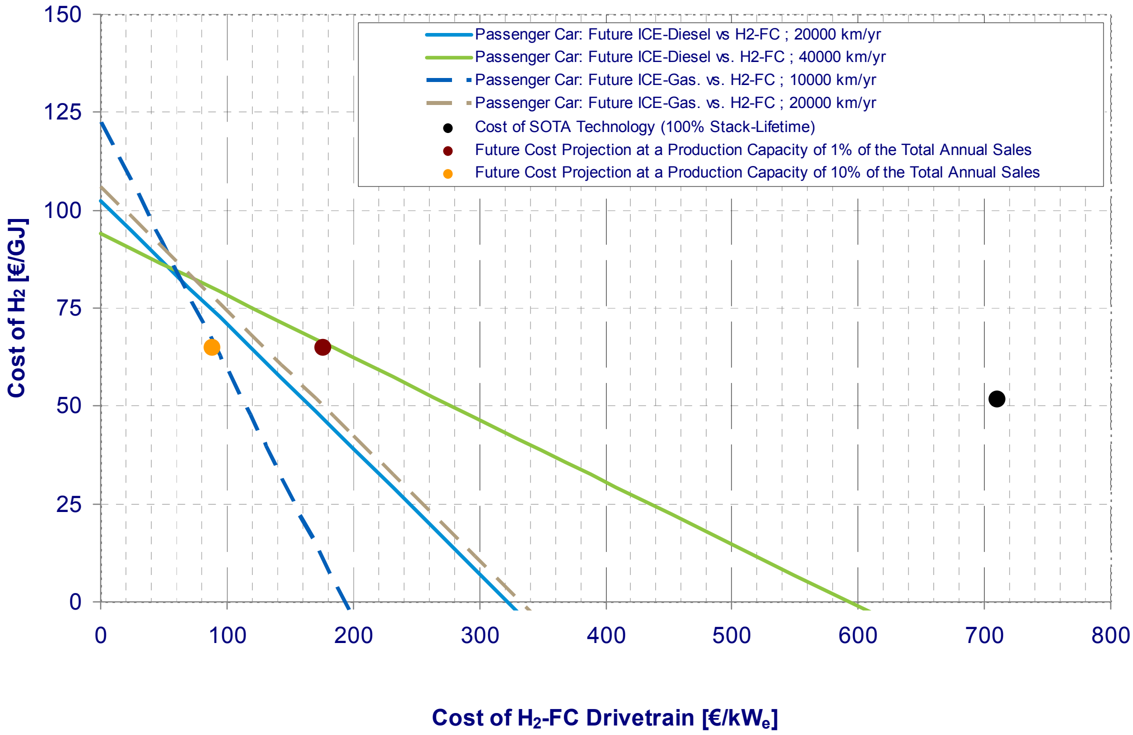


Figure 13: Windows of Opportunity for passenger cars based on SOTA FC and 2020 ICE technology, prices and policies

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030

With stricter policies one might expect an additional taxation of CO_2 emissions. Therefore, Figure 14 and Figure 15 show the effect on both the cost of fossil fuels and hydrogen if a CO_2 tax of 50 €/ton or 100 €/ton respectively was constituted (note that, for the fossil fuels, this tax is additional to existing European fuel taxation). The assumed CO_2 emission factors (see Chapter 3.5) lead to a higher increase in the total costs per unit service for the reference technology than for the hydrogen technology. Thus hydrogen fuel cell technologies' opportunities are raised further.

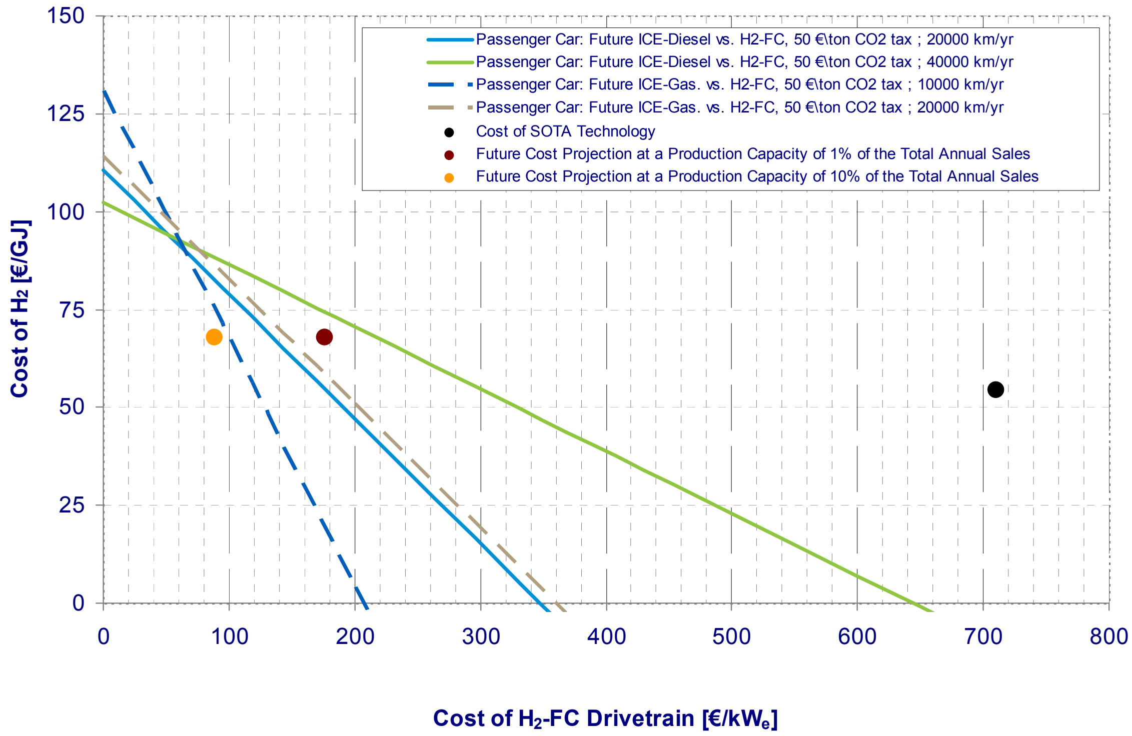


Figure 14: Windows of Opportunity for passenger cars based on SOTA FC technology and 2020 ICE technology, prices and policies including a CO_2 tax of 50 €/ton

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR plus 2,8 €/GJ CO_2 tax. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales of passenger cars. The hydrogen cost reflects the projected average for the EU at 68 €/GJ plus 2,8 €/GJ CO_2 tax in 2030.

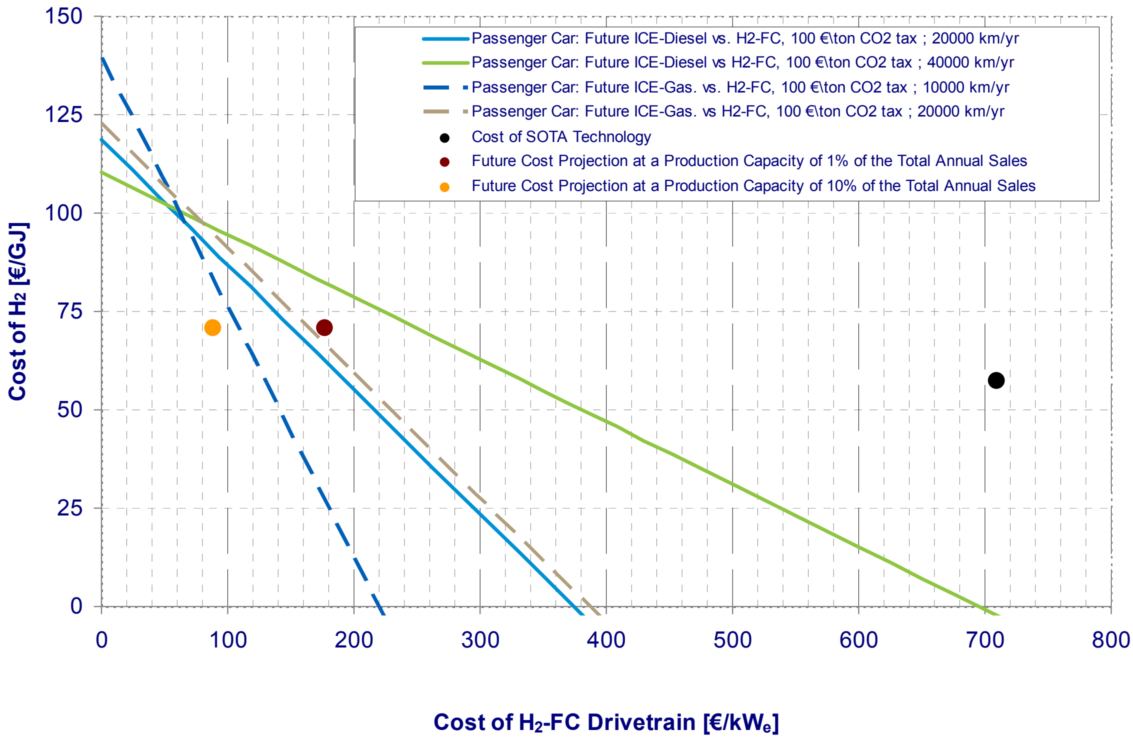


Figure 15: Windows of Opportunity for passenger cars based on SOTA FC technology and 2020 ICE technology, prices and policies including a CO_2 tax of 100 €/ton

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR plus 5,6 €/GJ CO_2 tax. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales of passenger cars. The hydrogen cost reflects the projected average for the EU at 68 €/GJ plus 5,6 €/GJ CO_2 tax in 2030.

4.3.1.3 H_2-FC Light Duty Trucks and Urban (City) Buses

In this chapter, opportunities for both SOTA and assumed future (2020 - 2025) fuel cell drivetrains in light duty truck and urban (city) bus applications are analysed. Annual production capacities of 1% and 10% of annual sales of the specific application are assumed for the calculations (see Chapter 3.4.3). The total number of light duty trucks and city buses sold in Europe per year has been estimated to approximately 2 million and 10 000 units respectively (city buses estimated at 25% of all buses in Europe) (see also the Case Studies Report R2H4008PU).

Light Duty Trucks

Figure 16 illustrates that both SOTA and future hydrogen fuel cell based drivetrains show high economic potential to be used in light duty trucks. Purely based on economics, already SOTA technology could be competitive to ICE running on diesel and diesel-hybrids at an annual mileage of 75 000 km. Future

(2020-2025) hydrogen fuel cell based drivetrains could even become cheaper than all shown reference cases (compared on a cost per unit service basis).

Developments in ICE technologies, which become necessary due to stricter emission policies lead to a significant increase in engine investment costs, which are not balanced out by their higher efficiency. This is amplified by higher costs of conventional fuels by 2020 – 2025 and reflected by the Windows of Opportunities in Figure 16.

At the same time the additional costs for hybrid drivetrains will have decreased to 20%, which is also not balanced out by the increase in efficiency of 16%.

Consequently, as hydrogen fuel cell drivetrains have a much higher efficiency and learning curve effects will have lead to a significant reduction in their cost, they might build an attractive business case for light duty trucks.

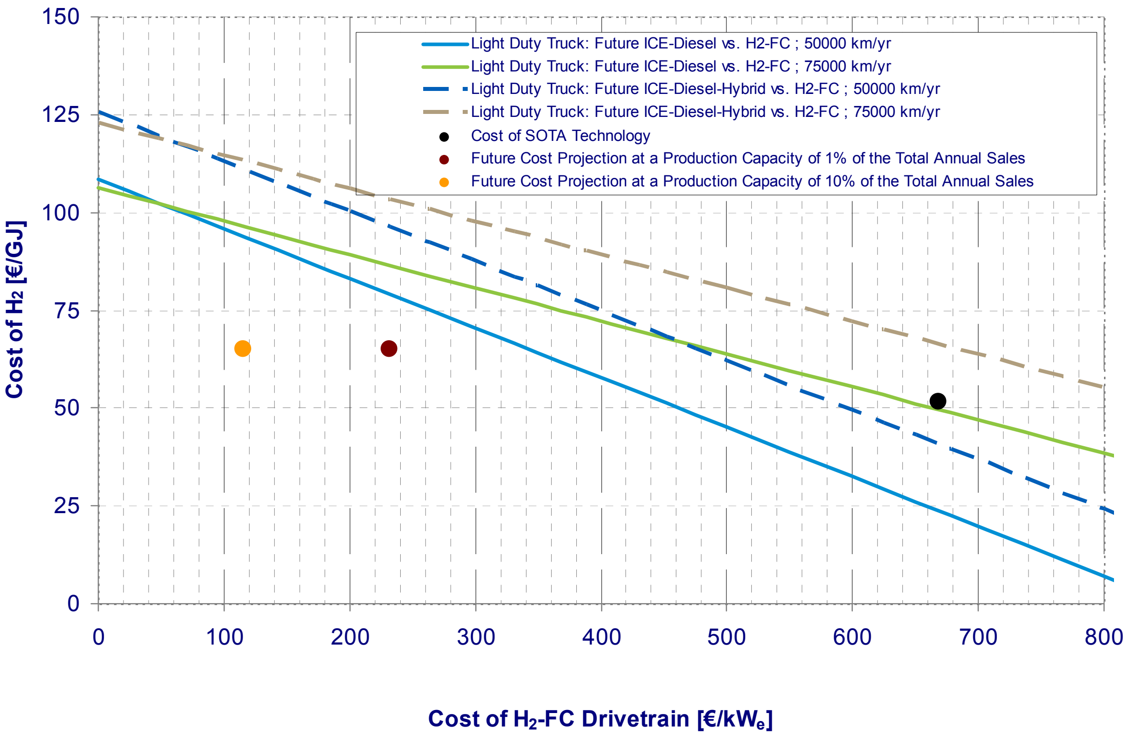


Figure 16: Windows of Opportunity for light duty trucks based on SOTA FC and 2020 ICE technology, prices and policies.

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030.

City Buses

Figure 17 shows projections of the present and future economic situations for urban fuel cell buses. In the case of an annual production capacity of 10% of all annual city bus sales in Europe (accounting for 1000 units per year) and considering projected future technology, prices and policies, a price of hydrogen of approximately 55 €/GJ, purely based on economics, would enable competitiveness for hydrogen fuel cell technologies in city buses. In the current analyses, projected hydrogen cost without forecourt cost and VAT amount to less than 50 €/GJ (see Figure 9).

High fuel consumption due to necessary big engines in combination with high annual mileage is significant. Consequently this leads to a bigger impact of fuel costs on the cost per unit service than investment or maintenance costs.

In the case of the urban bus, other considerations such as air quality, and the political desire for a low carbon energy chain in public transportation, could prove sufficient to tip the business case to a more favourable one.

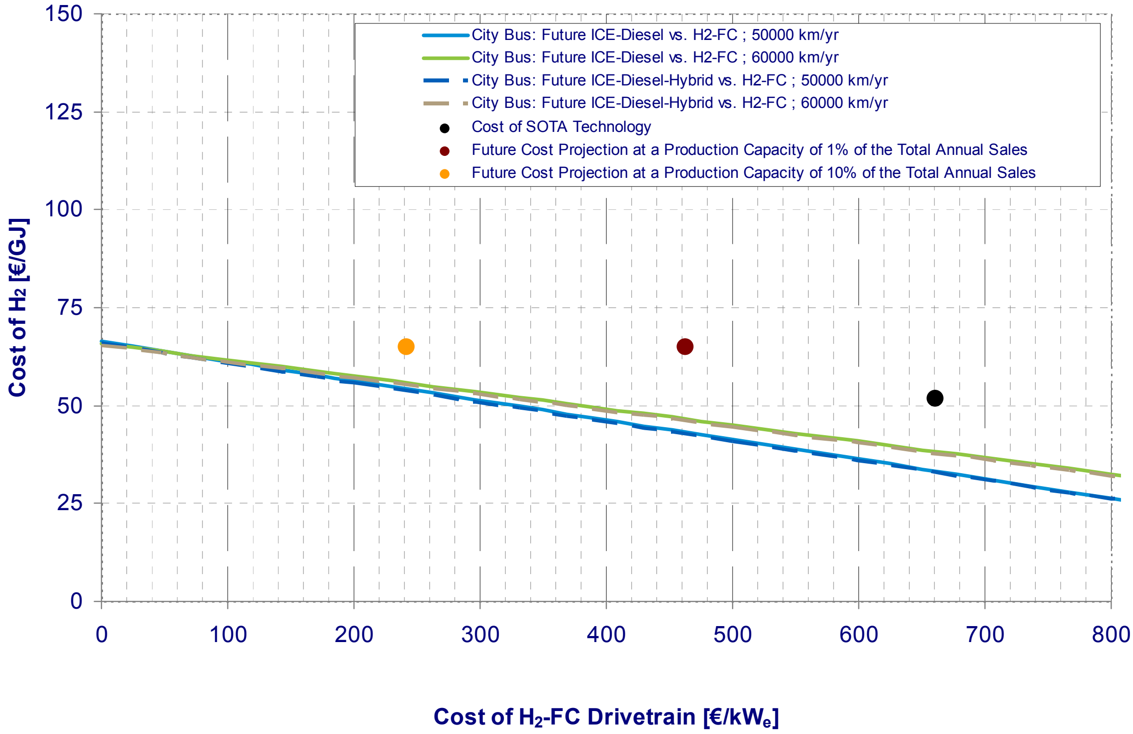


Figure 17: Windows of Opportunity for city buses based on SOTA FC and 2020 ICE technology, prices and policies

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030.

4.3.1.4 Other potential H_2-FC Applications

To identify market opportunities of SOTA and future H_2-FC technologies, all transport applications are analyzed using the same methodology as for the passenger car cases (Chapter 4.3.1.2), except that for the reference technologies no future projections have been made. Hence, the Windows of Opportunity are evaluated based on SOTA technologies only, whereas drivetrain costs are both evaluated for SOTA and projected for 2020-2025 FC technology. Production capacities of 1% and 10% of annual sales in the specific field of application are assumed for the future projections.

Five fields of applications have been identified to be most promising besides passenger cars and light duty trucks:

- Forklifts
- Sightseeing Boats
- Outdoor Utility Vehicles
- Scooter
- License-free Cars

Except for scooters, all cases incorporate relatively high reference engine costs due to low production volumes. This leads to bigger windows of opportunity for H_2-FC technologies.

Considering the cases, where electrical reference technologies are involved, the H_2-FC drivetrain only differs from the electrical drivetrain by its hydrogen storage, smaller battery and fuel cell system. The electromotor used in both drivetrain technologies will be the same. Hence, an increase in the sales of either H_2-FC or electrical drivetrains will lead to reduced costs of the electromotor for both technologies. This is different than in the case of internal combustion engines, for which costs will increase almost certainly, leading to bigger windows of opportunities for H_2-FC drivetrains that, on their side, will become cheaper in the future.

Although using batteries for storage of electrical energy is more efficient than using hydrogen with a fuel cell, the limited range of applications using batteries can lead to a positive business case for hydrogen fuel cells as a range extender. This is illustrated in Figure 18, which shows an increase in the range of electrical forklifts above their battery capacity's limitation by going from 8/5 to 24/5 operation. In this case, batteries have to be exchanged and recharged separately. Using hydrogen fuel cells instead would lead to reduction of the cost per unit service.

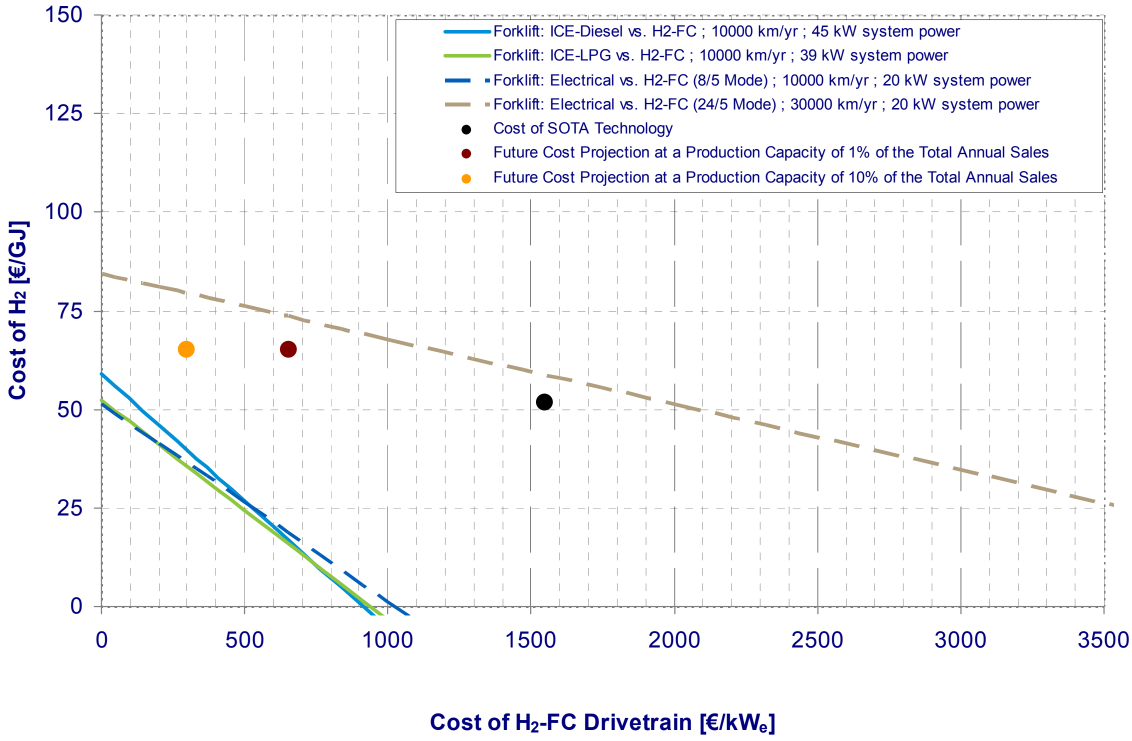


Figure 18: Windows of Opportunity for forklifts based on SOTA FC and reference technologies, prices and policies.

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030

Figure 19 illustrates the economic potential of current hydrogen fuel cell technology for sightseeing boats. At about 1900 hours of annual operation, H_2-FC drivetrains are, purely based on economics, competitive to internal combustion engines running on diesel. As the number of 30 annually produced units is very small, learning in this case won't lead to significant cost reductions and, because of that reason, is not considered in this study. However, it should be mentioned that in the case of sightseeing boats there are environmental reasons to switch to H_2-FC- or battery- electric drivetrains might already provide enough incentives on their own. The reduction of engine-noise could, for example, lead to higher comfort for passengers.

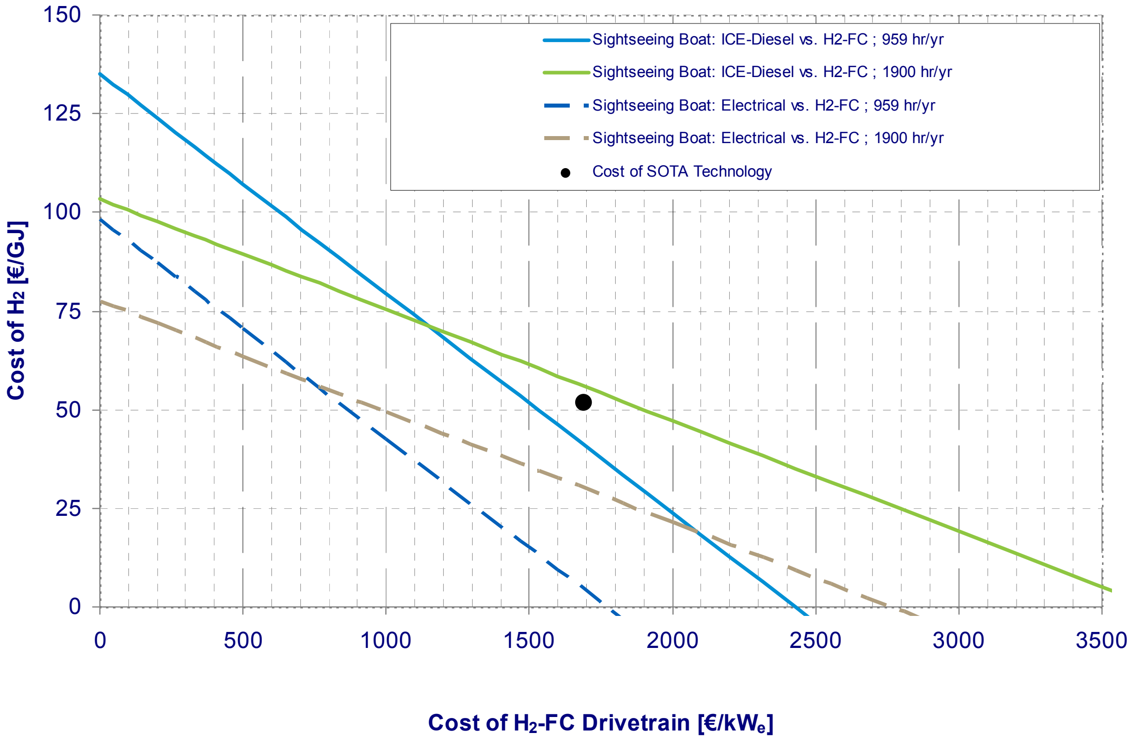


Figure 19: Windows of Opportunity for sightseeing boats based on SOTA FC and reference technologies, prices and policies

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR.

Figure 20 illustrates opportunities for hydrogen fuel cells to be used in outdoor utility vehicles. Purely based on cost, electrically driven outdoor utility vehicles are less attractive than vehicles with an ICE running on diesel. But it has to be mentioned that also in case of outdoor vehicles environmental reasons often play a more important role than costs. Hydrogen fuel cell drivetrains could hereby provide a compromise. Provided that a production capacity of at least 1% of all annual sales is installed, hydrogen fuel cell drivetrains could be a cost-competitive replacement for electrical drivetrains in outdoor utility vehicles.

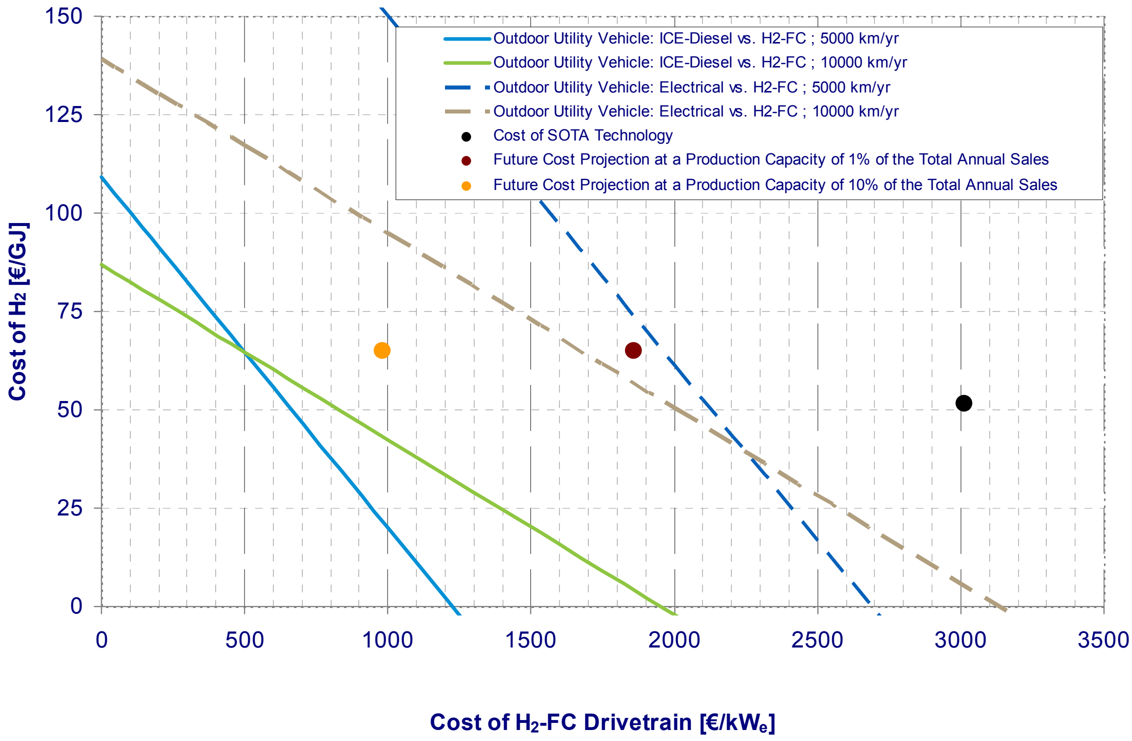


Figure 20: Windows of Opportunity for outdoor utility vehicles based on SOTA FC and reference technologies, prices and policies

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030

Figure 21 shows a steep slope of the Lines of Equality, leading to narrow Windows of Opportunities, i.e. only small allowable H_2-FC drivetrain costs. One of the main reasons here are comparably cheap reference drivetrains, especially in the case of scooters using internal combustion engines. However, although SOTA hydrogen fuel cell drivetrain costs are still too high for scooters, the large annual sales in this field of application could lead to cost-competitiveness compared to electrical drivetrains (low mileage) at a production capacity of 10% of all scooters sold annually.

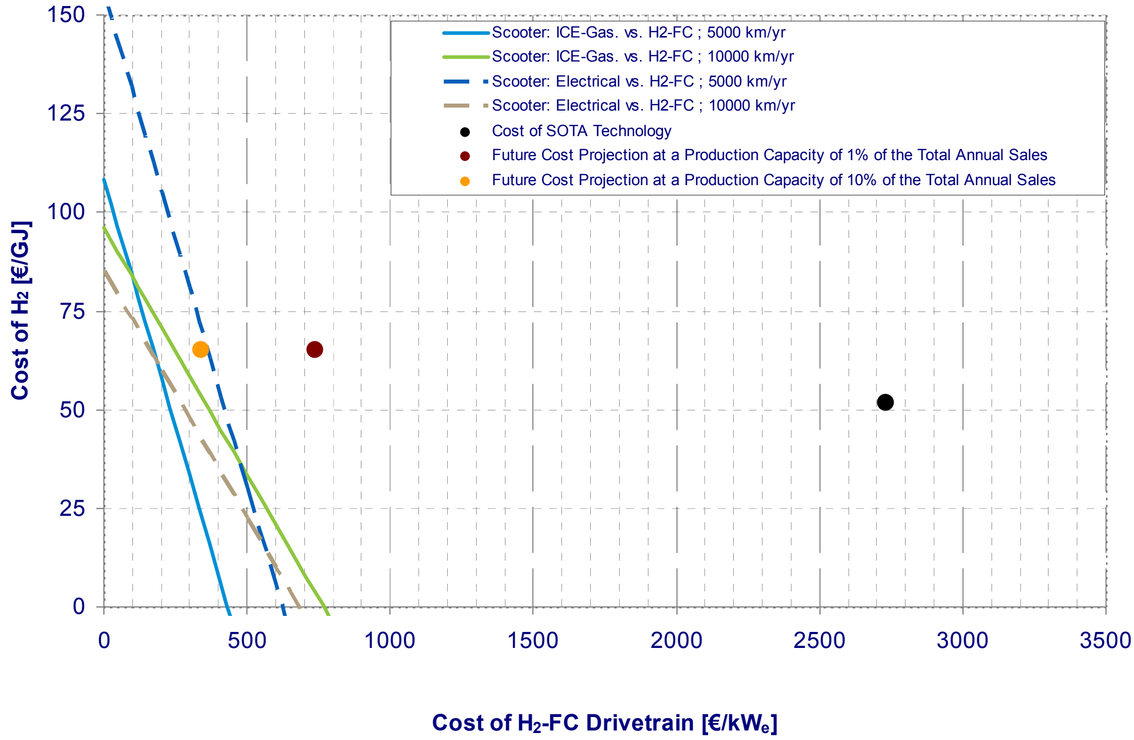


Figure 21: Windows of Opportunity for scooters based on SOTA FC and reference technologies, prices and policies

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030

Figure 22 demonstrates the case of licence-free cars. Compared to the other options shown above, they, purely from an economic perspective, do not seem as attractive for hydrogen fuel cell drivetrains. But, as 10% of the annual sales means an annual number of 3500 vehicles and city environmental issues will become even more important in the future, license-free cars will certainly become an opportunity for hydrogen fuel cells as development proceeds and cost go down.

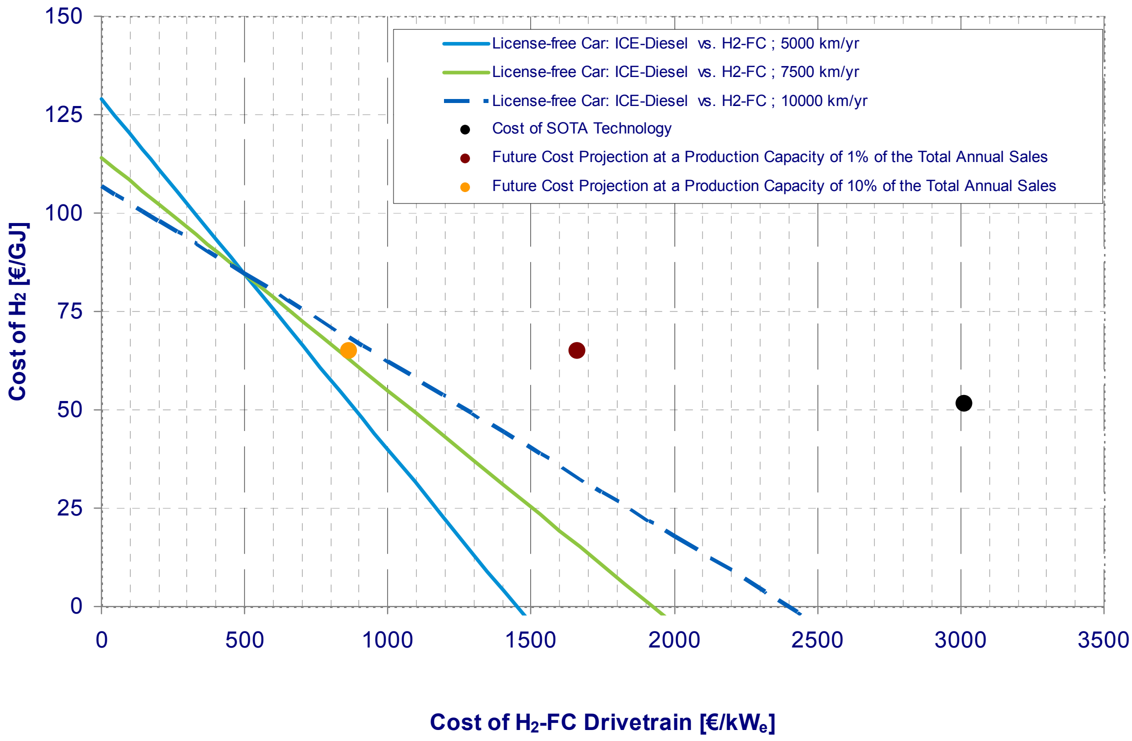


Figure 22: Windows of Opportunity for license-free cars based on SOTA FC and reference technologies, prices and policies.

The black data point reflects SOTA H_2-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR. The red and yellow data points reflect future (2020-2025) H_2-FC specs at production capacities of 1% and 10% of the total annual sales. The hydrogen cost reflects the projected average for the EU at 68 €/GJ (about 8,2 €/kg) in 2030

4.3.2 Stationary applications

The situation for the applications in the stationary market is more complex than for transport due to a wider range of power (1-1000 kW), diversity in fuel choice (hydrogen; natural gas; LPG; biogas) associated with a variety of fuel cell types, and a wider range in load factor (from a few hrs/yr for back-up to continuous operation).

CHP (Central Heat and Power) applications provide both electricity and heat. Consequently their success on the market for continuous operating applications is influenced by both demand for heating systems and electricity. In this case of high annual usage, CHP systems compete with electricity from the grid and mature heating applications. The most important market driver is therefore total cost of ownership. In the case of back-up systems with a very low annual usage, reliability is the main market driver.

In this study the CHP applications and back-up power applications will be treated separately, although CHP units can in principle also be used as back-up power in case of grid outage.

4.3.2.1 Back-up Power

Due to the low operating hours required for back-up power (see Figure 23), the efficiency and energy cost of the fuel cell system are of minor importance. For small power systems like in the telecom sector, the reference back-up solution is the battery-UPS (Uninterruptible Power Supply). These batteries can provide power for a limited amount of time due to the battery capacity. A PEM fuel cell UPS can provide power for practically unlimited time provided that the hydrogen supply is secured, giving this solution a higher reliability. One standard B50 cylinder filled with H_2 at 200 bar can provide approximately 10 kWh of back-up power. The reference cost level for the telecom UPS is around 3000 €/kW_e, a value in reach for hydrogen based PEMFC systems at this moment.

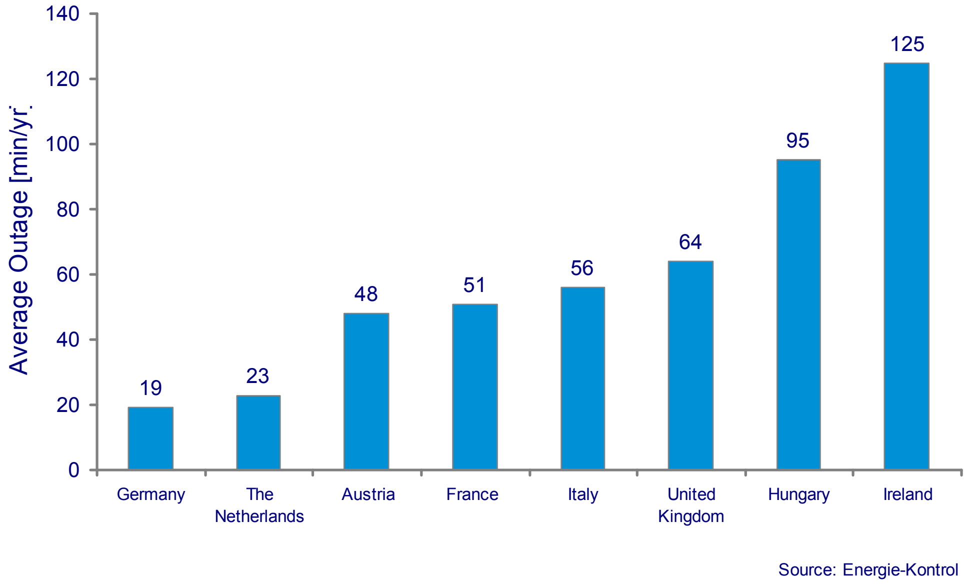


Figure 23: Average power outage time in min/year for different countries in 2006 caused by faults or unplanned

Larger back-up systems around 100 kW use a diesel generator as the main generator in combination with a battery to overcome the start-up time. In order to guarantee the reliability of the diesel generator the maintenance of these systems is an important item. Due to the requirement of short start-up time, the PEMFC is the fuel cell system of choice for fuel cell back-up solutions. It can operate from room temperature and start up much quicker than ICE based solutions, which also leads to less battery capacity necessary as buffer. The size and relative cost of the hydrogen storage facility becomes more important for the larger back-up systems. The size, the requirement for fast start-up and for lifetime compare well to PEMFC systems for passenger cars.

4.3.2.2 CHP Application

The CHP application is characterised by a large number of operating hours per year and cost/kWh is the main driver. The applications considered are residential (1 kW) and small industrial (250 kW) applications.

For CHP applications natural gas is the dominant choice of fuel. In most countries the infrastructure is present and the fuel can be easily reformed and cleaned which makes it well suited for fuel cell applications. The economy of the CHP application depends strongly on:

- Electricity cost and feed-in tariff
- Natural gas cost
- Reference technology heating efficiency
- Fuel cell electrical and heating efficiency
- Fuel cell investment cost (additional to reference technology cost) and lifetime
- System load factor (depends on heat/electricity demand and feed-in regulation)

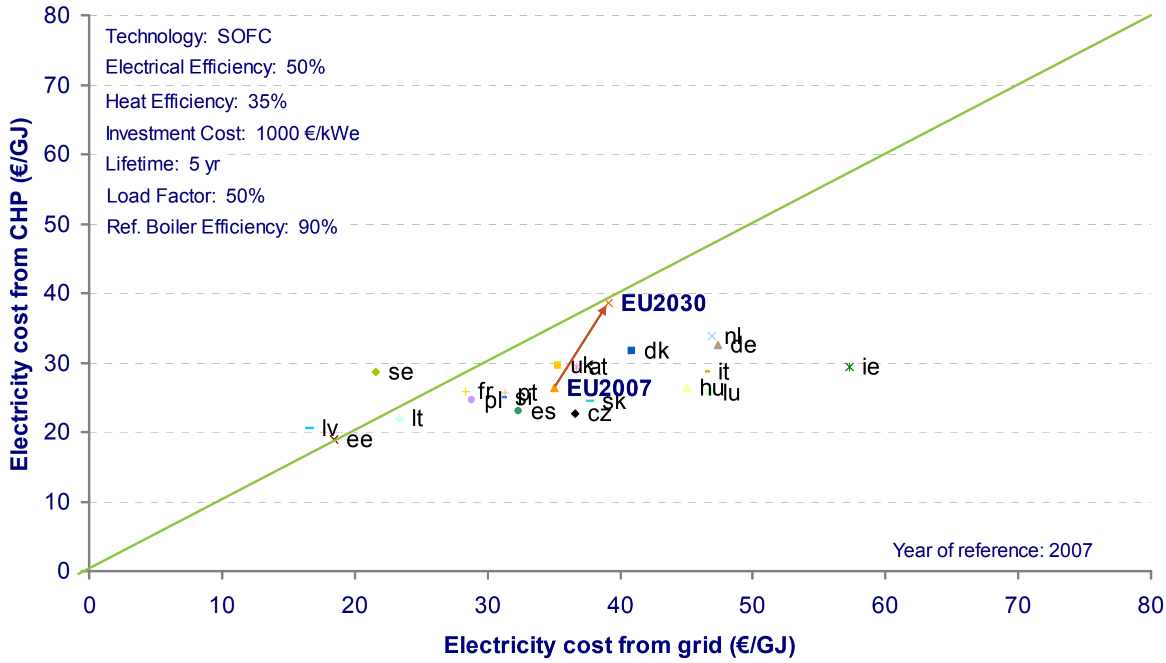


Figure 24: Economy of INDUSTRIAL CHP applications on NG in different countries

An example on how the electricity and natural gas cost in the different countries of the EU influence the economy is shown in Figure 24 for small industrial applications. At the straight line the cost of electricity from the CHP system equals the cost of electricity from the grid for specifications as shown in the graph. Countries, whose natural gas and grid electricity prices (both for 2007) lead to a data point lying below the line would, in principle, be more interesting for the introduction of CHP applications. The SOFC fuel cell system investment cost of 1000 €/kW$_e$ as mentioned in Figure 24 and Figure 25 is a target cost value for 2020 - 2025.

Taking the price scenario from Appendix A: for gas and electricity into account and applying it to the EU as a whole, CHP becomes less attractive in time (EU2007 compared to EU2030) if the assumed price scenario is valid, i.e. a steeper increase of gas price compared to electricity price until 2030.

For residential CHP applications the situation is comparable to the industrial CHP applications as shown in Figure 25, taking the consumer energy prices into account. For 2030 the high efficiency condensing boiler won't be the system of reference any more (see case study).

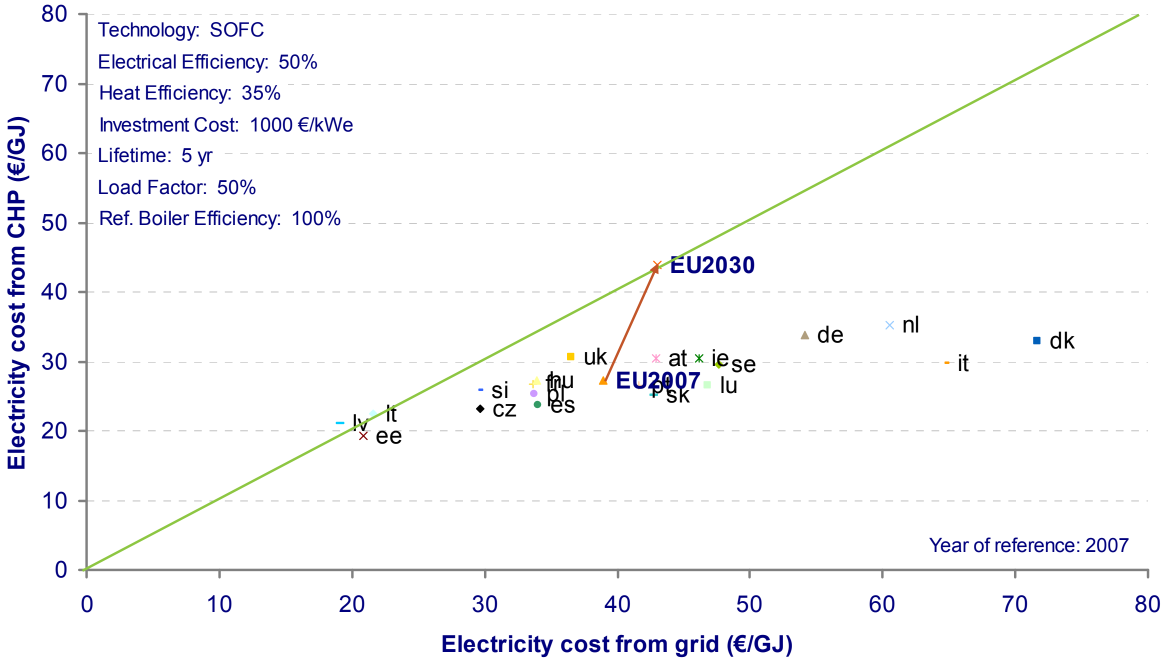


Figure 25: Economy of RESIDENTIAL CHP applications on NG in different countries

4.4 CO_2 Emissions

The CO_2 emissions from the different production pathways and the EU-mix for 2030 from Table 9 are presented in Figure 26. The CO_2 emissions for the production pathways are taken from the well to wheel studies in the Concawe project [2], which were also used in the HyWays study.

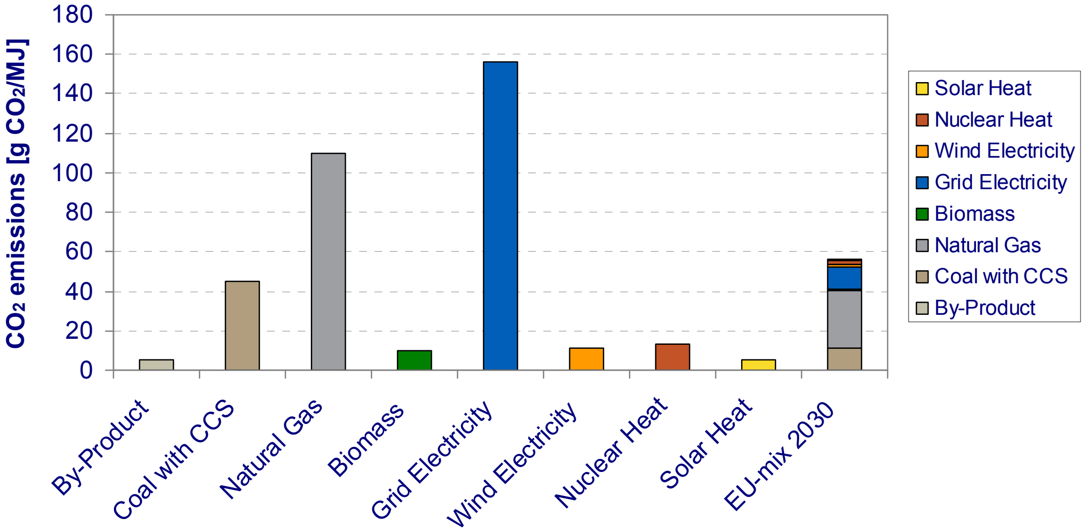


Figure 26: CO_2 emissions for the different pathways in the hydrogen production mix for 2030 from the Concawe project

4.4.1 Transport applications

The use of hydrogen in transport applications can reduce CO_2 emissions. The reduction depends on the source for the hydrogen and the energy source for the reference technology. The maximum reduction occurs when (off-shore) wind energy is used for the hydrogen production using electrolysis compared to diesel or gasoline ICE. Battery operated electrical vehicles have a lower CO_2 emission than fuel cell operated electrical vehicles assuming that the hydrogen for the fuel cell vehicles is produced by electrolysis from the same energy source as for charging the batteries.

For the applications where H_2-ICE are used, the CO_2 emission factor for the hydrogen should be much lower in order to obtain the same CO_2 emission reduction compared to the same application using fuel cells.

In Figure 27 the CO_2 emission of 3 reference vehicles and their fuel cell vehicles are compared for hydrogen from different sources. With a CO_2 emission factor for hydrogen production between 150 and 180 gCO_2/MJ the effect on total CO_2 emissions will be negligible. The emission factor using the HyWays mix is also provided and the distance to the line of the reference vehicle provides the potential CO_2 reduction.

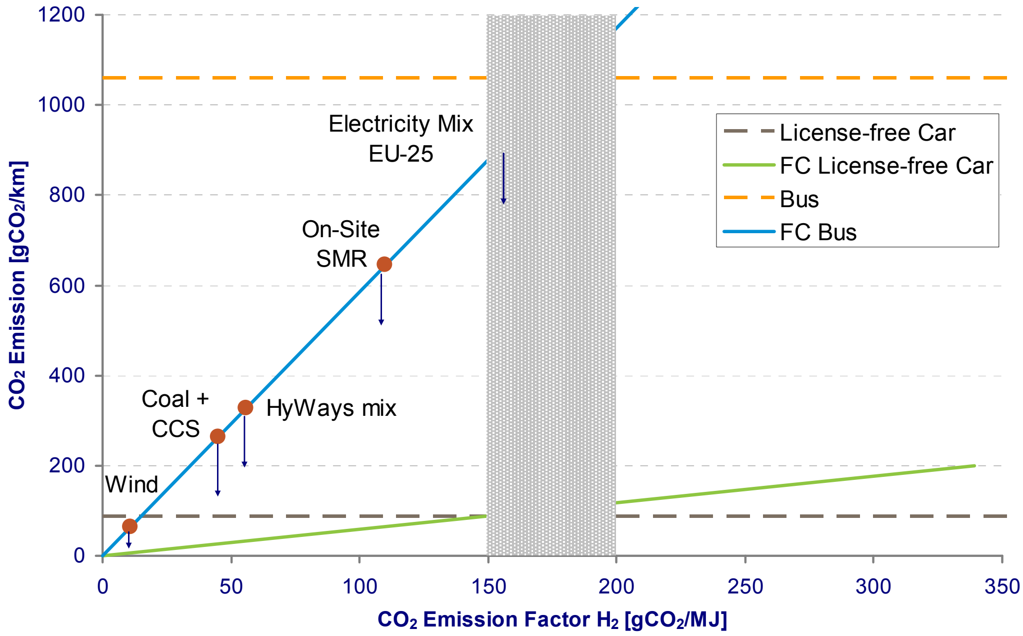


Figure 27: CO_2 emission of the reference vehicle running on diesel and FC vehicle using hydrogen from different sources

The bar shows the range of CO_2 emission factors for H_2 for which the WTW CO_2 emissions of the FC vehicle and the reference vehicle are equal

Multiplication of this distance with the average mileage and the number of vehicles in Europe gives the potential CO_2 reduction for Europe, which is presented in Figure 28. For the calculation the present number of vehicles are used and the assumption that the H_2-ICE/fuel cell replaces all fossil fuel combustion engines. The passenger car market has the largest reduction potential reaching 270 Mton/year, if fuel cells are used. In case of the H_2-ICE operated passenger cars, the potential is practically halved. The buses and forklifts CO_2 reduction potential is an order of magnitude lower than for passenger cars; the other applications have a reduction potential of 3 orders of magnitude or less compared to the case of passenger cars.

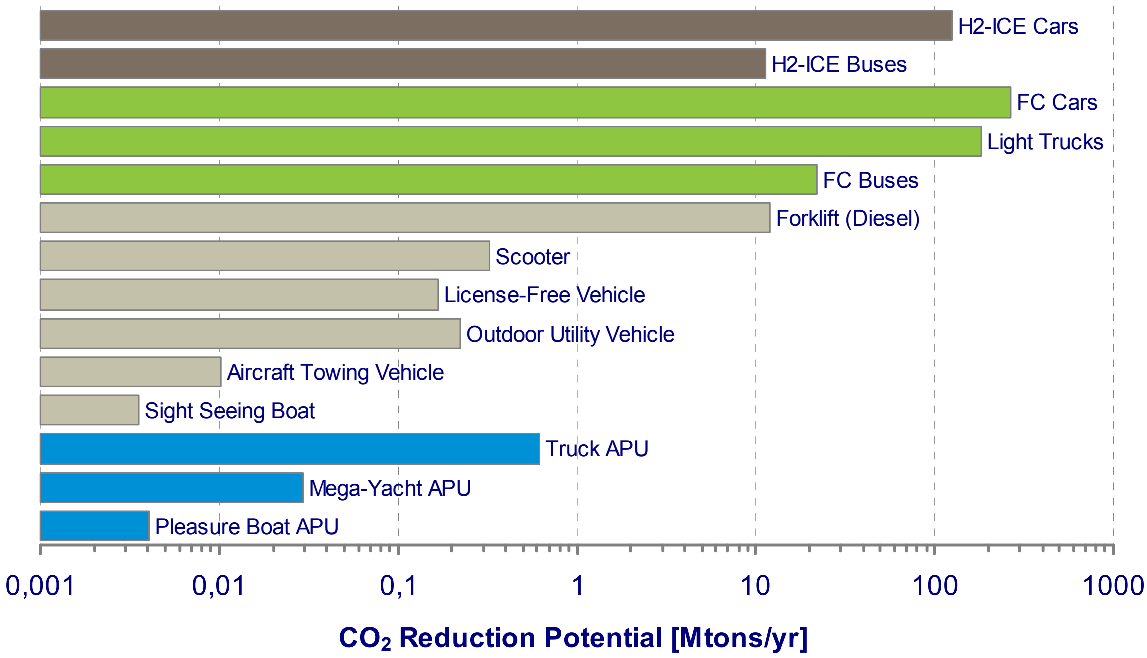


Figure 28: CO_2 reduction potential for Europe for the different applications using the H_2 production mix from HyWays

When the CO_2 emission reduction potential per installed capacity is calculated, the picture is different, as is shown in Figure 29. The passenger car has the lowest potential per kW_e due to an efficient reference technology, low operating hours and part load operation. The largest CO_2 emission reduction potential per installed capacity is obtained when engine idling for electricity generation is replaced by a fuel cell system for electricity production/ battery charging as in the truck APU, the mega-yacht APU and pleasure boat APU as can be seen in Figure 29.

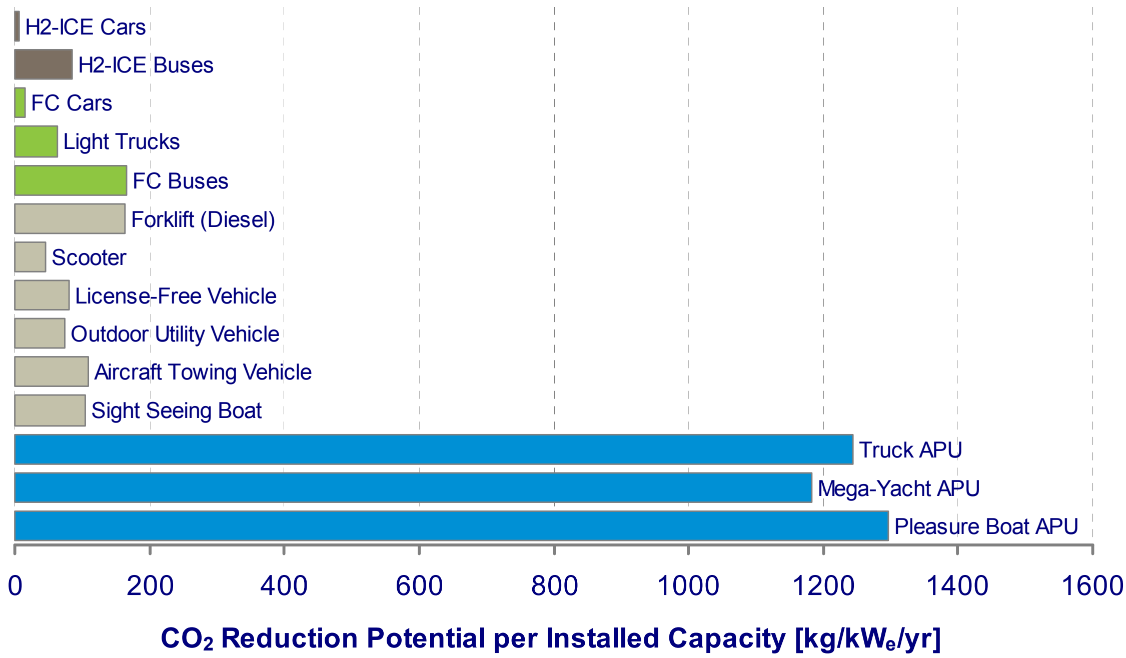


Figure 29: CO_2 reduction potential for different applications and per installed capacity of the conversion unit

In order to reach the maximum potential CO_2 emission reduction, the hydrogen produced by electrolysis of wind energy is the preferred source. In Figure 30 the required wind power capacity for the production of all the hydrogen from wind is estimated using a wind load factor of 30% and electrolyser efficiency (LHV) of 70%. In order to produce the hydrogen for the FC passenger cars by this process, the installed wind turbine capacity in Europe has to increase 8-fold from 48 GW (status 2006) to 386 GW and only be used for hydrogen production. If the hydrogen is used for the H_2-ICE passenger cars, the installed wind turbine capacity has to double once more due to the lower efficiency of the H_2 combustion engine compared to the fuel cell.

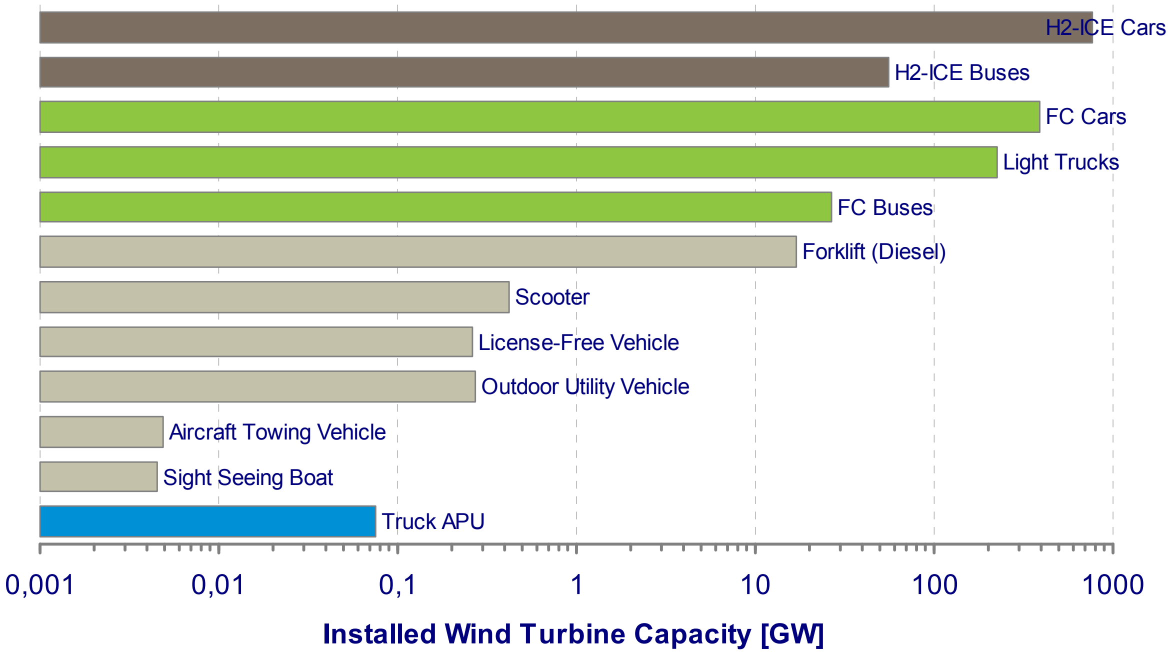


Figure 30: Estimated required capacity of wind turbines for the hydrogen production by electrolysis per application

4.4.2 Stationary applications

The CO_2 emissions and emission reductions for the telecom back-up power solutions are interesting due to the required power for the battery conditioning for the reference system. The CO_2 emission reduction potential for the telecom back-up power is calculated at 0,33 Mton/yr. For the hospital back-up application the reduction is even smaller due to the small amount of operating hours/year.

The CO_2 emission reduction potential for the CHP applications is substantial as shown in Figure 31. The upper 2 bars are for the large scale CHP market assuming 2 different fuel cell technologies. The middle bar is for the residential CHP applications and the bottom 2 are for back-up systems. Note the logarithmic scale.

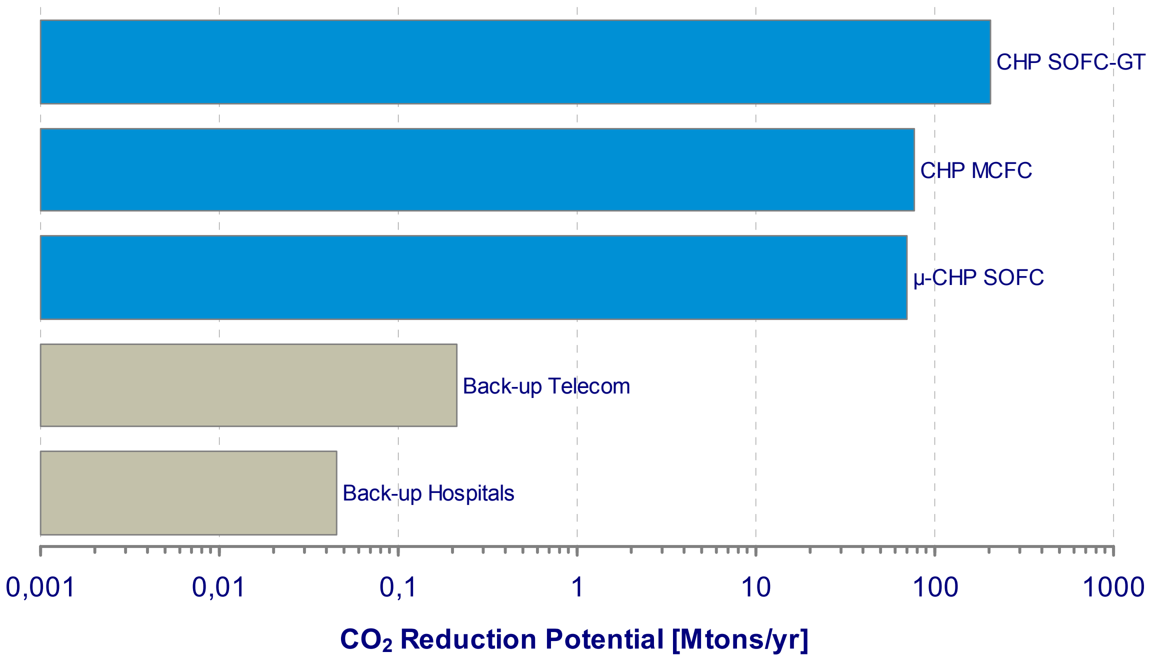


Figure 31: CO_2 reduction potential for stationary applications

The CO_2 emission reduction potential for the μ-CHP market on the basis of SOFC is calculated as 70 Mton/yr using the high efficiency boiler as the reference technology. For the larger CHP systems a potential CO_2 reduction of 200 Mton CO_2/yr exist when CHP systems on the basis of SOFC +GT or 76 Mton CO_2/yr for MCFC that provide the same heat as produced in the EU in 2004.

The reduction is calculated on the basis of the different efficiencies for the technologies as shown in Table 10.

Table 10: Assumptions for the efficiencies of the technologies for industrial CHP

CHP technology	Electric efficiency	Thermal efficiency
Reference technology	40%	50%
SOFC + GT	60%	30%
MCFC	50%	40%

The CO_2 reduction potential per installed kW is shown in Figure 32. For the back-up applications the CO_2 reduction is small due to the limited amount of operating hours. The SOFC + gas turbine provides the largest CO_2 reduction per installed kW_e due to a large number of operating hours and a high electrical efficiency. It is assumed here that the application is heat controlled and excess electricity can be delivered to the grid.

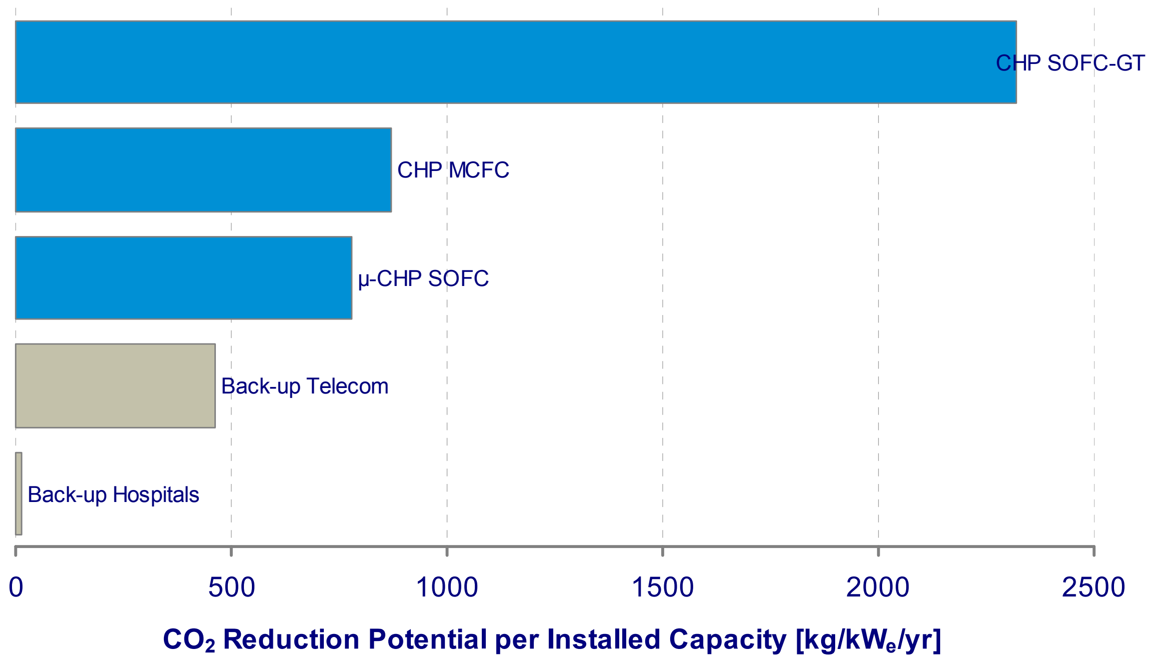


Figure 32: CO_2 reduction potential per installed kW for stationary applications

5. Discussion

5.1 Opportunities for Fuel Cell and Hydrogen Applications

In this study following applications have been identified as potential PEMFC markets:

- Forklifts in 24/5 operation
- Sightseeing Boats
- Outdoor Utility Vehicles
- Scooter
- License-free Cars
- Light Duty Trucks
- Passenger Cars, subject to system cost reductions being realised
- Back-up systems for telecommunication
- Urban buses, subject to other civic considerations adding to the business case

A study has been conducted on “Identification and characterization of near-term direct hydrogen proton exchange membrane fuel cell markets” [6] for the US DOE (Department of Energy). The markets identified in the DOE study confirm some of this study’s conclusions as can be seen in following table:

Table 11: Near-term PEMFC markets in the USA

Near-term Markets (By 2008)		Mid-term Markets (Beyond 2012)	
Backup Power	**Specialty Vehicles**	**Backup Power**	**Specialty Vehicles**
- Telecom. - Emergency response communications - Federal agencies – FAA, NOAA, USCG	- Forklifts in distribution centres - Ground support equipment in airports	- Railways - Electric utilities - Data centres - Water and wastewater utilities - Financial service providers - Other government agencies (backup power for buildings, police stations, fire stations) - Healthcare - Airports - Manufacturing - Grocery stores	- Automatic guided vehicles - Turf maintenance vehicles - Industrial tow tractors - Mining vehicles - Golf carts

Again, this study should be considered as first-order analysis that only aims at indicating the potential of fuel cell and hydrogen technologies for further research. Assumed current production capacities and current cumulative numbers of applications produced (see Chapter 3.4.3) were used to calculate the basis of cost values but are not necessarily valid. SOTA cost values reflect possible costs if optimal conditions and operation are enabled. Cumulative learning or universal applicability of fuel cells to different fields of applications was not taken into account but needs further investigation. Consequently, results shown are not intended to make a positive business case or bring a full stop to one. Highly potential applications deserve a much more in-depth evaluation of their full economic and environmental possibilities. This report is meant to provide a guide in choosing applications and the right starting points for further research.

Forklifts and outdoor utility vehicles are taken as promising examples for niche applications for the following discussion.

Forklifts in 24/5 operation and fuel cell back-up systems for telecommunications are identified as near term markets in this study too. They provide advantages over battery energy systems due to the limited energy storage capacity of the battery.

The market sizes for forklifts in the US and in Europe are also comparable at approximately 150 000 and 164 000 annually sold vehicles [16].

Outdoor utility vehicles, similar to ground support equipment in airports as mentioned in the DOE study [6], show potential to become an initial market due to the better part load characteristic of the fuel cell drivetrain over the ICE. The market sizes for such outdoor utility vehicles in the US and in Europe are comparable as well at approximately 10 000 and 20 000 annually sold vehicles [16].

In case of passenger cars, this study estimates that at an annual production capacity between 1 and 1,5 million units, the implementation plan's target for 2015 road propulsion FC drivetrains of 100 €/kW [1] could be reached, if technological learning and future policies and fuel prices are included (see Figure 13).

In a PSI and a HyWays report cumulative production of 5 million and approximately 2 to 3 million units respectively are stated in order to approach competitiveness with conventional cars [15] [03]. This is in the same order of magnitude.

By comparing the combined market size of niche applications (about 200 000 in total) to the size of a mass market such as that of passenger cars (Europe: about 15 million annually sold cars) and looking upon the mentioned production capacities necessary to reach cost-competitiveness to conventional cars, it can be questioned if niche applications can contribute significantly to reductions in the cost of FC systems.

The power of niche applications is about an order of magnitude lower than for passenger cars and operation profiles are different. This could mean that the translation of technological experience into development of mass market components and systems might not be straight forward. Also, niche applications don't necessarily contribute to the development of a public refuelling infrastructure due to their main use in commercial or industrial fields of operation.

But, as all other FC/H_2 applications, niche applications will contribute positively to the development of hydrogen policies and permits development of people's perception of its variety and its safe handling as it becomes more common.

Light duty trucks are suitable for a cost-competitive use of FC drivetrains even before their use in passenger cars. With a European market size of 2 million annually sold vehicles and their similarity to passenger cars they would contribute to the build-up of a large-scale refuelling infrastructure and technological development that can be directly translated to passenger cars. Furthermore, due to their high number they could contribute to a large reduction in CO_2 emissions.

Economics of urban FC buses show good prospects, if the hydrogen price in 2020-2025 is below 55 €/GJ. If hydrogen is produced from natural gas via steam methane reforming, 55 €/GJ reflects a natural gas price of approximately 14 €/GJ - 1,2 times today's (mean 2007) price. The price of hydrogen at bus depots, for example for public transportation, might be less than the price at public refuelling stations. VAT might not be included and forecourt costs reduced due to less operational costs, high utilisation and hydrogen throughput.

Furthermore, FC buses are an interesting option for urban public transportation and thus communities. The use of FC buses is beneficial for the local air quality, might be a symbol for the civic desire for sustainability, thus promoting a shift towards the use of public transportation and could contribute to establishing a public refuelling infrastructure. Hydrogen infrastructure for fleet operated city buses and light duty trucks should be located in areas, which are easily accessible for public refuelling. Combined with the present refuelling network they could serve as starting point for refuelling hydrogen passenger cars, which are especially interesting as their absolute CO_2 reduction potential is the highest of all considered applications due to their large number in Europe.

Besides mass production, cost reductions of FC drivetrains will be achieved via technological research and development. The following sub-chapter explains possibilities for cost reductions by breaking down and analysing the cost of the PEMFC system's components.

5.2 Cost Breakdown of PEMFC Systems

In order to achieve the assumed learning curve effects necessary to close cost-gaps as illustrated in Chapter 4.3.1.2, research needs to be extended. The breakdown of the H_2-FC drivetrain cost as shown in the Figure 33, Figure 34, Figure 35 and Figure 36 provide a mean for the analysis of potential cost reductions.

Figure 33 and Figure 35 illustrate the share in relative cost (€/kW_e) of the different drivetrain components for both SOTA and future fuel cell outdoor utility vehicles and fuel cell passenger cars. The applications differ in two ways: Outdoor utility vehicles have a system power of 4kW, whereas passenger cars' power is 80kW, thus leading to smaller costs per kW. Furthermore outdoor utility vehicles represent niche applications where an annual production capacity of 2000 already represents 10% of the total annual sales in this field of application. In the case of passenger cars, 1% of the annual sales means a production capacity in the order of 150 000 units, which leads to further cost reductions due to learning and economies of scale.

The PEMFC system has the highest share in the overall drivetrain cost. The components' shares in the total cost of the PEMFC system are further split in Figure 34 and Figure 36.

Figure 33 and Figure 34 show cost breakdowns for a platinum price of 2000 $/troz, which was used throughout this study, whereas Figure 35 and Figure 36 are based on a platinum price of 900 $/troz as used in the TIAX study [10].

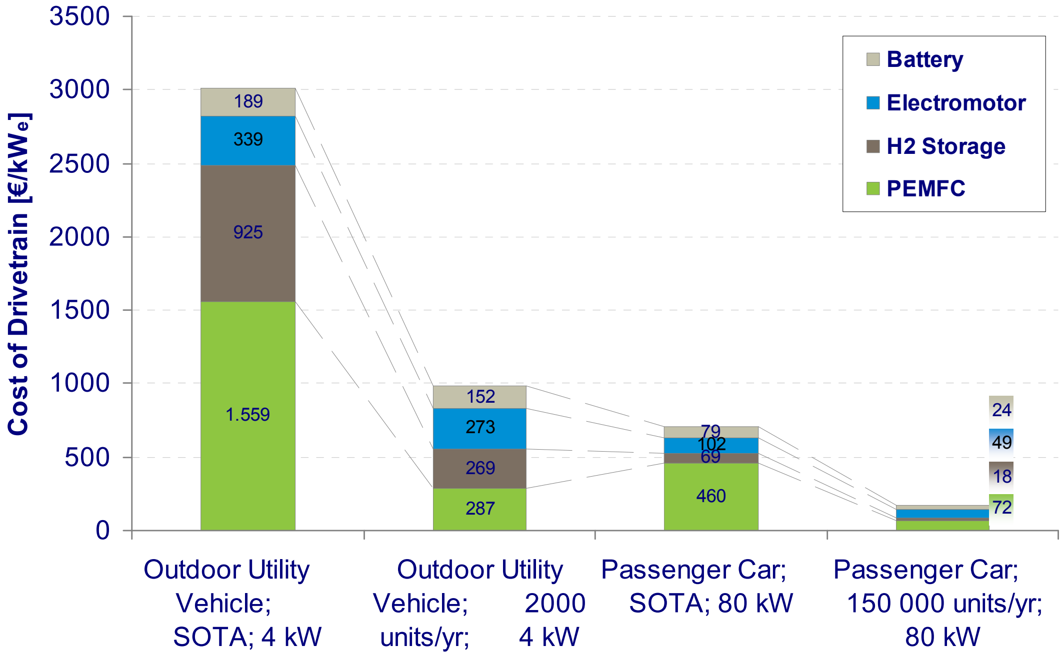
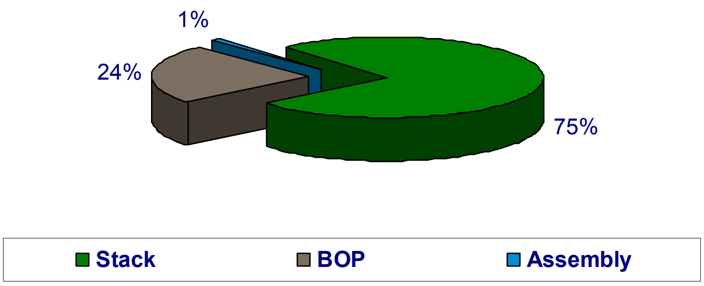


Figure 33: Breakdown of drivetrain cost for annual production capacities of 1000 and 500 000 units and system powers of 10 and 100 kW$_e$ (Pt price of 2000 \$/troz)



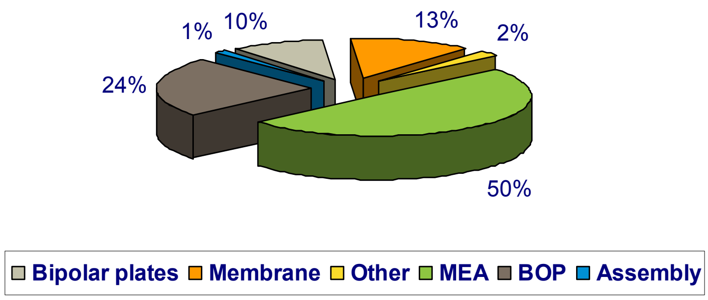


Figure 34: Breakdown of PEMFC cost into its components (Pt price of 2000 \$/troz)

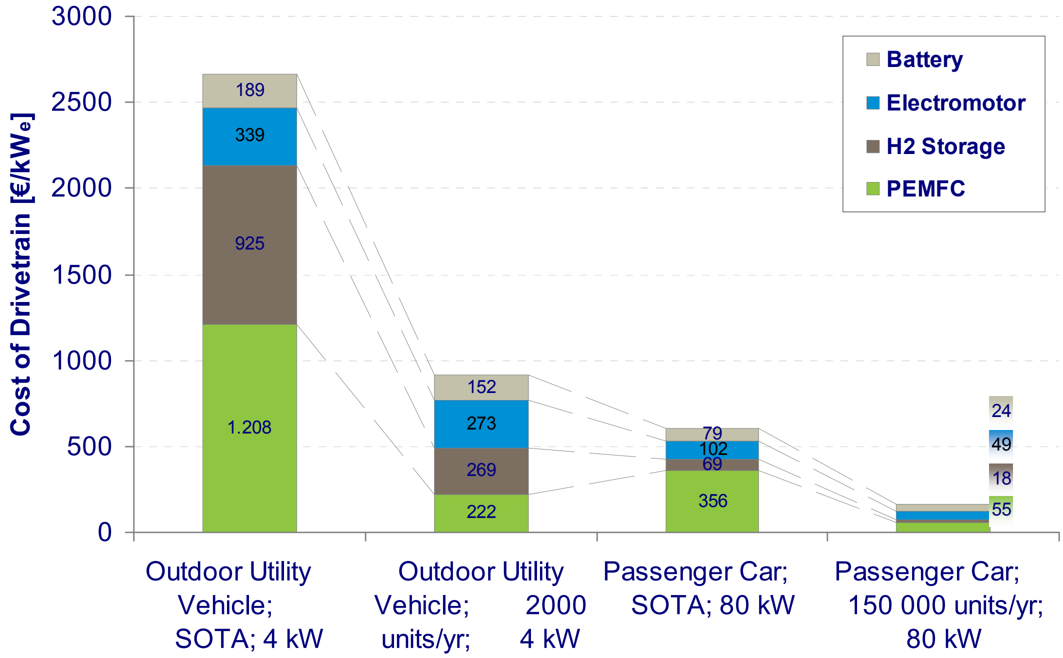
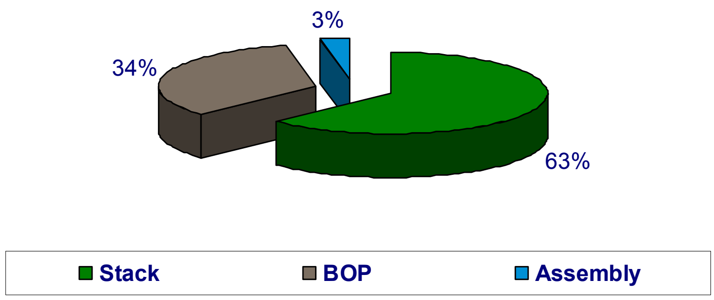


Figure 35: Breakdown of drivetrain cost for annual production capacities of 1000 and 500 000 units and system powers of 10 and 100 kW$_e$ (Pt price of 900 \$/troz)



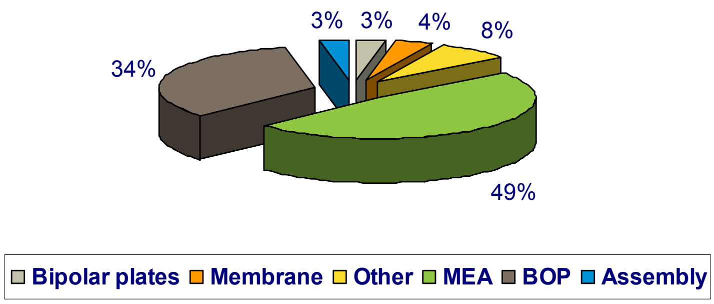


Figure 36: Breakdown of PEMFC cost into its components (Pt price of 900 \$/troz)

It can be seen that the cost-contribution of the MEA (membrane electrode assembly) to the total cost of the PEMFC and thus to the overall fuel cell drivetrain is sensitive towards the price of platinum due to necessary high loadings. But, in the shown cases, an increase in the platinum price of 122% leads to an increase in the costs of the total FC drivetrain of only 7% to 17%, depending on the considered production capacity and system power.

Thus, the contribution of platinum to the total cost of the whole FC drivetrain is similar to all other components and about one fifth. Consequently, significant reductions in the cost of the whole FC drivetrain can only be achieved by reducing the costs of all components.

Therefore, three main fields for research have been identified to have big potential for cost reductions:

- Increase in the power density of the fuel cell in order to reduce material needs and hence material costs,
- Use of less platinum or other materials than platinum as catalyst and
- Increase the durability of the fuel cell stack and system as a whole.

5.3 Price of Hydrogen

The windows of opportunity shown in the results part of this report illustrate that the chances of FC technologies are much dependent on the price of hydrogen.

For the cost-evaluation of SOTA and future FC technology against the windows of opportunity, a projection for the 2030 hydrogen price of 68 €/GJ or 8,2 €/kg respectively (including 10€/GJ for forecourt costs, 6,7€/GJ for distribution and 19% VAT) has been used (see Chapter 4.2). Depending on the production pathway, the hydrogen production cost (excluding VAT, forecourt and distribution costs) could also be more than 70 €/GJ (for example from on-site electrolysis using grid electricity) or less than 20 €/GJ for by-product hydrogen.

The targeted hydrogen costs taken from the Implementation plan [1] are:

- 2,5 €/kg or 20,8 €/GJ for hydrogen production from fossil fuels (mainly NG)
- 5,0 €/kg or 41,7 €/GJ for hydrogen production from renewable sources
- 2,5 €/kg or 20,8 €/GJ for distribution of hydrogen and fuelling station costs

If these target values are reached, even more opportunities for FC applications will arise. It should be noted that cost of hydrogen is sensitive to feedstock prices, i.e. also towards the price of natural gas, which is linked to the price of oil as well. As energy prices have been fluctuating a lot over the last couple of years, this may explain the difference between the projections used in this report and the implementation plan’s targets given above. However, even with fuel cell’s high efficiency, the success of FC applications will depend on the cost of hydrogen, which needs to be as low as possible. Thus, more research and development needs to be performed on side of hydrogen production and distribution possibilities too.

6. Conclusions

6.1 Opportunities

Applications with following characteristics are generally favourable for the use of FC technology:

- High annual usage (mileage or hours of operation)
- Small system power, which means low (engine) investment costs
- Low fuel consumption (equals high fuel efficiency); otherwise the cost of hydrogen becomes a limiting factor.

Forklifts in 24/5 (or even longer) operation and outdoor utility vehicles with battery-electric drivetrains are identified as near term markets for fuel cell drivetrains, although their relatively small market sizes do not contribute a lot to cost reductions due to mass production. However, the limited energy storage capacities of batteries and relatively high engine investment costs for the electrical drivetrains lead to cost-competitiveness of state-of-the-art fuel cell drivetrains. In the case of forklifts, multiple batteries per application are necessary to be exchanged during its operation, which causes even higher investment costs.

For similar reasons, battery powered backup systems (for example for telecommunication) represent an attractive near-term market for fuel cell backup systems as well as they provide higher reliability.

Light duty trucks are identified as an attractive near-term application as they show the favourable characteristics mentioned above; i.e. high annual mileage with relatively low fuel consumption of a medium sized engine.

Light duty truck hybrids include higher investment cost for the engine, which does not seem to be compensated by their lower fuel consumption. Thus, in the case of light duty trucks, hybrids show an even higher opportunity than internal combustion engines for the use of fuel cell drivetrains.

Passenger cars have similar characteristics as light duty trucks. But, as their average annual mileage is lower, they only become attractive on a mid-term basis when cost reductions through learning (research) have been achieved.

The challenge for buses is bigger due to much higher fuel consumption and the higher power of the drivetrain required.

Lots of potential for CO_2 emission reductions has been identified for many different hydrogen production pathways on a European scale. Transport applications, especially passenger cars, show the highest possibility for CO_2 reductions because of the large amount of vehicles being used.
The potential of CO_2 reduction for small and large high temperature fuel cell stationary CHP applications is large due to the higher electrical efficiency than competing technologies using natural gas.

If prices for fossil fuels increase, CO_2 taxation is introduced and stricter emissions and green house gas policies are implemented (leading to additional measures and thus investment costs for conventional technologies, which are probably not balanced out by their higher efficiency), more applications will become attractive for the use of FC/H_2 technologies.

6.2 Gaps & Priorities

In the case of H_2-ICE, the allowable cost of hydrogen is much lower than in the case of fuel cells and even much lower than the projected 68 €/GJ. Hence, it will be difficult to turn H_2-ICE into a commercial success, if it does not provide any advantage over other technologies that are unmatched by them.

Cost reductions by technological development are a main priority to make fuel cells more competitive to conventional technologies. This could include:

- Increase in the power density of the fuel cell in order to reduce material needs and hence material costs
- Use of less platinum or other materials than platinum as catalyst
- Increase durability (lifetime) of the fuel cell stack and system as a whole

In order to create favourable conditions for H_2-FC technologies, political commitment to hydrogen as an important future energy carrier is necessary. The following possibilities could support successful implementation:

- Stricter regulations on pollutants and green house gas emissions
- Favourable taxation of hydrogen compared to conventional fuels, for example CO_2 taxation and less or no excise duty on hydrogen
- Increase funds for and coordination of R&D projects and activities
- Demonstration projects; use of FC technology in fleets
- Increase in coordinating EU wide rollout of hydrogen infrastructure (production sites, distribution network and refuelling stations)

7. References

[1] HFP "Implementation Plan – Status 2006"; March 2007

[2] "Well-to-Wheels analysis for future automotive fuels and power trains in the European context", version 2b, 2006 (http://ies.jrc.ec.europe.eu/WTW)

[3] HyWays, Roadmap, 2007 (www.HyWays.de)

[4] www.energy.eu, last visited November 2007

[5] carma.org, last visited November 2007

[6] K. Madahevan et al.; "Identification and characterization of near-term direct hydrogen proton exchange membrane fuel cell markets", April 2007

[7] "Well to Tank Technology Pathways and Carbon Balance", Roads2HyCom Report R2H4003PU from WT4.3; December 2008, available to download from www.roads2hy.com/WP4.html

[8] "Tank to User Technology Pathways and Carbon Balance", Roads2HyCom Report R2H4004P from WT4.4, December 2008, available to download from www.roads2hy.com/WP4.html

[9] "Snapshots of Hydrogen uptake in the future - A comparison study", Roads2HyCom Report R2H4001PU1 from WT4.1, September 2007; available to download from www.roads2hy.com/WP4.html

[10] E. J. Carlson et al, "Cost Analysis of PEM Fuel Cell Systems for Transportation" report NREL/SR-560-39104; September 2005

[11] "Cost Analysis of Fuel Cell Systems for Transportation Compressed Hydrogen and PEM Fuel Cell System" Report D0006 SFAA No. DE-SCO2-98EE50526; October 2004

[12] G.J. Kramer et al.: "Clean and green hydrogen", WHEC 16; Lyon France, June 2006

[13] B. D. James et al: "V.A.2 Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell System for Automotive Applications", FY 2008 Annual Progress Report of the DOE Hydrogen Program, http://www.hydrogen.energy.gov/pdfs/progress08/v_a_2_james.pdf

[14] McKinsey&Company: "DRIVE – The Future of Automotive Power", Germany, 2006

[15] S. Hawkins, N. Hughes: "Technological Characterisation of Hydrogen Fuel Cell Vehicles", PSI, IKSHEC Social Science Working Paper No. 22, 01.05.2005

[16] K. Mahadevan et al: “Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets”, Batelle, DOE Contract No. DE-FC36-03GO13110, April 2007

Appendix A: Energy price calculations for different cases

Variation of energy prices in EU-25

An inventory of energy prices in January 2007 for gasoline, diesel, natural gas and electricity for EU-25 is made and shown in Figure 37. This figure shows that a large scatter between the countries exist, with the lower prices mainly in the eastern EU countries. A variation of a factor 3 or more is observed for gas and electricity. For gasoline and diesel, which are traded on the world market, the variation is from 1,3 to 1,7.

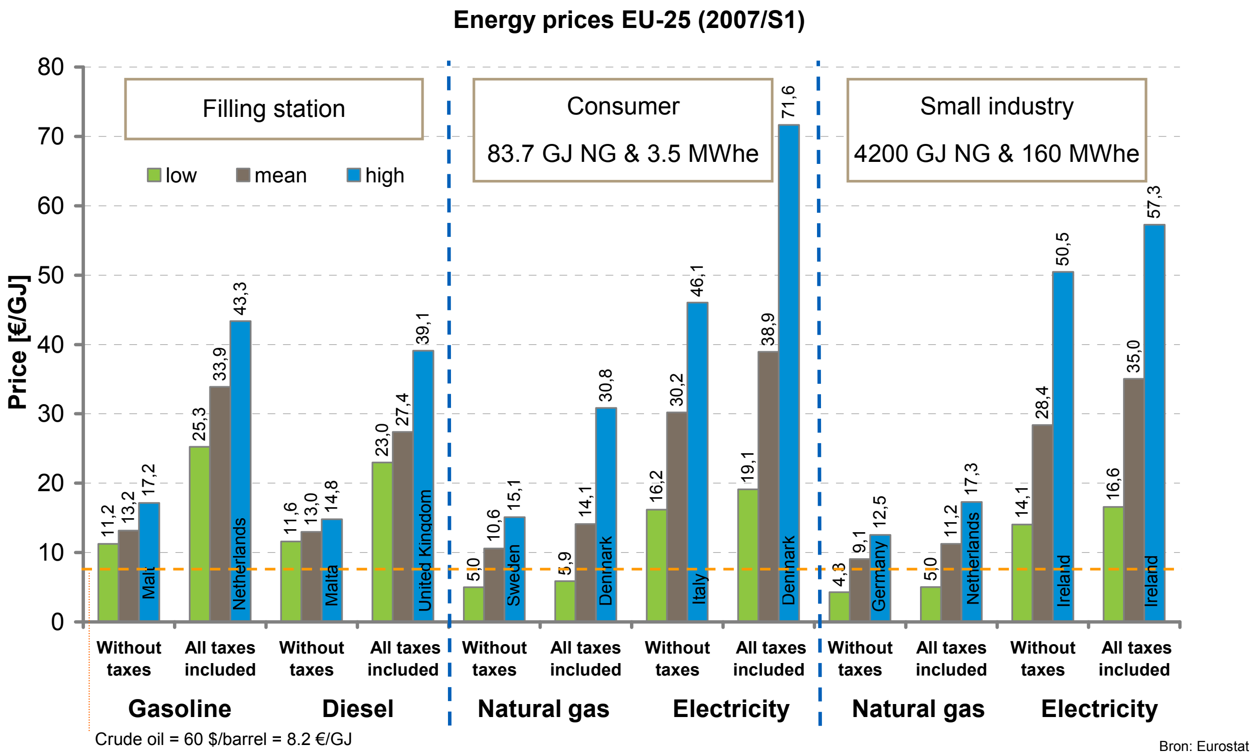


Figure 37: Minimum (low), mean and maximum (high) energy prices (€$_{2007}$) within the EU-25 on 1st January 2007

Prices are presented without taxes and with all taxes included

Energy price scenarios are used and described in:

> Dag Martinsen, Volker Krey and Peter Markewitz, Implications of high energy prices for energy system and emissions--The response from an energy model for Germany, Energy Policy, Volume 35, Issue 9, September 2007, Pages 4504-4515.

In which they state:

> *The **reference scenario** is based on the assumptions of (EWI/Prognos, 2005) and the corresponding oil price development is similar to other price scenarios which were developed prior to 2005 (e.g. EIA, 2005; EU Commission, 2003; IEA, 2005). The **high price scenario** has been derived from the International Energy Outlook's High Oil Price scenario (EIA, 2006). The **price shock scenario's** dynamics as well as the price level is motivated by the Super-Spike scenario of (Goldman Sachs, 2005). Recent energy scenarios (EIA, 2006; EWI/Prognos, 2006; IEA, 2006) employ oil prices in their reference scenarios that lie between the reference and the high price scenarios adopted for this analysis, corresponding to around 55–60 US-$/bbl in 2030.*

Based on the crude oil prices in US-$, the development of the cross-border import prices in € for crude oil, natural gas, hard coal and mineral oil products was determined from an analysis of currency relations between US-$ and € (1,1 US-$/€) and price relations of mineral oil products, natural gas and hard coal as compared to crude oil for the last 30–35 years (Horn, 2007). This analysis justifies the simple assumption of long-term constant relations for the future. The resulting projections of prices for imported energy carriers up to 2030 are shown in Figure 38.

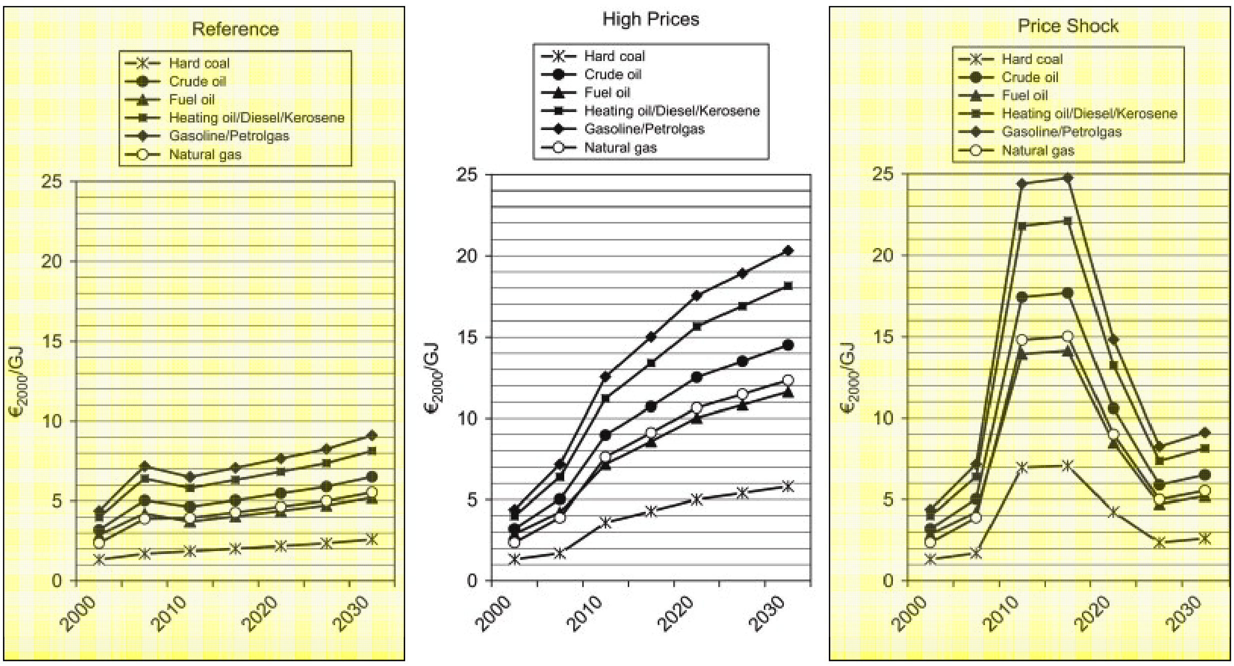


Figure 38: Price scenarios of imported energy carriers in €$_{2000}$/GJ. The high prices scenario will be used as a basis for the case study

Methodology for determination of energy prices at the point of use for the case study

For the present energy price (2007) the steps are as follows:

1. Collect the low, mean and high values for January 2007 from Figure 37

2. Convert to currency $€_{2000}$ by dividing these values with the inflation factor from 2000 to 2007 of 1,164 [Eurostat].

For 2030 the steps for determining the energy prices are as follows:

1. Collect for 2030 the crude oil price (oil_{2030} = 14 $€_{2000}$/GJ) and natural gas price (gas_{2030} = 12 $€_{2000}$/GJ) from the **high prices scenario** of Figure 38.

2. The crude oil price in Jan 2007: oil_{2007} = 7,1 $€_{2000}$/GJ.

   – (Using for oil 60 $/barrel; 0,7575 € = 1 $; 159 l/barrel; 0,835 kg/l; 41,7 MJ/kg; $€_{2000} = €_{2007}/1,164$)

3. Fuel price with $taxes_{2030}$ = Fuel price with $taxes_{2007}$ + 1,42*(oil_{2030}-oil_{2007})

   – The factor 1,42 is obtained from the gasoline and diesel price increase between 2007 and 2008 of 5,0 €/GJ compared to the crude oil price increase of 3,5 €/GJ (Figure 39).

4. Fuel price without $taxes_{2030}$ = Fuel price without $taxes_{2007}$ + 1,2*(oil_{2030}-oil_{2007})

   – The factor 1,2 is the factor 1,42 from step 4 divided by 1,19, which is (1 + mean VAT) in the EU-25 for gasoline and diesel; the factor 1,2 accounts for higher transport costs, the refinery efficiency losses etc.

5. Assume a linear coupling between oil price and gas price, at a crude oil price of oil_{2007} =7,1 $€_{2000}$/GJ the gas price gas_{2007} = 6,0 $€_{2000}$/GJ using Figure 38.

6. Repeat steps 4 and 5 for the gas price using the difference between gas_{2030}-gas_{2007}.

   – For gas the same factors as for oil are used; 1,42 with taxes and 1,2 without taxes.

7. Repeat steps 4 and 5 for the electricity price using the difference between oil_{2030}-oil_{2007}. The factor without tax is 0, the factor with tax is 0,5.

   – The factor without and with tax is based on the mean historical relation (1991-2006) for EU-15 between household electricity prices and crude oil price; see Figure 40.

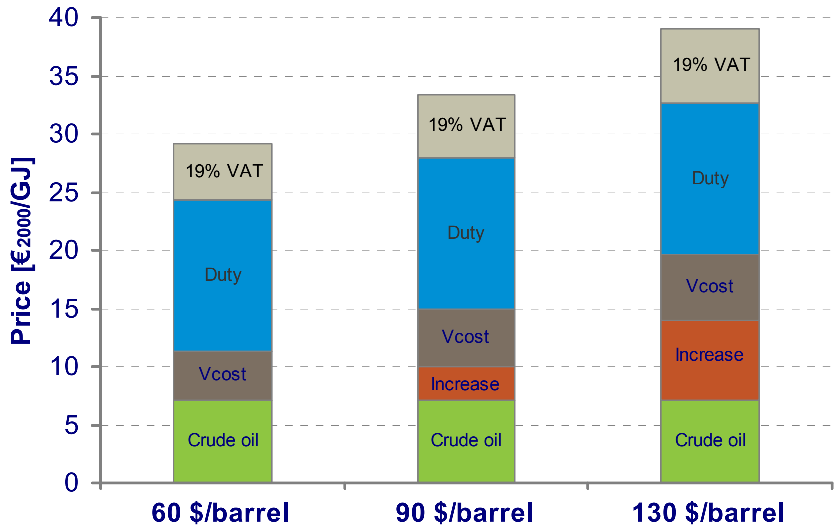


Figure 39: Relation between crude oil price increase and consumer price increase for the mean EU-25 price in 2007 and 2008 (prices in both cases on the 1st January)

The increase until 2030 has been extrapolated using the price scenario. The duty is kept constant.

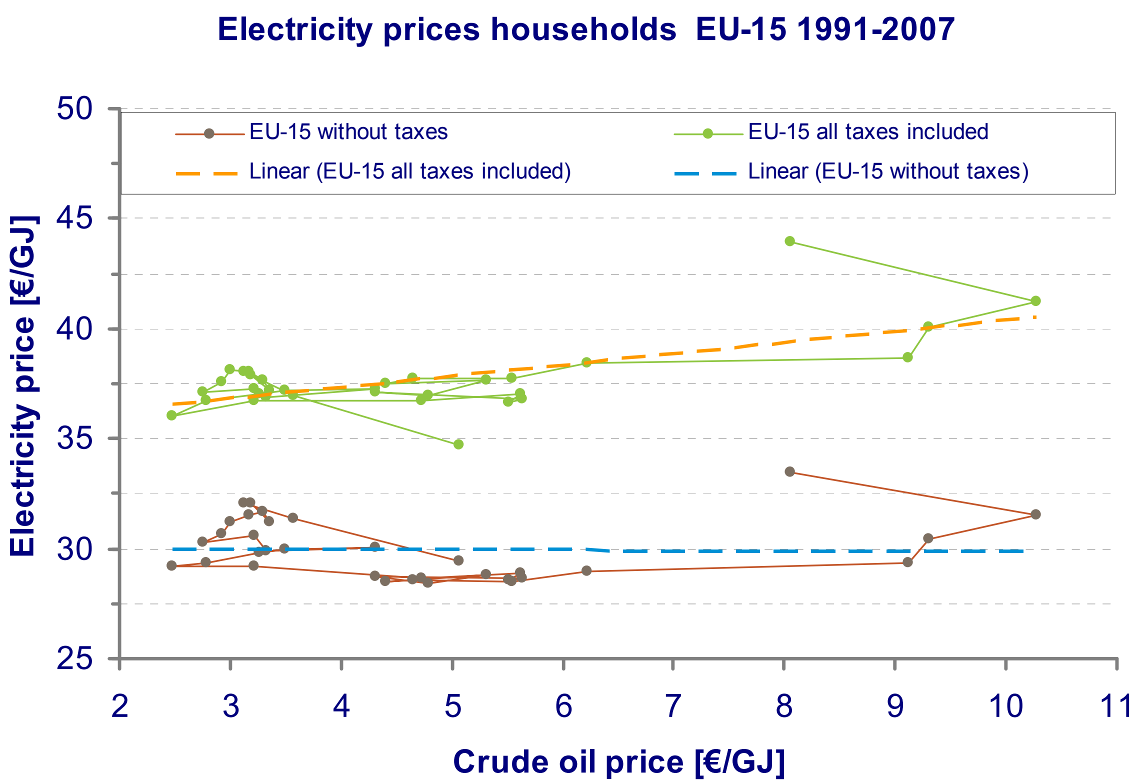


Figure 40: EU-15 household electricity prices vs crude oil price from 1991-2007

These steps lead to the following energy prices in 2007 and 2030 in €$_{2000}$ as shown in Table 12 for the lowest, highest and average prices in the EU countries.

Table 12: Energy price variation in the EU countries with all taxes included for consumers and small industry using the different world market prices for oil and gas in 2007 and 2030 from the high price scenario

€$_{2000}$ All taxes included	World market		Consumer				Small Industry	
	Crude oil €/GJ	Gas €/GJ	Gasoline €/GJ LHV	Diesel €/GJ LHV	Gas €/GJ LHV	Electricity €/GJ	Gas €/GJ LHV	Electricity €/GJ
low 2007			21,7	19,7	5,1	16,4	4,3	14,2
mean 2007	7,1	6,0	29,1	23.5	12,1	33.4	9,6	30,1
high 2007			37,2	33.6	26,5	61,5	14,9	49,2
low 2030			31,6	29,6	13.6	19,9	12,9	17,7
mean 2030	14,0	12,0	39,0	33.4	20,6	36,9	18,2	33.6
high 2030			47,1	43.5	35,0	65,0	23.4	52,7

This variation in energy prices enables regions or communities to estimate the effect of their present day energy price on the fuel cost of the reference technology.

Appendix B: CO_2 emissions scenario calculations

In Table 13 the WTW emission factors are provided for conventional fuels. For transport the fuel use (in MJ/km) should be used in order to calculate the emissions in gCO_2/km in the third column. For stationary applications the efficiency in (MJ/kWh) of the process is used for calculation of the emission in gCO_2/kWh in the last column (in this example 40% efficiency or 9 MJ/kWh). The value for biogas is negative since use of biogas will prevent emission of methane into the air, which has a much larger GHG factor.

For diesel an energy density of 35,3 MJ/l is used, for gasoline 31,0 MJ/l.

Table 13: Well to wheel emission factors for other fuels (Sources Concawe);

Concawe (WTW)	Mean [gCO_2/MJ]	*1,4 MJ/km* [gCO_2/km]	*9,0 MJ/kWh* [gCO_2/kWh]
Diesel	87	124	
Gasoline	85	121	
Natural gas	63		566
Biogas	-67		-600

In Table 14 the fuel use for transport (in MJ/km) should be used for the application considered in order to calculate CO_2 emissions in gCO_2/km in the last but one column. For stationary applications use the efficiency in (MJ/kWh) for calculation of the emissions in gCO_2/kWh in the last column. The CO_2 emissions in gCO_2/MJ is estimated using the average of the low and high values for the well to wheel emission factors as shown in Table 14, multiplied by the fuel use of 144 km/kgH_2 and divided by the energy density of 120 MJ/kgH_2. In the HyWays study hydrogen is provided at 700 bar. The effect on the CO_2 emissions of a lower pressure like 100 bar for applications other than transport is smaller than the effect of variation in the pathways for the specific source, and is here neglected.

Table 14: Well to wheel/electricity emission factors for different H_2 sources (Sources www.HyWays.de) and Concawe); FC car efficiency HyWays: 144 km/kgH_2

Concawe (WTW) Compressed H_2	*Low* [gCO_2/km]	*High* [gCO_2/km]	*Mean* [gCO_2/km]	Mean gCO_2/MJ	*1,4 MJ/km* [gCO_2/km]	*9,0 MJ/kWh* [gCO_2/kWh]
Onsite SMR	81	103	92	110	157	991
Waste wood	8	13	10,5	13	18	113
Offshore wind	0	18	9	11	15	97
Coal gasification + CCS	30	45	37,5	45	64	404

In Table 15 the fuel use for transport in MJ/km for batteries should be used in order to calculate the last column. If the electricity is used for producing hdyrogen an electrolyser efficiency 65% (LHV) = 77% (HHV) is used to calculate the CO_2 emissions for hydrogen production from the countries electricity mix in the fifth column. For stationary applications use the efficiency in (MJ/kWh) for calculation of the emission in gCO_2/kWh.

Table 15: Emission factors from electricity production in different countries (Source www.energy.eu and carma.org)

Electricity	*Emissions*	*Energy*	*Electric*	*H_2*	*Electric*	***0,6 MJ/km***
	Mton CO_2	TWh	gCO_2/kWh	gCO_2/MJ	gCO_2/MJ	gCO_2/km
NL	59	98,6	598	218	166	93
DE	323	636	508	185	141	79
FR	41,5	571	73	26	20	11
UK	192,3	399	482	175	134	75
PL	151	162	932	339	259	145
CZ	51	84,3	605	220	168	94
SW	3,2	144,3	22	8	6	3
DK	21,4	45,6	469	171	130	73
EU-25	1347	3143	429	156	119	67
Offshore wind			30	11	8	5

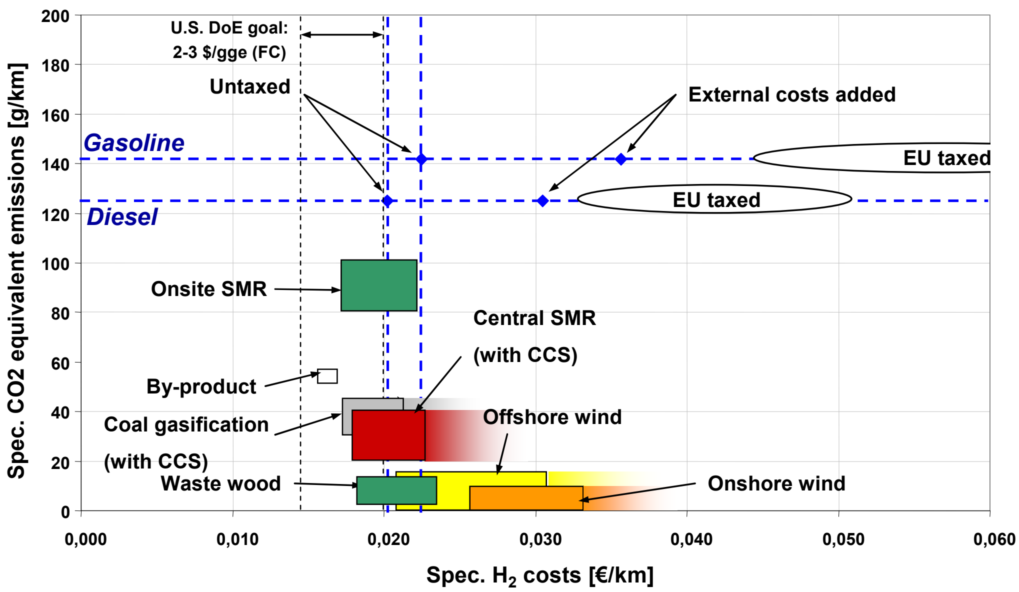


Figure 41: HyWays results on specific H_2 costs and CO_2 equivalent emissions for passenger cars

Appendix C: Case Studies

8. Case Study Fuel Cell Passenger Vehicle

8.1 Description of application

Passenger vehicles provide individual mobility for up to 9 persons. The vehicles are mainly used for commuter traffic, business travel and leisure travel. The main fuels used are gasoline and diesel. The average mileage for these vehicles in Europe is 13 200 km/yr [1].

8.2 Description of reference technology

Many small and large manufacturers of passenger vehicles exist. The range of vehicles is very broad, from the recently announced Tata vehicle of 2500$ to the >1M€ Bugatti Veyron. The reference technology chosen here is the widely used mid-size family car with 4-5 seats, the typical characteristics shown in Table 16.

Table 16: Typical characteristics of the passenger vehicle (2005)

Application	Unit	Diesel engine	Gasoline engine
Power level	kW	*80*	*80*
Efficiency; energy use	MJ/km	*1.95*	*2.02*
Typical cost complete system	€	*25.000*	*25.000*
Specific cost energy system	€/kW	*46*	*35*
Lifetime	year	*15*	*15*
Type of “fuel”	-	*Diesel*	*Gasoline*
Type of “fuel” supply	-	*Fuelling station*	*Fuelling station*
Type of “fuel” storage	-	*Tank (60 l)*	*Tank (60 l)*
Typical storage capacity	MJ	*20000*	*18000*
Range/fuel charge	km	*1000*	*800*
Availability	%/yr		
Maintenance		*Every 25000 km*	*Every 25000 km*

Efficiency improvement of the engines can be expected for the future (2020) [2] to 1.67 MJ/km for gasoline and 1.56 MJ/km for diesel engines. The economic advantage of the lower fuel use will be partly off-set by the increased engine costs [1]. Developments on gasoline and diesel engines for efficiency improvement are described in [7] and summarised in Table 17 and Table 18.

Table 17: Developments in GHG reduction for gasoline vehicles

	Benefits in terms of CO_2 emission	Cost (€)
Normal evolution (see § 2.1 of [7])	*10 - 15 % (see **)*	
Downsizing	10 - 22 %	150 – 600
Stratified combustion	10 - 16 %	500 – 1000
Variable valve actuation	3 - 18 %	50 – 700
Controlled auto ignition	10 - 20 %	
Cylinder deactivation	10 - 15%	
Downsizing + {VCR or stratified or deactivation}	up to 30% ?	

** Partly combinable with enhancement in the following lines of the table.

Table 18: Developments in GHG reductions for diesel vehicles

	Benefit in terms of CO_2 emission	Cost (€)
Downsizing	5-10%	50 – 150
Advanced turbocharging	5-10%	80 - 150
Variable valve actuation	3-4% (urban driving)	150 - 700
Advanced Injection technology	3-4%	150 - 400
Extreme intake gas cooling	3-5%	50-100
Reduction of engine frictions	3-7%	
Cylinder deactivation	5%	50
Thermal Management	1-2% (more in frequent starting use)	

Stricter emission obligations posed by the EU for lowering the CO2 emissions from the average fleet of vehicles from a manufacturer to 120 g CO2/km (well-to-tank) will also increase the need for fuel efficiency. The advantage of fuel cell systems compared to the internal combustion engine on exhaust air quality will decrease in time.
Other engine concepts with a reduced functionality will increase their market share like the electric car and the plug-in hybrid car due to battery development. Fast recharging of the batteries to make these vehicles also fully functional would require an electrical connection of 1 MW or more.

8.3 Description of the market

The European sale of passenger vehicles was 15.36 million vehicles in 2006, approximately 30% of the world market. The main manufacturers with their global production are shown in Table 19. Most manufacturers have different brands and cooperation as well as financial interests between the manufacturers exists. In Europe more than 50% of the vehicles sold run on diesel. This is favoured by the higher efficiency and, in most countries, lower diesel price compared to gasoline. Gasoline is the favourite fuel for low mileage users because of the cheaper engine, and for sporty drivers due to the better acceleration characteristics.

Table 19: Main manufacturers of passenger vehicles

Manufacturer	Country	Global production (2006) *1000
Toyota	JP	6800
GM	USA	5708
VOLKSWAGEN	DE	5430
FORD	USA	3801
Honda	JP	3550
PSA	FR	2961
Nissan	JP	2513
Hyundai	S-Korea	2231
RENAULT	FR	2086
Suzuki	JP	2004
Total all manufacturers		51953

The developments in the car industry are directed to lower greenhouse gas emissions per kilometre, due to stricter regulations. The EU target is 120 gCO_2/km average emission (well-to-tank) for new cars in 2012 through an “integrated approach”.

- 130 g on the vehicle side.
- 10 g through additional measures on car components (tyres, airco etc.) and increased use of biofuels.

A further emission reduction is envisaged afterwards (ERTRAC research target 95 gCO_2/km in 2020).
Improvements in engine efficiency as well as different concepts like hybridization of the energy system are on-going. Plug-in hybrids, that use battery charging from the grid, can reduce local CO_2 emissions from the vehicle. Due to the relative smaller engine size of the hybrid vehicles, the maximum speed of these vehicles is reduced, although still higher than the European speed limits.

8.4 Description of FC/H2 technology for the application

The H_2 PEMFC passenger vehicle has the advantage of the noiseless, odourless and environmental friendly vehicle that can be refuelled in minutes. The power of the fuel cell system is comparable to the power of the reference vehicle. The characteristics of the envisaged passenger vehicle are shown in Table 20 [2].

A hybrid version of fuel cell and batteries is envisaged for improved traction and reduction of dynamic demand compared to a fuel cell system only. In this case also brake energy can be recovered. The hybrid version could also have plug-in capabilities for further reduction of energy consumption, assuming that some of the hydrogen is produced by electrolysis.

Almost all main car manufacturers are developing or demonstrating the combination of fuel cell systems with passenger vehicles, the largest demonstrations being:

- Daimler, who has manufactured 65 Mercedes A-class fuel cell vehicles.
- Honda, who starts limited production of the Honda FCX Clarity for lease.

Table 20: The characteristics of the envisaged fuel cell passenger vehicle

Application	Unit	H_2 PEMFC passenger vehicle
Power level	kW	*80*
Efficiency; energy use	MJ/km	*0.84*
Lifetime	year	*15*
Type of "fuel"	-	*Hydrogen*
Type of "fuel" supply	-	*Filling station*
Type of "fuel" storage	-	*Tank; pressurized 700 bar*
Typical storage capacity	MJ	*360*
Range/fuel charge	km	*400 on H_2*
Availability	%/yr	
Maintenance		*Every 25000 km*

The maintenance requirements of the fuel cell vehicle are expected to be lower than for the ICE engine because of the absence of high temperature rotating equipment and the off-gas system.

8.5 Economic boundary conditions for FC/H2 technology

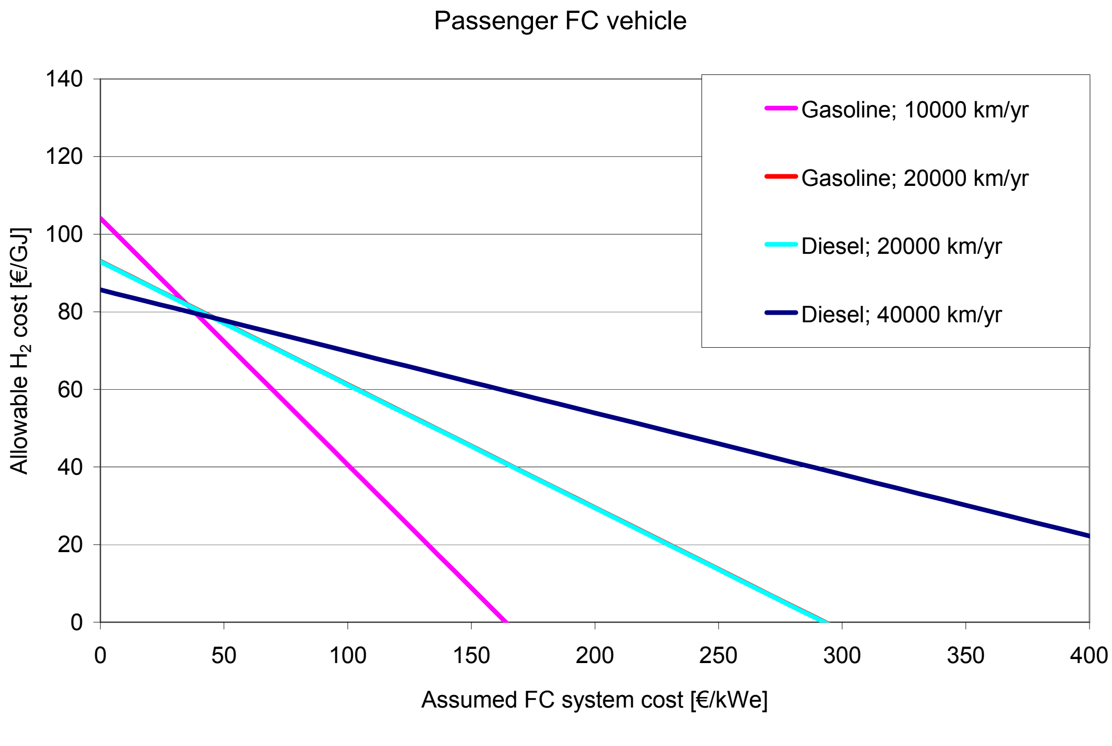


Figure 42: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre for passenger vehicles with a yearly mileage of 10 000 and 20 000 km on gasoline and 20 000 and 40 000 km on diesel. All taxes included for the fuel

The reference technology, 80 kW ICE operating on gasoline or diesel is considered for the economic evaluation. The average European diesel and gasoline prices in 2007 are used for the economic evaluation. In Figure 42 the allowable cost of H_2 as a function of the assumed FC system cost is shown at the same cost per kilometre as the reference vehicle. Yearly mileages of 10 000 and 20 000 km for gasoline and 20 000 and 40 000 km for diesel are considered. Figure 42 is based on the input in Table 21.

The prices are with all taxes included for the engine, the maintenance (extracted from [3]) as well as the fuel. For the fuel cell system the maintenance is expected to have half the cost of the gasoline engine since there is no high temperature rotating equipment. The effect of interest rates on the results is neglected.

Table 21: Background table for Figure 42 for the same cost in €/km for a passenger vehicle with a gasoline or diesel ICE compared to a fuel cell system, only taking into account fuel cost and engine cost

Reference system		Gasoline	Gasoline	Diesel	Diesel
Engine cost	€/kW	35.0	35.0	45.6	45.6
Power	kW	80	80	80	80
Lifetime	yr	15	15	15	15
Distance	km/yr	10000	20000	20000	40000
Specific investment cost	€/km	0.019	0.009	0.012	0.006
Fuel cost	€/GJ	29.1	29.1	23.5	23.5
Fuel use	MJ/km	2.02	2.02	1.95	1.95
Specific fuel cost	€/km	0.059	0.059	0.046	0.046
Engine maintenance cost	€/km	0.020	0.020	0.030	0.030
Total cost	€/km	0.097	0.088	0.088	0.082
FC system					
Power	kW	80	80	80	80
Lifetime	yr	15	15	15	15
Distance	km/yr	10000	20000	20000	40000
Fuel use	MJ/km	0.84	0.84	0.84	0.84
Engine maintenance cost	€/km	0.010	0.010	0.010	0.010

Assumed FC system cost €/kWe		Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0		104	93	93	86
200		-23	30	29	54
500		-213	-66	-66	6
1000		-531	-224	-225	-73
2000		-1166	-542	-542	-232
4000		-2436	-1177	-1177	-549

The fuel cell vehicle is economically attractive if in Figure 42 the combination of cost of hydrogen and the cost of the fuel cell engine are below the line for the reference technology. The lifetime of the fuel cell system is assumed as 15 years, the same as for the reference technology. If the lifetime is lower, than the fuel cell system cost should be read as the costs including replacement costs of the fuel cell.

The lifetime of the batteries for the (hybrid) fuel cell vehicle is expected to last more than
250 000 km, equivalent to the expected lifetime of the batteries in current hybrids (Toyota offers a 160 000 km warranty on the battery pack [4]). The batteries are not taken into account in this analysis.

Fuel cost scenarios
The effect of the different diesel fuel costs on the assumed fuel cell system costs and the allowed hydrogen costs is provided in Figure 43 For reference, the following average European diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (21.7 €/GJ)
- The mean 2007 value with all taxes (29.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (47.1 €/GJ)

This figure shows that the effect of different diesel fuel prices on the economy is significant; with a high spread due to the efficiency of the ICE vehicle. The effects from the developments until 2030 on the economy of the reference vehicle are assumed to compensate each other. These developments are higher engine prices in order to reach lower emissions and higher efficiency of the engine, thereby reducing fuel costs [1].

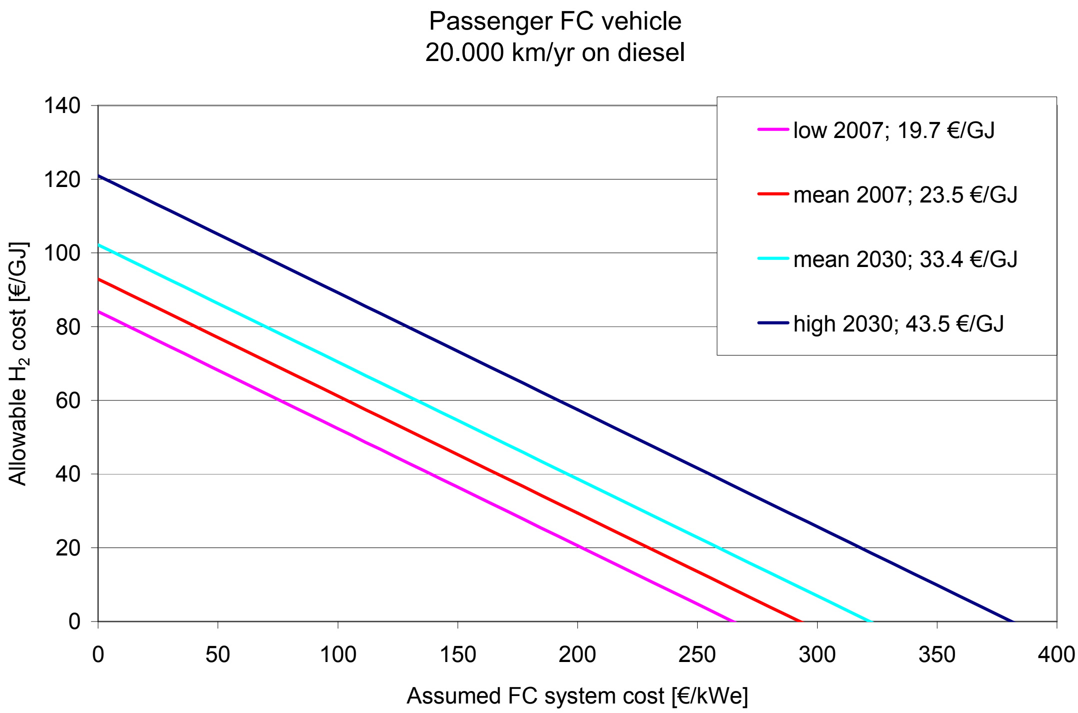


Figure 43: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of diesel with all taxes included

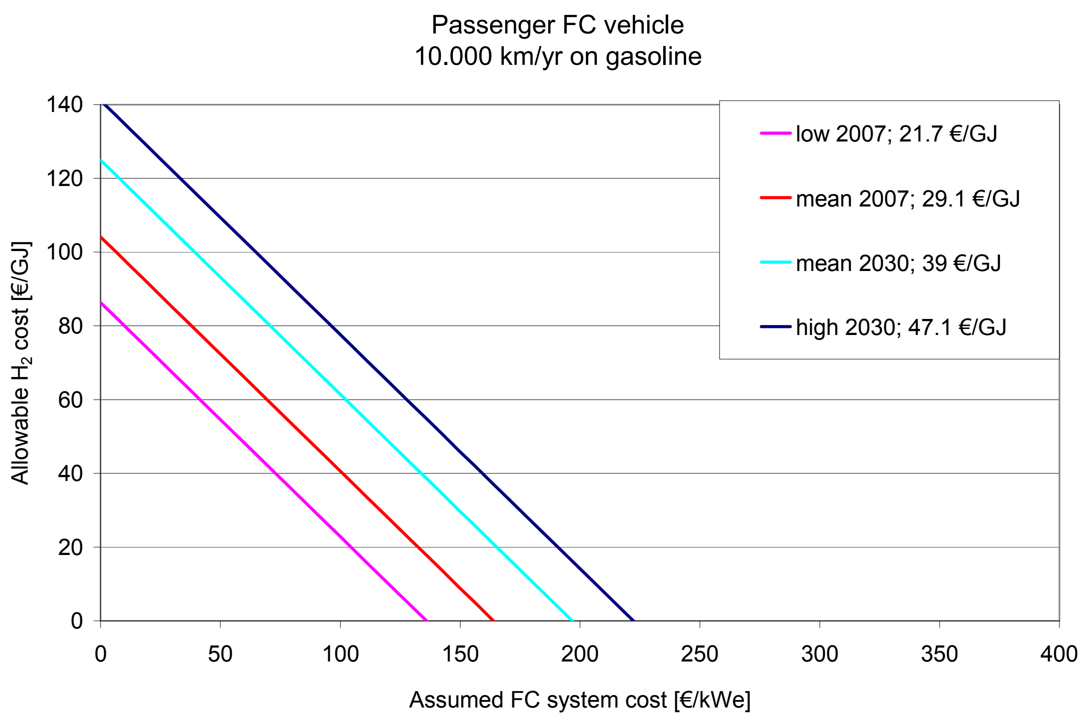


Figure 44: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of gasoline with all taxes included

8.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

The CO_2 emission from the ICE passenger vehicle is calculated for future vehicles as 136 gCO_2/km using diesel and 133 gCO_2/km using gasoline. The emission factor from the CONCAWE study [4] of 87 gCO_2/MJ is used for diesel as well as gasoline. The CO_2 emissions and emission factors for the hydrogen fuel cell passenger vehicles in different countries are shown in Table 22. In this table it is assumed that the hydrogen is produced by electrolysis. In Table 23 the CO_2 emissions and emission factors for the fuel cell passenger vehicle are presented in relation to the source for the hydrogen.

Table 22: CO_2 emission factors for fuel cell vehicles (4th column) in different countries (Source www.energy.eu [5] and carma.org [6])

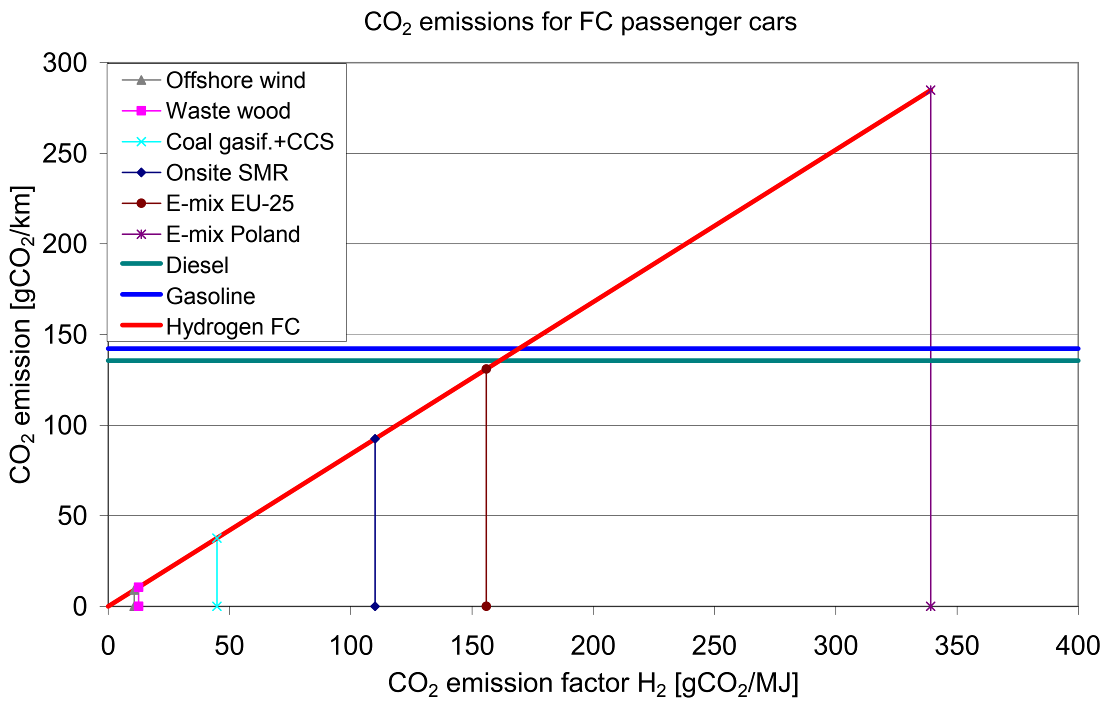
Electricity	*Electricity E-mix*	*H2 from E Electrolysis*	*Hydrogen* ***0.84 MJ/km***
	gCO_2/MJ	gCO_2/MJ	gCO_2/km
NL	166	218	183
DE	141	185	155
FR	20	26	22
UK	134	175	147
PL	259	339	285
CZ	168	220	185
SW	6	8	7
DK	130	171	143
EU-25	119	156	131
Offshore wind	8	11	9

Table 23: CO_2 emission for fuel cell vehicle in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***0.84 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/km
Onsite SMR	110	92
Waste wood	13	11
Offshore wind	11	9
Coal gasification + CCS	45	38

CO_2 reduction potential per service and for the potential market.
The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 45. Only sources that are below the green line for diesel or the blue line for gasoline have a positive impact on global warming compared to diesel or gasoline.

The maximum CO_2 reduction for the diesel license-free vehicle market can be obtained by replacing diesel from fossil fuel sources with fuel cells operating on hydrogen produced by electrolysis of off shore wind electricity. This is calculated by multiplying the maximum reduction potential of the service (≈ 125 gCO_2/km) with the mileage/year (≈ 13200 km/yr), the number of new units/year (≈ 15.400.000) and the lifetime of the vehicles (≈ 15 year). The maximum CO_2 reduction is then approximately 380 Mton CO_2/yr.



– **Figure 45: CO_2 emission reduction potential for replacement of diesel and gasoline passenger vehicles**

8.7 Conclusions and recommendations

The following general conclusions can be taken:
If hydrogen is produced by electrolysis, the electricity for this should be produced in a sustainable way in order to obtain significant CO_2 reduction

8.8 References

1. DRIVE the future of Automotive Power; McKinsey&Company; 2006
2. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
3. Information from www.anwb.nl
4. http://www.hybridcars.com/faq.html
5. www.energy.eu, *last visited November 2007*
6. carma.org, *last visited November 2007*
7. “Tank to user: Adequation technology/objective and carbon balance” Report on WT4.4 of Roads2HyCom; June 2008

9. Case study H2-ICE passenger vehicle

9.1 Description of application

Passenger vehicles provide individual mobility for up to 9 persons. The vehicles are mainly used for commuter traffic, business travel and leisure travel. The main fuels used are gasoline and diesel. The average mileage for these vehicles in Europe is 13 200 km/yr [1].

9.2 Description of reference technology

Many small and large manufacturers of passenger vehicles exist. The range of vehicles is very broad, from the recently announced Tata vehicle of 2500$ to the >1M€ Bugatti Veyron. The reference technology chosen here is the widely used mid-size family car with 4-5 seats, the typical characteristics shown in Table 24.

Table 24: Typical characteristics of the passenger vehicle (2005)

Application	Unit	Diesel engine	Gasoline engine
Power level	kW	*80*	*80*
Efficiency; energy use	MJ/km	*1.95*	*2.02*
Typical cost complete system	€	*26.000*	*25.000*
Specific cost energy system	€/kW	*46*	*35*
Lifetime	year	*15*	*15*
Type of "fuel"	-	*Diesel*	*Gasoline*
Type of "fuel" supply	-	*Fuelling station*	*Fuelling station*
Type of "fuel" storage	-	*Tank (60 l)*	*Tank (60 l)*
Typical storage capacity	MJ	*20000*	*18000*
Range/fuel charge	km	*1000*	*800*
Availability	%/yr		
Maintenance		*Every 25000 km*	*Every 25000 km*

Efficiency improvement of the engines can be expected for the future (2020) [2] to 1.67 MJ/km for gasoline and 1.56 MJ/km for diesel engines. The economic advantage of the lower fuel use will be partly off-set by the increased engine costs [1].
Stricter emission obligations posed by the EU for lowering the CO_2 emissions from the average fleet of vehicles from a manufacturer to 120 g CO_2/km (well-to-tank) will also increase the need for fuel efficiency. The advantage of hydrogen over gasoline in the internal combustion engine on exhaust air quality will decrease in time.
Other engine concepts with a reduced functionality will increase their market share like the electric car and the plug-in hybrid car due to battery development. Fast recharging of the batteries to make these vehicles also fully functional would require an electrical connection of 1 MW or more.

9.3 Description of the market

The European sale of passenger vehicles was 15.36 million vehicles in 2006, approximately 30% of the world market. The main manufacturers with their global production are shown in Table 25. Most manufacturers have different brands and cooperation as well as financial interests between the manufacturers exists. In Europe more than 50% of the vehicles sold run on diesel. This is favoured by the higher efficiency and, in most countries, lower diesel price compared to gasoline. Gasoline is the favourite fuel for low mileage users because of the cheaper engine, and for sporty drivers due to the better acceleration characteristics.

Table 25: Main manufacturers of passenger vehicles

Manufacturer	Country	Global production (2006) *1000
Toyota	JP	6800
GM	USA	5708
VOLKSWAGEN	DE	5430
FORD	USA	3801
Honda	JP	3550
PSA	FR	2961
Nissan	JP	2513
Hyundai	S-Korea	2231
RENAULT	FR	2086
Suzuki	JP	2004
Total all manufacturers		51953

The developments in the car industry are directed to lower greenhouse gas emissions per kilometre, due toe stricter regulations. Efficiency improvement technologies and developments are described in [6]. The EU target is 120 gCO_2/km average emission (well-to-tank) for new cars in 2012 through an "integrated approach".

- 130 g on the vehicle side.
- 10 g through additional measures on car components (tyres, airco etc.) and increased use of biofuels.

A further emission reduction is envisaged afterwards (ERTRAC research target 95 gCO_2/km in 2020).

9.4 Description of H2-ICE technology for the application

The H_2-ICE passenger vehicle has the advantage of the odourless and environmental friendly vehicle that can be refuelled in minutes. Some examples of this technology have dual fuel capability, meaning that they can operate on gasoline as well as hydrogen. A low density of H_2 filling stations in the initial development of the hydrogen economy can be overcome using gasoline as fuel when hydrogen is not available. The characteristics of the envisaged passenger vehicle are shown in Table 26 [2].

Table 26: The characteristics of the envisaged H2 ICE passenger vehicle

Application	Unit	H_2 ICE passenger vehicle
Power level	kW	*80*
Efficiency; energy use	MJ/km	*1.68*
Lifetime	year	*15*
Type of "fuel"	-	*Hydrogen*
Type of "fuel" supply	-	*Filling station*
Type of "fuel" storage	-	*LH_2 tank or 700 bar tank*
Typical storage capacity	MJ	*960 (LH_2)*
Range/fuel charge	km	*570 on LH_2*
Availability	%/yr	
Maintenance		*Every 25000 km*

Some car manufacturers are developing H_2-ICE passenger vehicles:

- BMW.

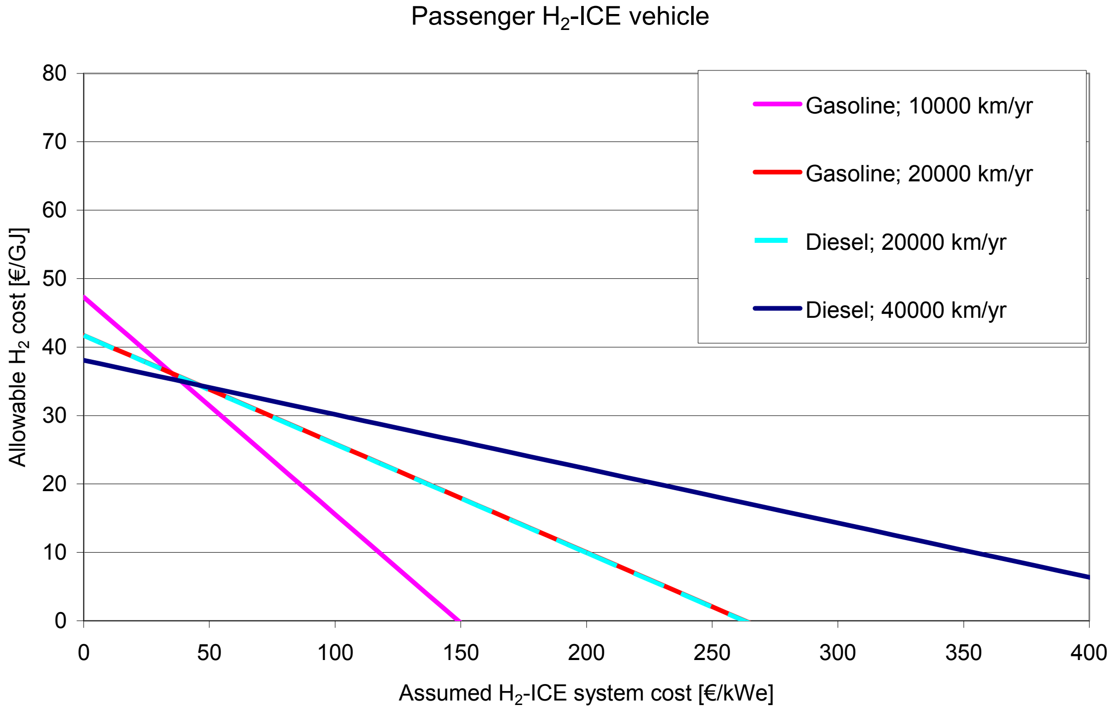
- Ford/Mazda
- Fiat

BMW offers the hydrogen dual fuel option on their luxurious 7 series (191 kW, 6 l ICE). The energy consumption of this vehicle is 4.3 MJ/km on H_2, leading to a 200 km range with the 8 kg (120 l) LH_2 storage tank.

Quantum Technologies provides a package for conversion of the gasoline Toyota Prius into a hydrogen hybrid. This provides a relative low cost option for obtaining experience with hydrogen as a transport fuel.

Alternative developments are the use of CNG as fuel. This will give lower CO_2 emissions than using hydrogen produced from natural gas, the nowadays widely used process for hydrogen production.

9.5 Economic boundary conditions for H_2-ICE technology



– **Figure 46: Allowable cost of H_2 as a function of the assumed H_2-ICE system cost at the same cost per kilometre for passenger vehicles with a yearly mileage of 10 000 and 20 000 km on gasoline and 20 000 and 40 000 km on diesel. All taxes included for the fuel**

The reference technology, 80 kW ICE operating on gasoline or diesel is considered for the economic evaluation. The average European diesel and gasoline prices in 2007 are used for the economic evaluation. In Figure 46 the allowable cost of H_2 as a function of the assumed H_2-ICE system cost is shown at the same cost per kilometre as the reference vehicle. Yearly mileages of 10 000 and 20 000 km for gasoline and 20 000 and 40 000 km for diesel are considered. Figure 46 is based on the input in Table 27.

The prices are with all taxes included for the engine, the maintenance (extracted from [3]) as well as the fuel. For the single fuel H_2-ICE system the maintenance is expected to be slightly lower than the cost of the gasoline engine since the off-gas system can be simpler. For dual fuel systems the maintenance costs will be slightly higher. The effect of interest rates on the results is neglected.

Table 27: Background table for Figure 46 for the same cost in €/km for a passenger vehicle with a gasoline or diesel ICE compared to a H2-ICE system, only taking into account fuel cost and engine cost

Reference system		**Gasoline**	**Gasoline**	**Diesel**	**Diesel**
Engine cost	€/kW	35.0	35.0	45.6	45.6
Power	kW	80	80	80	80
Lifetime	yr	15	15	15	15
Distance	km/yr	10000	20000	20000	40000
Specific investment cost	€/km	0.019	0.009	0.012	0.006
Fuel cost	€/GJ	29.1	29.1	23.5	23.5
Fuel use	MJ/km	2.02	2.02	1.95	1.95
Specific fuel cost	€/km	0.059	0.059	0.046	0.046
Engine maintenance cost	€/km	0.020	0.020	0.030	0.030
Total cost	€/km	0.097	0.088	0.088	0.082
H_2-ICE system					
Power	kW	80	80	80	80
Lifetime	yr	15	15	15	15
Distance	km/yr	10000	20000	20000	40000
Fuel use	MJ/km	1.68	1.68	1.68	1.68
Engine maintenance cost	€/km	0.018	0.018	0.018	0.018

Assumed H_2-ICE system cost €/kWe		Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0		53	48	42	38
200		-10	16	10	22
500		-106	-32	-38	-2
1000		-264	-111	-117	-41
2000		-582	-270	-276	-121
4000		-1217	-587	-593	-279

The H_2-ICE vehicle is economically attractive if in Figure 46 the combination of cost of hydrogen and the cost of the H_2-ICE engine are below the line for the reference technology.

Fuel cost scenarios

The effect of the different diesel fuel costs on the assumed fuel cell system costs and the allowed hydrogen costs is provided in Figure 47 For reference, the following average European diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (21.7 €/GJ)
- The mean 2007 value with all taxes (29.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (47.1 €/GJ)

This Figure shows that the effect of different diesel fuel prices on the economy is significant; with a high spread due to the efficiency of the ICE vehicle. The effects from the developments until 2030 on the economy of the reference vehicle are assumed to compensate each other. These developments are higher engine prices in order to reach lower emissions and higher efficiency of the engine, thereby reducing fuel costs.

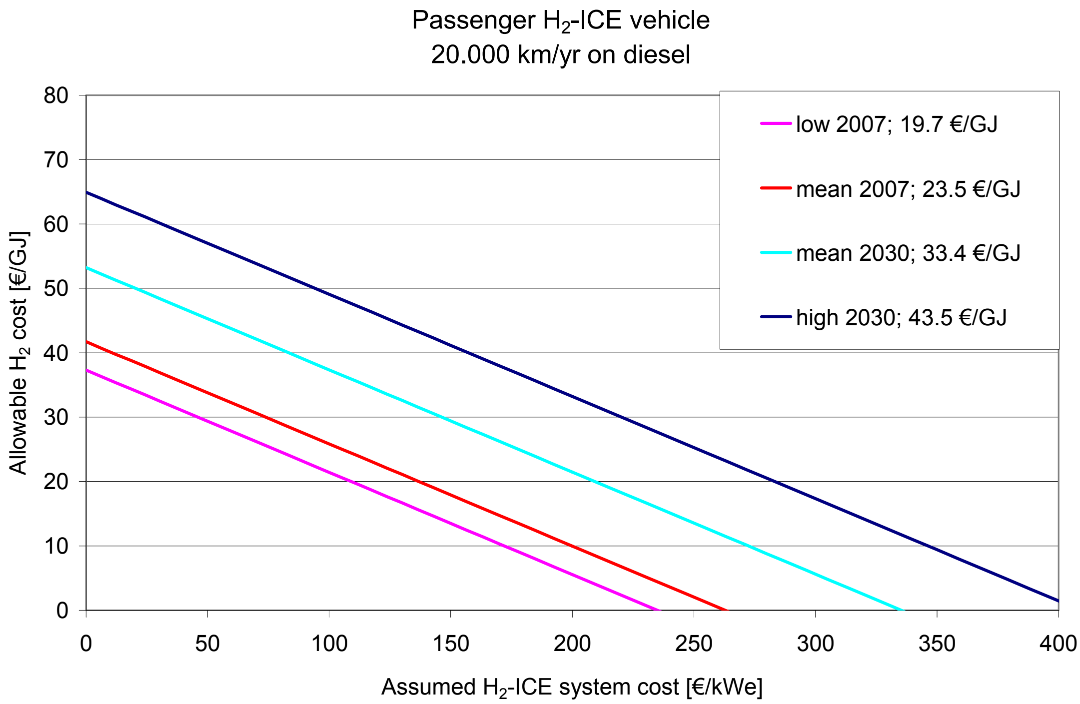


Figure 47: Allowable hydrogen costs vs. assumed H_2-ICE system cost of 4 different energy prices of diesel with all taxes included

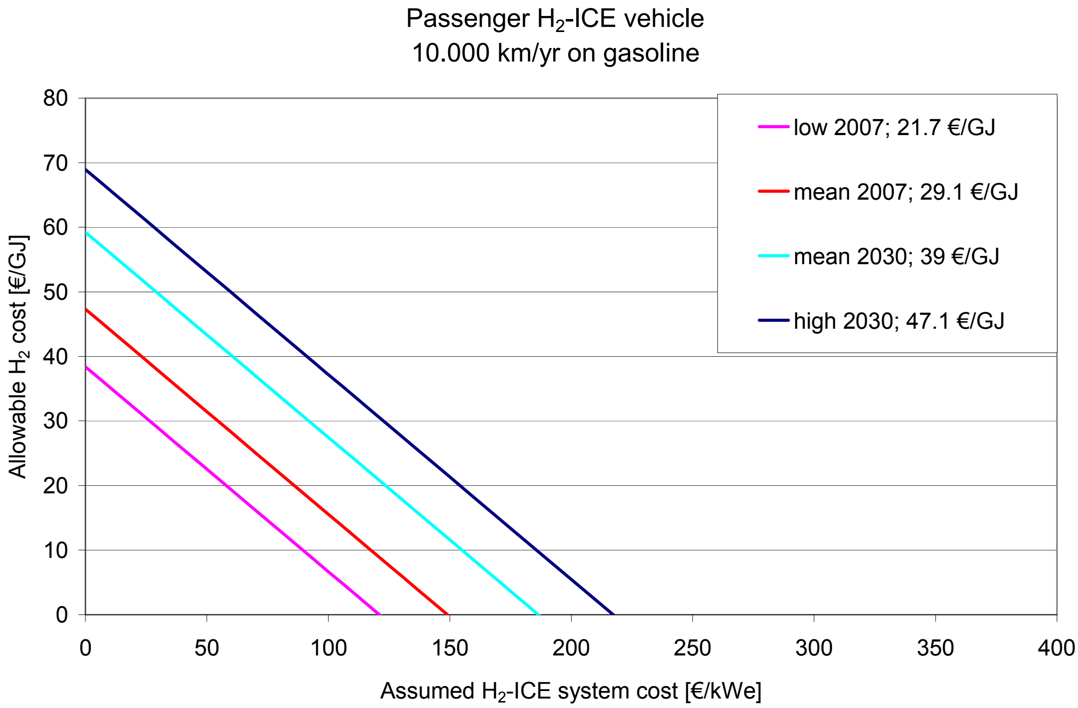


Figure 48: Allowable hydrogen costs vs. assumed H_2-ICE system cost of 4 different energy prices of gasoline with all taxes included

9.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology
The CO_2 emission from the ICE passenger vehicle is calculated for future vehicles as 136 gCO_2/km using diesel and 133 gCO_2/km using gasoline. The emission factor from the CONCAWE study [4] of 87 gCO_2/MJ is used for diesel as well as gasoline. The CO_2 emissions and emission factors for the hydrogen fuel cell passenger vehicles in different countries are shown in Table 28. In this table it is assumed that the hydrogen is produced by electrolysis and compressed. In Table 29 the CO_2 emissions and emission factors for the fuel cell passenger vehicle are presented in relation to the source for the hydrogen.

Table 28: CO_2 emission factors for fuel cell vehicles (4th column) in different countries (Source www.energy.eu [4] and carma.org [5])

Electricity	*Electricity E-mix*	*H_2 from E Electrolysis*	*Hydrogen* ***1.68 MJ/km***
	gCO_2/MJ	gCO_2/MJ	gCO_2/km
NL	166	218	366
DE	141	185	310
FR	20	26	44
UK	134	175	295
PL	259	339	570
CZ	168	220	370
SW	6	8	14
DK	130	171	287
EU-25	119	156	262
Offshore wind	8	11	18

Table 29: CO_2 emission for fuel cell vehicle in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***1.68 MJ/km***
Compressed H_2	gCO_2 /MJ	gCO_2/km
Onsite SMR	110	185
Waste wood	13	21
Offshore wind	11	18
Coal gasification + CCS	45	75

CO_2 reduction potential per service and for the potential market.
The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 49. Only sources that are below the green line for diesel or the blue line for gasoline have a positive impact on global warming compared to diesel or gasoline.

The maximum CO_2 reduction for the diesel license-free vehicle market can be obtained by replacing diesel from fossil fuel sources with fuel cells operating on hydrogen produced by electrolysis of off shore wind electricity. This is calculated by multiplying the maximum reduction potential of the service (≈ 115 gCO_2/km) with the mileage/year (≈ 13200 km/yr), the number of new units/year (≈ 15.400.000) and the lifetime of the vehicles (≈ 15 year). The maximum CO_2 reduction is then approximately 350 Mton CO_2/yr.

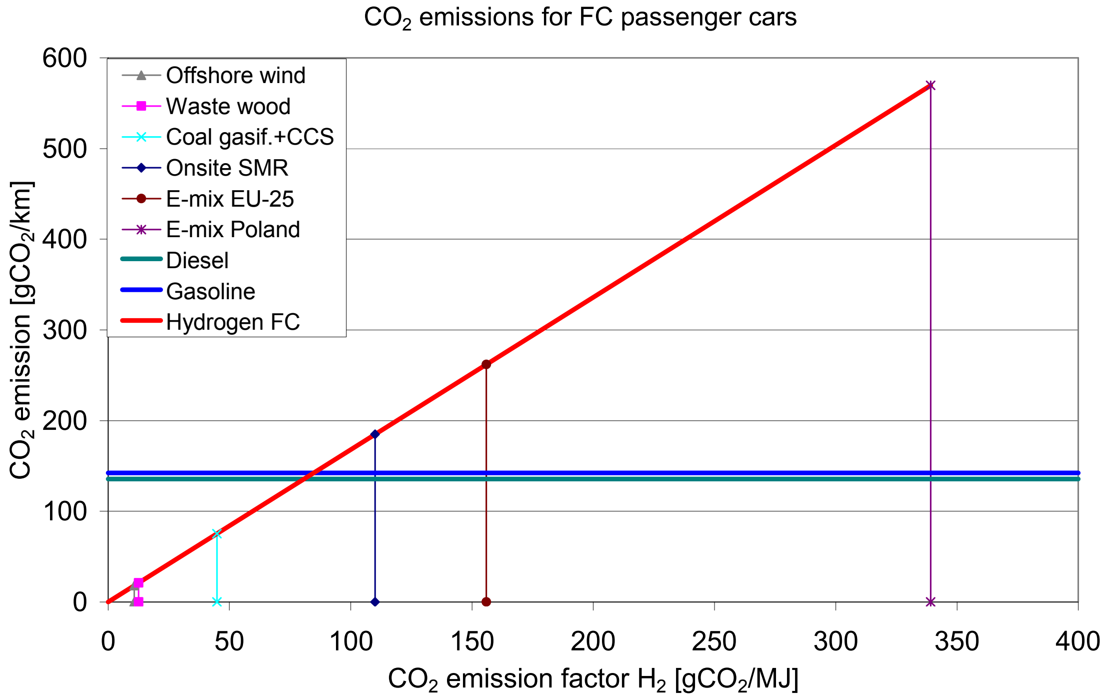


Figure 49: CO_2 emission reduction potential for replacement of diesel and gasoline passenger vehicles

9.7 Conclusions and recommendations

The following general conclusions can be taken:
If hydrogen is produced by electrolysis, the electricity for this should be produced in a sustainable way in order to obtain significant CO_2 reduction. The total amount of energy needed from source to user is higher than using diesel or gasoline

Recommendations:
From energy point of view only intermediate solution with potential CO_2 reduction. The fuel cell solution is much more efficient.

9.8 References

1. DRIVE the future of Automotive Power; Mc Kinsey&Company; 2006
2. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
3. Information from www.anwb.nl
4. www.energy.eu, *last visited November 2007*
5. carma.org, *last visited November 2007*
6. “Tank to user: Adequation technology/objective and carbon balance”, Roads2HyCom task 4.3 report; June 2008.

10. Case study Fuel Cell bus

10.1 Description of application

The main application of buses is the transport of passengers in the public sector. Here we can divide this application into two different types of buses:

- Long Range bus: This type of bus is used to transport passengers on long distances. Mostly the bus operates under full load.
- City bus: The location of this type is the city traffic. The main operation type of this bus is the part load.

Buses are one of the main passenger transport possibilities in cities. Therefore each city needs a big amount of passenger buses to ensure the needed transport performance.
Because of the heavy weight and the discontinuous driving cycle of each bus the engine power has to reach ca. 220 kW to ensure a reliable operation. For this study city buses are chosen.

10.2 Description of reference technology

Today, most buses are equipped with a Diesel internal combustion engine. An alternative to the single Diesel engine is to combine the Diesel engine with an electric motor to build a hybrid. With a series hybrid it is possible for the Diesel ICE to operate at the optimal operation points for each situation. The average speed of the city buses is below 50 km/h. Figure 50 shows a few examples of typical city buses.

Figure 50: Examples of city buses: Mercedes Citaro LE (left); MAN Lions City bus (right)

For this case study the Mercedes Citaro LE has been chosen as the typical substitute for a city bus. It is equipped with a Diesel ICE which has a performance of 220 kW. It is equipped with 45 seats and the standing room offers place for further 38 passengers. Table 30 shows the technical data of this bus. [1]

Table 30: Characteristics of the Mercedes Citaro LE

Application	Unit	Mercedes Citaro LE
Power level	kW	*220*
Efficiency; energy use	MJ/km	*12,2*
Typical cost complete system	€	*270000*
Specific cost energy system	€/kW	*46*
Lifetime	year	*15*
Type of “fuel”	-	*Diesel*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Fuel tank*
Typical storage capacity	MJ	*12580*
Range/fuel charge	km	*1000*
Availability	%/yr	--
Maintenance		--

The advantage of a FC is the lower fuel consumption. This advantage is reduced by the high acquisition costs of a FC. The Diesel engine will develop in the near future and reduce its fuel consumption. The hybrid is not the only solution to reduce the fuel consumption. A further possibility is the optimization of the combustion process.
Also the emissions of the Diesel engine will decrease. Technologies like SCR or the oxidation catalytic converter will increase their potential and decrease the emission advantage of the FC.

10.3 Description of the market

The market discussed in this study is the city bus. There are several producers that offer different types of city buses. The buses differ in the quantity of seats and the performance of the engine. In Table 31 the main supplier of city buses are shown.

Table 31: Market for city buses

Supplier	Country	Power	ICE vehicles /yr
Mercedes	D	≤ 220 kW	
MAN	D	≤ 265 kW	7.300 /2/
Solaris	PL	≤ 220 kW	
Volvo	SE	≤ 265 kW	
Scania	SE	≤ 230 kW	
Neoplan	D	≤ 260 kW	
Total			40.000

10.4 Description of FC/H2 technology for the application

Because of the special operation mode of a city bus and the specific parameters of a fuel cell it is a good alternative for a Diesel engine. The fuel cell has lower fuel consumption and lower emissions. The only disadvantages are the higher acquisition costs of a fuel cell system.
One advantage of the fuel cell is the efficiency. The efficiency of a fuel cell is higher as the efficiency of a Diesel ICE. Further the efficiency of a fuel cell is higher in the part load. This property is very important for the city bus application because the main operation mode is in part load.

Because of the lower exhaust emissions or the lower noise the FC bus is very qualified for the city operation. This reduces the stress on passengers and on the residents.
City buses require a big range of operation without refuelling while they are in use. After they have returned they can refuel at the local fuelling station of the mentioned company.
The specific parameters of the FC bus are shown in Table 32.

The following companies are developing or demonstrating the combination of fuel cell systems with city buses:

- Mercedes (D) has developed and demonstrated the Citaro BZ with a 250 kW fuel cell
- MAN (D) developed and demonstrated a FC bus with 120 kW

Table 32: The characteristics of the considered FC city bus

Application	Unit	H_2 PEMFC city bus
Power level	kW	*220*
Efficiency; energy use	MJ/km	*5,86*
Lifetime	year	*15*
Type of "fuel"	-	*Hydrogen*
Type of "fuel" supply	-	*Filling station*
Type of "fuel" storage	-	*Tank; pressurized*
Typical storage capacity	MJ	*1180*
Range/fuel charge	km	*200*
Availability	%/yr	
Maintenance		

10.5 Economic boundary conditions for FC/ H2 technology

The 2 technologies Diesel ICE and Diesel ICE hybrid have been considered for the economic evaluation. The Mercedes Citaro LE is used as the reference technology for this evaluation. The fuel consumption of the fuel cell is based on the calculation of the reduction factor between Diesel ICE and PEMFC from [6]. Because of the similar operation modes (full load/part load) the reduction factor is assumed to be equal to the reduction factor of the utility vehicle. Further optimization for fuel cell is thought to be for increased transient operation of bus. The average European energy prices for consumers or small companies in 2007 are used for the economic evaluation. In Figure 51 is shown a comparison of the allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre as the Citaro LE Diesel or Diesel hybrid. The mileages of 50000 and 60000 km/yr have been considered. The specific parameters of Figure 51 are based on Table 33. The fuel consumption of the hybrid is 12 % lower than the fuel consumption of the conventional Diesel engine. Figure 51 shows that the higher acquisition costs of the Diesel Hybrid leads to a higher potential for the H_2 fuel cell. This induces possible higher H_2 fuel cell costs or higher H_2 costs. If the FC is compared to the conventional Diesel ICE the potential for the costs would be smaller. An increased mileage would lead to an advantage of the Diesel hybrid to the conventional Diesel ICE because of the lower fuel consumption.

The prices are with all taxes included for the engine, the maintenance as well as the fuel.

Table 33: Background table for Figure 15 for the same cost in €/km for a city bus with a Diesel ICE and a Diesel hybrid compared to a fuel cell system, only taking into account fuel cost and engine cost

Reference system		**Diesel ICE**	**Diesel Hybrid**	**Diesel ICE**	**Diesel Hybrid**
Engine cost	€/kW	46	66	46	66
Power	kW	220	220	220	220
Lifetime	yr	15	15	15	15
Distance	km/yr	50000	50000	60000	60000
Specific investment cost	€/km	0,013	0,019	0,011	0,016
Fuel cost	€/GJ	23,5	23,5	23,5	23,5
Fuel use	MJ/km	12,20	10,70	12,20	10,70
Specific fuel cost	€/km	0,287	0,251	0,287	0,251
Engine maintenance cost	€/km	0,07	0,09	0,07	0,09
Total cost	€/km	0,366	0,358	0,364	0,356
FC system					
Power	kW	220	220	220	220
Lifetime	yr	15	15	15	15
Distance	km/yr	50000	50000	60000	60000
Fuel use	MJ/km	5,86	5,86	5,86	5,86
Engine maintenance cost	€/km	0,07	0,07	0,07	0,07

Assumed FC system cost €/kWe	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0	51	50	50	49
200	41	40	42	41
500	26	25	30	28
1000	1	0	9	7
2000	-49	-51	-33	-34
4000	-149	-151	-116	-118

The fuel cell bus is economical attractive if in Figure 51 the combination of H_2 costs and the acquisition costs are below the line of the reference technologies. The lifetime of the fuel cell system is also assumed to 15 years. If the lifetime of the fuel cell is lower the fuel cell has to be exchanged and the costs have to be added to the acquisition costs.

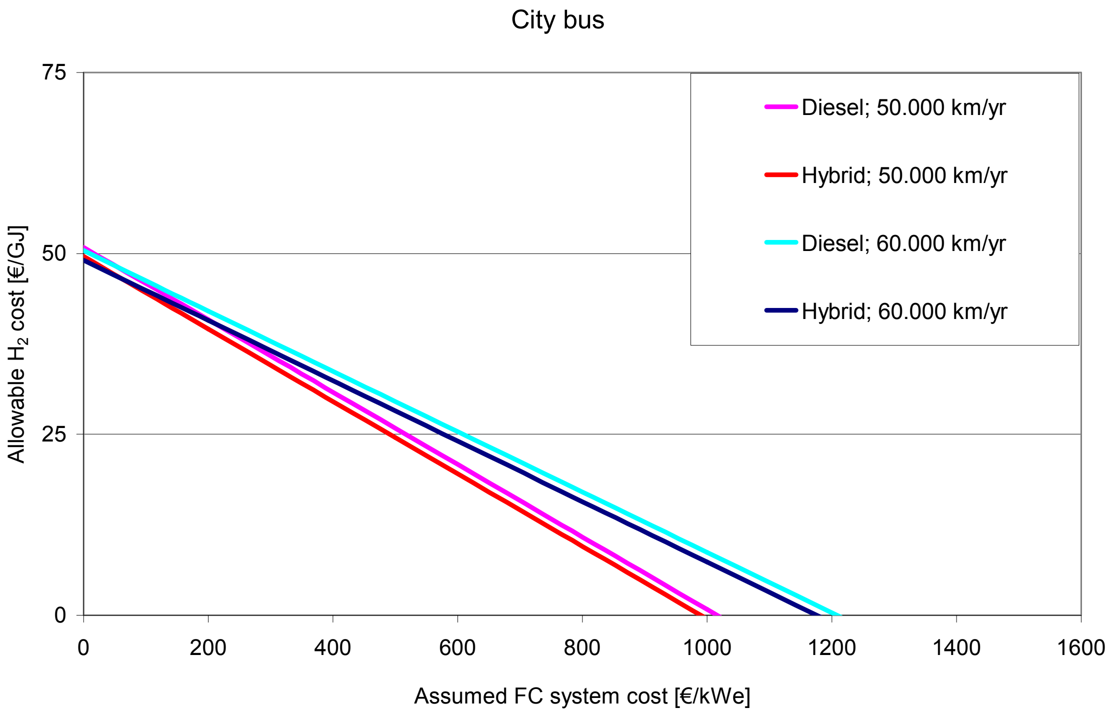


Figure 51: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre as for Diesel hybrid bus with a yearly mileage of 50 000 and 60 000 km and Diesel bus with a yearly mileage of 50 000 and 60 000 km. All taxes included

Fuel cost scenarios

In Figure 52 we see the influence of the increasing energy price on the fuel cell system in comparison to the reference technologies.
For reference, the following average European Diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (19.7 €/GJ)
- The mean 2007 value with all taxes (23.5 €/GJ)
- The mean 2030 value with all taxes (33.4 €/GJ)
- The high 2030 value with all taxes (43.5 €/GJ)

Both Figures show a wide spread of the graphs because of the high influence of the high fuel consumption of the Diesel engine. This scenario shows also that the higher acquisition costs of the Diesel hybrid leads to a higher potential for the FC. A higher mileage would compensate this disadvantage to the conventional Diesel engine.

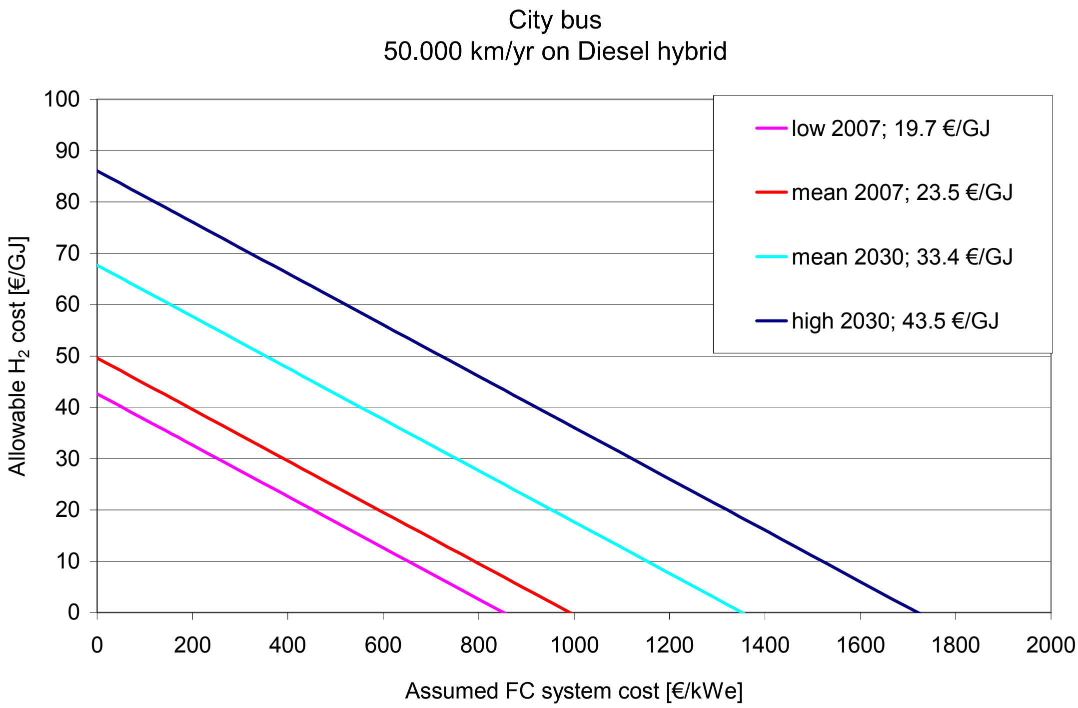


Figure 52: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of diesel with all taxes included

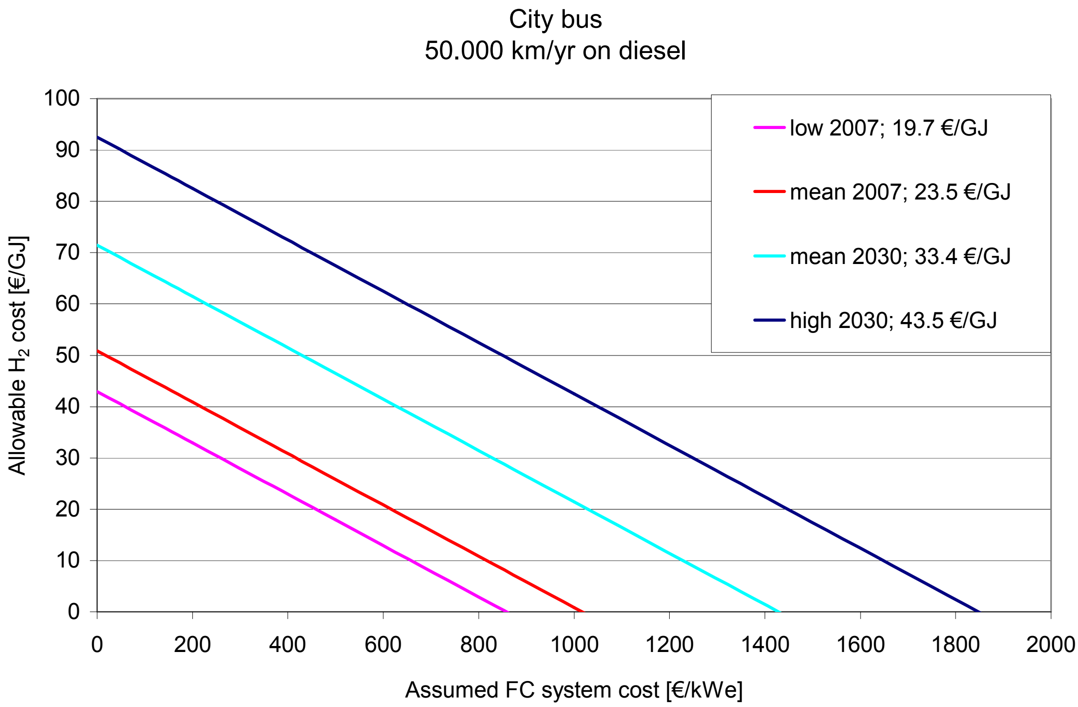


Figure 53: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of diesel with all taxes included

10.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and FC technology

The CO_2 emissions of the reference technologies have been compared to the CO_2 emissions of the H_2 FC system. The CO_2 emissions of the reference Diesel ICE have been calculated to 1060 gCO_2/km. The emissions of the Diesel hybrid have been calculated to 930 gCO_2/km. For the calculation the CO_2 factor from the CONCAWE study [3] of 87 gCO_2/MJ has been used.
In Table 34 the CO_2 emissions of the FC bus are shown. In this scenario the hydrogen is produced by electrolysis. In Table 35 the CO_2 emissions of the FC bus are shown in comparison to different H_2 production types.

Table 34: CO_2 emission factors for fuel cell bus (3rd column) in different countries (Source www.energy.eu /4/ and carma.org /5/)

Electricity	*Electricity E-mix*	*H_2 from E Electrolysis*	*Hydrogen* ***5.86 MJ/km***
	gCO_2/MJ	*gCO_2/MJ*	gCO_2/km
NL	166	218	1276
DE	141	185	1083
FR	20	26	155
UK	134	175	1028
PL	259	339	1987
CZ	168	220	1290
SW	6	8	47
DK	130	171	1001
EU-25	119	156	914
Offshore wind	8	11	64

Table 35: CO_2 emission for fuel cell bus in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***5,86 MJ/km***
CH2	gCO_2/MJ	gCO_2/km
Onsite SMR	110	645
Waste wood	13	74
Offshore wind	11	63
Coal gasification + CCS	45	263

CO_2 reduction potential per service and for the potential market

In Figure 54 is displayed how the different hydrogen production types influence the CO_2 emission reduction. All sources that are below the green line for Diesel or the blue line for Diesel hybrid reduce the CO_2 emissions.
The maximum CO_2 reduction is calculated by the CO_2 emissions 1000 gCO_2/km. times the mileage/year (≈50 000 km/yr) times the number of units (600 000). This number can be approximated by the lifetime of the unit (15 year) and the yearly market sale, which are approximately 40 000 vehicles per year.
This leads to a maximum CO_2 reduction of 30 Mton CO_2/yr.

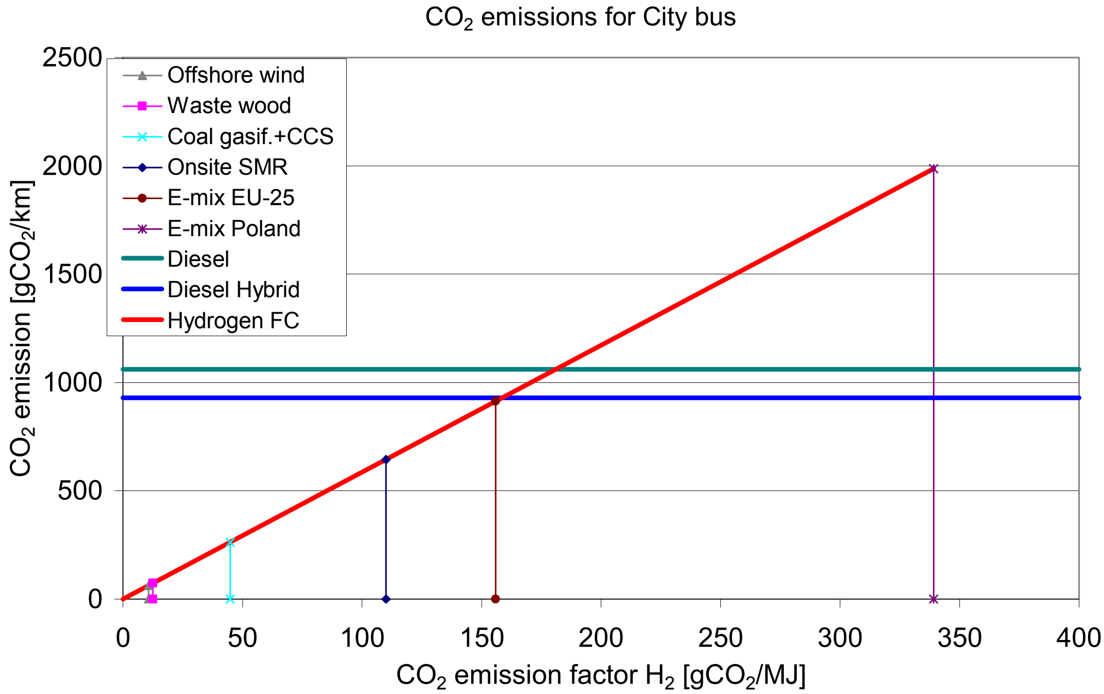


Figure 54: CO_2 emission reduction potential for replacement of Diesel and Diesel hybrid

10.7 Conclusions and recommendations

These scenarios implicate several points:

- The fuel cell increases its advantage with higher mileages because of the lower fuel consumption
- The CO_2 emissions of the FC with the E- mix Poland are much higher than the emissions of the Diesel engine

Recommendations:

- The fuel cell could be a good alternative for the Diesel engine. The noise and the CO_2 emissions are important for the traffic in cities. The costs for fuel cells have to be reduced to make them competitive even with lower mileages. The H_2 price has a big influence on the economy of the fuel cell.
- The source of the hydrogen should have a low CO_2 footprint.

10.8 References

1. http://www.mercedes-benz.de
2. http://www.man.de/MAN/de/
3. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
4. www.energy.eu, *last visited November 2007*
5. carma.org, *last visited November 2007*
6. Content Case study, utility vehicle, ECN

11. Case study H_2-ICE bus

11.1 Description of application

The main application of buses is the transport of passengers in the public sector. Here we can divide this application into two different types of buses:

- Long Range bus: This type of bus is used to transport passengers on long distances. Mostly he operates under full load.
- City bus: The location of this type is the city traffic. The main operation type of this bus is the part load.

Buses are one of the main passenger transport possibilities in cities. Therefore each city needs a big amount of passenger buses to ensure the needed transport performance.
Because of the heavy weight and the discontinuous driving cycle of each bus the engine power has to reach ca. 220 kW to ensure a reliable operation. For this study city buses are concluded.

11.2 Description of reference technology

Today the most buses are equipped with a Diesel internal combustion engine. An alternative to the single Diesel engine is to combine the Diesel engine with an electric motor to build a hybrid. With a series hybrid it is possible for the Diesel ICE to operate at the optimal operation points for each situation. The average speed of the city buses is below 50 Km/h. Figure 55 shows a few examples of typical city buses.

Figure 55: Examples of city buses: Mercedes Citaro LE (left); MAN Lions City bus (right)

For this case study the Mercedes Citaro LE has been chosen as the typical substitute for a city bus. He is equipped with a Diesel ICE which has a performance of 220 kW. It is equipped with 45 seats and the standing room offers place for further 38 passengers. Table 36 shows the technical data of this bus. /1/

Table 36: Characteristics of the Mercedes Citaro LE

Application	Unit	Mercedes Citaro LE
Power level	kW	*220*
Efficiency; energy use	MJ/km	*12,2*
Typical cost complete system	€	*270000*
Specific cost energy system	€/kW	*46*
Lifetime	year	*15*
Type of "fuel"	-	*Diesel*
Type of "fuel" supply	-	*Filling station*
Type of "fuel" storage	-	*Fuel tank*
Typical storage capacity	MJ	*12580*
Range/fuel charge	km	*1000*
Availability	%/yr	--
Maintenance		--

A H_2 ICE DI engine could reach the same efficiency as the Diesel engine if the compression ratio increases. This is shown in /7/ for a part load operation. Therefore the fuel consumption of the H_2 ICE would be similar to the conventional Diesel engine. A H_2 ICE could also be equipped with an electric motor to build a hybrid.
An important advantage of the H_2 ICE is the low emissions. A H_2 ICE has very low HC emissions. The HC emissions emerge from lubrication in the combustion chamber. The only high emissions are NOx emissions which could be prevented by special mixture ratios. Conventional exhaust gas treatments could reduce the NOx emissions to reach future requirements.
To reduce the fuel consumption of the Diesel engine and the H_2 ICE DI the combustion process will be optimized. This will reduce the advantage of the FC and the H_2 ICE will become more attractive.

11.3 Description of the market

The market discussed in this study is the city bus. There are several producers which offer different types of city buses. The buses differ in the quantity of seats and the performance of the engine.
In Table 37 the main supplier of city buses are shown.

Table 37: Market for city buses

Supplier	Country	Power	ICE vehicles /yr
Mercedes	D	≤ 220 kW	
MAN	D	≤ 265 kW	7300 /2/
Solaris	PL	≤ 220 kW	
Volvo	SE	≤ 265 kW	
Scania	SE	≤ 230 kW	
Neoplan	D	≤ 260 kW	
Total			

11.4 Description of H2 ICE technology for the application

The H_2 ICE has lower emissions as the conventional Diesel engine. Lower emissions are very important for the operation in city. This will reduce air pollution and the stress on passengers and on the residents.
Because of the special operation mode of a city bus a combination with an electric motor is recommended. The city bus mainly operates in part load, which is a disadvantage for the H_2 ICE. The H_2 ICE has the highest efficiency in full load operation. With a series hybrid it is possible for the H_2 ICE to operate at the optimal operation points for each situation. A second advantage is the possibility of using the brake energy of the bus.
A further advantage is the acquisition costs. A H_2 ICE has the same cost as a conventional Diesel engine.
City buses have a big range to operate without refuelling while they are in use. After they have returned they can refuel at the local fuelling station of the mentioned company.
The specific parameters of the H_2 ICE DI bus are shown in Table 38.

The following companies are developing or demonstrating the combination of H_2 ICE systems with city buses:

- Mercedes (D) has developed a H_2 ICE bus and presented in at the expo 2000
- MAN (D) developed and demonstrated the MAN H2876 LUH 01 with 200 kW

Table 38: The characteristics of the considered H_2 ICE DI city bus

Application	Unit	H_2 ICE city bus
Power level	kW	*220*
Efficiency; energy use	MJ/km	*12,2*
Lifetime	year	*15*
Type of “fuel”	-	*Hydrogen*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Tank; pressurized*
Typical storage capacity	MJ	*3660*
Range/fuel charge	km	*200*
Availability	%/yr	
Maintenance		

11.5 Economic boundary conditions for H2 ICE technology

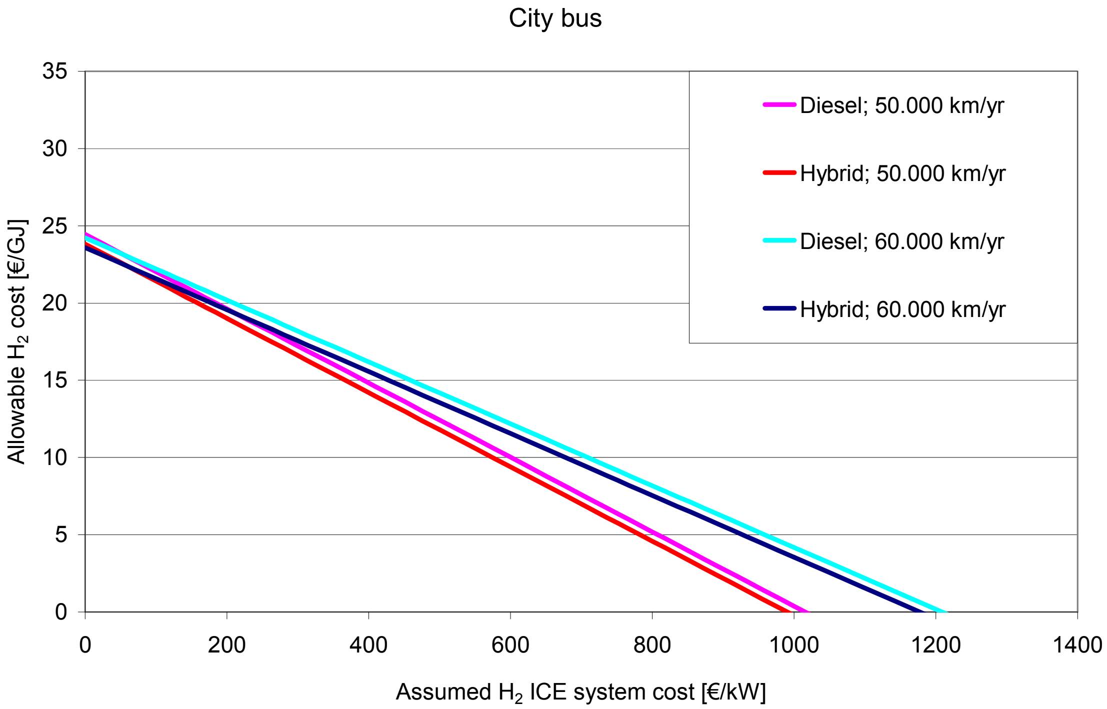


Figure 56: Allowable cost of H_2 as a function of the assumed H_2 ICE system cost at the same cost per kilometre as for Diesel hybrid bus with a yearly mileage of 50 000 and 60 000 km and Diesel bus with a yearly mileage of 50 000 and 60 000 km. All taxes included

The 2 technologies Diesel ICE and Diesel ICE hybrid have been considered for the economic evaluation. The Mercedes Citaro LE is used as the reference technology for this evaluation. The fuel consumption of the H_2 ICE is similar to the reference technology because of the identical efficiency /7/. The average European energy prices for consumers or small companies in 2007 are used for the economic evaluation. In Figure 56 is shown a comparison of the allowable cost of H_2 as a function of the assumed H_2 ICE system cost at the same cost per kilometre as the Citaro LE Diesel or Diesel hybrid. The mileages of 50000 and 60000 have been considered. The specific parameters of Figure 56 are based on Table 39. The fuel consumption of the hybrid is 12% lower than the fuel consumption of the conventional Diesel engine. Figure 56 shows that the higher acquisition costs of the Diesel Hybrid leads to a higher potential for the H_2 ICE. The acquisition costs of the hydrogen engine are similar to the Diesel engine costs. Therefore the potential of the H_2 costs is higher as for fuel cell systems. If the H_2 ICE is compared to the conventional Diesel ICE the potential for the costs would be smaller. An increased mileage would lead to an advantage of the Diesel hybrid to the conventional Diesel ICE because of the lower fuel consumption.

The prices are with all taxes included for the engine, the maintenance as well as the fuel.

Table 39: Background table for Figure 56 for the same cost in €/km for a city bus with a Diesel ICE and a Diesel hybrid compared to a H_2 ICE DI, only taking into account fuel cost and engine cost.

Reference system		Diesel ICE	Diesel Hybrid	Diesel ICE	Diesel Hybrid
Engine cost	€/kW	46	66	46	66
Power	kW	220	220	220	220
Lifetime	yr	15	15	15	15
Distance	km/yr	50000	50000	60000	60000
Specific investment cost	€/km	0,013	0,019	0,011	0,016
Fuel cost	€/GJ	23,5	23,5	23,5	23,5
Fuel use	MJ/km	12,20	10,70	12,20	10,70
Specific fuel cost	€/km	0,287	0,251	0,287	0,251
Engine maintenance cost	€/km	0,07	0,09	0,07	0,09
Total cost	€/km	0,366	0,358	0,364	0,356
H_2 ICE DI system					
Power	kW	220	220	220	220
Lifetime	yr	15	15	15	15
Distance	km/yr	50000	50000	60000	60000
Fuel use	MJ/km	12,2	12,2	12,2	12,2
Engine maintenance cost	€/km	0,07	0,07	0,07	0,07

Assumed H_2 ICE DI system cost €/kWe	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0	24	24	24	24
200	20	19	20	20
500	12	12	14	14
1000	0	0	4	4
2000	-24	-24	-16	-16
4000	-72	-72	-56	-57

The H_2 ICE bus is economical attractive if in Figure 56 the combination of H_2 costs and the acquisition costs are below the line of the reference technologies. The lifetime of the H_2 ICE is also assumed to 15 years. If the lifetime of the H_2 ICE is lower the H_2 ICE has to be exchanged and the costs have to be added to the acquisition costs.

Fuel cost scenarios

In Figure 57 we see the influence of the increasing energy price on the H_2 ICE in comparison to the reference technologies.
For reference, the following average European diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (19.7 €/GJ)
- The mean 2007 value with all taxes (23.5 €/GJ)
- The mean 2030 value with all taxes (33.4 €/GJ)
- The high 2030 value with all taxes (43.5 €/GJ)

Both Figures show a wide spread of the graphs because of the high influence of the high fuel consumption of the Diesel engine. This scenario shows also that the higher acquisition costs of the Diesel hybrid leads to a higher potential for the H_2 ICE. A higher mileage would compensate this disadvantage to the conventional Diesel engine.

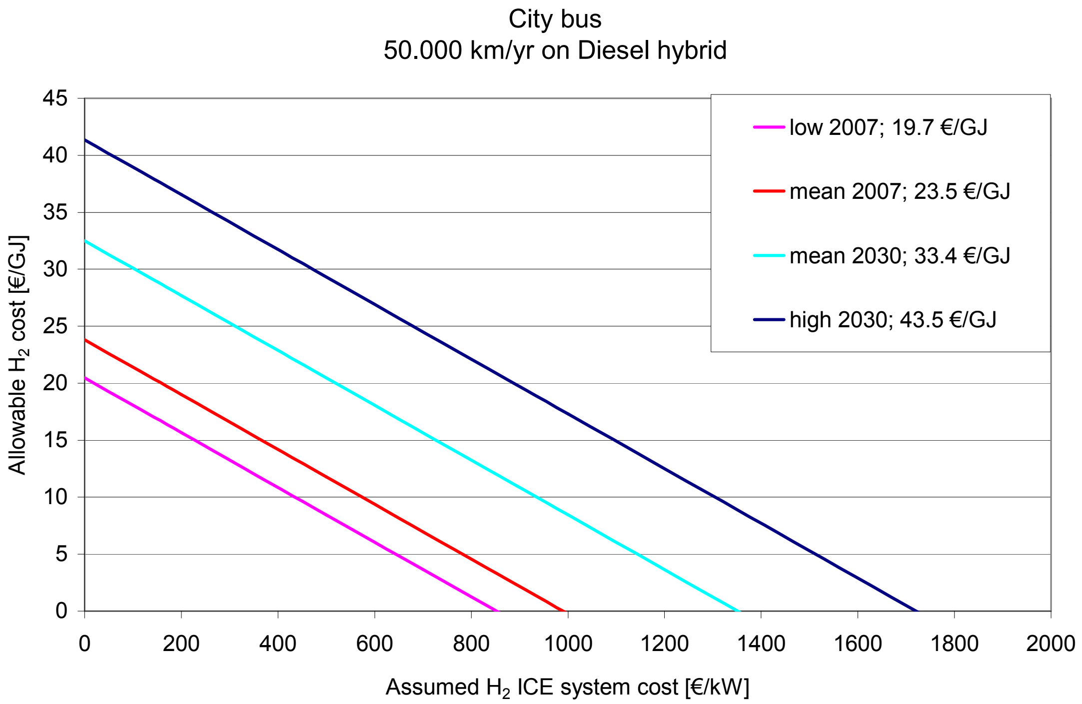


Figure 57: Allowable hydrogen costs vs. assumed H_2 ICE system cost of 4 different energy prices of diesel with all taxes included

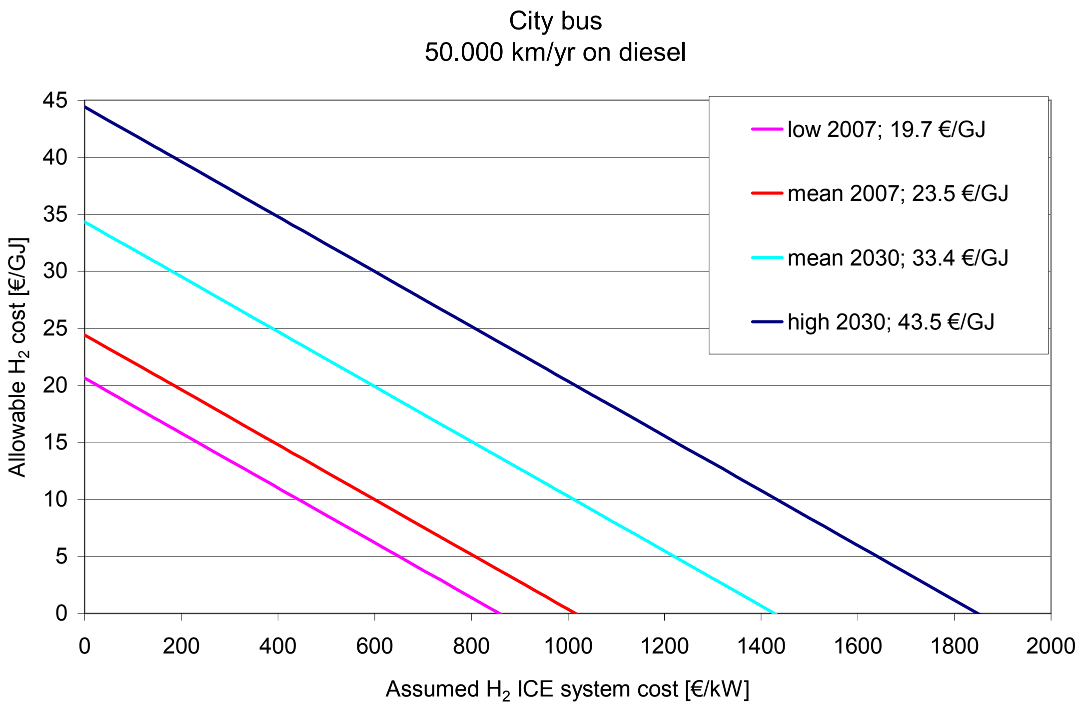


Figure 58: Allowable hydrogen costs vs. assumed H_2 ICE system cost of 4 different energy prices of diesel with all taxes included

11.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and H_2 ICE technology

The CO_2 emissions of the reference technologies have been compared to the CO_2 emissions of the H_2 ICE system. The CO_2 emissions of the reference Diesel ICE have been calculated to 1060 gCO_2/km. The emissions of the Diesel hybrid have been calculated to 930 gCO_2/km. For the calculation the CO_2 factor from the CONCAWE study [3] of 87 gCO_2/MJ has been used.

In the CO_2 emissions of the H_2 ICE bus are shown. In this scenario the hydrogen is produced by electrolysis. In Table 41 the CO_2 emissions of the H_2 ICE bus are shown in comparison to different H_2 production types.

Table 40: CO_2 emission factors for H_2 ICE bus (3rd column) in different countries (Source www.energy.eu /4/ and carma.org /5/)

Electricity	*Electricity E-mix*	*H_2 from E Electrolysis*	*Hydrogen* ***12.2 MJ/km***
	gCO_2/MJ	gCO_2/MJ	gCO_2/MJ
NL	166	218	2656
DE	141	185	2254
FR	20	26	323
UK	134	175	2139
PL	259	339	4137
CZ	168	220	2685
SW	6	8	98
DK	130	171	2083
EU-25	119	156	1902
Offshore wind	8	11	132

Table 41: CO_2 emission for H_2 ICE bus in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***12.2 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/MJ
Onsite SMR	110	1343
Waste wood	13	153
Offshore wind	11	131
Coal gasification + CCS	45	547

CO_2 reduction potential per service and for the potential market

In Figure 59 is displayed how the different hydrogen production types influence the CO_2 emission reduction. All sources which are below the green line for Diesel or the blue line for Diesel hybrid reduce the CO_2 emissions. In comparison to Diesel and Diesel Hybrid only Coal gasification + CCS, Waste wood and offshore wind have the potential to reduce the CO_2 emissions.

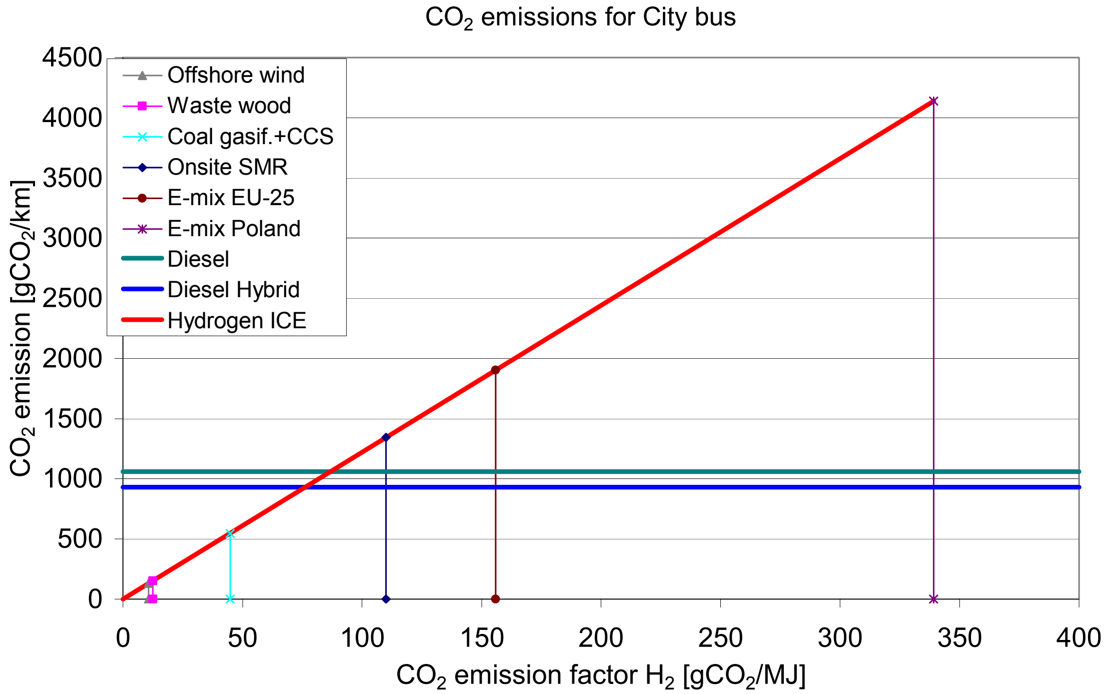


Figure 59: CO_2 emission reduction potential for replacement of Diesel and Diesel hybrid

The maximum CO_2 reduction is calculated by the CO_2 emissions 929 gCO_2/km. times the mileage/year (≈50000 km/yr) times the number of units (600000). This number can be approximated by the lifetime of the unit (15 year) and the yearly market sale, which are approx. 40000 vehicles per year.
This leads to a maximum CO_2 reduction of 27.9 Mton CO_2/yr

11.7 Conclusions and recommendations

These scenarios implicate several points:

- A H_2 ICE could reduce the emissions in the city
- The CO_2 emissions of the H_2 ICE are higher as the conventional Diesel engine with electrolysis by E- mix and SMR

Recommendations:

The H_2 ICE could be a good alternative for the Diesel engine. The emissions are lower than the emissions of the conventional Diesel engine and the demand charge is equivalent. The H_2 ICE is ready for mass production. The main problems are still the storage of H_2 and the infrastructure. The H_2 price has a big influence on the economy of the H_2 ICE.

11.8 References

1. http://www.mercedes-benz.de
2. http://www.man.de/MAN/de/
3. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
4. www.energy.eu, *last visited November 2007*
5. carma.org, *last visited November 2007*
6. Content Case study, utility vehicle, ECN
7. Gerbig F, Strobl W, Eichlseder H, Wimmer A, BMW Group Research and Technology (Germany), Graz University of Technology (SAE 2003) Potentials of the Hydrogen Combustion Engine with innovative Hydrogen- specific combustion processes, SAE 2004-V113

12. Case study Fuel Cell truck

12.1 Description of application

The main applications of light truck are the transport of passengers and goods. Here we can divide this application into two different types of light trucks:

- Light truck good transporter: This type of light truck is used to transport goods on long distances. Main operation type is Full Load. In urban condition the main operation is part load.
- Light truck passenger transporter: This type of light truck mainly operates also in Full Load. In urban condition the main operation is part load.

Light trucks built a main part in the transport sector. To cover the main demand a big amount of light trucks is necessary. Important preferences for these vehicles are low fuel consumption and a high transport capacity. Because of the high storage capacity and the long range each light truck has to reach an engine power of 60 kW to 135 kW.

12.2 Description of reference technology

Today the light trucks are equipped with a Diesel internal combustion engine. An alternative to the single Diesel engine is to combine the Diesel engine with an electric motor to build a hybrid. With a series hybrid it is possible for the Diesel ICE to operate at the optimal operation points for each situation.
Figure 60 shows a few examples of typical light truck.

Mercedes Sprinter 313 CDI   Fiat Scudo   Ford Transit

– **Figure 60: Examples of light trucks**

For this case study the Mercedes Sprinter 313 CDI has been chosen as the typical substitute for a light truck. He is equipped with a Diesel ICE which has a performance of 95 kW. The Mercedes Sprinter is available in different versions. In the extra long version the payload is about 2435 Kg. Table 42 shows the technical data of this bus. /1/

Table 42: Characteristics of the Mercedes Sprinter 313 CDI

Application	Unit	Mercedes Sprinter 313 CDI
Power level	kW	*95*
Efficiency; energy use	MJ/km	*2,05*
Typical cost complete system	€	*32000*
Specific cost energy system	€/kW	*46*
Lifetime	year	*15*
Type of “fuel”	-	*Diesel*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Fuel tank*
Typical storage capacity	MJ	*2696*
Range/fuel charge	km	*1315*
Availability	%/yr	--
Maintenance		--

The advantage of a FC is the lower fuel consumption. This advantage is reduced by the high acquisition costs of a FC. The Diesel engine will develop in the near future and reduce its fuel consumption. The hybrid is not the only solution to reduce the fuel consumption. A further possibility is the optimization of the combustion process.
Also the emissions of the Diesel engine will decrease. Technologies like SCR or the oxidation catalytic converter will increase their potential and decrease the emission advantage of the FC.

12.3 Description of the market

The market discussed in this study is the light truck. There are several producers which offer different types of light trucks. The trucks differ in the quantity of storage capacity and the performance of the engine. In Table 43 the main supplier of light trucks are shown.

– **Table 43: Market for light trucks**

Supplier	Country	Power	ICE vehicles /yr
Mercedes	D	≤ 135 kW	
FIAT	I	≤ 100 kW	160000 /2/
Volkswagen	D	≤ 128 kW	500000 /8/
Citroen	F	≤ 120 kW	160000 /9/
Peugeot	F	≤ 120 kW	
Opel	D	≤ 110 kW	
Renault	F	≤ 110 kW	
Ford	USA	≤ 105 kW	
Total			

12.4 Description of FC/H2 technology for the application

Because of the high operation grade of a light truck the fuel cell is a good alternative for a Diesel engine because of the lower fuel consumption and the lower emissions. The only disadvantage is the higher demand charge of a fuel cell system.

One advantage of the fuel cell is the efficiency. The efficiency of a fuel cell is higher as the efficiency of a Diesel ICE. Further the efficiency of a fuel cell is higher in the part load. This property is very important for light trucks which mainly operate in city traffic.
The lower noise and the lower emissions reduce the stress on inhabitants in charging areas.
Light trucks have to refuel at special hydrogen fuelling stations. Therefore a high dispersion is very important for a hydrogen powered light truck.
The specific parameters of the FC bus are shown in Table 44.

The following companies are developing or demonstrating the combination of fuel cell systems with light trucks:

- Mercedes (D) has developed a PEMFC powered light truck with 50kW

Table 44: The characteristics of the considered H_2 FC light truck

Application	Unit	H_2 FC light truck
Power level	kW	*95*
Efficiency; energy use	MJ/km	*1*
Lifetime	year	*15*
Type of “fuel”	-	*Hydrogen*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Tank; pressurized*
Typical storage capacity	MJ	*1000*
Range/fuel charge	km	*1000*
Availability	%/yr	
Maintenance		

12.5 Economic boundary conditions for FC/ H2 technology

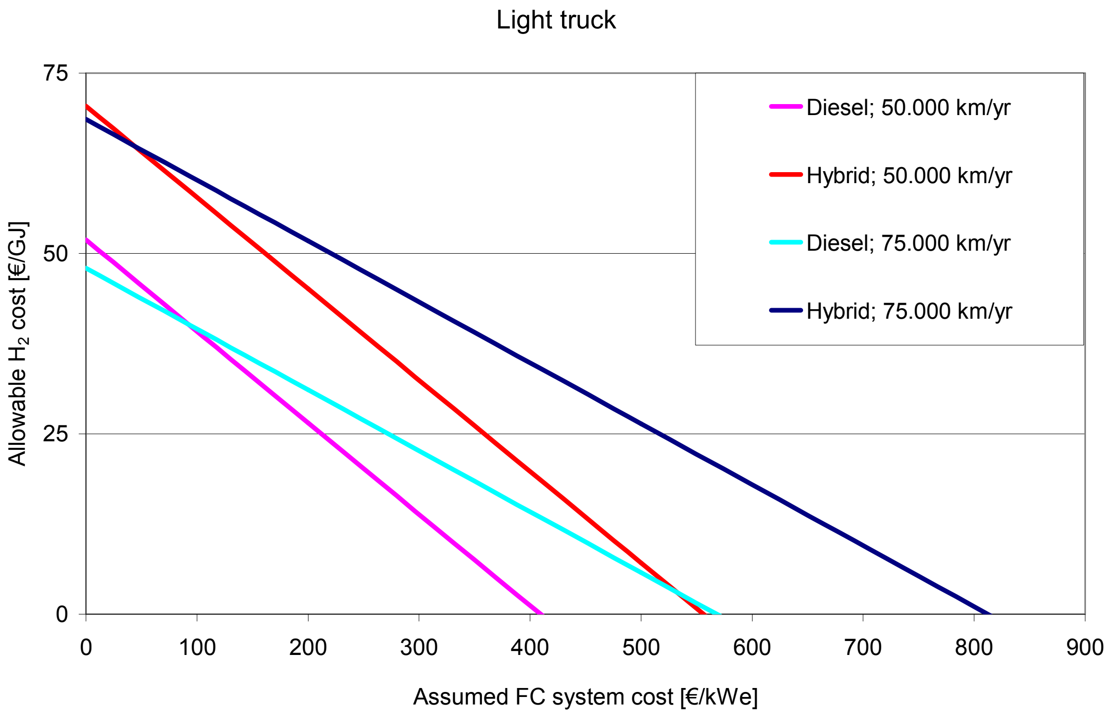


Figure 61: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre as for Diesel or Diesel hybrid light truck with a yearly mileage of 50 000 and 75 000 km. All taxes included

The 2 technologies Diesel ICE and Diesel ICE hybrid have been considered for the economic evaluation. The Mercedes Sprinter 313 CDI is used as the reference technology for this evaluation. The fuel consumption of the fuel cell is based on the calculation of the reduction factor between Diesel ICE and PEMFC from [6]. Because of the similar operation modes (full load/part load) the reduction factor is assumed to be equal to the reduction factor of the utility vehicle. Further optimization for fuel cell is thought to be for increased transient operation of light trucks. The average European energy prices for consumers/ small companies in 2007 are used for the economic evaluation. In Figure 61 is shown a comparison of the allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre as the Mercedes Sprinter 313 CDI Diesel or Diesel hybrid. The mileages of 50000 and 75000 have been considered. The specific parameters of Figure 61 are based on Table 45. The fuel consumption of the hybrid is 12% lower than the fuel consumption of the conventional Diesel engine. Figure 61 shows that the higher acquisition costs of the Diesel Hybrid leads to a higher potential for the H_2 fuel cell. This induces possible higher H_2 fuel cell costs or higher H_2 costs. If the FC is compared to the conventional Diesel ICE the potential for the costs would be smaller. An increased mileage would lead to an advantage of the Diesel hybrid to the conventional Diesel ICE because of the lower fuel consumption.

The prices are with all taxes included for the engine, the maintenance as well as the fuel.

Table 45: Background table for Figure 61 for the same cost in €/km for a light truck with a Diesel ICE and a Diesel hybrid compared to a fuel cell system, only taking into account fuel cost and engine cost

Reference system		**Diesel ICE**	**Diesel Hybrid**	**Diesel ICE**	**Diesel Hybrid**
Engine cost	€/kW	46	66	46	66
Power	kW	95	95	95	95
Lifetime	yr	15	15	15	15
Distance	km/yr	50000	50000	75000	75000
Specific investment cost	€/km	0,006	0,008	0,004	0,006
Fuel cost	€/GJ	23,5	23,5	23,5	23,5
Fuel use	MJ/km	2,05	1,80	2,05	1,80
Specific fuel cost	€/km	0,048	0,042	0,048	0,042
Engine maintenance cost	€/km	0,07	0,09	0,07	0,09
Total cost	€/km	0,120	0,138	0,118	0,138
H_2-FC system					
Power	kW	95	95	95	95
Lifetime	yr	15	15	15	15
Distance	km/yr	50000	50000	75000	75000
Fuel use	MJ/km	1,00	1,00	1,00	1,00
Engine maintenance cost	€/km	0,07	0,07	0,07	0,07

Assumed H_2 ICE DI system cost €/kWe	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0	52	70	48	69
200	27	45	31	52
500	-11	7	6	26
1000	-75	-56	-36	-16
2000	-201	-183	-121	-100
4000	-455	-436	-290	-269

The fuel cell light truck is economical attractive if in Figure 61 the combination of H_2 costs and the acquisition costs are below the line of the reference technologies. The lifetime of the fuel cell system is also assumed to 15 years. If the lifetime of the fuel cell is lower the fuel cell has to be exchanged and the costs have to be added to the acquisition costs.

Fuel cost scenarios

In Figure 62 we see the influence of the increasing energy price on the fuel cell system in comparison to the reference technologies.
For reference, the following European diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (19.7 €/GJ)
- The mean 2007 value with all taxes (23.5 €/GJ)
- The mean 2030 value with all taxes (33.4 €/GJ)
- The high 2030 value with all taxes (43.5 €/GJ)

Both Figures show a wide spread of the graphs because of the high influence of the high fuel consumption of the Diesel engine. This scenario shows also that the higher acquisition costs of the Diesel hybrid leads to a higher potential for the FC. A higher mileage would compensate this disadvantage to the conventional Diesel engine.

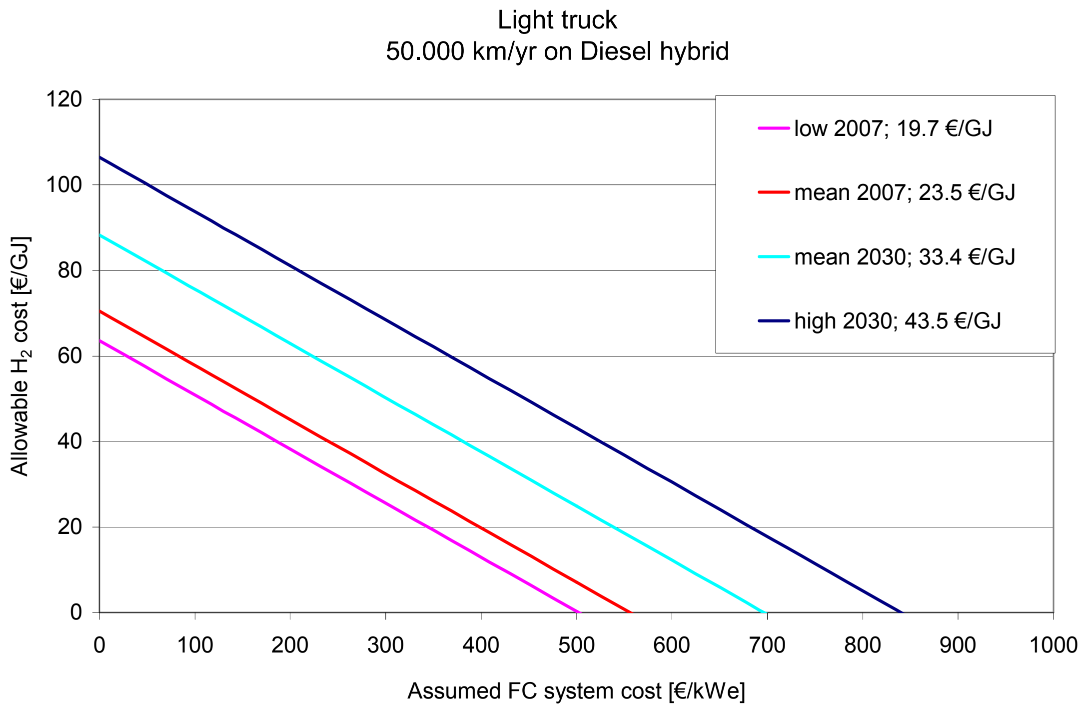


Figure 62: Allowable hydrogen costs vs. assumed H_2 FC system cost of 4 different energy prices of diesel with all taxes included

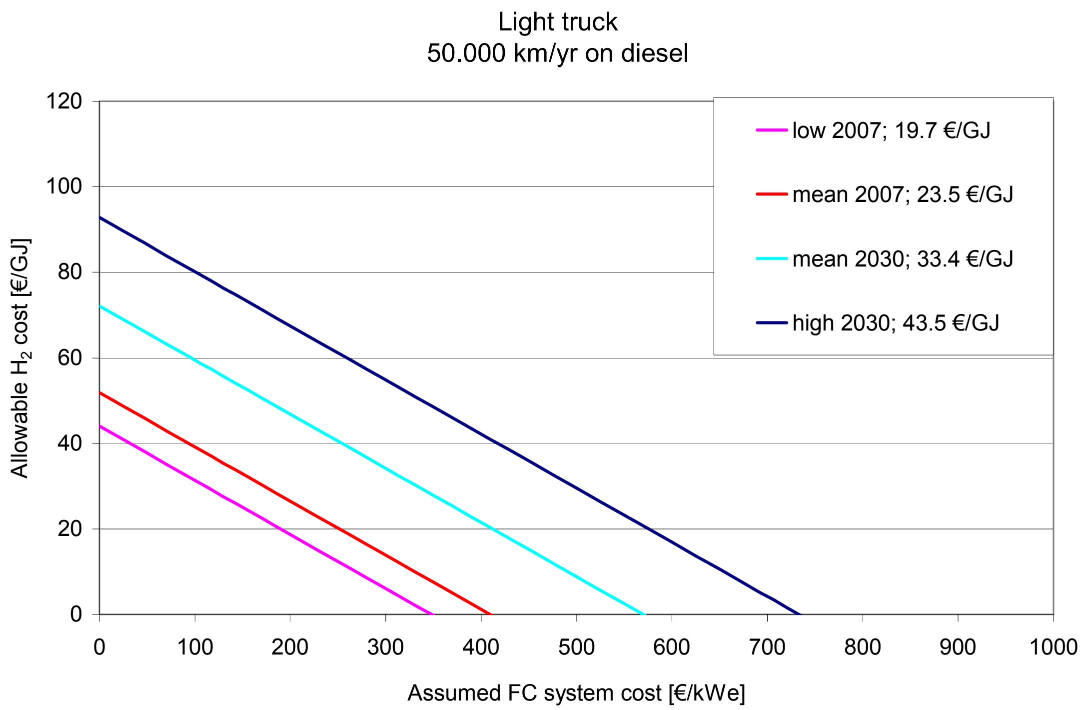


Figure 63: Allowable hydrogen costs vs. assumed H_2 FC system cost of 4 different energy prices of diesel with all taxes included

12.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and FC technology

The CO_2 emissions of the reference technologies have been compared to the CO_2 emissions of the FC/H_2 system. The CO_2 emissions of the reference Diesel ICE have been calculated to 178 gCO_2/km. The emissions of the Diesel hybrid have been calculated to 156 gCO_2/km. For the calculation the CO_2 factor from the CONCAWE study /3/ of 87 gCO_2/MJ has been used.
In Table 46 the CO_2 emissions of the FC light truck are shown. In this scenario the hydrogen is produced by electrolysis. In Table 47 the CO_2 emissions of the FC light truck are shown in comparison to different H_2 production types.

Table 46: CO_2 emission factors for H_2 FC light truck (3rd column) in different countries (Source www.energy.eu /4/ and carma.org /5/)

Electricity	*Electricity E-mix*	*H_2 from E Electrolysis*	*Hydrogen* ***1 MJ/km***
	gCO_2/MJ	gCO_2/MJ	gCO_2/MJ
NL	166	218	218
DE	141	185	185
FR	20	26	26
UK	134	175	175
PL	259	339	339
CZ	168	220	220
SW	6	8	8
DK	130	171	171
EU-25	119	156	156
Offshore wind	8	11	11

Table 47: CO_2 emission for H_2 FC light truck in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***1 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/MJ
Onsite SMR	110	110
Waste wood	13	13
Offshore wind	11	11
Coal gasification + CCS	45	45

CO_2 reduction potential per service and for the potential market

In Figure 64 is displayed how the different hydrogen production types influence the CO_2 emission reduction. All sources that are below the green line for Diesel or the blue line for Diesel hybrid reduce the CO_2 emissions. In comparison to Diesel and Diesel Hybrid only E- mix Poland would not reduce the CO_2 emissions. The CO_2 emissions of E- mix EU- 25 are equivalent to the emissions of the Diesel Hybrid.

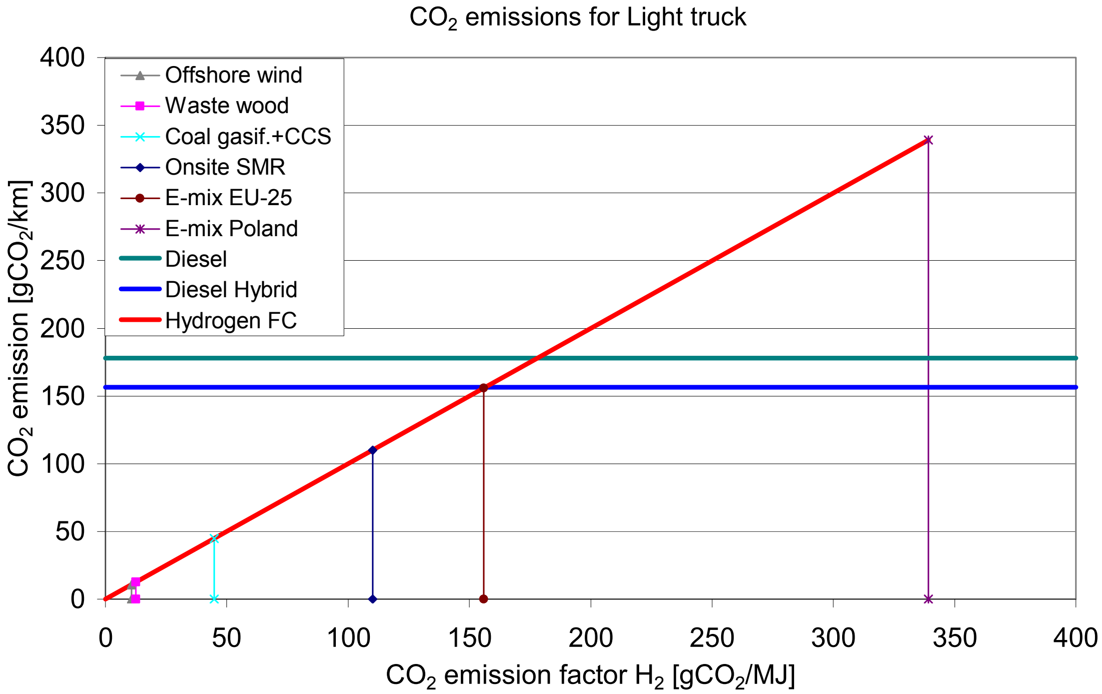


Figure 64: CO_2 emission reduction potential for replacement of Diesel and Diesel hybrid

The maximum CO_2 reduction is calculated by the CO_2 emissions 167 gCO_2/km. times the mileage/year (≈50,000 km/yr) times the number of units (30,000,000). This number can be approximated by the lifetime of the unit (15 year) and the yearly market sale, which are approx. 2,000,000 vehicles per year.
This leads to a maximum CO_2 reduction of 250.5 Mton CO_2/yr

12.7 Conclusions and recommendations

These scenarios implicate several points:

- The fuel cell increases its advantage with higher mileages because of the lower fuel consumption
- The CO_2 emissions of the FC with the E- mix Poland are much higher than the emissions of the Diesel engine

Recommendations:

The fuel cell could be a good alternative for the Diesel engine. The noise and the CO_2 emissions are important for the traffic in cities. The costs for fuel cells have to be reduced to make them competitive even with lower mileages. The H_2 price has a big influence on the economy of the fuel cell.

12.8 References

1. http://www.mercedes-benz.de
2. http://www.freenet.de/freenet/auto/news/auto/507380_1.html
3. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
4. www.energy.eu, *last visited November 2007*
5. carma.org, *last visited November 2007*
6. Content Case study, utility vehicle, ECN
7. Gerbig F, Strobl W, Eichlseder H, Wimmer A, BMW Group Research and Technology (Germany), Graz University of Technology (SAE 2003) Potentials of the Hydrogen Combustion Engine with innovative Hydrogen- specific combustion processes, SAE 2004-V113
8. http://www.autosport.at/article3823.html
9. http://de.cars.yahoo.com/05102007/348/city-transporter-fiat-peugeot-citro-n.html

13. Case study License-less vehicles

13.1 Description of application

License-free passenger vehicles provide mobility for persons that do not possess a driving license for passenger cars. These vehicles are interesting for people for whom it is difficult to obtain a driving license, or for people that have no regular driving license any more, or for young people between 16 and 18 (in Italy and Spain from 14 year). The vehicles are also used as small city cars. The top speed for these vehicles is restricted to 45 km/hr and the engine power to 4 kW (Directive 2002/24/CE): The average mileage for these vehicles is 5.000-6.000 km/yr.
Other names for this type of vehicles are minicars, microcars, quadricycles, license-exempt vehicles, licenseless vehicles and vehicles without a driver license. License-free utility vehicles are not considered in this case study.

13.2 Description of reference technology

All manufacturers use diesel internal combustion engines for license-free vehicles. Only Aixam has an electric version. In order to be license-free the power level is restricted to 4 kW and the maximum speed to 45 km/h. From all European manufacturers an example of their license-free vehicle is shown in Figure 65.

Figure 65: Examples of license-free vehicles from the European manufacturers

In this case study a diesel operated license-free vehicle is chosen as the reference technology and the relevant properties are provided in Table 48. The technical data of Table 48 are taken from the Casalini website [1].

The average mileage for these vehicles (in the Netherlands) is 5.000 to 6.000 km/year [2]. The typical cost of the 4 kW diesel engines is assumed as 2000 €. No particular data was found for the lifetime of this type of vehicle. The lifetime is assumed as 15 years. The standard maintenance requirement for the Aixam vehicle is provided [3].

Table 48: The characteristics of the diesel engine based license-free vehicle.

Application	Unit	License-free vehicle
Power level	kW	*4*
Efficiency; energy use	MJ/km	*1.06*
Typical cost complete system	€	*12.000*
Specific cost energy system	€/kW	*500*
Lifetime	year	*15*
Type of "fuel"	-	*diesel*
Type of "fuel" supply	-	*filling station*
Type of "fuel" storage	-	*tank*
Typical storage capacity	MJ	*630*
Range/fuel charge	km	*540*
Availability	%/yr	*> 99%*
Maintenance		*3 hrs/5000 km*

The license-free passenger vehicles have developed fast to represent "small" passenger cars. The specifications for license-free vehicles depend strongly on the legislation.
The market for the license-free vehicle has increased fast over the last years and the vehicles have become more attractive. Small companies produce the majority of the vehicles. Significant cost decrease can be expected when larger volumes of vehicles are produced. Efficiency improvement of the engines can be expected for the future.
Stricter emission restrictions posed by the EU (Euro 5 and Euro 6) will in future also apply to this type of vehicles, thereby improving the combustion engines. The advantage of fuel cell systems compared to the internal combustion engine on exhaust air quality will decrease in time.

13.3 Description of the market

The European production from the manufacturers of license-free vehicles was almost 40 000 vehicles in 2005, as shown in Table 49. The main segment for license-free vehicles is the passenger car like vehicle for 2 persons, the application in this study. The numbers from the manufacturers also contain the license-free utility vehicles, which are less than 10% of the production, and some sportier vehicles with a gasoline engine < 15 kW for which a license is required. The total market of license-free passenger vehicles is estimated at 35 000. The market leader is Aixam with over 12 000 license-free passenger vehicles. The opening of the European Market in 1997, thanks to the harmonisation of the European legislation to the French legislation for license-free vehicles, has resulted in a significant increase in production volumes. The manufacturers are located in France and Italy because initially the legislation for this type of vehicle was favourable in these countries. The vehicles all have a 4 kW diesel engine in order to fulfil the Directive 2002/24/CE. In the UK an electric version of the Aixam vehicle is sold as the Mega City. In Table 50 the distribution of the license-free vehicle over Europe is given, which shows that in France 45% of the vehicles are located, and Spain and Italy both have around 15% of the vehicles, leaving 25% to the rest of Europe.

Due to the small number of license-free vehicles produced, "normal" small vehicles for which a driving license is required are cheaper (e.g the Suzuki Alto is priced at 9000 €) than the license-free vehicle that are priced at 11.000-13.000 €. Road taxes are absent for license-free vehicles.

Table 49 : Manufacturers of license-free vehicles

Manufacturer	Country	Sales	Fuel use (l/100 km)
Aixam	FR	13980	2.96
Bellier	FR	(3000)*	3.15
Casalini	IT	1100	3
Chatenet	FR	2376	
Grecav	IT	2000	
Italcar	IT	(2000)*	
Simpa JDM	FR	2678	3.3
Ligier	FR	6628	
Microcar	FR	6894	
Piaggio	IT	900	
Total		39700	

* Numbers in brackets are estimates.

Table 50 : Number of license-free vehicles in different countries (Ref. AFQUAD 2006)

Country	Number of license-free vehicles (2005)
United Kingdom	4612
Austria	16303
BeNeLux	17633
Spain	50676
France	140000
Italy	49120
Portugal	17007
Other countries	8335

13.4 Description of FC/H2 technology for the application

The H_2 PEMFC license-free passenger vehicle has the advantage of the noiseless, odourless and environmental friendly vehicle that can be refuelled in minutes. The power of the fuel cell system is small (< 4 kW), which can be advantageous for market introduction of the license-free passenger vehicle. The drivers are the same as for the electric vehicle: noiseless and odourless and its green image, and with the extra driver of an extended driving range and fast refuelling. Due to the low speed of the vehicle, the refuelling station for the hydrogen should be nearby. The characteristics of the envisaged license-free passenger vehicle are shown in Table 20. A hybrid version of fuel cell and batteries is envisaged for improved traction and reduction of dynamic demand of the fuel cell. The efficiency of the fuel cell vehicle is calculated from the efficiency of the electric license-free utility vehicle from Aixam-MEGA (0.31 MJ/km) without the 80% recharging losses combined with a fuel cell system with 44% net efficiency on the LHV of H_2.

The following parties are developing or demonstrating the combination of fuel cell systems with license-free passenger vehicles:

- H_2 Logic (DK) has provided a unit of 1 kW for a MEGA city service vehicle.

Table 51: The characteristics of the envisaged fuel cell license-free vehicle

Application	Unit	H_2 PEMFC license-free vehicle
Power level	kW	*4*
Efficiency; energy use	MJ/km	*0.6*
Lifetime	year	*15*
Type of "fuel"	-	*Hydrogen*
Type of "fuel" supply	-	*Filling station*
Type of "fuel" storage	-	*Tank; pressurized*
Typical storage capacity	MJ	*180*
Range/fuel charge	km	*300 on H_2 and 25 on batteries*
Availability	%/yr	*Approx. 99%*
Maintenance		*Every 5000 km or 2*/yr; total 2-3 hrs/yr*

13.5 Economic boundary conditions for FC/H2 technology

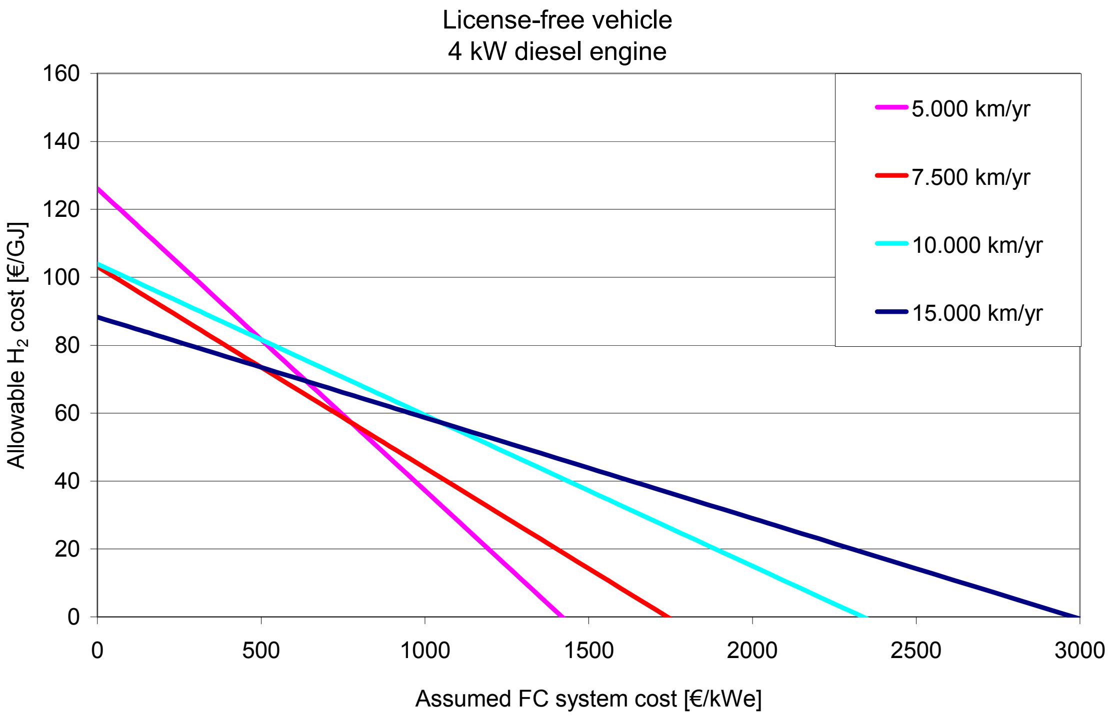


Figure 66: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre as for diesel license-free vehicles with a yearly mileage of 5.000, 7.500, 10.000 and 15.000 km. All taxes included for the fuel.

The reference technology, 4 kW diesel ICE is considered for the economic evaluation. For this economic evaluation the Casalini Idea is used as the reference vehicle. The average European diesel prices in 2007 are used for the economic evaluation. In Figure 66 the allowable cost of H_2 as a function of the assumed FC system cost is shown at the same cost per kilometre as the reference vehicle. Yearly mileages of 5.000, 7.500, 10.000 and 15.000 km/yr are considered. Figure 42 is based on the input in Table 52.

The prices are with all taxes included for the engine, the maintenance as well as the fuel. For the fuel cell system the maintenance is expected to be similar to the electric utility vehicle, except that battery replacement will be less expensive due to a lower number of batteries needed in the fuel cell system. The effect of interest rates on the results is neglected.

Table 52: Background table for Figure 66 for the same cost in €/km for a license-free passenger vehicle with a diesel ICE compared to a fuel cell system, only taking into account fuel cost and engine cost

Reference system		**Diesel ICE**	**Diesel ICE**	**Diesel ICE**	**Diesel ICE**
Engine cost	€/kW	500	500	500	500
Power	kW	4	4	4	4
Lifetime	yr	15	15	15	15
Distance	km/yr	5000	7500	10000	15000
Specific investment cost	€/km	0.027	0.018	0.013	0.009
Fuel cost	€/GJ	23.5	23.5	23.5	23.5
Fuel use	MJ/km	1.06	1.06	1.06	1.06
Specific fuel cost	€/km	0.025	0.025	0.025	0.025
Engine maintenance cost	€/km	0.07	0.07	0.07	0.07
Total cost	€/km	0.117	0.108	0.104	0.100
FC system					
Power	kW	4	4	4	4
Lifetime	yr	15	15	15	15
Distance	km/yr	5000	7500	10000	15000
Fuel use	MJ/km	0.60	0.60	0.60	0.60
Engine maintenance cost	€/km	0.04	0.05	0.04	0.05

Assumed FC system cost €/kWe		Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0		45	37	37	32
200		39	33	34	30
500		29	26	29	26
1000		13	16	21	21
2000		-19	-6	5	10
4000		-83	-48	-27	-11

The fuel cell vehicle is economically attractive if in Figure 66 the combination of cost of hydrogen and the cost of the fuel cell engine are below the line for the reference technology. The lifetime of the fuel cell system is also assumed as 15 years. If the lifetime is lower, than the fuel cell system cost should be read as the costs including replacement costs of the fuel cell.

The lifetime of the batteries for the (hybrid) fuel cell license-free vehicle is assumed to last 50.000 km. The supplier of the license-less electric utility vehicle states that the lifetime of the gel battery depends on its use and also on other parameters. Other suppliers of gel batteries state 800 times recharging. Information from the supplier shows that the maintenance of the engine is strongly dependent on the mileage and to a much lesser extent to the age of the vehicle. Only the standard maintenance costs and battery replacement costs are incorporated [3].

Fuel cost scenarios

The effect of the different diesel fuel costs on the assumed fuel cell system costs and the allowed hydrogen costs is provided in Figure 67. For reference, the following average European diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (21.7 €/GJ)
- The mean 2007 value with all taxes (29.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (47.1 €/GJ)

This Figure shows that the effect of different diesel fuel prices on the economy is significant; with a high spread due to the efficiency of the ICE vehicle. The effect of the developments until 2030 on the economy of the reference vehicle are assumed to compensate each other. These developments are higher engine prices in order to reach lower emissions and higher efficiency of the engine.

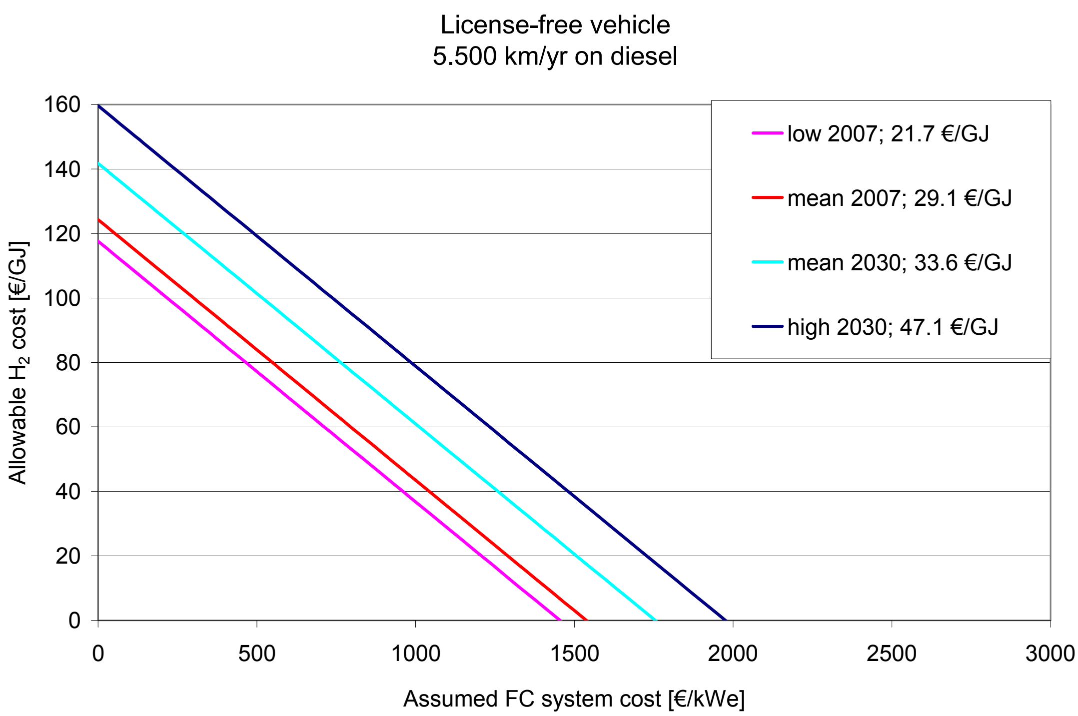


Figure 67: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of diesel with all taxes included

13.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

The CO_2 emission from the diesel ICE license-free passenger vehicle is calculated as 92 gCO_2/km using a diesel emission factor from the CONCAWE study [4] of 87 gCO_2/MJ. The CO_2 emissions and emission factors for the hydrogen fuel cell license-free vehicles in different countries are shown in Table 53. In this table it is assumed that the hydrogen is produced by electrolysis. In Table 54 the CO_2 emissions and emission factors for the fuel cell license-free vehicle are presented in relation to the source for the hydrogen.

Table 53: CO_2 emission factors for fuel cell vehicles (4th column) in different countries (Source www.energy.eu [5] and carma.org [6])

Electricity	*Electricity E-mix*	*H_2 from E Electrolysis*	*Hydrogen* ***0.6 MJ/kWh***
	gCO_2/MJ	gCO_2/MJ	gCO_2/km
NL	166	218	128
DE	141	185	109
FR	20	26	16
UK	134	175	103
PL	259	339	199
CZ	168	220	129
SW	6	8	5
DK	130	171	100
EU-25	119	156	92
Offshore wind	8	11	6

Table 54: CO_2 emission for fuel cell vehicle in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***0.6 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/km
Onsite SMR	110	65
Waste wood	13	7
Offshore wind	11	6
Coal gasification + CCS	45	26

CO_2 reduction potential per service and for the potential market
The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 68. Only sources that are below the green line for diesel have a positive impact on global warming compared to diesel.

The maximum CO_2 reduction for the diesel license-free vehicle market can be obtained by replacing diesel from fossil fuel sources with fuel cells operating on hydrogen produced by electrolysis of off shore wind electricity. This is calculated by multiplying the maximum reduction potential of the service (≈ 80 gCO_2/km) with the mileage/year (≈ 5500 km/yr), the number of new units/year (≈ 35.000) and the lifetime of the vehicles (≈ 15 year). The maximum CO_2 reduction is then approximately 0.23 Mton CO_2/yr.

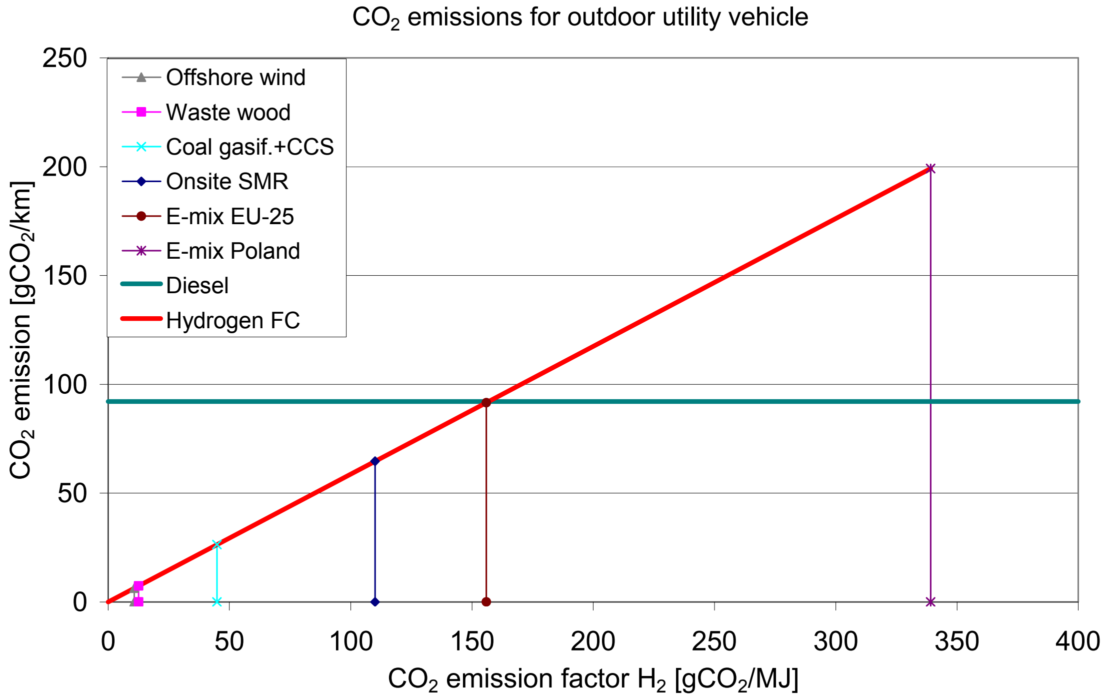


Figure 68: CO_2 emission reduction potential for replacement of diesel license-free vehicles

13.7 Conclusions and recommendations

The following general conclusions can be taken:
The manufacturers of these vehicles are small compared to car manufacturers and the license free vehicles are more expensive than the small cars.

Recommendations:
The power level for license-free vehicles is approximately 4 kW, which means that the fuel cell system costs are low compared to e.g. fuel cell system costs of passenger cars

13.8 References

1. http://www.ydea.it/
2. Personal communication JDM Dealer
3. Personal communication Jan Minten (Aixam-dealer).
4. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
5. www.energy.eu, *last visited November 2007*
6. carma.org, *last visited November 2007*

14. Case study Outdoor utility vehicles

14.1 Description of application

Transportation of goods with a limited weight and over relative short distances is the main application for utility vehicles. These goods can be for a variety of sectors and activities like:

- **Public sector:** municipalities, historic town centres, public safety, civil protection departments, railway stations, airports, hospitals, universities, communities, cemeteries, waste collection services, ecological and environmental services, postal services and fire departments.
- **Private sector and open spaces:** estates on the plains or hillside, parks and villas, maintenance of open spaces, farms, vineyards, woods, nursery gardening, floriculture and greenhouses.
- **Tourist sector:** holiday villages, camping sites, golf courses, parks, tourism-cultural sites, farm-holiday centres, riding schools residences and hotels, beaches, amusement parks, seaside resorts, sports centres, stadiums, ski resorts.
- **Services and industrial sector:** fair facilities, congress centres, commercial centres, catering services, flower auctions, industrial establishments, shipyards, harbour and airport facilities.

The utility vehicles are mainly used for short distances and within a designated public or private area. The required load capacity of the vehicle determines the sizing of the vehicle. Together with the top speed of the vehicle this sizes the engine capacity.

In Europe 2 classes of utility vehicles are defined (Directive 2002/24/CE):

- Light utility vehicles with an empty mass < 350 kg, an engine of maximum 4 kW and a maximum speed of 45 km/hr. Driving license requirement depend on the country. Also known as light quadricycles.
- Heavy utility vehicles with an empty mass < 550 kg and an engine of maximum 15 kW.

These 2 classes of utility vehicles are also used within this case study.

14.2 Description of reference technology

Gasoline and diesel internal combustion utility vehicles are used for outdoor applications. The maximum speed of the vehicles varies between 45 and 65 km/hr. The investment cost of these vehicles is low compared to trucks.
Electric utility vehicles are usable to good effect indoors and outdoors for high start-stop frequency transport applications. Electric utility vehicles are used mainly inside buildings and/or at business areas (98%) because of cost efficiency above ICE (time for starting to ride and maintenance of engine). Other advantages are air quality and noise. The electric utility vehicle can be recharged overnight using a standard electrical connection. The electric utility vehicle is mainly available as low speed (45 km/hr) vehicle. Some examples of outdoor utility vehicles are shown in Figure 69.

MEGA Multitruck | Casalini Sulkycar | Piaggio Kipper | Alke ATX 280E

– **Figure 69: Examples of outdoor utility vehicles**

In this case study the Aixam MEGA Multitruck is chosen as the typical example of the reference technology with a top speed of 45 km/h and available with a diesel (Table 55) as well as an electric engine (Table 56). The load capacity is 195 kg. A third version with a more powerful diesel engine and higher load capacity is also available; this one will not be further discussed. The technical data of Table 55 and Table 56 are taken from the Aixam-MEGA website [1].

The average mileage for the diesel based utility vehicles is higher than for the electric utility vehicle. The mileage for these vehicles varies between 600 and 13.000 km/yr [2]. For the MEGA Multitruck approx. 90% of the vehicles have diesel engines and 10% have electric engines. In combination with the relative low number of vehicles manufactured this explains the higher price of the electrical configuration compared to the diesel version. The typical cost of the 4 kW diesel engine is assumed as 2000 €. No particular data was found for the lifetime of this type of vehicle. The lifetime is assumed as 15 years. The standard maintenance requirement for the MEGA Multitruck is provided [2].

Table 55: The characteristics of the diesel engine based utility vehicle

Application	Unit	MEGA diesel 400
Power level	kW	*4 (Kubota engine)*
Efficiency; energy use	MJ/km	*1.24*
Typical cost complete system	€	*11.000*
Specific cost energy system	€/kW	*500*
Lifetime	year	*15*
Type of “fuel”	-	*diesel*
Type of “fuel” supply	-	*filling station*
Type of “fuel” storage	-	*tank*
Typical storage capacity	MJ	*850*
Range/fuel charge	km	*650*
Availability	%/yr	*> 99%*
Maintenance		*3 hrs/5000 km*

Table 56: The characteristics of the electric engine based utility vehicle

Application	Unit	MEGA electric
Power level	kW	*4 (Advanced Technology; 48V)*
Efficiency; energy use	MJ/km	*0.31*
Typical cost complete system	€	*17.600*
Specific cost energy system	€/kW	*2250*
Lifetime	year	*15*
Type of “fuel”	-	*electricity*

Type of "fuel" supply	-	*Electricity grid 220V;16A*
Type of "fuel" storage	-	*Gel type battery pack: 12 of 12V; 40Ah* *8 hrs recharging time*
Typical storage capacity	MJ	*21*
Range/fuel charge	km	*80*
Availability	%/yr	*> 99% without recharging* *Approx. 70-90% including recharging*
Maintenance		*Every 5000 km or 2*/yr; total 2-3 hrs/yr*

Utility vehicles will also develop in the next decades. Stricter emission restrictions posed by the EU (Euro 5 and Euro 6) will also apply this type of vehicles, thereby improving the combustion engines. The advantage of fuel cell systems compared to the internal combustion engine on exhaust air quality will decrease in time.

For battery operated utility vehicles the technology of fast-charging batteries is interesting. This can eventually lift the barrier of the limited range of electric vehicles. The status of the development at Toshiba is:
A new lithium-ion battery from Toshiba may hold promise for the future of electric vehicles. The electronics giant unveiled in 2007 a battery that takes only a minute to recharge to 80 percent of its full strength, making it by far the fastest recharging lithium-ion battery available. The Super Charge ion Battery can recharge to 90 percent of full capacity in less than five minutes and fully charges in less than 10 minutes. The prototype uses nano-materials technology to allow for faster charging without the inherent problems of charging with larger lithium particles.
Toshiba expects its batteries to be used in battery-powered bicycles, motorcycles, automated guided vehicles, electric forklift trucks and construction machinery. The company also said the new system is a promising candidate for emergency power sources, electric power regeneration in wind power systems and stabilization of electric power supply, with applications in hybrid and electric cars also planned.

If the fast-charging batteries mature into cost effective energy storage systems for transportation this will form a serious competitor to fuel cell systems. The fast charging option requires a high power connection, as an example a power supply of 150 kW is required for 3 min. charging of 25 MJ energy storage.

The cost of the battery operated electric utility vehicle can become lower when electric vehicles (battery of fuel cell) become more common. The number of electric vehicles is still small.

14.3 Description of the market

The market chosen is the market for utility vehicles. Some producers also describe their products as light commercial vehicles without reference to the European classification (≤ 4 kW; ≤ 15kW). The market is split up in power level and type of engine, whenever the information is available.
The European suppliers and their yearly production is shown in Table 57. The number of non-European vehicles in this market is small.

Table 57: Market for utility vehicles

Supplier	Country	Power	ICE vehicles /yr	Electric vehicles/yr	Total vehicles/yr
Aixam-MEGA	FR	≤ 4 kW ≤ 15 kW	}1200	100	1300
Spijkstaal	NL	various		500	500
Piaggio Ape	IT	≤ 15 kW	9800	none	9800
Alke	IT	≤ 15 kW			
Casalini Sulkycar	IT	≤ 4 kW			
Bellier Transporter	FR	≤ 4 kW	y	y	
Ligier Pro	FR	≤ 4 kW	< 1000		
Italcar	IT	≤ 4 kW	y	y	
Grecav	IT	≤ 4 kW	y		
VEM	IT	≤ 15 kW			
Total					

The market for utility vehicles is much larger outside Europe, e.g. in India Piaggio sells 140.000 light commercial vehicles/yr (cargo + passenger subsegment), which is a market share of 34%. The light commercial vehicles also include the Porter and Quargo, that have an engine power larger than 15 kW and are therefore above the European category of heavy utility vehicles [3].

The number of electric vehicles (<3,5 ton) on European roads is estimated to be approximately 13000, of which 10100 are registered in France (ref. Piaggio [3]).

14.4 Description of FC/H2 technology for the application

The H_2 PEMFC utility vehicle combines the advantage of the noiseless, odourless and environmental friendly electric vehicle with the extended driving range of the diesel version. The power of the fuel cell system can be small, which can be advantageous for market introduction of the fuel cell utility vehicle. The drivers are the same as for the electric vehicle: Indoor operation possible; noiseless and odourless and its green image with an extended driving range. Due to the low speed of the vehicle and its operation in restricted areas, the refuelling station for the hydrogen should be nearby. The characteristics of the envisaged fuel cell utility vehicle are shown in Table 58. The efficiency of the fuel cell vehicle is calculated from the efficiency of the electric vehicle from Table 56 without the 80% recharging losses combined with a fuel cell system with 44% net efficiency on LHV of H_2.

The following parties are developing or demonstrating the combination of fuel cell systems with utility vehicles:

- ECN (NL) has demonstrated HydroGEM, the fuel cell version of the GEM electric utility vehicle using a in-house developed 5 kW fuel cell.
- VEM (IT) demonstrates 10 utility vehicles with a 2.5 kW fuel cell from Axane for the HyChain project.
- The Toro Company (USA) have shown 2 hydrogen-powered fuel cell utility vehicles. They use fuel cells from Nuvera and Hydrogenics.

- Energy Partners (USA) developed 8 kW demonstration fuel cell utility vehicles based on John Deere's "Gator" vehicles using metal hydride storage systems.
- H_2 Logic (DK) has provided a unit of 1 kW (Ballard?) for a MEGA city service vehicle.

Table 58: The characteristics of the envisaged fuel cell utility vehicle

Application	Unit	H_2 PEMFC utility vehicle
Power level	kW	*4*
Efficiency; energy use	MJ/km	*0.6*
Lifetime	year	*15*
Type of “fuel”	-	*Hydrogen*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Tank; pressurized*
Typical storage capacity	MJ	*180*
Range/fuel charge	km	*300*
Availability	%/yr	*Approx. 99%*
Maintenance		*Every 5000 km or 2*/yr; total 2-3 hrs/yr*

14.5 Economic boundary conditions for FC/H2 technology

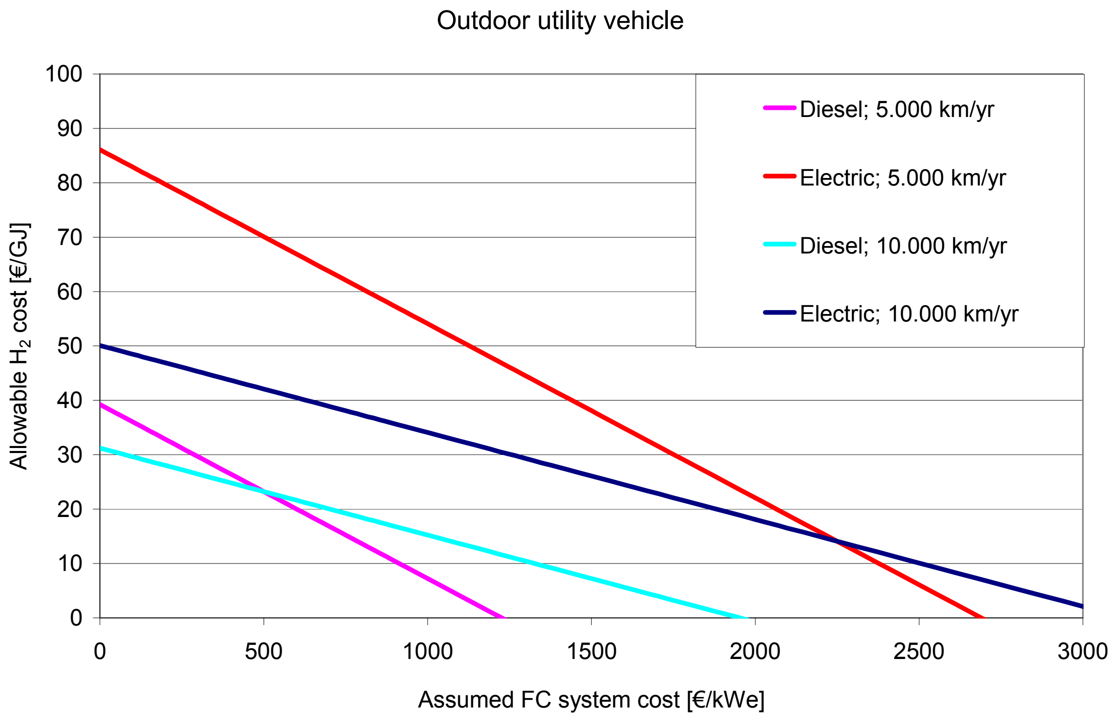


Figure 70: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre as for light electric or diesel utility vehicles cars with a yearly mileage of 5.000 and 10.000. All taxes included

The 2 reference technologies, diesel ICE and electric engine are considered for the economic evaluation. For this economic evaluation the MEGA Multitruck is used as the reference vehicle. The average European energy prices for consumers/ small companies in 2007 are used for the economic evaluation. In

Figure 70 the allowable cost of H_2 as a function of the assumed FC system cost is shown at the same cost per kilometre as the diesel or electric MEGA Multitruck. Yearly mileages of 5.000 and 10.000 km/yr are considered.

Figure 70 is based on the input in Table 59. The figure shows that the market for that is covered by the electric version is easier within economical reach than the market covered by the ICE version. The FC system becomes less attractive compared to the electric version when the average mileage is increased, caused by the high efficiency of the electric version. However the restricted range limit for the electric version is not addressed in the figure, which is an important selling item for the FC system.

The lifetime of the gel batteries is assumed to last 50.000 km. The supplier of the electric vehicle states that the lifetime of the gel battery depends on its use and also on other parameters. Its warranty is 2 years or 1050 cycles Other suppliers of gel batteries state 800 times recharging. Information from the supplier shows that the maintenance of the engine is strongly dependent on the mileage and to a much lesser extent to the age of the vehicle. Only the standard maintenance costs and battery replacement costs are incorporated [1].

The prices are with all taxes included for the engine, the maintenance as well as the fuel. For the fuel cell system the maintenance is expected to be similar to the battery vehicle, except that battery replacement will be less expensive due to a lower number of batteries needed in the fuel cell system. The effect of interest rates on the results is neglected.

Table 59: Background table for

Figure 70 for the same cost in €/km for a utility vehicle with a diesel ICE and the electric engine compared to a fuel cell system, only taking into account fuel cost and engine cost

Reference system		**Diesel ICE**	**Electric**	**Diesel ICE**	**Electric**
Engine cost	€/kW	500	2250	500	2250
Power	kW	4	4	4	4
Lifetime	yr	15	15	15	15
Distance	km/yr	5000	5000	10000	10000
Specific investment cost	€/km	0.027	0.120	0.013	0.060
Fuel cost	€/GJ	23.5	30.1	23.5	30.1
Fuel use	MJ/km	1.24	0.31	1.24	0.31
Specific fuel cost	€/km	0.029	0.009	0.029	0.009
Engine maintenance cost	€/km	0.07	0.07	0.07	0.07
Total cost	€/km	0.122	0.200	0.108	0.140
FC system					
Power	kW	4	4	4	4
Lifetime	yr	15	15	15	15
Distance	km/yr	5000	5000	10000	10000
Fuel use	MJ/km	0.60	0.60	0.60	0.60
Engine maintenance cost	€/km	0.06	0.06	0.06	0.06

Assumed FC system cost €/kWe	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0	39	86	31	50
200	33	80	28	47
500	23	70	23	42
1000	7	54	15	34
2000	-25	22	-1	18
4000	-89	-42	-33	-14

The fuel cell vehicle is economically attractive if in

Figure 70 the combination of cost of hydrogen and the cost of the fuel cell engine are below the line for the reference technology. The lifetime of the fuel cell system is also assumed as 15 years. If the lifetime is lower, than the fuel cell system cost should be read as the costs including replacement costs of the fuel cell. This Figure 42 also shows that replacement of electric utility vehicles by fuel cell vehicles is cost effective at higher fuel cell/hydrogen costs than for the diesel ICE utility vehicle.

Fuel cost scenarios

The effect of the different fuel costs on the assumed fuel cell system costs and the allowed hydrogen costs is provided in Figure 71. For reference, the following average European electricity prices in $€_{2000}$ for small industries are considered:

- The low 2007 value with all taxes (14.2 €/GJ)
- The mean 2007 value with all taxes (30.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (52.7 €/GJ)

This Figure shows that the effect of different electricity prices on the economy is small since the battery operated system is very efficient, and therefore the effect of the energy price is small. Similar calculations using the diesel ICE vehicle and presented in Figure 72 shows lower values but with a higher spread due to the lower efficiency of the ICE vehicle.

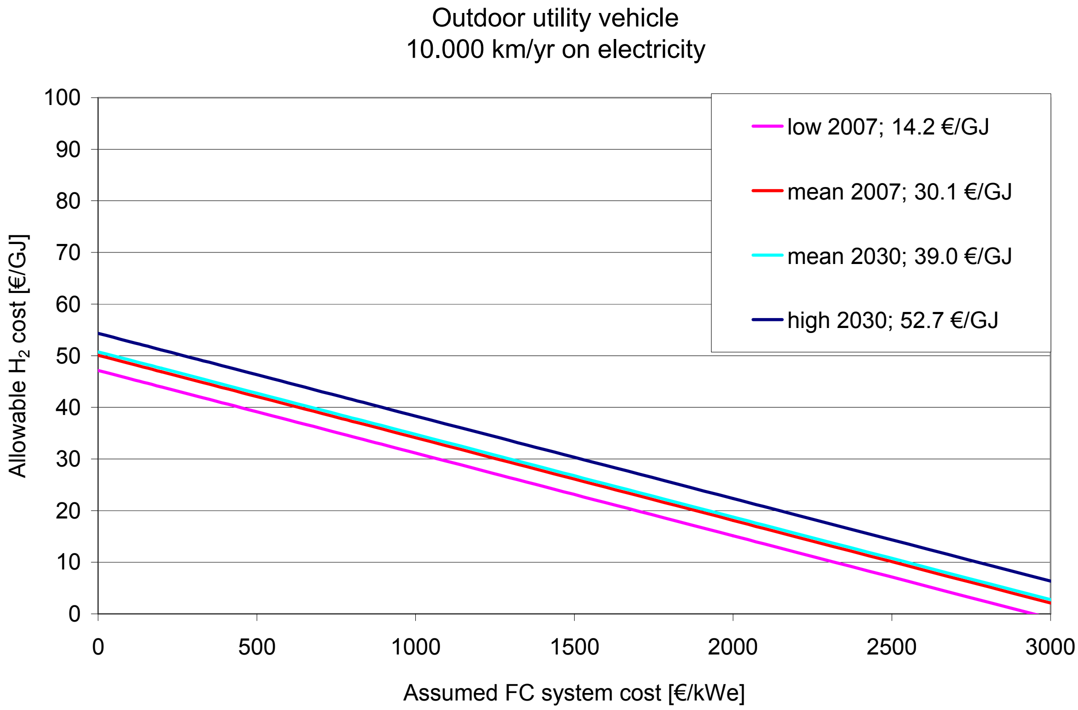


Figure 71: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of electricity with all taxes included

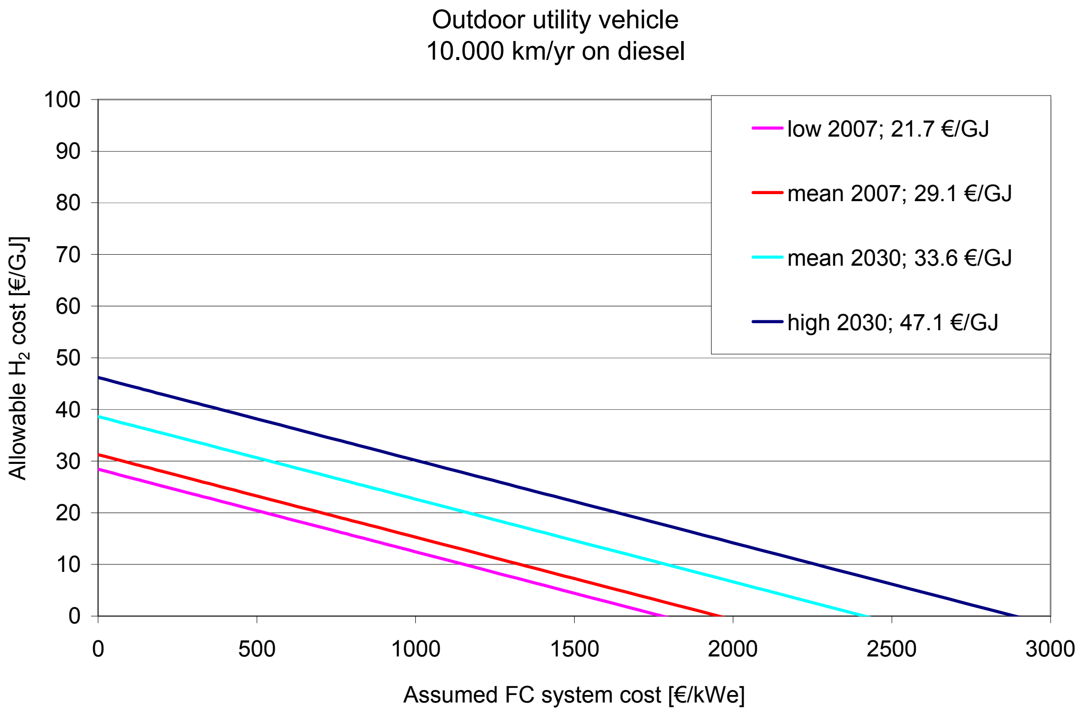


Figure 72: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of diesel with all taxes included

14.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

The CO_2 emission from the diesel ICE utility vehicle is calculated as 108 gCO_2/km using a diesel emission factor from the CONCAWE study [4] of 87 gCO_2/MJ. The CO_2 emissions from the electric utility vehicle and the hydrogen fuel cell utility vehicle are shown in Table 22. In this table it is assumed that the hydrogen is produced by electrolysis. The CO_2 emission factors for the energy carrier electricity and hydrogen are also provided in this table. In Table 23 the CO_2 emissions for the fuel cell vehicle are presented in relation to the source for the hydrogen.

Table 60: CO_2 emission factors for electric vehicles (3rd column) and fuel cell vehicles (5th column) in different countries (Source www.energy.eu [5] and carma.org [6])

Electricity	*Electricity E-mix*	*Electric **0.3 MJ/km***	*H_2 from E Electrolysis*	*Hydrogen **0.6 MJ/kWh***
	gCO_2/MJ	gCO_2/MJ	gCO_2/MJ	gCO_2/MJ
NL	166	52	218	128
DE	141	44	185	109
FR	20	6	26	16
UK	134	42	175	103
PL	259	80	339	199
CZ	168	52	220	129
SW	6	2	8	5
DK	130	40	171	100
EU-25	119	37	156	92
Offshore wind	8	3	11	6

Table 61: CO_2 emission for fuel cell utility vehicle in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***0.6 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/MJ
Onsite SMR	110	65
Waste wood	13	7
Offshore wind	11	6
Coal gasification + CCS	45	26

CO_2 reduction potential per service and for the potential market

The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 73. Only sources that are below the green line for diesel have a positive impact on global warming compared to diesel. When comparing fuel cell to electric vehicles, only hydrogen from waste wood and from coal gasification with CCS from the options considered have a CO_2 reduction compared to the CO_2 emissions from the average EU-25 electricity production. If electricity is used to produce hydrogen, the CO_2 emissions from the fuel cell vehicle are 2.5 times the emission from battery operated electric vehicles when the same way of electricity production is considered, as can be observed from Table 22.

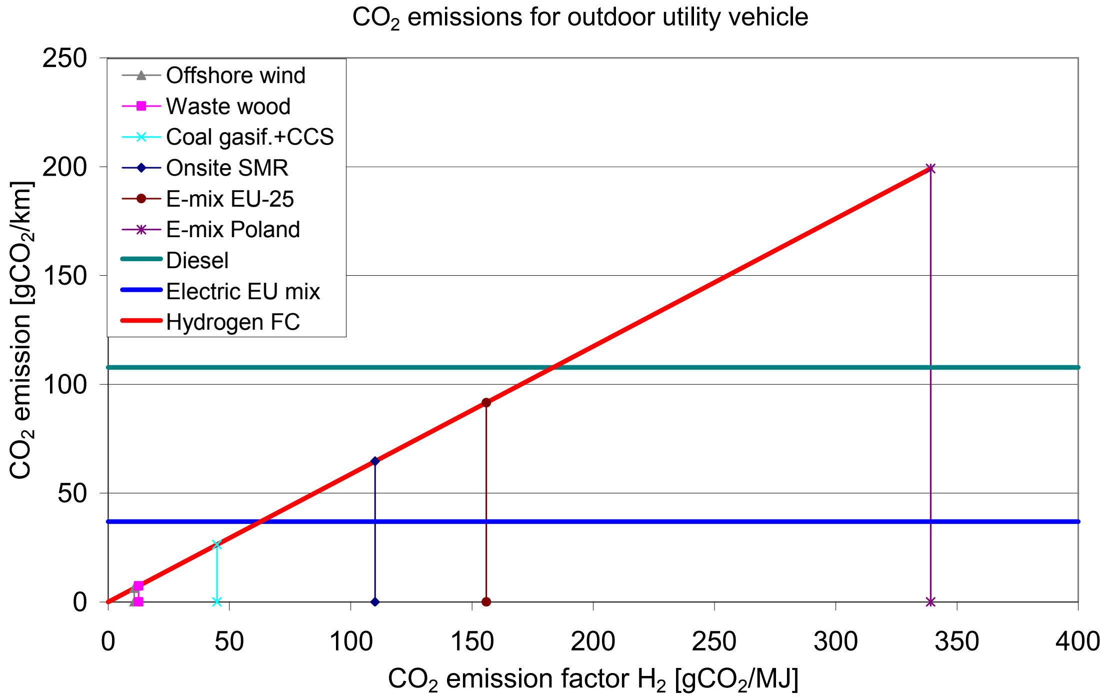


Figure 73: CO_2 emission reduction potential for replacement of diesel and electric utility vehicles

The maximum CO_2 reduction for the diesel ICE utility vehicle market is calculated by multiplying the maximum reduction potential of the service (≈ 100 gCO_2/km) times the mileage/year (≈ 5000 km/yr) times the number of units (300.000). The number of units can be approximated by the lifetime of the unit (15 years) and the yearly market sale, which are approx. 20.000 vehicles per year.
The maximum CO_2 reduction is then 0.15 Mton CO_2/yr.

14.7 Conclusions and recommendations

The following general conclusions can be taken:

- Replacement of electric utility vehicles by fuel cell vehicles is cost effective at higher fuel cell/hydrogen costs than for the diesel ICE utility vehicle.
- The CO_2 reduction potential for replacement with a fuel cell of the electric utility vehicle is much smaller than for the diesel ICE utility vehicle.
- If hydrogen is produced from electrolysis, the CO_2 emission of the fuel cell utility vehicle is 2.5 greater than from the battery operated electric vehicle using the same source of electricity.

Recommendations:
There is a market for green, noiseless, and clean utility vehicles for which customers are prepared to pay a premium. The power level for small utility vehicles is approximately 4 kW, which means that the fuel cell system costs are low compared to e.g. fuel cell system costs of passenger cars. The utility vehicles are operated in designated areas; therefore a single hydrogen refuelling location is required. This makes these vehicles ideal to get operating experience from the transport sector at low cost.

14.8 References

1. http://www.mega-electric.co.uk/pdf/datasheet_pickup.pdf
2. Personal communication Jan Minten (Aixam-MEGA)
3. Piaggio annual report 2006
4. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
5. www.energy.eu, *last visited November 2007*
6. carma.org, *last visited November 2007*

15. Case study Scooter

15.1 Description of application

Traffic congestion is increasing dramatically in major cities around the world. In many large cities, journey speeds are less than 10 mph on average and less than 3 mph in the city centre. Hours get lost, gas gets wasted, vehicles get stuck and frustration rises. Inner city parking is expensive and scarce, gas prices have reached an all time high, the escalating cost of gasoline is creating unprecedented demand for hybrid and alternative fuel vehicles, public transportation is inflexible and unpopular…so, in this context, a strong market has been created for electric vehicles. The Electric Scooter is supposed to replace all the high polluting gasoline scooters, mopeds and motorcycles that are used by over 100 million riders in Asia and Europe. This kind of vehicle can be a smart choice for commuters, city dwellers, fleet operators, delivery services, municipalities.

In Europe, this class of vehicles is defined in the Directive 2002/24/CE:

- motorcycles, i.e. two-wheel vehicles without a sidecar (category L3e) or with a sidecar (category L4e), fitted with an engine having a cylinder capacity of more than 50 cm3 if of the internal combustion type and/or having a maximum design speed of more than 45 km/h,

The electric bike and electric scooter industry is heading toward a market size of 100,000,000 units yearly in five to ten years. We include electric scooters, now at less than 100,000 unit sales in these worldwide numbers, since the electric scooter will be the "green" vehicle of choice to replace the 70 million gasoline mopeds, motor scooters and motorcycles sold yearly.
Gasoline powered two wheelers include motorcycles, mopeds, and motor scooters – with a market size larger than 70 million units per year, roughly estimated for 2006. Asia Pacific is the largest user of all at around 58 million. The seventy million units include: motor scooters 50cc-29 million, mopeds-13 million, motorcycles below 250cc-27 million, and motorcycles above 250cc-1 million.
Motorcycles are more powerful and faster machines than the Electric Scooters, but could be replaced by battery/fuel cell hybrid motorcycles someday. For much of the world, the motorcycle, motor scooter or moped is the “step up from a bicycle” vehicle for people who cannot afford, or have no place to park and drive a car. Electric Bicycles are often a replacement for this role – powered two-wheelers that do not pollute, and are less expensive to buy and own than gasoline powered motorcycle, motor scooter or moped.

15.2 Description of reference technology

Gasoline is today the most popular energy vector for scooters, but even the electric scooter is supposed to replace a really great number of gasoline scooters, mopeds and motorcycles during the next decades.
The performances and the technical characteristics of this kind of vehicles are very different depending primarily on the size of the engine and then on the mission (private use, public sector, services and so on)

In this case study, two famous scooters have been identified as reference technology, the Vespa Piaggio LX 125 (gasoline scooter) and the Vectrix Electric Scooter.

Figure 74: Vespa Piaggio LX 125

Table 62: The characteristics of the gasoline engine based scooter

Application	Unit	Vespa LX 125
Engine type		*Single-cylinder, air cooled, two valve four stroke*
Cylinder capacity	cc	*124*
Max power at shaft	kW	*7,46 at 8000 rpm*
Transmission		*Twist and go" automatic transmission (CVT) with automatic clutch*
Length	mm	*1800*
Width	mm	*740*
Dry weight	kg	*110*
Fuel tank capacity	l	*8,6*
Max speed	km/h	*91*
Type approval		*Euro 3*
Consumption		*39 km/l@60 km/h*
Type of fuel		*Gasoline*
Type of fuel supply		*Filling station*
Type of fuel storage		*Tank*
Typical cost complete system	€	*3.000*
Typical cost engine system	€	*500*

The Vespa description on the Piaggio web-site:
The Vespa 125, with its compact steel body, which guarantees strength and durability, together with the engine performance, offers an incredible easy handling that sets the Vespa LX in a category of its own. Quiet, clean and economical, the Vespa LX 125 provides greater performance with lower fuel consumption, noise and emission. The elegant easy-to-read instrument panel that features a speedometer, fuel gauge, digital clock as well as a turning-signal indicator, low and high beam and oil level indicator, is completed with a LED for the anti-theft immobiliser. The new Vespa LX125: the future of urban transport.

Vectrix Electric Scooter

Figure 75: Vectrix electric scooter

The Vectrix offers all the benefits of a traditional gasoline-powered scooter but without the noise, pollution, expensive maintenance, oil changes, and expensive trips to the gas station. The Vectrix is engineered to provide an eco-friendly, powerful alternative for commuting and recreational needs, the Vectrix has superior handling.

Table 63: The characteristics of the electric scooter

Application	Unit	Vectrix Electric Scooter
Motor type		*Brushless DC, radial air-gap motor*
Power	kW	*Peak power 20,2* *Maximum continuous power: 7 kW*
Torque	Nm	*Maximum torque: 65 Nm* *Maximum continuous torque: 22 Nm*
Gearbox		*Coaxial integrated rear-wheel mounted planetary gear drive*
Battery		*Nickel Metal Hydride*
Battery capacity		*3.7 kWh*
Battery Voltage		*125 V*
Charger		*1.5 kW on-board battery charger;* *110V-220V (50/60Hz)*
Recharge time		*2 hours (80%)*
Discharge cycles		*1.700*
Estimated life		*10 years or 80.000 km*
Weight	kg	*210*
Max speed	km/h	*100*
Acceleration		*0-80 km/h in 6.8 seconds* *0-50 km/h in 3.6 seconds*
Range		*110 km @ 40 km/h*
Emissions		*Polluting: zero* *CO2: zero* *Acoustic: negligible*
Maintenance		*minimal*
Typical cost complete system	€	*10.500*
Typical cost engine system	€	*3500*

The electric scooter is coming into prominence with practical products and will be a significant player in the electric transportation movement going forward. Moreover, if the technology of the fast charging batteries will mature into cost effective energy storage systems for transportation, as recently announced by Toshiba, this kind of vehicle will seriously become competitive even with respect to the fuel cell vehicles.

15.3 Description of the market

In cities and urban area, small vehicles like scooters become more and more popular with the growing intensity of traffic and congestion. Tough scooters are a convenient mode of transportation, their intensive use can result in significant environmental and health problems as known, e.g., from several Asian cities. In this context, it is evident the growth of the market for electric bike and scooters.
There are five independent factors that are coming together at the same time in the history of mankind that will influence this continued growth of the electric bikes and scooters:

i. Increasing market economy growth of the wealth of people all over the world but particularly in China and in India.
ii. High gasoline prices with high oil prices dominated by general turmoil
iii. Concern about global warming and the movement to alternative energy
iv. Higher quality products with better technology like lighter lithium batteries that provide longer range and better performance.

v. Rapid urbanization of the human race leading to high density cities with no room for parking of cars, and limited surface roads that will require two-wheelers for much of personal transport.

Factors 2/3/4/5 are impacting Europe and the USA now and the sense is that electric bike and electric scooter will be gaining more users in those locales. The rest of the world awaits economic growth similar to the China miracle of the past ten years before these vehicles are affordable to the mass public in countries like Africa, South America and Southeast Asia: this economic growth eventually will happen but it will take a long time.

Gasoline powered two wheelers include motorcycles, mopeds and motor scooters, with a market size larger than 70 million units per year, roughly estimated for 2006. Asia pacific is the largest user of all at around 58 million. The seventy million units include: motor scooters 50cc-29 million, mopeds – 13 million, motorcycles below 250cc – 27 million and motorcycles above 250cc – 1 million.
In some studies[2] of electric scooter sales it has been assumed that the electric scooters will be a replacement for the gasoline motor scooter and moped that sold 42 million combined units in 2006. Motorcycles are more powerful and faster machines than the ESs but could be replaced by battery/fuel cell hybrid motorcycles someday. For much of the world the motorcycle, motor scooter or moped is the “step up from a bicycle” vehicle for people who cannot afford, or have no place to park and drive a car.

The dominant electric bike producer and user in China, as yearly sales continue to climb and soon will be over 20 million units. Reports of many India bike makers suggest that market for electric bikes in India is about to explode similar to China. Europe and the USA are on the verge of beginning a market surge as well with Europe expected to be ahead of the USA. With the continued high price of oil and gasoline and increasing parking and traffic congestion, Americans and Europeans are now more likely to give consideration to the use of the electric bike for short trips to market and work.
Even electric scooters appear to be on the verge of major expansion in production and sales in China and India as well as in Europa and USA but at lower sales number levels: the combination of new electric scooter design using improved lithium Ion batteries and a marketing focus will stimulate this expansion.
In the following tables some numbers are given concerning sales of electric bikes, scooters and electric scooters.

Table 64: Worldwide Electric Bike Sales (estimates)

	2005	2006	2007	2008	2009
China	12,000,000	14,000,000	17,000,000	21,000,000	24,000,000
India	20,000	50,000	100,000	200,000	500,000
Japan	197,000	200,000	200,000	200,000	200,000
Europe	180,000	190,000	220,000	400,000	750,000
Taiwan	9,000	10,000	10,000	10,000	10,000
SE Asia	25,000	30,000	35,000	40,000	45,000
USA	100,000	120,000	150,000	180,000	200,000
Total	**12,531,000**	**14,600,000**	**17,695,000**	**22,030,000**	**25,710,000**

[2] EBWR reports 2007

Table 65: Worldwide Mini Scooter Sales (estimates)

	2005	2006	2007	2008	2009
China	60,000	70,000	80,000	90,000	100,000
India	5,000	7,000	10,000	10,000	10,000
Japan	25,000	25,000	25,000	25,000	25,000
Europe	100,000	100,000	100,000	100,000	100,000
Taiwan	9,000	9,000	9,000	9,000	9,000
SE Asia	30,000	30,000	35,000	35,000	40,000
USA	1,800,000	2,000,000	2,000,000	2,000,000	2,000,000
Total	**2,029,000**	**2,241,000**	**2,259,000**	**2,269,000**	**2,284,000**

Table 66: Worldwide Electric Scooter Sales

	2005	2006	2007	2008	2009
China	10,000	16,000	50,000	100,000	200,000
India	1,000	2,000	5,000	10,000	20,000
Europe	1,000	1,500	4,000	8,000	15,000
USA	1,000	1,500	3,000	5,000	10,000
RoW	1,000	2,000	3,000	5,000	8,000
Total	**14,000**	**23,000**	**65,000**	**128,000**	**253,000**

Table 67: Estimated Gasoline Scooter and Moped Sales

–	– Millions
– ***China***	– 22
– ***India***	– 7
– ***Indonesia***	– 5
– ***Thailand***	– 2
– ***Europe***	– 1.4
– ***South America***	– 1.4
– ***Taiwan***	– 0.4
– ***North America***	– 0.2
– ***RoW***	– 0.6
– **Total**	– **40**

15.4 Description of FC/H2 technology for the application

Powering scooter with PEM fuel cell is a very attractive alternative in terms of environmental advantages like noiseless, odourless and without harmful emissions: a suitable combination of PEM fuel cell and battery (or supercapacitors) can lead to a vehicle with an improved range respect to the simple electric version. The power of the fuel cell system should be small, that means low cost and easier market introduction.

The reference vehicle chosen is the electric FC scooter Hysyrider®, developed by the Hysylab laboratory of Envipark (Torino, Italy), a centre of excellence on hydrogen technologies: it is a fuel cell based scooter coupling the advantages of individual mobility (flexibility, efficiency, etc) and hydrogen technologies (environmental impact, sustainability, etc.).

Hysyrider® scooter is a flexible, clean, non pollutant way of transport; it has been proofed in outdoor as well as in indoor application, giving back good results in areas as safety, stability, autonomy, flexibility and comfort. Hysyrider® is based on hybrid architecture: the fuel cell (300 W, 20 cells) works in parallel with a battery pack (7.2 Ah). The parallel operation is based on a DC/DC converter used to boost and stabilise the fuel cell voltage at the battery pack voltage became lower than a fixed value. The hydrogen storage is made through the use of a hydride vessel (200 Nlitres) allowing a couple of hours of operation in maximum speed mode (20 km/h). The thermal energy co generated by the fuel cell is used to warm the vessel in order to optimise the hydrogen desorption. The air supply system consists in a blower allocated directly on the fuel cell and it is controlled by the motor power request.

Figure 76: the HYSYRIDER ® Scooter

Table 68: Characteristics of the HYSYRYDER® scooter

Application	**Unit**	**Hysyrider ® Scooter**
Motor type		*Brushless DC,*
Power	W	*250 W, 500 W peak power*
Battery		*Lead Acid*
Battery capacity	Ah	*7.6 Ah*
Battery Voltage	V	*48 V*
Recharge time		*7-9 h (batteries)* *1 h metal hydride tank*
Weight	kg	*80*
Max speed	km/h	*30*
Range		*60km @ 20 km/h*

Emissions		*Polluting: zero* *CO2: zero* *Acoustic: negligible*
Maintenance		*minimal*
Fuel Cell		*Arcotronics, 20 cells, 20-10V, 400 W*
H2 tank		*2 Metal Hydride H200 Bond by LabTech 200 NI*
Typical cost complete system	€	*3.000*

Another fuel cell scooter has been realized and shown for the firs time in 2004 by Aprilia: Aprilia Atlantic Zero Emission Fuel Cell

Figure 77: Aprilia Atlantic Zero Emission Fuel Cell Scooter

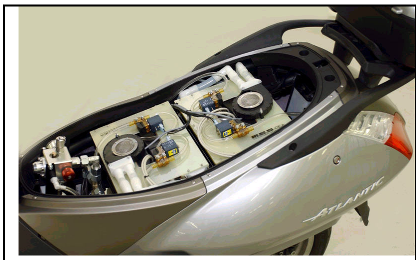
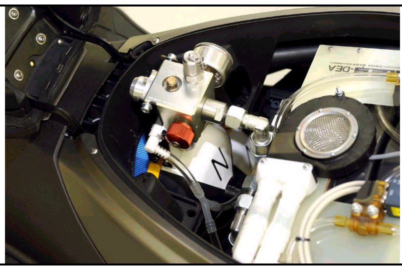
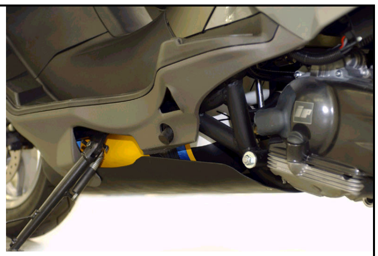
		
Fuel Cell 2 x 3 kW	H2 valve to fuel cells	H2 bottle and electric motor

Figure 78: Some components of the Aprilia Fuel Cell Scooter

The advanced model is equipped with a 6kW (about 8hp) PEM fuel cell which is fitted, together with the hydrogen storage and electrical engine, in the normal engine compartment of the scooter. A top speed of around 85km/h can be achieved and the riding range is up to 150km in urban use.

Table 69: Characteristics of the Aprilia Fuel Cell Scooter

Application	Unit	Hysyrider ® Scooter
Motor type		*Brushless DC*
Power	W	*6*
Weight	kg	*160*
Max speed	km/h	*85*
Range		*150km @ urban use*
Emissions		*Polluting: zero* *CO_2: zero* *Acoustic: negligible*
Fuel Cell		*MES-DEA*
Typical cost complete system	€	*N.D. (prototype)*

Even Vectrix has proposed a fuel cell version of their electric scooter in a hybrid configuration: this fuel cell maxi scooter features a fully-integrated 500 Watt Protonex NGenTM fuel cell system that continuously charges the battery pack, which in turn provides to drive the motor. The fuel cell shuts off automatically when the battery pack is fully charged. This scooter boasts a top speed of 100 km/h and rapid acceleration from 0 – 80 km/h in fewer than 7 seconds.

Table 70: Vectrix fuel cell hybrid scooter specifications

Application	Unit	Vectrix fuel cell electric scooter
Fuel Cell		*Fully integrated onboard Protonex NGen fuel cell* *Fuel source: hydrogen* *Fuel Cell output: 500 W*
Motor type		*Brushless DC, radial air-gap motor*
Power	kW	*Peak power 20 at 3000 rpm* *Maximum Current 275 Amps*
Torque	Nm	*Maximum torque: 65 Nm* *Maximum continuous torque: 22 Nm*
Gearbox		*Integrated rear-wheel mounted planetary gear drive*
Battery		*Nickel Metal Hydride*
Rated battery capcity		*20 Ah, 2,5kWh*
Battery Voltage		*125 V*
Recharge options		*On-board 500 Watt Fuel Cell or 110V-220V outlet*
Recharge time		*5 hours (80%) with Fuel Cell or 2 hours 110V*
Discharge cycles		*1.700*
Estimated life		*10 years or 80.000 km*
Weight	kg	*198*
Max speed	km/h	*100*
Acceleration		*0-80 km/h in 6.8 seconds* *0-50 km/h in 3.6 seconds*
Range		*250 km @ 40 km/h*
Emissions		*Polluting: zero* *CO_2: zero* *Acoustic: negligible*
Maintenance		*minimal*
Typical cost complete system	€	*ND*

Figure 79: Vectrix Fuel Cell Hybrid Scooter

Another interesting prototype has been shown by the British company Intelligent Energy: in 2005 this company claimed the world's first purpose-built, fuel-cell motorbike, the Emissions Neutral Vehicle, dubbed ENV. Powered by a 6kW 48 volt motor and with energy supplied from Intelligent Energy's 1kW hydrogen fuel cell, the ENV is currently capable of 50mph (80km/h) and is still under development - by the time the bike reaches market (no time frame yet), it can be expected it will reach most speed limits and exceed its current range of 100 miles (160 kilometres). The ENV weighs just 80 kilograms, has disc brakes and a belt drive and will face some very tough competition in the fuel cell two-wheel market as it evolves over the next few years.

To enhance performance during peak power demand (ie when accelerating), the fuel cell is hybridized with a battery pack to provide a 6kW peak load to the motor.

The company claims the bike is one of the first designed from scratch as a fuel cell motorcycle rather than being adapted from an existing design.

Figure 80: Intelligent Energy Fuel Cell Scooter

Table 71: ENV fuel cell scooter characteristics

Application	Unit	ENV fuel cell scooter
Fuel Cell		*1 kW Intelligent Energy air-cooled*
Motor type		*Brushed motor*
Power	kW	*6 kW, 48 VDC*
Motor controller		*Brusa Direct Current*
Storage Battery		*4 x 12 V Lead Acid*
Hydrogen storage		*High pressure composite cylinder*
Hydrogen energy		*2.4 kWeh*
Hydrogen refuel time		*Less than 5 minutes*
Max speed	km/h	*80*
Acceleration		*0-32 km/h in 4.3 seconds* *0-48 km/h in 7.3 seconds* *0-80 km/h in 12.1 seconds*
Range		*160 km*
Emissions		*Polluting: zero* *CO_2: zero* *Acoustic: negligible*
Maintenance		*minimal*
Typical cost complete system	€	*ND*

15.5 Economic boundary conditions for FC/H2 technology

The 2 reference technologies, gasoline ICE and electric engine are considered for the economic evaluation: the Vectrix scooter has been chosen as reference vehicle. Concerning the energy price, the average European energy prices for consumers/small companies in 2007 are used. In Figure 82 the allowable cost of H_2 as a function of the assumed FC system cost is shown at the cost/km as the gasoline or electric Vectrix Scooter: the fuel cell vehicle will be economically attractive if in Figure 82 the combination of cost of hydrogen and the cost of fuel cell engine will stay below the line for the reference technology

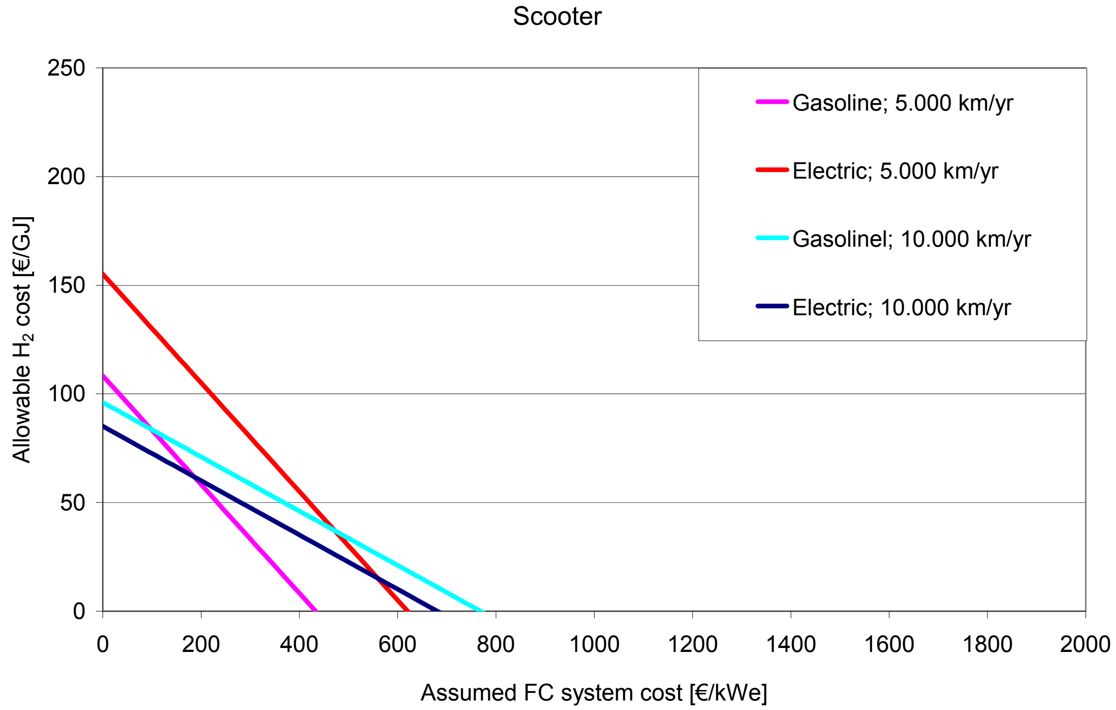


Figure 81: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost/km as for electric or gasoline scooter with a yearly mileage of 5.000 and 10.000 km, all taxes included

Table 72: Background table for Figure 81 for the same cost in €/km for a scooter with a gasoline ICE and the electric engine compared to a fuel cell system, only taking into account fuel cost and engine cost

Reference system		**Gasoline ICE**	**Electrical**	**Gasoline ICE**	**Electrical**
Engine cost	€/kW	70	400	70	400
Power	kW	7	7	7	7
Lifetime	yr	10	10	10	10
Distance	km/yr	5000	5000	10000	10000
Specific investment cost	€/km	0,010	0,056	0,005	0,028
Fuel cost	€/GJ	29,1	30,1	29,1	30,1
Fuel use	MJ/km	0,81	0,20	0,81	0,20
Specific fuel cost	€/km	0,024	0,006	0,024	0,006
Engine maintenance cost	€/km	0,02	0,01	0,02	0,01
Total cost	€/km	0,053	0,072	0,048	0,044
FC system					
Power	kW	5	5	5	5
Lifetime	yr	10	10	10	10
Distance	km/yr	5000	5000	10000	10000
Fuel use	MJ/km	0,40	0,40	0,40	0,40
Engine maintenance cost	€/km	0,01	0,01	0,01	0,01

Assumed FC system cost €/kWe	Allowable H2 cost €/GJ	Allowable H2 cost €/GJ	Allowable H2 cost €/GJ	Allowable H2 cost €/GJ
0	108	155	96	85
200	58	105	71	60
500	-17	30	34	23
1000	-142	-95	-29	-40
2000	-392	-345	-154	-165
4000	-892	-845	-404	-415

Fuel cost scenarios

The effect of the different fuel costs on the assumed fuel cell system costs and the allowed hydrogen costs is provided in Figure 83. For reference, the following average European electricity prices in $€_{2000}$ for small industries are considered:

- The low 2007 value with all taxes (14.2 €/GJ)
- The mean 2007 value with all taxes (30.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (52.7 €/GJ)

This Figure 82 shows that the effect of different electricity prices on the economy is small since the battery operated system is very effective, and therefore the effect of the energy price is small. Similar calculations using the gasoline ICE vehicle and presented in Figure 83 shows lower values but with a higher spread due to the lower efficiency of the ICE vehicle. Comparison with Figure 42 shows that the effect of the mileage on the allowable H_2 costs in order to be cost competitive is much larger that the effect of the fuel or electricity price.

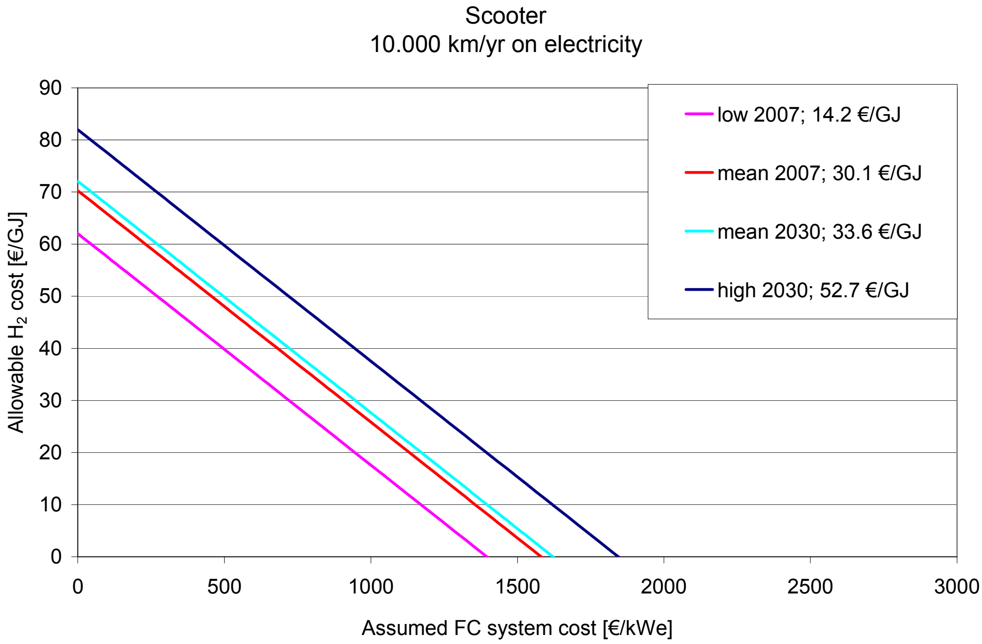


Figure 82: Allowable hydrogen cost vs. assumed FC system cost of 4 different energy prices with all taxes included

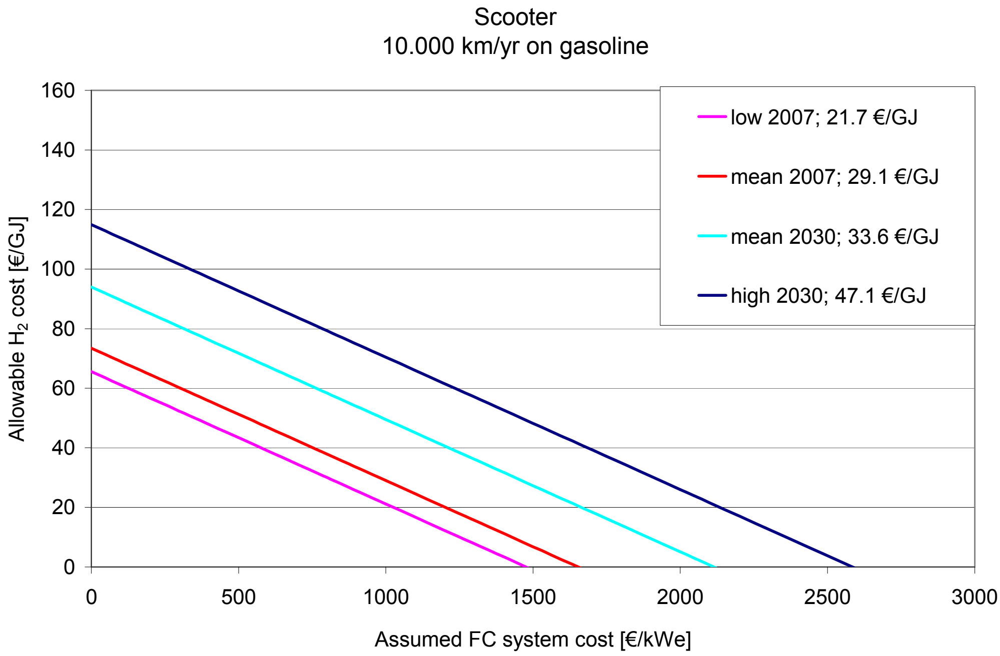


Figure 83: Allowable hydrogen cost vs. assumed FC system cost of 4 different energy prices of gasoline with all taxes included

15.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

The CO_2 emission from the gasoline ICE scooter is calculated as 90 g CO_2/km, using average values supplied by the scooter makers. The CO_2 emissions from the scooters and the hydrogen fuel cell scooters are shown in Table 73. In this table it is assumed that the hydrogen is produced by electrolysis. The CO_2 emission factors for the energy carrier electricity and hydrogen are also provided in this table. In Table 74 the CO_2 emissions for the fuel cell vehicle are presented in relation to the source for the hydrogen.

Table 73: CO_2 emission factors for electric vehicles (3rd column) and fuel cell vehicles (5th column) in different countries (Source www.energy.eu [5] and carma.org [6])

Electricity	*Electricity E-mix*	*Electric **0.3 MJ/km***	*H2 from E Electrolysis*	*Hydrogen **0.6 MJ/kWh***
	gCO_2/MJ	gCO_2/km	gCO_2/MJ	gCO_2/km
NL	166	52	218	128
DE	141	44	185	109
FR	20	6	26	16
UK	134	42	175	103
PL	259	80	339	199
CZ	168	52	220	129
SW	6	2	8	5
DK	130	40	171	100
EU-25	119	37	156	92
Offshore wind	8	3	11	6

Table 74: CO_2 emission for fuel cell scooter in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***0.6 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/km
Onsite SMR	110	65
Waste wood	13	7
Offshore wind	11	6
Coal gasification + CCS	45	26

CO_2 reduction potential per service and for the potential market

The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 84. Only sources that are below the green line for gasoline/diesel have a positive impact on global warming compared to gasoline. When comparing fuel cell to electric vehicles, only hydrogen from waste wood and from coal gasification with CCS from the options considered have a CO_2 reduction compared to the CO_2 emissions from the average EU-25 electricity production. If electricity is used to produce hydrogen, the CO_2 emissions from the fuel cell vehicle are 2.5 times the emission from battery operated electric vehicles when the same way of electricity production is considered, as can be observed from Figure 84.

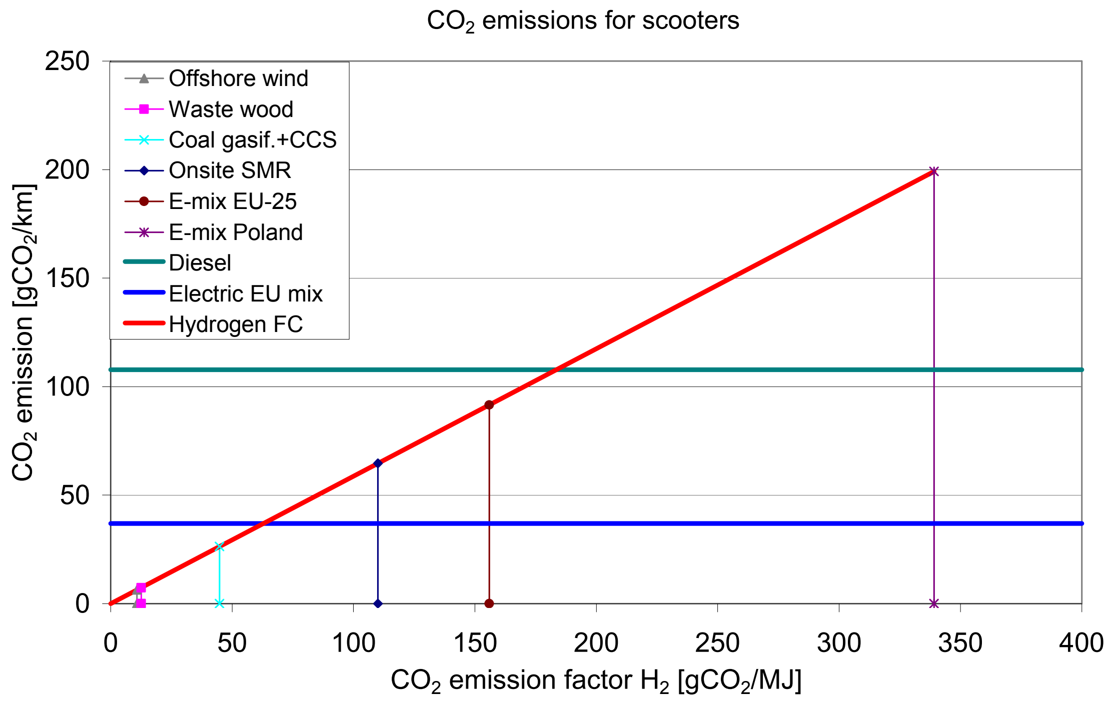


Figure 84: CO_2 emission reduction potential for replacement of gasoline and electric scooters

The maximum CO_2 reduction for the gasoline ICE scooter market is calculated by multiplying the maximum reduction potential of the service (≈90 gCO_2/km) times the mileage/year (≈ 5000 km/yr) times the number of units (1.4 millions in Europe) The maximum CO_2 reduction is then 0.63 Mton CO_2/yr.

15.7 Conclusions and recommendations

The following general conclusions can be taken:

- Replacement of electric scooter by fuel cell vehicles is cost effective at higher fuel cell/hydrogen costs than for the ICE scooter
- The CO_2 reduction potential for replacement with a fuel cell of the electric scooter is much smaller than for the diesel ICE scooter.
- If hydrogen is produced from electrolysis, the CO_2 emission of the fuel cell scooter is 2.5 greater than from the battery operated electric vehicle using the same source of electricity.

Recommendations:
There is a market for green, noiseless, and clean scooters for which customers are prepared to pay a premium. The power level for these vehicles is approximately 5-10 kW, which means that the fuel cell system costs are low compared to e.g. fuel cell system costs of passenger cars. The primary target markets for this kind if vehicles

(fuel cell scooters) could include executive commuters, delivery services and municipalities (e.g. police, traffic wardens, post office, national parks, etc).

15.8 References

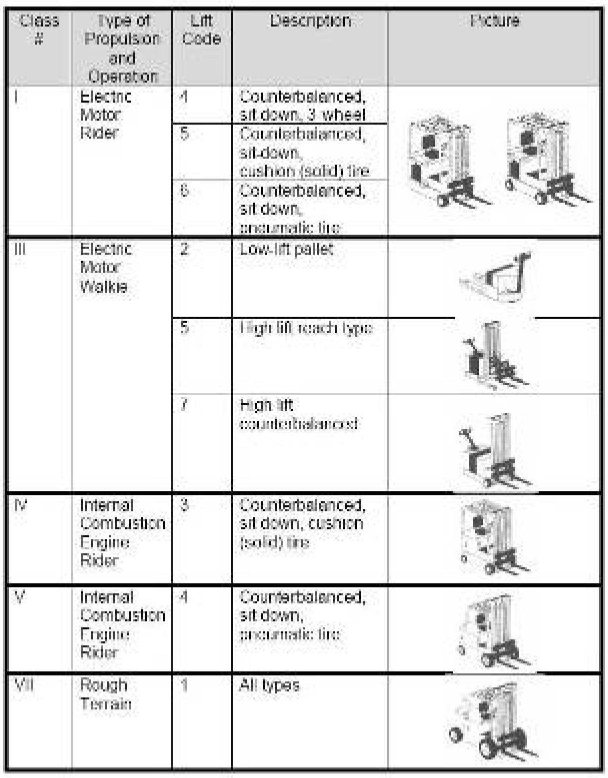
1. http://www.mega-electric.co.uk/pdf/datasheet_pickup.pdf
2. Personal communication Jan Minten (Aixam-MEGA)
3. Piaggio annual report 2006
4. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
5. www.energy.eu, *last visited November 2007*
6. carma.org, *last visited November 2007*
7. Electric Bikes Worldwide Reports 2007, Eight Edition

16. Case study Forklift

16.1 Description of application

A Forklift truck (also called a lift truck, a High/Low, a forklift, a stacker-truck or a sideloader) is a powered industrial truck used to lift and transport materials. The modern forklift truck was developed in the 1920s by various companies including the transmission manufacturing company Clark and the hoist company Yale & Towne Manufacturing. The forklift truck has since become an indispensable piece of equipment in manufacturing and warehousing operations.
Different designs of forklifts exist for various uses, various power trains, different sizes and loads:

- from low-lift pallet to counterbalanced trucks
- 3 or 4 wheeled forklifts
- Forklift trucks are available in many variations and load capacities. In a typical warehouse setting most forklifts used have load capacities between one to five tons. However, machines of over 50 tons lift capacity have been built.



Forklift Classes and Lift Codes

Class #	Type of Propulsion and Operation	Lift Code	Description	Picture
I	Electric Motor Rider	4	Counterbalanced, sit down, 3 wheel	
		5	Counterbalanced, sit-down, cushion (solid) tire	
		6	Counterbalanced, sit down, pneumatic tire	
III	Electric Motor Walkie	2	Low-lift pallet	
		5	High lift reach type	
		7	High lift counterbalanced	
IV	Internal Combustion Engine Rider	3	Counterbalanced, sit down, cushion (solid) tire	
V	Internal Combustion Engine Rider	4	Counterbalanced, sit down, pneumatic tire	
VII	Rough Terrain	1	All types	

Figure 85: Forklift classes and lift codes (source: US department of energy)

16.2 Description of the reference technology

Forklifts can be powered by an internal combustion engine that can be fuelled with LPG, CNG, gasoline or diesel fuel. But the most popular ones are the diesel and LPG versions that equip about half of the world total forklift fleet.

The US LPG forklift fleet is now 500 000 vehicles which represents about 1/5 of the total fleet in the US and in the UK, the sales of LPG forklifts represented about 1/3 of the large forklift sales in 2005 (source: The British Industrial Truck Association).
In Europe, the predominant technology is the battery powered forklift but on a global scale, shares are more balanced with about 1/3 for each technology.

Electric forklifts are powered by either batteries or fuel cells that provide power to electric motors. The motors may be either DC or AC types. Electric forklifts are mainly chosen for their noiseless and emission-free performances.

Table 75: The characteristics of the diesel engine based forklift (based on Manitou MSI 20/30 models)

Application	Unit	Reference technology
Power level	kW	*45*
Efficiency; energy use	MJ/km	*13*
Typical cost complete system	€	12 000
Specific cost energy system	€/kW	80
Lifetime	year	10
Type of “fuel”	-	diesel
Type of “fuel” supply	-	filling station
Type of “fuel” storage	-	tank/liquid fuel
Typical storage capacity	MJ	2600

Table 76: The characteristics of the LPG engine based forklift (based on Manitou MSI 20/30 LPG model)

Application	Unit	Reference technology
Power level	kW	39
Efficiency; energy use	MJ/km	13
Typical cost complete system	€	12 000
Specific cost energy system	€/kW	85
Lifetime	year	10
Type of “fuel”	-	LPG
Type of “fuel” supply	-	filling station
Type of “fuel” storage	-	tank/gaseous fuel
Typical storage capacity	MJ	2600

Table 77: The characteristics of the electric engine based forklift (based on Linde electric forklift)

Application	Unit	Reference technology
Power level	kW	20
Efficiency; energy use	MJ/km	2
Typical cost complete system	€	16 000
Specific cost energy system	€/kW	600 (engine and batteries)
Lifetime	year	10
Type of “fuel”	-	electricity
Type of “fuel” supply	-	electrical grid
Type of “fuel” storage	-	battery (48 V /575 Ah)
Typical storage capacity	MJ	100

The average mileage for forklifts can be as high as 30 000 km but 20 000 km is a standard figure. Furthermore, mileage is not so important for forklifts as standstill steps fill a major share of the workload of such vehicles. For the convenience of the results as well as homogeneity with other vehicles, costs will be expressed in €/km.

Little by little, the park of forklifts is being transformed into an all-electric park. Though, outdoor forklifts and rough terrain may remain ICE vehicles.

Battery-powered forklifts are typically powered by lead-acid batteries that can typically provide enough power for one 8-hour shift, which translates into 5 to 6 hours of constant usage. The primary advantages of battery-powered forklifts are that they produce zero emissions and they can be used indoors. However, the disadvantage of the battery-powered forklift is battery change-out and downtime, which impacts productivity and increases costs of operation. In a typical operation, battery change-out takes 20 to 45 minutes. Charging the battery takes 8 hours, plus 8 hours of cooling time before the battery can be used. Due to this slow charging speed, multiple shift operations must typically keep extra batteries charged and available.
So we will consider a fourth case of a battery-powered forklift, driven a 24 hour basis for 5 days a week. The corresponding mileage will be three-times the one of the other vehicles (30 000 km/yr instead of 10 000 km/yr) because of the three shifts.

Table 78: The characteristics of the electric engine based forklift for a 24/5 use (based on data collected for the US department of energy)

Application	Unit	Reference technology
Power level	kW	20
Efficiency; energy use	MJ/km	2
Typical cost complete system	€	25 000
Specific cost energy system	€/kW	1000 (engine and 3 batteries)
Lifetime	year	10
Type of “fuel”	-	electricity
Type of “fuel” supply	-	electrical grid
Type of “fuel” storage	-	battery (48 V /575 Ah)
Typical storage capacity	MJ	100

16.3 Description of the market

The European market for forklifts represented 405,000 new units in 2007 (which is approximately 45% of the world forklift market). This figure represents an increase of 15% on the 353,000 units sold in 2006 with most of this increase coming from Eastern Europe countries.
Among this, there were:

- 214 650 warehousing forklifts
- 190 350 counter-balanced forklifts

In terms of technology for powering, European forklifts are mainly electric ones: 60% of the European forklifts sold are electric powered trucks.

Below are the top ten manufacturers of the Industrial Forklift Trucks market in terms of worldwide sales for 2005 – 2006:

1. Toyota Industries (Japan)
2. KION Group (Germany) - Linde and Still brands
3. NACCO Industries, Inc. (USA) - Yale and Hyster brands

4. Jungheinrich (Germany)
5. Crown Equipment Company (USA)
6. Mitsubishi Heavy Industries (Japan) - Mitsubishi and Caterpillar brands
7. Cargotec (Finland) - Kalmar brand
8. Komatsu Limited (Japan)
9. Manitou (France)
10. Nissan Motor Company (Japan)

The forklift suppliers and their detailed sales for the European market are shown in Table 5.

Table 79: European sales for the 10 main forklift suppliers

Supplier	Country	Power (aggregate of traction power and lift power)	Total vehicles/yr
Toyota Industries	JAP		12 000
KION	GER	15-40 kW for electric forklifts 30-75 kW for thermal forklifts	112 600
NACCO	USA		30 300
Jungheinrich	GER	28-70 kW	75 000
Crown equipment	USA	>20kW	
Mitsubishi-Caterpillar	JAP	30-40 kW	14 400
Cargotec	FIN		50% in Europe 1,343 Meuros
Komatsu	JAP		17% in Europe
Manitou	FR	20-60 kW	7000
Nissan Motor Company	JAP		5000-6000*

*2004 figures

16.4 Description of FC/H2 technology for the application

A fuel cell embedded in a forklift will combine the advantages of the electric forklifts which are already in use now and the higher autonomy of the thermal engines version. Plus, fuel cell will allow for more power output which is one of the most important criteria for forklifts. And a fuel cell allows removal of the large battery packs in the truck, thus gaining some space.
Some fuel cell forklift projects exist and are being demonstrated:

- NACCO and Hydrogenics have a 10 kW fuel cell – electric hybrid forklift
- Toyota developed the FCHV-F, a forklift powered by a fuel cell that was developed with Toyota Motors and Toyota Industries
- ExxonMobil-QuestAir develop a reformer-fuel cell forklift which is fuelled with conventional fuels.

The applications will be analysed using the following characterisations in order to understand the needs, the cost and the required improvements for cost reduction.

Table 80: The characteristics of the fuel cell engine based forklift

Application	Unit	Reference technology
Power level	kW	20-45
Efficiency; energy use	MJ/km	4 - 7
Lifetime	year	10
Type of “fuel”	-	Hydrogen
Type of “fuel” supply	-	filling station
Type of “fuel” storage	-	Tank, pressurized
Typical storage capacity	MJ	

16.5 Economic boundary conditions for FC/H2 technology

The 2 reference technologies, diesel ICE and LPG ICE are considered for the economic evaluation. For this economic evaluation the reference characteristics of the vehicles are taken from Table 75 to Table 77. The average European energy prices for consumers/ small companies in 2007 are used for the economic evaluation. In Figure 86 the allowable cost of H_2 as a function of the assumed FC system cost is shown.

Yearly mileages of 10.000 and 20.000 km/yr are considered. Figure 86 is based on the input in
Table 81. The figure shows that the market covered by the electric forklifts is easier to reach for hydrogen fuel cells, especially when yearly mileage increases. On figure 2, for 20.000 km/yr of yearly mileage, a FC system cost of 1500 €/kWe can be made economical if hydrogen cost is very low.
On the contrary ICE forklifts will be much more difficult to overcome even if Diesel forklifts, on a 20.000 km basis, can be economically replaced by fuel cell ones.
More precisely, LPG forklifts will be the toughest competitors for hydrogen fuelled forklifts especially when distance increases because of the lower prices both for LPG and LPG engine.

When one considers the use of battery powered forklifts to be used on a 24 hours a day basis, the replacement of the three batteries to ensure a continuous work could be largely covered by the use of a fuel cell filled with hydrogen. Figure 86 below, provides the insurance that fuel cell could easily overcome the batteries in this case.

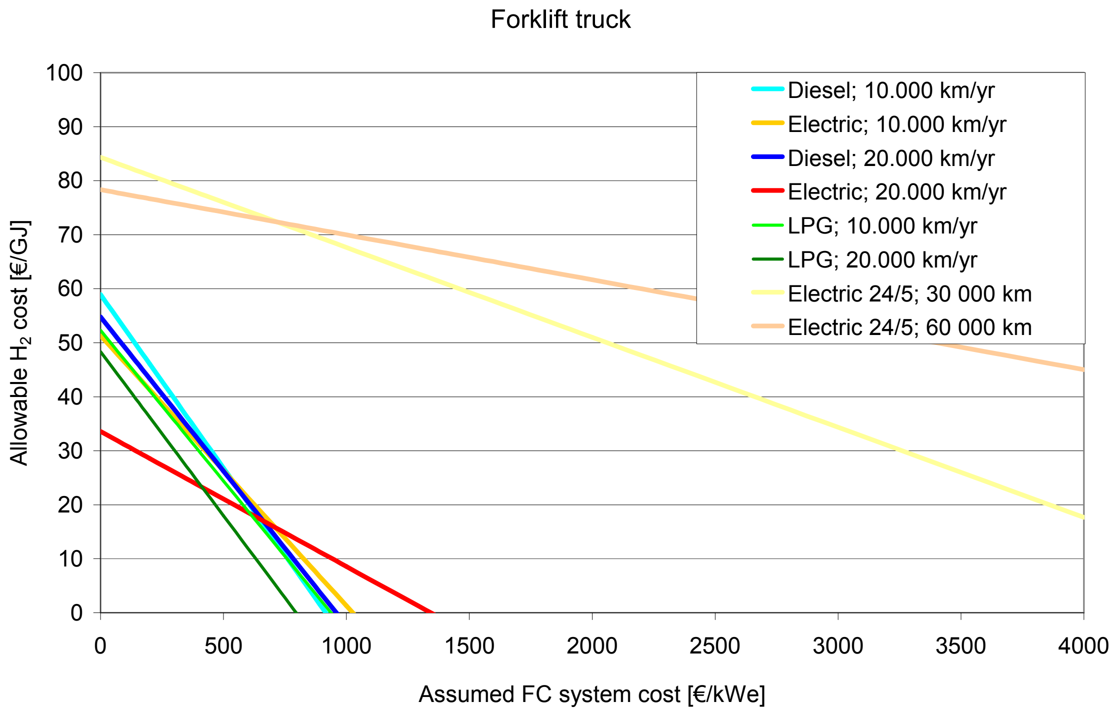


Figure 86: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kilometre with a yearly mileage of 10.000 and 20.000 km for diesel, electric and LPG forklift trucks. All taxes included

Table 81: Background table for Figure 86 for an ICE on diesel or on LPG, an electric vehicle and a fuel cell system, only taking into account fuel cost and engine cost

Reference system		**Diesel ICE**	**LPG ICE**	**Electrical**	**Electrical 24/5**
Engine cost *Power* *Lifetime* *Distance*	€/kW kW yr km/yr	80 45 10 10000	85 39 10 10000	600 20 10 10000	1000 20 10 30000
Specific investment cost	€/km	0.036	0.033	0.120	0.067
Fuel cost *Fuel use*	€/GJ MJ/km	23.5 13.00	20.1 13.00	30.1 2.00	30.1 2.00
Specific fuel cost	€/km	0.306	0.262	0.060	0.060
Vehicle maintenance cost	€/km	0.12	0.12	0.07	0.27
Total cost	€/km	0.462	0.415	0.254	0.401
FC system					
Power Lifetime Distance Fuel use	kW yr km/yr MJ/km	45 10 10000 7.00	39 10 10000 7.00	20 10 10000 4.00	20 10 30000 4.00
Engine maintenance cost	€/km	0.05	0.05	0.05	0.06
Assumed FC system cost		Allowable H2 cost	Allowable H2 cost	Allowable H2 cost	Allowable H2 cost
€/kWe		€/GJ	€/GJ	€/GJ	€/GJ

0		59	52	51	84
200		46	41	41	81
500		27	24	26	76
1000		-5	-3	1	68
2000		-70	-59	-49	51
4000		-198	-171	-149	18

Fuel cost scenarios

In order to have a common basis for the economical calculations, it is important to use the same energy prices in the comparisons. This chapter will provide a common basis for the following energy prices:

- Diesel and gasoline at public filling stations
- Gas and electricity for households
- Gas and electricity for small businesses

The energy prices are presented with all taxes included and are provided in $€_{2000}$ currency. The prices including all taxes are used since these are the prices consumers need to pay. These values can be used to calculate in a final overview the room for duty taxes or required subsidies for equal mileage costs. The background for the scenario price estimation is provided in Appendix A. The 2007 energy prices (from Eurostat) are used and for 2030 a high price scenario is used comparable with 130 $/barrel oil in the currency of 2007.

The procedure for the price determination in 2030 assumes that the taxation on the different energy carriers will not change in the future. The effect of the procedure for 2030 is that the ratio between the maximum prices and the minimum prices in the EU-25 decreases compared to the 2007 situation. The resulting energy price scenarios with taxes in Table 82 for consumers and small industry in $€_{2000}$/GJ for 2007 and 2030 are:

Table 82: Energy prices with all taxes included for consumers and small industry

	Consumer			83.7 GJ/yr	3500 kWh/yr	Small Industry	
In $€_{2000;}$ all taxes included	**Gasoline**	**Diesel**	**LPG**	**Gas**	**Electricity**	**Gas**	**Electricity**
	€/GJ	**€/GJ**	**€/GJ**	**€/GJ**	**€/GJ**	**€/GJ**	**€/GJ**
low 2007	21.7	19.7		5.1	16.4	4.3	14.2
mean 2007	29.1	23.5	20.1	12.1	33.4	9.6	30.1
mean 2030	39	33.4		20.6	36.9	18.2	33.6
high 2030	47.1	43.5		35	65.0	23.4	52.7

The reference value to be used throughout the case study is the mean 2007 value with all taxes, shown with yellow background in Table 82. For LPG, the average price comes from the IEA statistics for the industrial sector in 2007.

We can see that the effect of a varying diesel price is very important. Basically, an increasing diesel price eases the penetration of the fuel cell forklifts. Moreover, petroleum products tend to become more and more expensive and this trend will make fuel cell forklifts become more and more attractive on an economical point of view (see Figure 87).

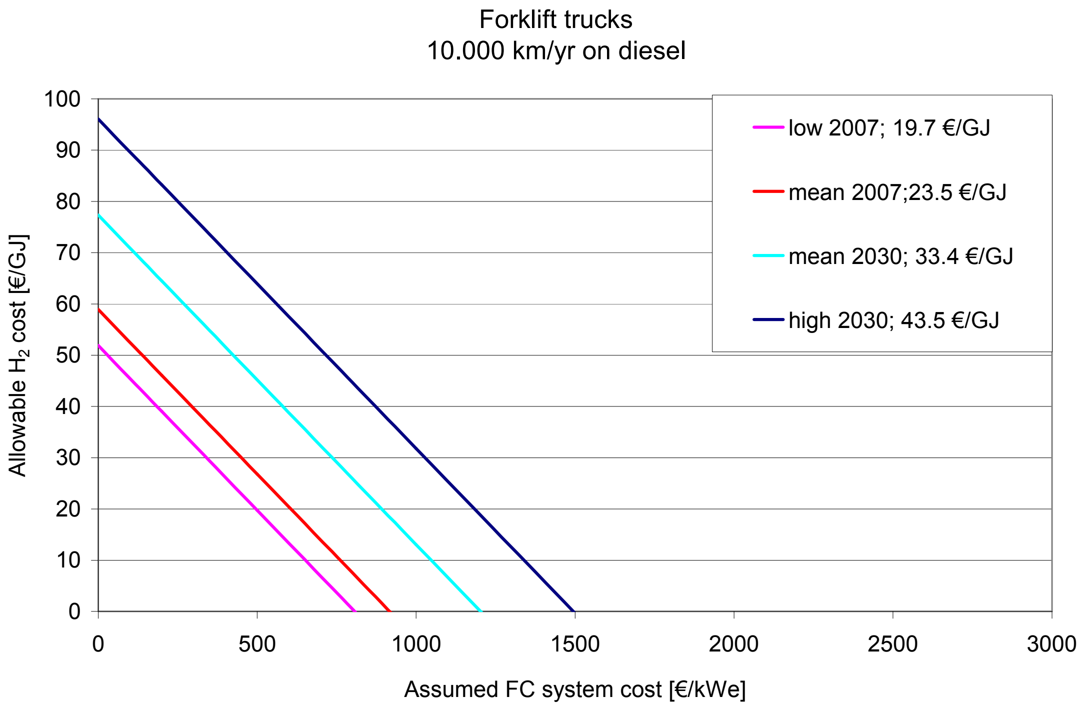


Figure 87: Allowable hydrogen costs *vs.* assumed FC system cost of 4 different energy prices of diesel fuel with all taxes included

For electric forklifts, we can also see a great influence of the price of electricity. But when comparing the economic conditions for penetration of fuel cell forklifts in 2007 and 2030, we can see that no major evolutions can be waited (see, mean prices 2007 and 2030 in Figure 88).

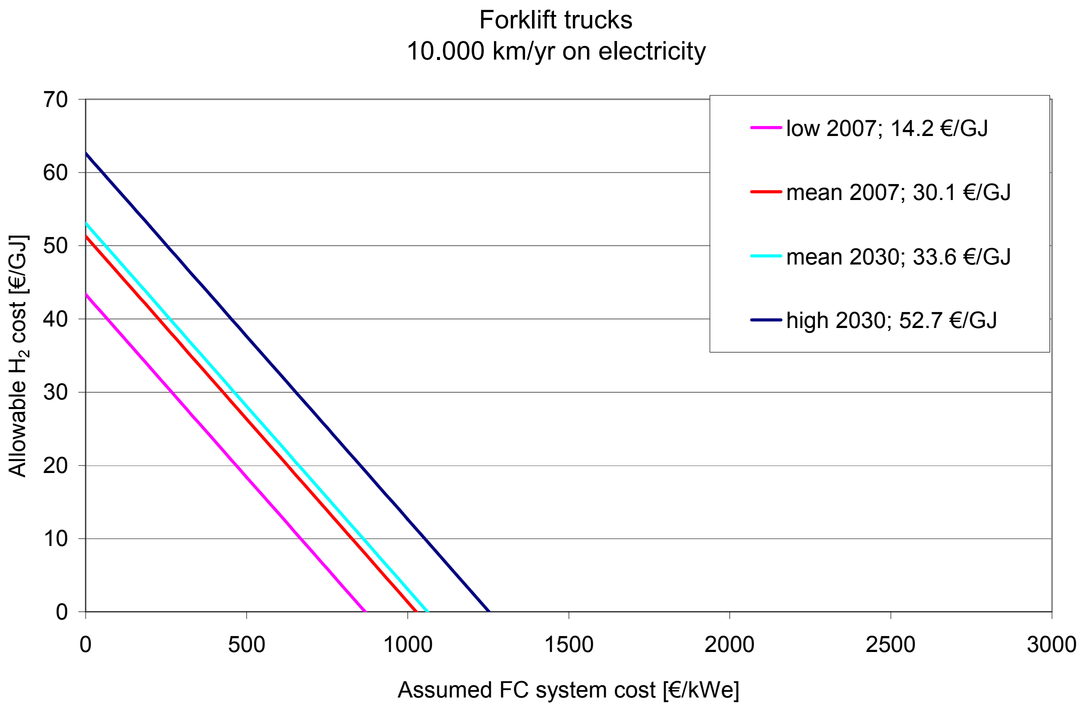


Figure 88: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of electricity with all taxes included

For the labour-intensive forklift, used 24 hours a day, the influence of the price of electricity is the same as for the "usual" forklift.

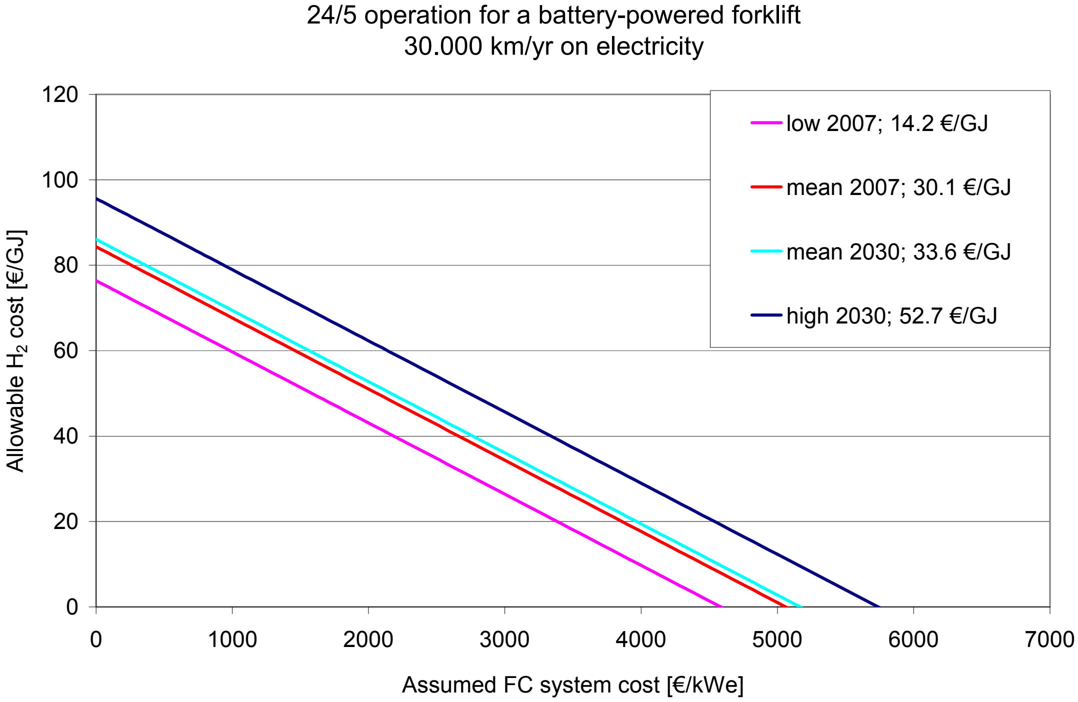


Figure 89: Allowable hydrogen costs *vs.* assumed FC system cost of 4 different energy prices of electricity with all taxes included for the case of 24/5 operation

16.6 CO2 reduction potential Source-to-User

The CO_2 emission from the ICE Diesel forklift has been estimated as 1131 gCO_2/km using a standard Diesel emission factor of 87 gCO_2/MJ. For the LPG version of the forklift, a corresponding CO_2 emission of 961 gCO_2/km has been calculated. (see Table 83)

Table 83: CO_2 emission factors of ICE forklift trucks

	Mean	***13 MJ/km***
	gCO_2/MJ	gCO_2/km
Diesel	87	1131
LPG	74	961

Table 84: CO_2 emissions for fuel cell forklift

	Mean	***7 MJ/km***
Compressed H_2	gCO_2/MJ	gCO_2/km
Onsite SMR	110	770
Waste wood	13	88
Offshore wind	11	75
Coal gasification + CCS	45	314

The CO_2 reduction potential depends strongly on the source where the hydrogen comes from, if hydrogen is used as an energy carrier for the application, see Figure 90. Only sources that are below the green line for Diesel have a positive impact on global warming compared to Diesel. So, only hydrogen produced from coal gasification with carbon capture and storage, offshore wind electricity source, waste gasification and on-site SMR have a potential to reduce CO_2 emissions compared to hydrocarbon fuels.

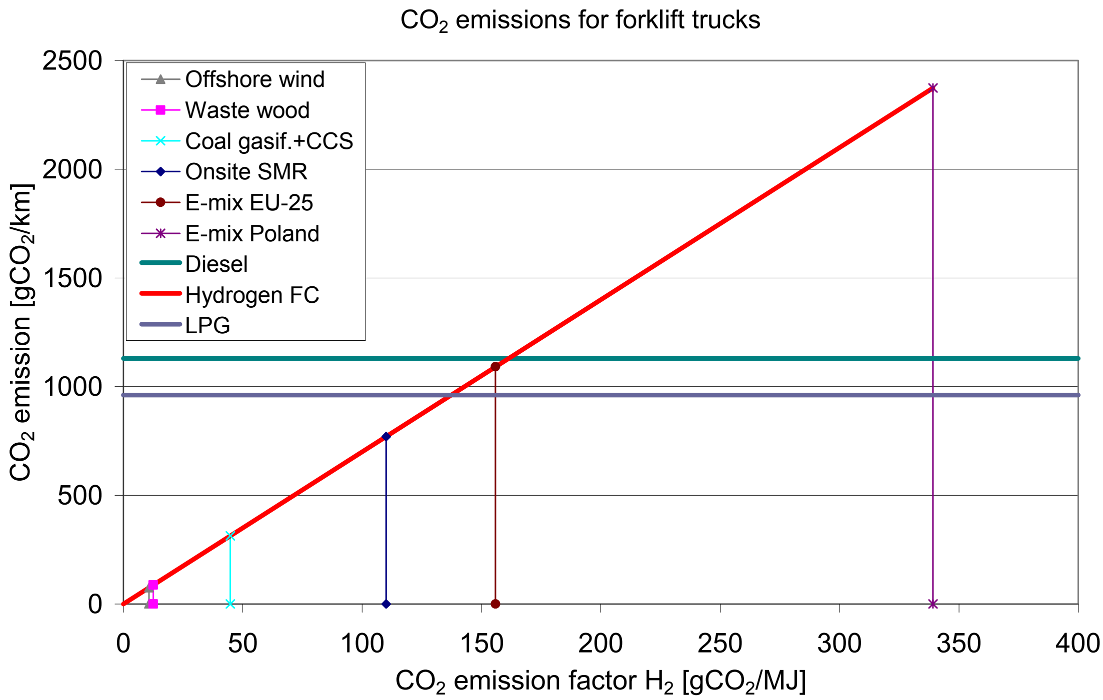


Figure 90: CO_2 emission reduction potential for transport

The maximum CO_2 reduction can happen compared to a Diesel ICE forklift truck. This maximum reduction can be around **1000 gCO_2/km**. The average mileage/year of such vehicles is 10.000 km.
The number of units will be approximated by the lifetime of the units (10 years) and the yearly market sales for Europe. The European forklift market has been described in chapter 16.3 and represents 405 000 units per year of which 40% uses diesel.
The corresponding CO_2 reduction for the diesel forklifts amounts to **16 Mton of CO_2/yr**. The corresponding CO_2 reduction for replacing the electric forklifts with hydrogen based fuel cell forklifts is small or can be negative, since it depends strongly on the source for the hydrogen and electricity, whereas the electric forklifts have a higher efficiency.

16.7 Conclusions and recommendations

We can analyse the previous results and summarize them by:

- Fuel cell forklifts will improve the replacement of ICE forklifts which is done now by replacing them with battery-electric forklifts. Autonomy will be improved and on-site noise and emission performances will be kept. Thus, fuel cell forklift will face a higher competition on an economical level when one will intend to replace an electric forklift as no major favourable evolution for hydrogen compared to electricity is waited by 2030.
- The CO_2 reduction potential for replacement with a fuel cell of the electric forklift is much smaller than for the ICE forklifts (Diesel and LPG).

- The potential CO_2 emission reduction is 16 Mton/yr if fuel cell forklifts are used instead of Diesel ICE vehicles.

But, it will be difficult for fuel cell vehicles to replace the electric ones as they offer the same advantages (noiseless, emission free, good energetic efficiency) with some drawbacks for the moment (supply of hydrogen, costs) unless the forklifts are operated 24 hrs/day and daily battery replacement is required.

16.8 References

1. Heggies Australia report 10-4754R3, 2006
2. European manufacturers association of materials handling
3. News analysis from http://www.forkliftaction.com/
4. Brookhaven National Laboratory: http://training.bnl.gov/demo/JPM/Forklift%20Classes%20and%20Lift%20Codes.pdf
5. Massachusetts Institute of Technology
6. Environment Protection Agency: http://epa.gov/otaq/regs/nonroad/2002/r02022g.pdf
7. Identification and characterization of near-term direct hydrogen proton exchange membrane fuel cell markets, Battelle for the US DOE, April 2007

17. Case study Aircraft towing vehicle

17.1 Description of application

The ground handling of aircrafts with towing tractors is the focus of this case study. The application of aircraft towing tractors can be divided into two segments:

- Pushback towing

The pushback tractor must be able to pull and push a large aircraft from the gate. Pushback tractors could be fully automated with optional manual overrides. They tend to perform a short high intensity task, and then are shut down until they are next needed. The average pushback takes no more than 20 minutes. [1]

- Long distance towing

In comparison to the pushback application, the long distance towing is mainly used for gate to gate and maintenance towing. The towing is performed at higher speed and can take up to 2 hours. [1]

17.2 Description of reference technology

The technology used for both applications is divided into two segments:

- Towbar tractors
- Towbarless tractors

Figure 91: Towbar tractor from Schopf [3]

Figure 92: Towbarless tractors from Goldhofer [2]

Manufacturers of pushback tractors and long-distance aircraft towing tractors are currently experiencing burgeoning orders, the result of increased activity at airports worldwide. However, while the towbarless concept now dominates the long-distance towing market, the pushback sector continues to see strong sales in conventional towbar units. [1]

For pushback applications the design needs to be as simple and less complicated as possible. In comparison to a high speed towing application where you need a complex control system in order to monitor all forces that are applied during high speed operation. This also leads to less maintenance costs for the conventional towbar tractors. Furthermore the drivers need to be less skilled compared to towbarless staff, but a disadvantage can be seen in the requirement for additional manpower on the ramp to fix the towbar on the aircraft.
Towbarless tractors have higher speed, which is a clear advantage at long distance operation.

The annually operation time of the tractors depend mainly on the airports. Smaller airports use them for 500 hours a year, while airports like Frankfurt expect an annually operation of 5000 hours. The overall lifetime goes up to 50.000 hours. [1]

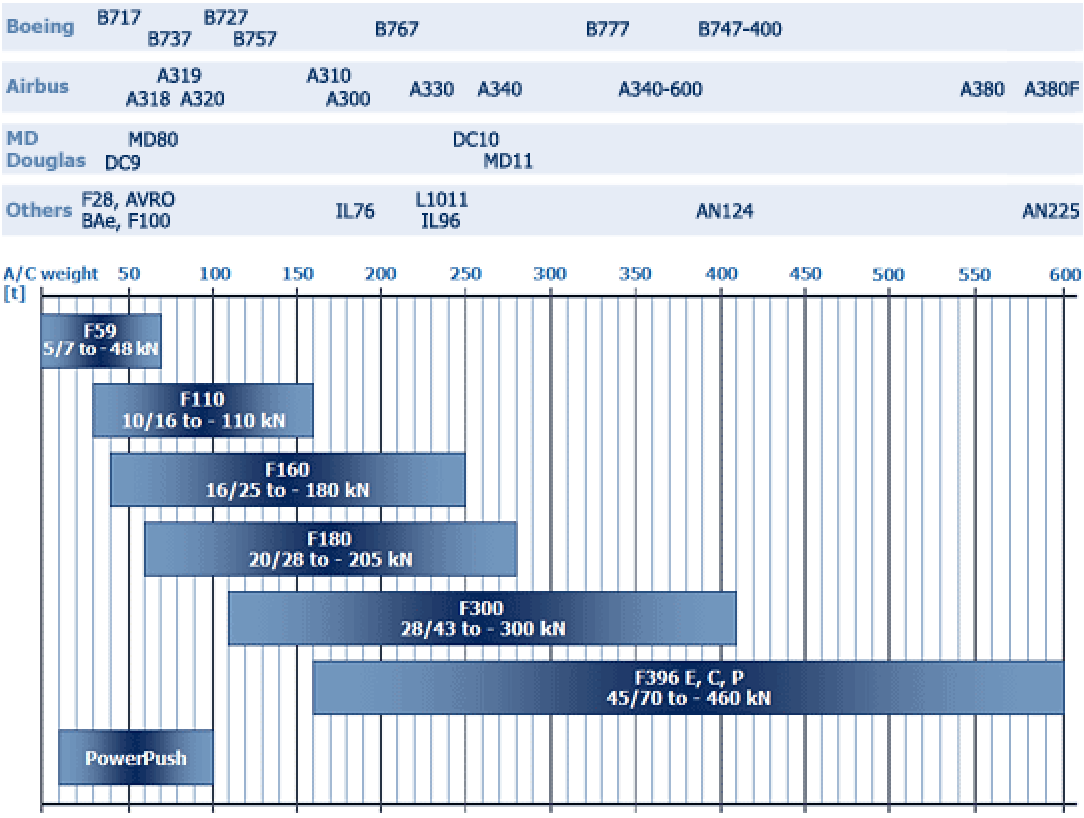


Figure 93: Towbar products from Schopf Maschinenbau GmbH [3]

All towing tractors are equipped with diesel engines. The engine power for small single aisle aircrafts (up to 160t) is around 75kW, according to the tractor F110. The new A380 that is in service since the end of 2007 requires a tractor with an engine up to 330kW, like the F396P.

No information was found, that producers currently switch to alternative engine concepts. In contradiction the manufacturer Kamag stated that large engines require up to 450 hp (330kW) are simply not available when fuelled by liquefied petroleum gas. [1]
Similar problems exist with biodiesel. For an engine to work effectively on biodiesel, it requires occasional long runs, which ensure that the heat generated burns off unwanted

material that builds up in the engine. Pushback operations, which encompass considerable engine idling, simply don't generate those kinds of conditions. [1]
The company Goldhofer states that they are carrying out research into producing an electrically powered unit, but albeit not in the short term. They also state that it is going to be very difficult to build a towbarless tractor for high-speed operations that has an electric drive. For simple pushback operations at the gate it is easier, because once a manoeuvre has been completed the tractor can be plugged in and the batteries recharged. Goldhofer further states that an electrical system of any kind will work out more expensive than for a standard diesel engine, because the cost of batteries remains high. [2]

Consequently, the size of the F110 from Schopf Maschinenbau GmbH is chosen as a typical example of pushback tractors for regional aircrafts that can be compared with a tractor based on hydrogen and fuel cell technology. The F110 is also a comparable tractor to the diesel fuelled GT35 from TUG Technology Corporation that was analysed in a study by the US DOE where it was compared against an artificial electrical tractor called 350E for pushback operations. [5]

17.3 Description of the market

As described previously, the market for aircraft towing is divided into towbar and towbarless tractors. Two manufacturers, the German company Goldhofer and the US manufacturer FMC Technologies, dominate the latter. Goldhofer produces 50-60 towbarless tractors annually. The volume increases by 15 per cent annually. [1]
The result of increased airport activities worldwide also leads to a high demand of towbar tractors for pushback operations, where Schopf Maschinenbau GmbH is one of the major manufacturers. Annually production capacity cannot be given.

As shown in the picture 3, the market is split up in power level, which directly leads to certain aircraft types that can be handled with each tractor. Focus of the following analysis is given to the pushback operation, hence towbar tractors preferred, in the size for single aisle aircrafts like the 737 or the A320 family.

17.4 Description of FC/H2 technology for the application

A H_2 PEM FC system for aircraft towing operations is not in operation at the moment. Some information was found about a project of a fuel cell pushback tractor equipped with a Lynntech PEM system. Performance and technical data are not available.

Figure 94: NMC-Wollard Tow Tractor Powered with Lynntech Fuel Cell

Therefore it can only be assumed how a fuel cell system for pushback operations might look like. The reference for the assumptions of the fuel cell tractor is an electrical system and a diesel system that was described in a US DoE study. The data is given below:

Table 85: Data of an electric pushback, a diesel pushback tractor and a FC tractor [5], [8]

Reference system		**Diesel TT**	**350E**
Energy source		Diesel	Flooded Battery
Power	kW	75	75
Usage per day	h	4	4
Days per year	days	350	350
Fuel cost	€/GJ	23,5	30,1
Fuel use	GJ /day	0,32	0,04
Specific fuel cost	€/day	**7,473**	**1,114**
Fast charge investment	€	-	17500
Vehicle price	€	**86.200**	**93.000**
Complete Operating costs	€/year	58.222	49.543
Operating costs	€/day	**166,35**	**141,55**
Specific vehicle costs	€/kW	**1149**	**1240**
FC system			
Power	kW	75	75
Days per year	days	350	350
Fuel use	GJ/day	0,074	0,074
Hydrogen Costs	€/GJ	50	50
Specific fuel costs	€/day	**3,7**	**3,7**

17.5 Economic boundary conditions for FC/H2 technology

Firstly, it should be mentioned that aircraft pushback tractors have significantly low energy consumption during the day with a comparatively high system power.
Regarding the system power of 75kW, it will not make sense to replace the batteries by a H_2 PEMFC system only, but to develop a hybrid system of fuel cells and batteries. To find the perfect balance of fuel cell power versus battery power, a load profile of the tractor during day operation is essential. Since this data is not available at the moment, it is negligible for this study.
Regarding the significantly low energy consumption during the day, it can be stated that full system power only occurs for very short times. Otherwise the energy consumption would be higher.
A load profile shows the average power needed and this would be the design power size of the fuel cell system. The batteries would supply the extra amount of energy for peak loads.
Assuming a fuel cell system efficiency of 50% and taken the 10,56 kWh of energy needed per day into account, the hydrogen stored onboard the tractor is around 21kWh. This is less than a 1kg of hydrogen or around 7,3 Nm^3.

The energy consumption for pushback tractors is remarkably low!

The purchasing costs for the diesel towing tractor are €86.200 and for the electrical tractor €93.000.
This is the target price of the fuel cell system, the hydrogen storage onboard and the fuelling equipment at the airport. It should be mentioned that the fuelling station is an investment to be taken for more than just one vehicle.
The given operating costs in Table 85 include maintenance and fuel costs, with the portion of the fuel being almost negligible. Therefore the following graph shows the boundary

conditions of the complete fuel cell vehicle purchasing and operating costs compared to a diesel and an electrical towing truck.

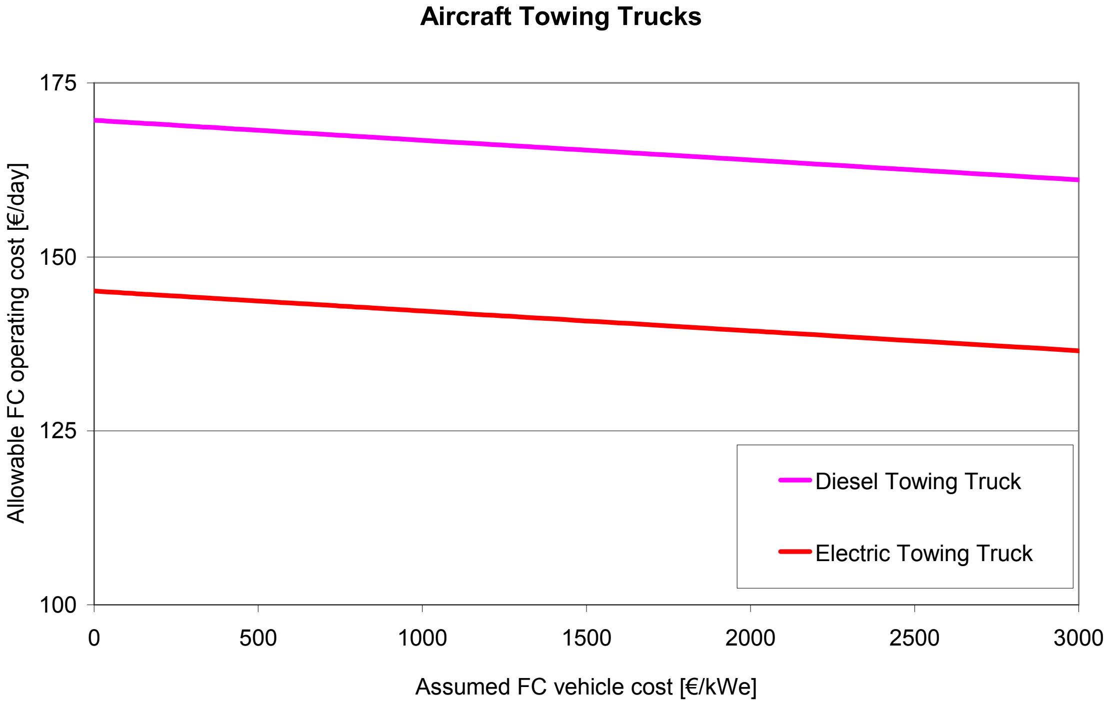


Figure 95: Boundary conditions for a fuel cell tractor

As stated before, the amount of data available for towing trucks is quite scarce. Therefore the first calculation for boundary conditions dealt with the complete truck and not with the engine versus fuel cell only, as shown above. The following calculation is based on a cost estimation of the diesel engine and the electrical engine and shows the boundary conditions of the fuel cell system and hydrogen price only.

The price of the diesel engine is estimated as 100€/kW, which is twice the cost of the diesel engine in a light truck, and as 200€/kW. As picture 6 shows, the difference is not remarkable. The estimation for the electrical engine with 190€/kW is calculated with the diesel engine price + (Price Electrical Truck – Diesel Truck) per kW; =100 + (93000 – 86200)/75.

Table 86 Alternative data for Diesel and Electrical pushback tractor

Reference system		Diesel	Diesel	Diesel	Electrical	Electrical
		1400 hrs/yr; 5,351 €/km	2800 hrs/yr; 4,011 €/km	1400 hrs/yr; 5,886 €/km	1400 hrs/yr; 2,786 €/km	2800 hrs/yr; 1,561 €/km
Engine cost	€/kW	100,0	100,0	200,0	190,7	190,7
Power	kW	75	75	75	75	75
Lifetime	yr	10	10	10	10	10
Operation	hr/yr	1400	2800	1400	1400	2800
Specific investment cost	€/yr	0,536	0,268	1,071	1,021	0,511
Fuel cost	€/GJ	33,4	33,4	33,4	33,6	33,6
Fuel use	MJ/hr	80,00	80,00	80,00	10,00	10,00
Specific fuel cost	€/hr	2,672	2,672	2,672	0,336	0,336
Engine maintenance cost	€/hr	2,14	1,07	2,14	1,43	0,71
Total cost	€/hr	5,351	4,011	5,886	2,786	1,561
FC system						
Power	kW	75	75	75	75	75
Lifetime	yr	10	10	10	10	10
Operation	hr/yr	1400	2800	1400	1400	2800
Fuel use	MJ/hr	18,50	18,50	18,50	18,50	18,50
Engine maintenance cost	€/hr	1,43	0,71	1,43	1,43	0,71

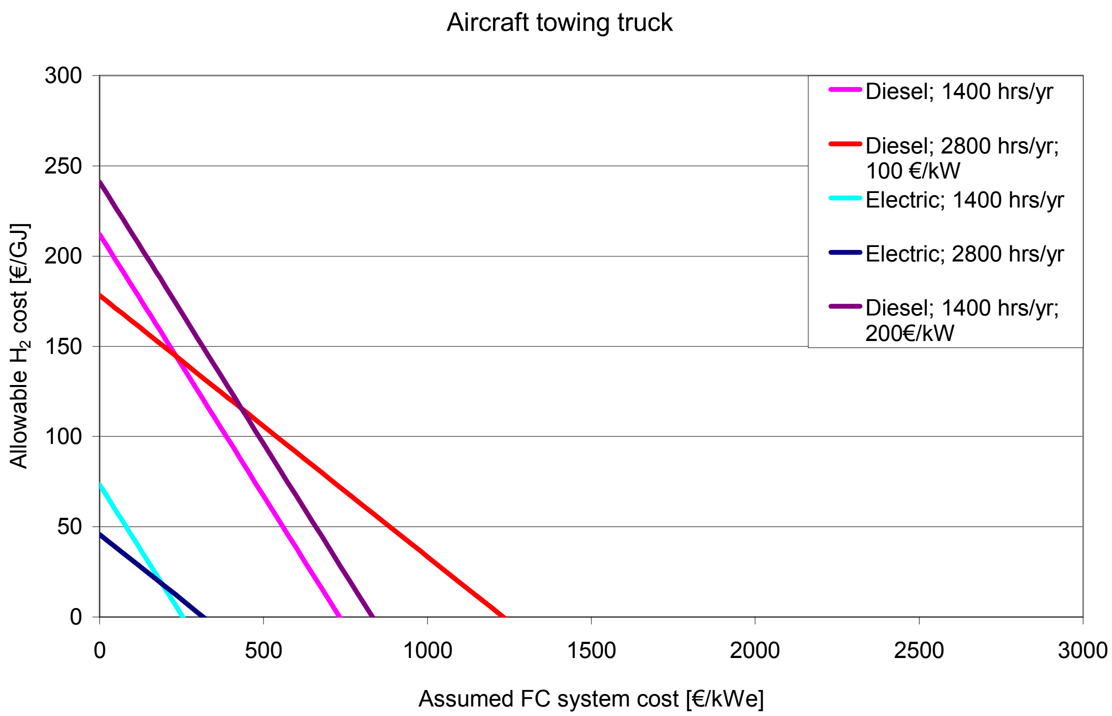


Figure 96: Boundary conditions for the fuel cell system versus diesel and electrical engine

17.6 CO2 and other emissions

CO_2 emission of reference and fuel cell technology

The CO_2 emission from the diesel aircraft towing truck is calculated as 6900 gCO_2/hr using a diesel emission factor from the CONCAWE study of 87 gCO_2/MJ. The CO_2 emissions and emission factors for the hydrogen fuel cell aircraft towing truck in different countries are shown in Table 87. In this table it is assumed that the hydrogen is produced by electrolysis.

Table 87: CO_2 emission factors for fuel cell aircraft towing truck (4th column) in different countries [9], [10]

Electricity	*Electric E-mix*	*H2 from E Electrolysis*	*from H2* ***18.5 MJ/hr***
	gCO_2/kWh	*gCO_2/MJ*	gCO_2/hr
NL	598	218	4028
DE	508	185	3418
FR	73	26	489
UK	482	175	3244
PL	932	339	6274
CZ	605	220	4072
SW	22	8	149
DK	469	171	3159
EU-25	429	156	2885
Offshore wind	30	11	201

In Table 88 the CO_2 emissions and emission factors for the fuel cell aircraft towing truck are presented in relation to the source for the hydrogen.

Table 88: CO_2 emission for fuel cell aircraft towing truck in relation to the source for the hydrogen

Concawe (WTW)	*Mean*	***18.5 MJ/hr***
Compressed H_2	*gCO_2/km*	gCO_2/hr
Onsite SMR	92	2036
Waste wood	10.5	232
Offshore wind	9	199
Coal gasification + CCS	37.5	830

CO_2 reduction potential per service and for the potential market

The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 97. Only sources that are below the green line for diesel have a positive impact on global warming compared to diesel. Replacing the electric towing trucks with fuel cell towing trucks does have a negative impact on CO_2 emissions if both electrical energy sources are the same. Due to efficiency losses in the electrolysis and in the fuel cell, the battery tractor has lower CO_2 emissions.

The maximum CO_2 reduction for the diesel aircraft towing truck market can be obtained by replacing diesel from fossil fuel sources with fuel cells operating on hydrogen produced by electrolysis of off shore wind electricity. This is calculated by multiplying the maximum reduction potential of the service (≈ 6700 gCO_2/hr, Diesel engine emission minus Offshore wind) with the average operating hours per year (≈ 1460 hrs/yr), the number of new units/year (≈ 50) and the lifetime of the aircraft towing truck (≈ 25 year). The maximum CO_2 reduction is then approximately 12,2 kton CO_2.

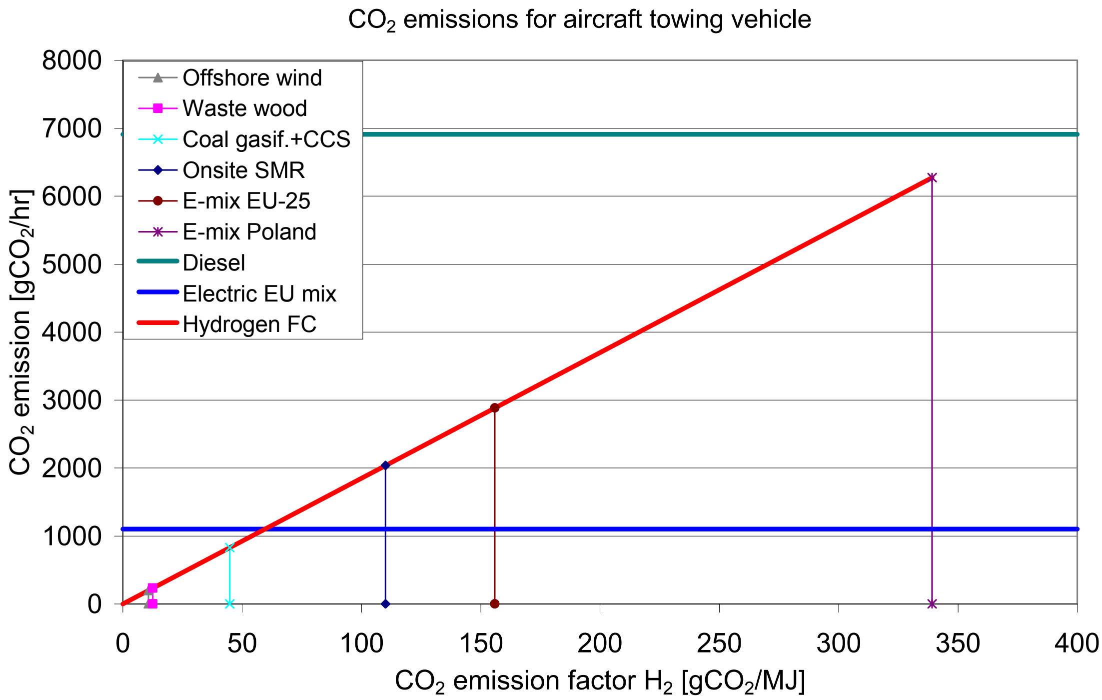


Figure 97: CO_2 emission reduction potential for replacement of diesel aircraft towing truck

Regarding the working conditions for the ground staff at the airports other emissions should also be noted.
Besides CO_2, the diesel tractor emits the following gases [5]:

- 167gCO /day
- 425gNO_x / day
- Particulate matter of 32,35 gPM / day.

Further more the noise emissions of the airport can be reduced with the usage of battery or fuel cell tractors.

17.7 Conclusions and recommendations

The following general conclusions can be taken:

- Electrical engine and other alternatives to diesel engine have not found its way to all application for aircraft towing yet.
- Pushback tractors are due to its low energy consumption interesting to replace diesel with electrical engines
- An environmentally benefit to replace batteries with fuel cells and hydrogen cannot be shown at this status.
- Electrical tractors contribute to reduce emissions at the airport and to enhance the working conditions for the ground stuff. The latter is probably the most important advantage and this should be the driver for airports to replace diesel tractors.

Recommendations:
At the current status of information it makes economically and ecologically sense to replace diesel pushback tractors with electric tractors. Due to the very low energy consumptions but high power peaks, hybrid systems of fuel cells and batteries should be the focus of future investigations for aircraft towing tractors.

17.8 References

1. Janes Airport Review 2008 “Pushback market remains Buoyant”
2. www.goldhofer.com, last visited May 2008
3. www.shopf-gse.com, last visited May 2008
4. www.isecorp.com, last visited May 2008
5. US DoE IN/EXT-07-12270 “Cost Benefit Analysis Modelling Tool for Electric verus ICE Airport Ground Support Equipment – Development and Results”
6. www.umweltbundesamt.de, last visited May 2008
7. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
8. The currency rate €/$ is 1. This is the average exchange of the year 2000
9. www.energy.eu
10. carma.org

18. Case study Passenger Aircraft

18.1 Basis of the data

Data of this report was retrieved mainly from the studies completed under the "Liquid Hydrogen Fuelled Aircraft - System Analysis - CRYOPLANE" (5th Framework Program of the European Communities. Contract No. G4RD-CT-2000-00192 Duration of Contract: April 2000 – May 2002.

Quote (From the Final Technical Report)
The objectives of this were to develop a conceptual basis for applicability, safety, and full environmental compatibility, and to investigate medium/long term scenarios for a smooth transition from kerosene to hydrogen in aviation. This system analysis covers all relevant technical, environmental, societal and strategic aspects providing a sound basis for initiating larger scale activities preparing for the development and introduction of liquid hydrogen as an aviation fuel.
Unquote

In order make best use of already available data on a very complex subject like the introduction of LH_2 fuelled aircraft into the market and evaluate the impact on CO_2 emissions and the operational costs a review of WP8 was conducted for this project.

18.2 Description of application

The objective of WP2 of the Cryoplane project was to identify aircraft configurations, which meet the requirements of efficient and safe operation in all aircraft categories, from "Business Jets" to "Very Large Long Range Aircraft". Their performance and DOC should be analysed and compared to conventional aircraft.

Based on data coming from the other work packages configurations of the selected aircraft categories have been developed. Aircraft performances have been calculated and compared with conventional aircraft.

The work on Aircraft configurations WP2 was separated into two main groups of tasks; the conventional und unconventional configurations.

Conventional aircraft configurations have been evaluated for those categories, which were selected before, whereas unconventional categories were developed in a more general way.

18.3 Description of reference technology

For a selection of transport aircraft, ranging from regional turboprops to very large, long-range jet aircraft like the A380 (Figure 1), a comparison has been made between kerosene and LH_2 fuelled versions. The tank layout turned out to be the driver for the configurationally design as LH_2 requires 4 times more storage volume than kerosene for the same energy content and additionally must be stored pressurized. Calculations on the weigh for the LH_2 tank structure have shown that the use of wing tanks would be too heavy (read details in section S/M Range A/C). The optimal choice for the tank layout depends on the aircraft category. For seven categories of aircraft, three basic tank layouts are proposed.

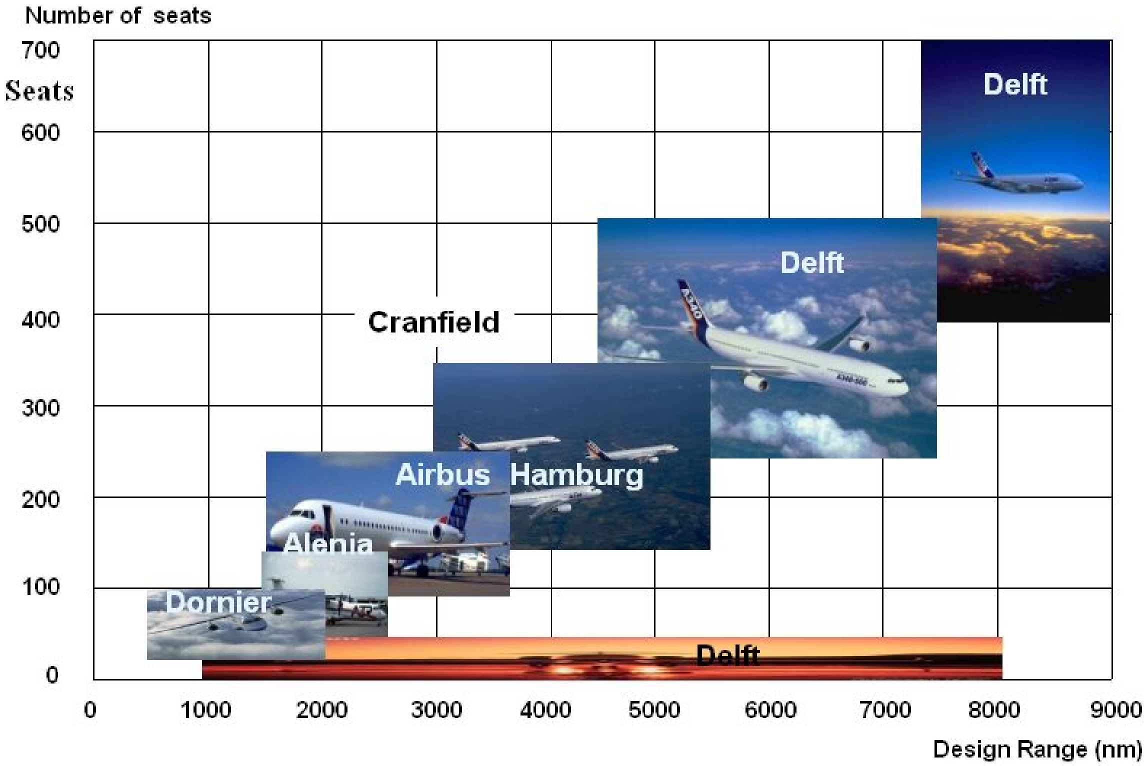


Figure 98: Range of aircraft categories

For "Small Regional Aircraft" and "Business Aircraft" tanks are arranged in the fuselage aft of the rear pressure bulkhead only. For "Regional aircraft up to 100 seats" (turboprop as well as jet) and "Short/Medium Range Aircraft" tanks are arranged behind the aft pressure bulkhead and on top of the fuselage. For "Long Range Aircraft" and "Very Large Long Range Aircraft" (VLLR) tanks are proposed in the fuselage aft of the rear pressure bulkhead and between the cabin and the cockpit.

Small Regional Aircraft and Business Aircraft

Figure 99: Small Regional Aircraft

The simplest solution, the tank behind the aft pressure bulkhead, is only feasible from a centre of gravity location consideration when the fuel weight fraction is small. Hence it is applicable only to the “Small Regional Aircraft”. Because of the similarity in size this concept was applied on “Business Aircraft” as well. To reduce the impact of the single tank on the centre of gravity, a wider fuselage was adapted than usual. An exploratory study revealed yet an excessive centre of gravity travel, probably requiring a combination of fly-by-wire and a very large horizontal tail, or operational restrictions to the centre of gravity. As a result, the aircraft will suffer from increased trim drag and reduced maximum lift.

Regional 100-seater Aircraft.

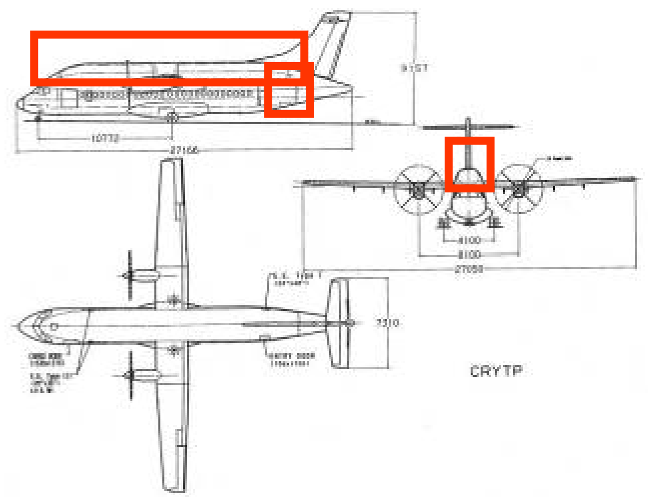


Figure 100: Business aircraft

For larger fuel fractions and thus range, the fuel in the aft tank must be balanced by a more forward tank. For the “Regional aircraft up to 100 seats” (turbo-prop and turbo-jet) and “Short/Medium Range Aircraft” the fuselage diameter is too small to enable a catwalk parallel to and beside the forward tank, to serve as the cockpit-cabin connection. This forces the tank on top of the fuselage, thereby creating a weight and profile drag penalty. Special attention must be paid to disk burst, as this might lead to an explosion of the LH_2 in the top tank. Therefore a dry bay must be created. As a consequence, this configuration is less efficient as the other solutions. It is expected that the top tank does not pose a threat to the passengers in case of fire, as the LH_2 will boil off, evaporate and rise upwards.

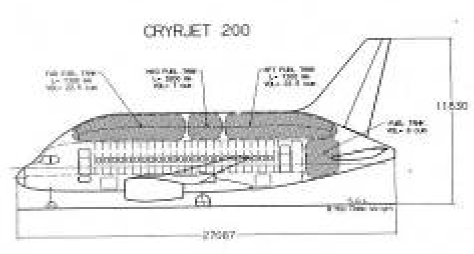


Figure 101: Regional turboprop aircraft

Figure 102: Regional Jet Aircraft

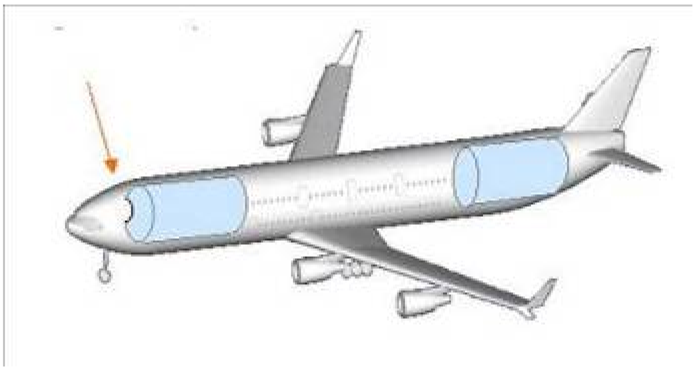
Short and Medium Range Aircraft

For the “Short/Medium Range Aircraft” (S/M Range A/C) tanks in an enlarged and thickened inner wing were investigated as well. It was found that the lower aerodynamic efficiency due to the oversized wing negated the benefits of the smaller top tanks. Therefore, an alternative configuration was selected with a larger tail cone volume and increased top tank cross section. The most efficient solution is to incorporate two tanks in the fuselage, one in the front and one in the rear. They balance each other and bring the least increase in construction weight and wetted area.

Figure 103: Revised configuration short/medium range aircraft

Long Range Aircraft and Very Long Range Aircraft.

For the “Long Range Aircraft” and “Very Large Long Range Aircraft” the fuselage diameter is large enough to allow for a catwalk between cockpit and cabin alongside the forward tank. However, the structural aspects of the front tank as part of the pressure vessel have not been examined and need careful study. The same holds for the cockpit-cabin interconnection. If this interconnection can be eliminated (as discussed after the events of 11. September 2000), this layout would be feasible for aircraft of smaller size or narrower fuselage as well. The very large long-range aircraft is very similar to the one shown, except a three-deck layout in order to remain within the 80x80x80 box.



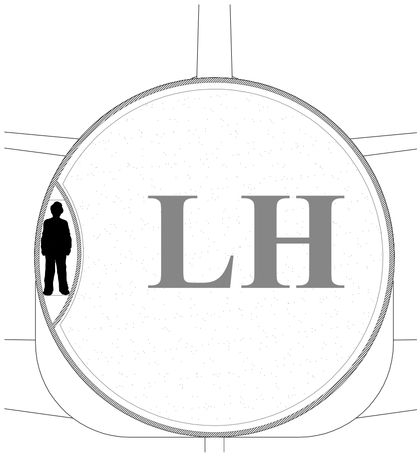


Figure 104: Location of the catwalk between cockpit and cabin alongside the forward tank

18.4 Description of the market

Air traffic has experienced strong growth over a long time, and it is predicted that such growth will continue at rates of 4 – 5 % p.a. over the next decades. Current traffic losses in the aftermath of September 11th 2001 are expected to be only temporary. Assuming continuing worldwide economic growth, saturation of air traffic is not yet in sight. For the aircraft manufacturers, this is a highly welcome prospect, because only one third of their production is for replacement of old aircraft, two thirds of the production serves the needs of traffic growth.

18.5 Description of LH2 technology

Fuel System Architecture
An overall systems architecture has been defined which is adaptable to alternative tank arrangements as suitable for different aircraft categories (see Work Package 2).

Framework specifications have been prepared for the Fuel system in general, the system specific to the selected Example Aircraft, and for the major components.

The principle architecture selected, featuring one active tank per engine plus passive tanks feeding into these, is flexible and can be applied to other different tank arrangements.

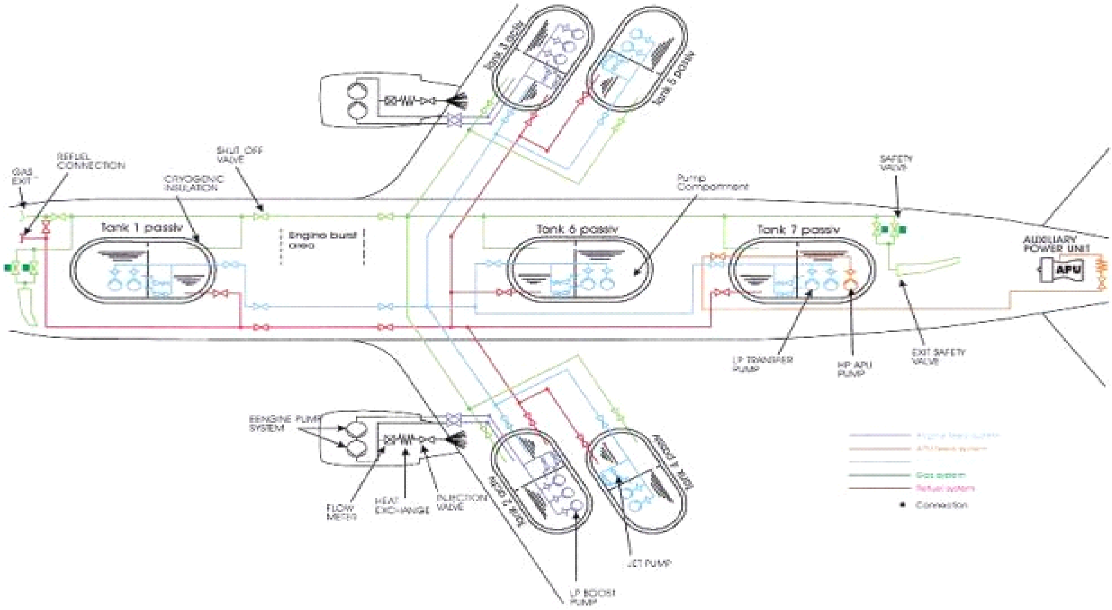


Figure 105: Fuel system architecture for the selected example aircraft

The passive tanks serve as an additional storage tank feeding the active one.
A return line from the HP (high pressure) pump outlet to the fuel tank is required in order to keep the hydrogen liquid at very low flow rates and provide F/L (Feed Line) and HP pump chill down.

The engine is fed from the respective active tank:

- this active tank is equipped with three main tank pumps inside the pump compartment,
- two pumps are working in normal operation, the third is in stand by,
- a jet pump system shall secure the filling of the pump compartment.

The main function of the system will be

- feeding liquid hydrogen up to the engine high pressure pump inlet.
- storing liquid hydrogen without out-gassing for 12 hours,

The minimum requirements of the system were

- Ground operations at ambient conditions (~ 1.2 bar, 22 K) with link to a ground out-gassing burn stack.
- No vent for taxiing, take-off and flight.
- Tank pressure to stay > 1 bar

About 8 to 12 tons of LH_2 stored in approx. 180 m^3 volume must be stored in order to cope with the requirement of a medium range aircraft.

Mini Requirements Specifications
“Mini Requirements Specifications” were prepared for Piping (inc. compensators and elbows), Armatures (Valves and Outlets), Pumps and Tanks. Based on those specifications, a systematic analysis has been made on each component. The aim of such analysis have been to identify show stoppers in the development of the systems and components and to select

- The onboard fuel system shall store the required mass of fuel and provide the engines with the required quantity/ quality of LH_2.
- The APU located in the tail cone of the aircraft shall be a separate hydrogen consumer.
- The liquid hydrogen fuel is stored within independent tank group systems. For aerodynamic reason tank fairings can be applied. The outer tank structure can be likewise the aerodynamic outer tank surface.
- The tanks can be connected to each other on the liquid/ gas side to ensure all necessary sub system functions like fuel transfer/ cross feed and gas drainage.
- Refuelling and defuelling of the tank group systems shall be done simultaneously via the refuelling line using one common coupling.
- If necessary provision shall be made to purge the fuel manifold and any engine cavities
- A cockpit indication/ fuel control and metering unit system shall account for the properties of hydrogen.
- The combustor shall meet all performance requirements of the respective engine. This includes high combustion efficiency, good durability, and stable flame during engine transients, reliable ignition, acceptable combustor exit temperature profile for turbine durability, low pressure loss, and low emissions.

It is an essential requirement to achieve at least the NO_X emission levels of the conventionally kerosene fuelled engine with an additional 80 % reduction.

The projected NO_X emission levels shall be met for the 'ICAO LTO Cycle' (ref. 1) and for the 'cruise' condition.

LH_2 Storage System
Liquid storage (two-phase fluid with a liquid/gas interface):
  - easy ground operations,
  - Tank pressure fluctuation during flight.

Synergies with other systems
As this application of FC technology could be also applied on conventional kerosene fuelled aircraft using a separate LH_2 tank the evaluation is presented in the 23: Case study Aircraft APU

<u>Simulated Engines.</u>
Four engines were selected – three turbofans (BRM710-48, V2527A5 and Trent884) and one turboprop (PW120) - trying to cover different aircraft sizes and ranges according Aircraft Configuration requirements. The simulations included different configurations – heat exchanger at different aerodynamic engine sections - as well as the influence of fuel temperatures. Design points were fixed at Sea Level Static (SLS); these were computed by closely matching public data - basically cycle, net thrust and Specific Fuel Consumption (SFC). Off-design simulations were then done and the results compared with cruise data in the public domain. The results at cruise conditions for aircraft-engine combinations were good: they matched well the available data in the public domain.

All engine data were provided: in particular, performance, weight, emission parameters and dimensions. In-depth studies were carried out for the two cases of a fuel heat exchanger placed at exit of the low-pressure turbine and in the external aerodynamic stream. Two different fuel temperatures were studied; these two temperatures were fixed to cover fuel control system requirements. Data of estimated engines, based on current conventional engines but improved to the technology standard expected in year 2010, were also provided.

The possible dimensional changes on turbines, beside simple dimensional nozzle changes, have been considered; the dimensional changes required are minimal and are easily feasible in the case of conventional engines.

18.6 Economic boundary conditions for FC/H2 technology

Parametric Study

All aircraft designs have been compared to check their consistency. The tank layouts have already been discussed. The design weights show a remarkable trend of almost constant empty versus MTOW fraction of 0.68, i.e. independent of aircraft category or size (Figure 106).

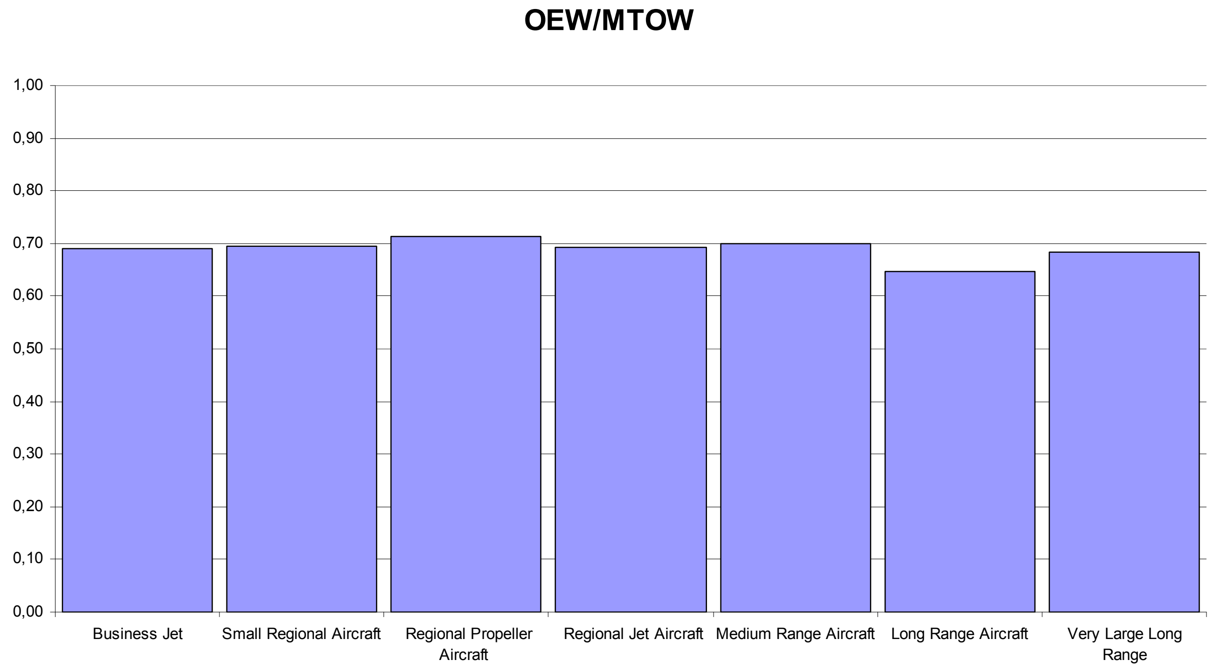


Figure 106: Fraction of operating empty weight/maximum take off weight

On the other hand, the increase in these design weights themselves due to LH_2 application does show some dependency, especially the MTOW (Figure 107). Irregularities may be noticed for the business jet and the VLLR category. This is to be expected since the business jet has a disproportionate fuel fraction and the VLLR is penalized by its three-deck layout. The latter is caused by the fact that this layout also affects the pressurized fuselage fuel tanks, thereby dramatically increasing their weight.

The consistency in operational cost penalty to be paid for the improvement in emissions has been investigated as well. Considering the fact that no technology leap is required for implementation of LH_2, aircraft prices have been estimated on basis of empty weight only and no additional development costs have been assumed. The production price of LH2 was assumed to come down from a high factor 5 more expensive than kerosene now to equal in 2037, based on the same energy content. The energy consumption increase of LH_2 aircraft is dependent on aircraft category due to the efficiency of the various tank layouts. The increase of energy consumption per pax nm ranges from 9 to 14 % if the configuration is not geometrically restricted as is the case for the business jet and the very large long-range aircraft. The 100-seater regional jet performs a little worse due to its very stubby fuselage as indicated in an earlier figure.

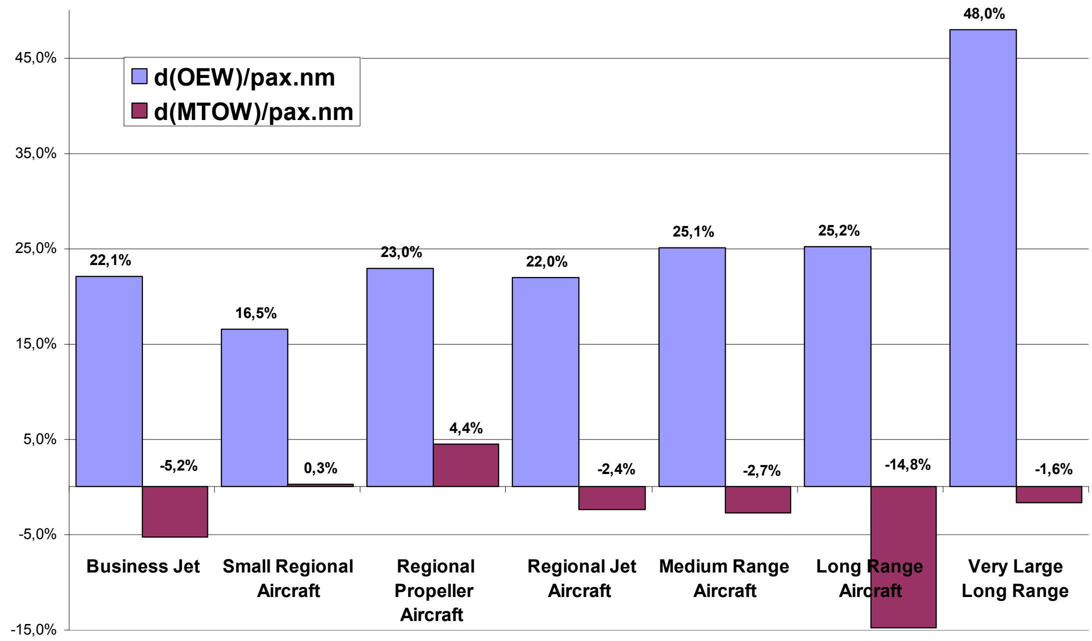


Figure 107: Dependencies between operating empty weight and max. take off weight for H2 fuelled Aircraft

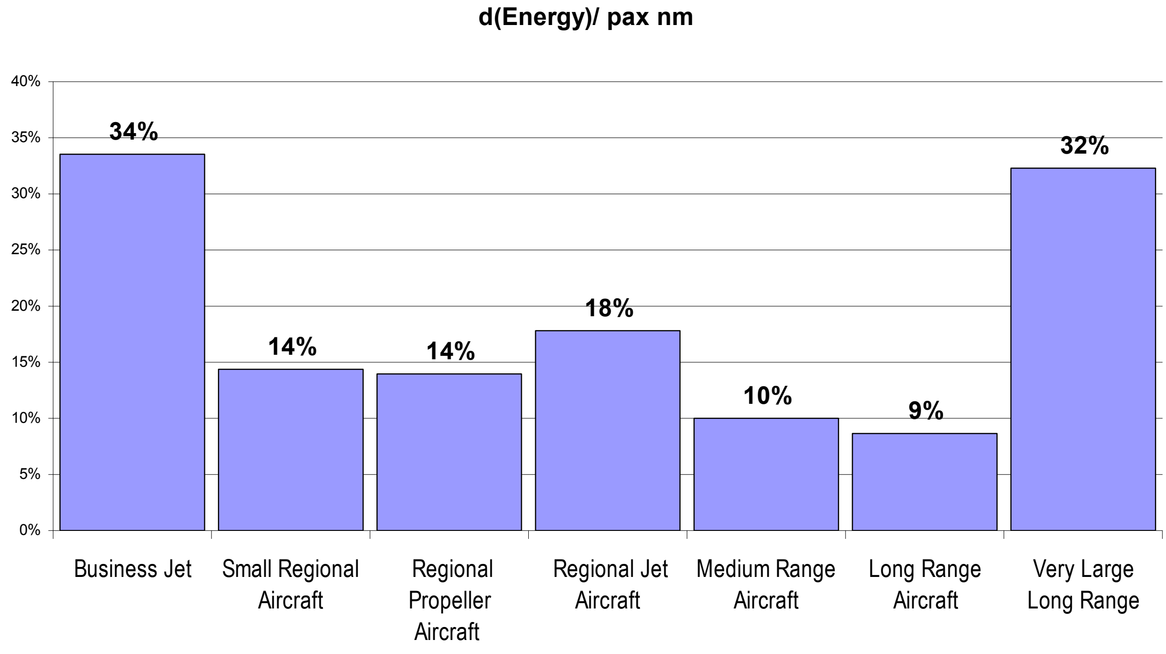


Figure 108: Change of energy consumption for H_2 fuelled aircraft

All these considerations combined lead for a 1000 nm mission to a 25 % higher DOC now, decreasing to a break-even point in 2040. Obviously, this outcome is heavily dependent on fuel price development of both fuel types.

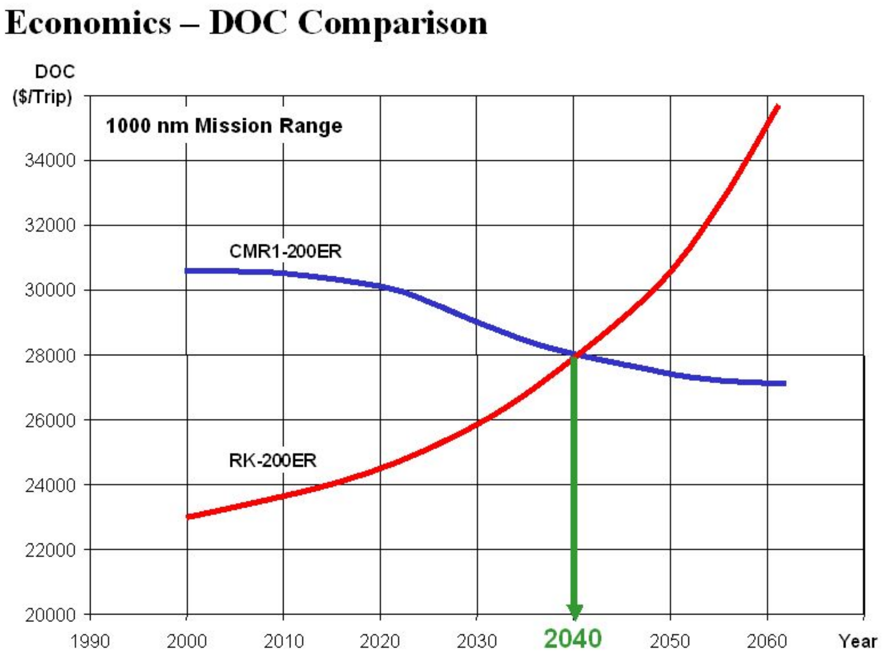


Figure 109: Calculated beak even point in case of RK-200ER and CMR-200ER

Transition Scenarios

In addition to solving technical problems related to the airframe, propulsion system, fuel system architecture, etc., there is also a need for the evaluation of the practical feasibility of using hydrogen for civil aviation. This could be accomplished by the compilation of a number of transition scenarios, which imply changing from a conventional fleet of aircraft to a LH_2-fuelled fleet, over a certain time period. In doing so, one may either change over at a global or at a more detailed regional level. The scenarios provide information on which transition rate is feasible without burdening the airline operator too much. Furthermore, each scenario indicates the volume of LH_2 required for a realistic transition scenario, as well as the emission volumes produced according to each scenario.

Global Transition Scenarios

Based on the global traffic and fleet forecasts, three scenarios have been developed to describe the transitions from kerosene aircraft to liquid hydrogen aircraft. Results are presented per aircraft class and region. Aircraft movements, shares of traditional kerosene aircraft and liquid hydrogen aircraft have split up required fleet and new aircraft. Estimations have been made for the differences in fuel consumption and emission figures. Results are presented for a 50-year period 2000-2050.

Scenario 1 assumes a rather smoothed, stepwise approach. This scenario was selected knowing that an operation of a hydrogen fuelled aircraft will not be attractive to the marked at this time due to “high” costs for hydrogen. In this scenario, the introduction of liquid hydrogen aircraft will start in 2015 in Europe for both small and medium-sized aircraft (respectively classes 2-5, <90 seats and 6-9, 90 - 220 seats). Ten years later, liquid hydrogen will be introduced on the large aircraft (classes 10-14, >220 seats) flying in Europe.

After Europe has succeeded, North America will introduce five years later hydrogen fuelled aircraft. In 2024 Asia & Pacific will introduce small and medium sized liquid hydrogen aircraft. Ten years later, large aircraft will follow. Latin America, Africa and the Middle East are the less developed regions, so Latin America and Africa & Middle East are the latest regions to introduce liquid hydrogen aircraft. In 2027 the introduction will start for both small and medium-sized aircraft, and in 2037 the large aircraft will follow.

From the introduction year on, all new-build aircraft for the region will be liquid hydrogen aircraft. This implies that the manufacturers are still producing both types of aircraft (kerosene and liquid hydrogen) until 2037.

<u>Scenario 2</u> requires policy regulation from ICAO to lead to a worldwide 'smooth' introduction of liquid hydrogen aircraft in 2015 on both small and medium-sized aircraft (classes 2-9, <=220 seats) and in 2025 on large aircraft (classes 10-14, >220 seats).

In this scenario it is assumed that both kerosene and liquid hydrogen aircraft are produced by the manufactures until five years after the introduction-year, i.e. until 2020 for small and medium-sized aircraft and 2030 for large aircraft. The production scheme of liquid hydrogen aircraft is by increments of 20% per year.

After 2040 all small and medium-sized aircraft in service will be liquid hydrogen and all large aircraft in service will be liquid hydrogen by 2050. It may be assumed that this scenario may not work without any political initiative.

<u>Scenario 3</u> assumes that ICAO will make a worldwide decision in 2020 about the use of liquid hydrogen aircraft and oblige the airlines to use liquid hydrogen aircraft after 2025 for new small and medium-sized aircraft and after 2035 for new large aircraft. The ICAO-decision assures, that from the introduction year on (small+medium: 2025; large: 2035), A/C manufactures will build only liquid hydrogen aircraft.

The following table gives the summary of the results of the three scenarios. As can be concluded from those results, political pressure is needed to assure a 100% liquid hydrogen fleet in 2050. Scenario 1, which assumes a stepwise region by region approach for introduction of cryoplanes and only stimulating policies without binding pressures also comes quite closely to the 100% replacement. The introduction year however is quite soon and no extensive testing of a prototype will be possible. This scenario is the most market driven scenario: no need of political initiatives may be taken into account and no global introduction at once is expected.

Table 89: Indication of Year When 100% CRYOPLANEs (if earlier than 2050) is Achieved, or the Percentages in 2050

100% year or 2050 percentage					
		Scenario 1 High	Scenario 1 Low	Scenario 2 High	Scenario 3 High
Small aircraft	World	94%	93%	2040	94%
	Europe	2043	2042	2040	96%
Medium aircraft	World	97%	97%	2040	95%
	Europe	2044	2044	2040	96%
Large aircraft	World	75%	73%	2050	65%
	Europe	93%	92%	2050	64%

Using detailed analysis of aircraft fleet demand, figures on aircraft movements and weekly number of flights for each scenario, the fuel consumption and emissions were calculated on a weekly basis. From the NO_x emission curves it could be concluded that whatever scenario might apply, NO_x emission volumes as of today cannot, probably, be achieved before a 50 years time span. In the meantime NO_x emissions will increase from today's level by about factor 2 (Scenario 1) to 4 (continuing use of kerosene) caused by traffic growth.

18.7 Global mean climate response from transition scenarios

Estimating the global mean climate impact change resulting from a realistic transition to cryoplane technology between 2015 and 2050 with a linear climate response model, we determine a typical value of about 25% reduction in radiative forcing at the 2050 time slice with tendency to increasing reduction thereafter.

Depending on the speed of the transition to cryoplanes best estimates range between 16% and 29% climate impact reduction (Figure 110). The respective best estimates for the various contributions are shown. The columns represent global mean values, as calculated by means of a linear response model. The rightmost panel shows the sum of all displayed components, not including further contributions from soot and sulphur aerosols as well as water vapour increases. Due to inherent scientific uncertainties with respect to the individual climate impact contributions of the various effects considered here (CO_2 and NO_x emissions, contrails), the respective uncertainty range widens to between 14% and 40% at 2050.

Further sources of potential importance (Contrail cirrus, CO_2 emitted during the production process) could not be quantified here, but can be included in the assessment as soon as the level of scientific understanding has improved.

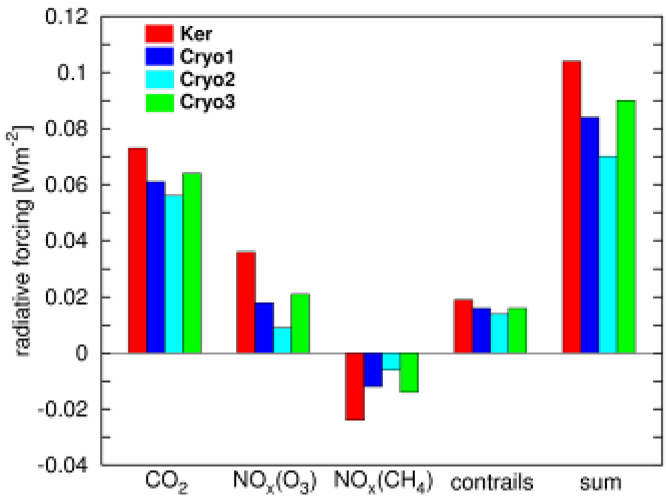


Figure 110: Radiative forcing (in W/m^2) of CO_2, NO_x (either due to ozone or methane changes), and contrails to be expected at year 2050 for a conventional aircraft increase scenario (Ker) and three different transition scenarios to cryoplanes

19. Case study canal sightseeing boat

19.1 Description of application

Canal sightseeing boats are boats that are used to show tourists the interesting and beautiful landmarks from the waterfront. The boats are used in towns with waterways and the size of the boats can be determined by the size of the bridges that have to be crossed. The tourists are mostly seated on benches and the boats can be covered with glass windows that provide a good view and protect from bad weather, depending on the climate.

19.2 Description of reference technology

Most canal sightseeing boats use diesel internal combustion, although electric boats get more interest due to the environmental rules from the city councils and/or because the electric boats are noiseless and odourless. These 2 advantages of electric boats are appealing to the tourists. In order to keep the cost and size of the electric propulsion system within reasonable limits, the top speed of the boat can be reduced. An example of a canal sightseeing boat is shown in Figure 111.

Figure 111: Example canal sightseeing boat in Amsterdam

In this case study a diesel operated as well as electric operated canal sightseeing boats are chosen as the reference technology and the relevant properties are provided in Table 90. The canal sightseeing boat operator in Delft provided the technical data. (www.rondvaartbootdelft.nl) [1]. Their boats have a capacity of 44 passenger for the diesel version and 48 passengers for the electric version. In Delft the boats are operated 7 months/year or 958 hrs/year (effective). If boats are operated all year it is assumed that the operating time doubles to 1900 hrs/year (effective).

The economic lifetime of the energy system is approximately 10 years, for both the diesel engine as well as the batteries. After these 10 years a major overhaul of the system is needed. The lifetime of the boat itself is much longer.

Table 90: The characteristics of the sightseeing boats.

Application	Unit	Diesel operated sightseeing boat	Electric operated sightseeing boat
Power level	kW	*67*	*16*
Efficiency; energy use	MJ/hr	*61*	*15*
Typical cost sightseeing boat	€	*120.000*	*120.000*
Specific cost energy system	€/kW	*260*	*1500*
Lifetime energy system	year	*10*	*10*
Type of “fuel”	-	*Diesel*	*Electric*
Type of “fuel” supply	-	*Filling station; jerry cans*	*Grid connection*
Type of “fuel” storage	-	*Fuel tank*	*Batteries*
Typical storage capacity	MJ	*7000*	*300*
Range/fuel charge	hrs	*100*	*20*
Availability	%/yr	*> 99%*	*> 99% (excluding recharging time at night)*
Maintenance		*16 hrs/year*	*8 hrs/year*

Most boats are custom built or built in small series. The speed in canals is in most cities restricted; therefore the engine size of canal sightseeing boats can be small.

19.3 Description of the market

The market for canal sightseeing boats is small, a rough estimate comes to 1000 boats. Assuming a lifetime of the boats of 25 years, the annual number of new boats amounts to 40/year. Most boats are custom built or built in small series by small shipbuilders. Dutch shipbuilders build around 10 passenger boats/year (not all sightseeing boats)

19.4 Description of FC/H2 technology for the application

The H_2 PEMFC canal sightseeing boat has the advantage of the noiseless, odourless and environmental friendly boat that can be refuelled in minutes compared to the diesel engine version. This is very attractive to tourists. The power of the fuel cell system for this application is comparable to the power of fuel cell cars and can be expected to become commercial in the future. Because it is a boat, the refuelling station for the hydrogen should be at the waterfront. The characteristics of an envisaged canal sightseeing boat are shown in Table 91. A hybrid version of fuel cell and batteries is envisaged for improved traction and reduction of dynamic demand of the fuel cell. The efficiency of the fuel cell vehicle is calculated from the efficiency of the electric canal sightseeing boat without the 80% recharging losses combined with a fuel cell system with 45% net efficiency on the LHV of H_2.

Table 91: The characteristics of the envisaged fuel cell sightseeing boat

Application	Unit	H_2 PEMFC sightseeing boat
Power level	kW	*16*
Efficiency; energy use	MJ/hr	*30*
Lifetime	year	*10*
Type of “fuel”	-	*Hydrogen*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Tank; pressurized*
Typical storage capacity	MJ	*300*
Range/fuel charge	hrs	*15 on H_2 and 3 on batteries*
Availability	%/yr	*Approx. 99%*
Maintenance		*Every 5000 km or 2*/yr; total 2-3 hrs/yr*

The following parties are building the combination of fuel cell systems with sightseeing boats, see Figure 112:

- Fuel Cell Boat BV is building a fuel cell sightseeing boat for Lovers in Amsterdam (NL); capacity 100 passengers and a 70 kW fuel cell propulsion system. [2]
- ZEMship is building a fuel cell sightseeing boat for Hamburg (DE); it can carry over 100 passengers and has 2*50 kW fuel cell propulsion system. [3]

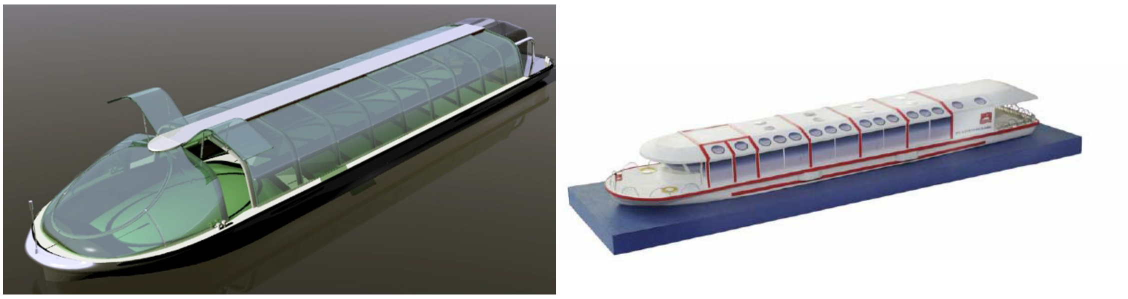


Figure 112: Artist impression of the fuel cell sightseeing boat for Amsterdam (left) and Hamburg (right)

19.5 Economic boundary conditions for FC/H2 technology

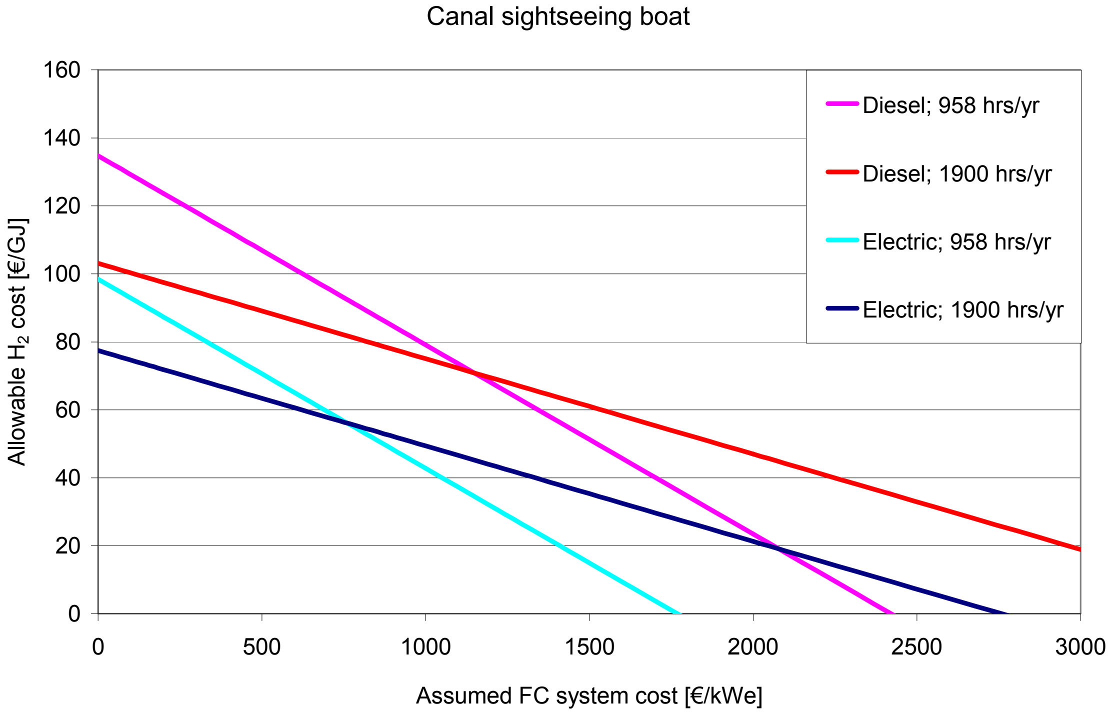


Figure 113: Allowable cost of H_2 as a function of the assumed 16 kW FC system cost at the same cost per hour as for 67 kW diesel or 16 kW electric sightseeing boats with a yearly operating time of 958 or 1900 hrs. All taxes included for the fuel

The 2 reference technologies, 67 kW diesel ICE and 16 kW electric engine are considered for the economic evaluation. The boat with the 67 kW diesel ICE will have a higher top speed than the electric version. For the fuel cell alternative, the fuel cell can be kept small and some extra power can be obtained from the batteries to increase the top speed and manoeuvrability. In that case, the size of the electric engine has to be increased. The average European diesel and electricity prices in 2007 are used for the economic evaluation. In Figure 113 the allowable cost of H_2 as a function of the assumed FC system cost is shown at the same cost per hour as the reference sightseeing boat. Yearly operating hours of 958 and 1900 are considered. The results are based on the input in Table 92.

The prices are with all taxes included for the engine, the maintenance as well as the fuel. For the fuel cell system the maintenance is expected to be similar to the electric sightseeing boat, except that battery replacement will be less expensive due to a lower number of batteries needed in the fuel cell system at 1900 operating hours/year. The effect of interest rates on the results is neglected.

Table 92: Background table for Figure 113 for the same cost in €/hr for a sightseeing boat with a fuel cell system compared to a diesel ICE or electric boat, only taking into account fuel cost and engine cost

Reference system		**Diesel ICE**	**Diesel ICE**	**Electric**	**Electric**
Engine cost	€/kW	257	257	1500	1500
Power	kW	67	67	16	16
Lifetime	yr	10	10	10	10
Distance	hr/yr	959	1900	959	1900
Specific investment cost	€/yr	1.793	0.905	2.504	1.263
Fuel cost	€/GJ	23.5	23.5	30.1	30.1
Fuel use	MJ/hr	61.1	61.1	14.9	14.9
Specific fuel cost	€/hr	1.435	1.435	0.449	0.449
Engine maintenance cost	€/hr	2.56	1.79	1.74	1.64
Total cost	€/hr	5.784	4.125	4.696	3.355
FC system					
Power	kW	16	16	16	16
Lifetime	yr	10	10	10	10
Distance	hr/yr	958.5	1900	958.5	1900
Fuel use	MJ/hr	30.0	30.0	30.0	30.0
Engine maintenance cost	€/hr	1.74	1.03	1.74	1.03

Assumed FC system cost €/kWe		Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0		135	103	98	77
200		124	97	87	72
500		107	89	71	63
1000		79	75	43	49
2000		23	47	-13	21
4000		-88	-9	-124	-35

The fuel cell vehicle is economically attractive if in Figure 113 the combination of cost of hydrogen and the cost of the fuel cell engine are below the line for the reference technology. The lifetime of the fuel cell system is also assumed as 10 years. If the lifetime is lower, than the fuel cell system cost should be read as the costs including replacement costs of the fuel cell.

The lifetime of the batteries for the Delft electric sightseeing boat is approximately 1000 cycles which means in their case about 10 year lifetime. For twice the operating hours half of the lifetime is expected and batteries need replacement once for a 10 year economic lifetime of the power system. The maintenance costs are based on the experience of the Delft sightseeing boat operator [1].

Fuel cost scenarios

–

The effect of the different diesel fuel costs on the assumed fuel cell system costs and the allowed hydrogen costs is provided in Figure 114. For reference, the following average European diesel prices in $€_{2000}$ are considered:

- The low 2007 value with all taxes (21.7 €/GJ)
- The mean 2007 value with all taxes (29.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)

- The high 2030 value with all taxes (47.1 €/GJ)

This Figure shows that the effect of different diesel fuel prices on the economy is significant; with a high spread due to the efficiency of the ICE vehicle. The effects of the developments until 2030 on the economy of the sightseeing boat are assumed to compensate each other. These developments are higher engine prices in order to reach lower emissions and higher efficiency of the engine.

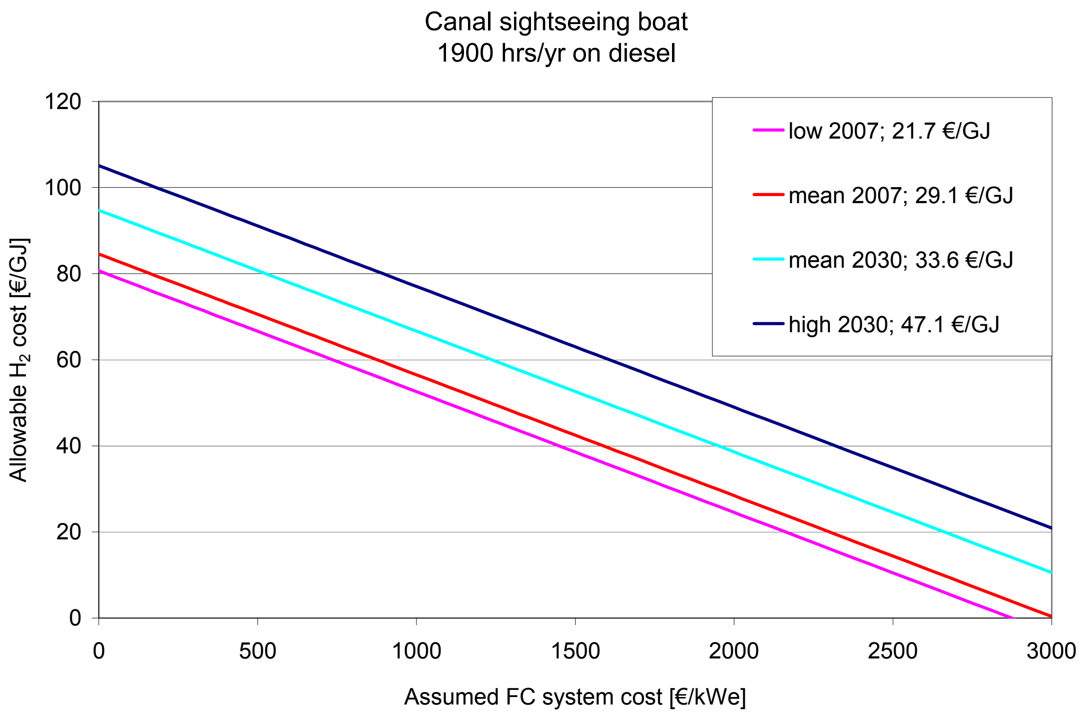


Figure 114: Allowable hydrogen costs vs. assumed 16 kW FC system cost of 4 different energy prices of diesel with all taxes included. The diesel engine has 67 kW capacity

19.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology
The CO_2 emission from the diesel sightseeing boat is calculated as 5200 gCO_2/hr using a diesel emission factor from the CONCAWE study [4] of 87 gCO_2/MJ. The CO_2 emissions and emission factors for the hydrogen fuel cell sightseeing boats in different countries are shown in Table 93. In this table it is assumed that the hydrogen is produced by electrolysis. In Table 94 the CO_2 emissions and emission factors for the fuel cell sightseeing boat are presented in relation to the source for the hydrogen.

Table 93: CO_2 emission factors for fuel cell sightseeing boats (4th column) in different countries (Source www.energy.eu [5] and carma.org [6])

Electricity	*Electricity E-mix*	*H_2 from E Electrolysis*	*Hydrogen* ***30 MJ/hr***
	gCO_2/MJ	gCO_2/MJ	gCO_2/hr
NL	166	218	6531
DE	141	185	5543
FR	20	26	793
UK	134	175	5260
PL	259	339	10174
CZ	168	220	6603
SW	6	8	242
DK	130	171	5122
EU-25	119	156	4678
Offshore wind	8	11	325

Table 94: CO_2 emission for fuel cell sightseeing boat in relation to the source for the hydrogen

Concawe (WTW) [4]	Mean	***30 MJ/hr***
Compressed H_2	gCO_2/MJ	gCO_2/hr
Onsite SMR	13295	3302
Waste wood	1517	377
Offshore wind	1301	323
Coal gasification + CCS	5419	1346

CO_2 reduction potential per service and for the potential market

The CO_2 reduction potential depends strongly on the source of hydrogen as shown in Figure 115. Only sources that are below the green line for diesel have a positive impact on global warming compared to diesel.

The maximum CO_2 reduction for the diesel sightseeing boat market can be obtained by replacing diesel from fossil fuel sources with fuel cells operating on hydrogen produced by electrolysis of off shore wind electricity. This is calculated by multiplying the maximum reduction potential of the service (≈ 4900 gCO_2/hr) with the average operating hours per year (≈ 1900 hrs/yr), the number of new units/year (≈ 20) and the lifetime of the boats (≈ 25 year). The maximum CO_2 reduction is then approximately 4.6 kton CO_2/yr.

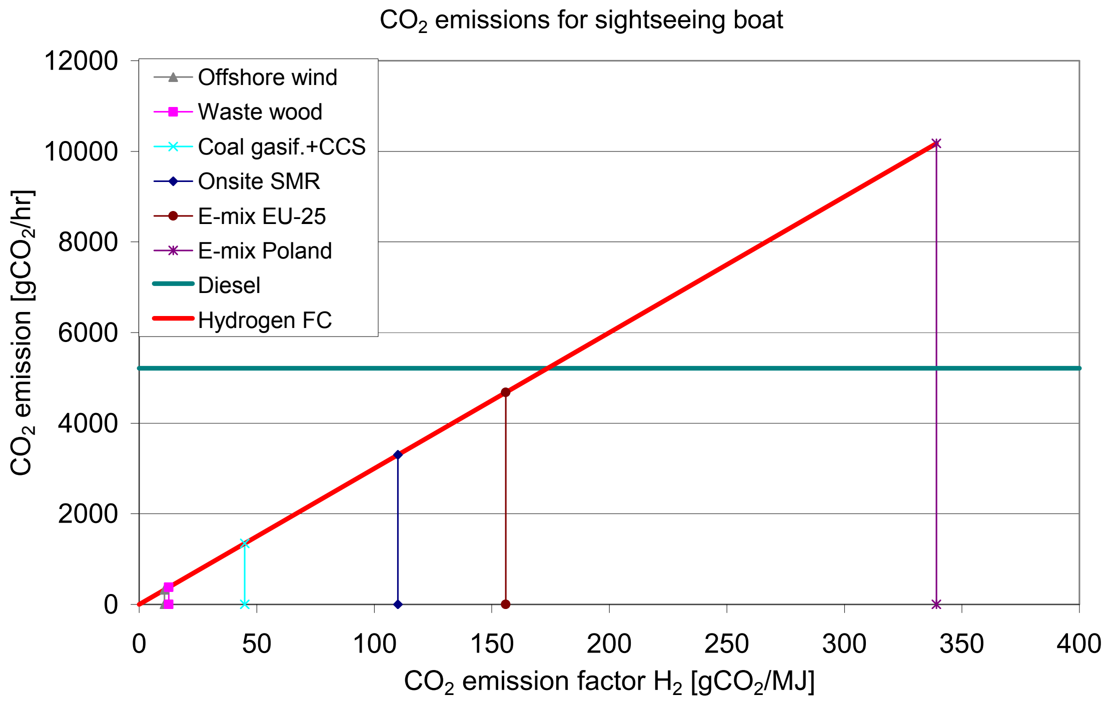


Figure 115: CO_2 emission reduction potential for replacement of diesel sightseeing boat

19.7 Conclusions and recommendations

The following general conclusions can be taken:
The large number of operating hours for the sightseeing boat is attractive for fuel cells. The filling with hydrogen requires a filling station at the shore whereas diesel can be refuelled using cans.

Recommendations:
There is a market for green, noiseless, and clean sightseeing boats for which customers are prepared to pay a premium. The power level for sightseeing boats is approximately 16 kW, which means that the fuel cell system costs are low compared to e.g. fuel cell system costs of passenger cars.

19.8 References

1. www.rondvaartbootdelft.nl and personal communication Anton Brands
2. http://www.fuelcellboat.nl/
3. http://www.zemships.eu/
4. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)
5. www.energy.eu, *last visited November 2007*
6. carma.org, *last visited November 2007*

20. Case study Truck APU

20.1 Description of application

A large numbers of transport trucks idle during times when they are not actively driving. The power needed during these times is called “hotel load” because it is the power necessary for the comfort of the driver while at rest. This is more common in North America. Several studies have been carried out, studying the behaviour of drives of long-haul trucks in the US, that have shown that trucks may idle 6 to 16 hours out of the day and consume about 4 litre diesel per hour that the engine is idling [1]. The amount of emissions produced is not insignificant during idling. Therefore several US policy-making bodies have started to pass legislation in an effort to curtail truck idling. For example the state of California has decided to ban idling for sleeper berth trucks for more than 5 min..

Auxiliary Power Units (APUs) are possibility to reduce idling. APUs are often considered as an early application of fuel cells. The potential benefits of fuel cell APUs in trucks are reduced maintenance, emissions, increased fuel efficiency and noise reduction. Several reports conclude that trucks for FC APUs are only worthwhile if drivers sleep overnight in the truck (ADL, 2001). Because of the need for power for the “hotel load”. APU use for congested roads and power special applications is often to big and sporadic if the APU only would be used for these purposes. Heavy duty trucks idle their main engines primarily to power climate control systems (heating and cooling in cabin) and electric accessories (televisions, lights, computers, etc.) [2]. In Table 95 an example of the long-haul truck power requirements is exemplified.

Table 95: An example of the long-haul truck power requirements is exemplified

	Average appliance power (W)	Estimated maximum same-time power requirement (W)
Air conditioner	2 200	*2200*
Battery charger	800	
Coffee pot	700	
CD player and speaker	100	
Computer	100	*100*
Converter	350	
Frying Pan	1350	
Stove	1000	
Water Pump	600	
Hair dryer	1000	
Light bulb	100	*100*
Microwave	1500	
Radio	200	*200*
Refrigerator	350	*350*
Television	100	*100*
Toaster	1200	
VCR	100	*100*
Total	11050	*2950*

The required load is dependent on the estimated maximum same-time power requirement of the truck during hotel load of the truck. A typical maximum power is 4-6 kW (Broderik, 2001).

20.2 Description of reference technology

The diesel engine in a heavy-duty truck is dimensioned for operation at a high load to meet the propulsion requirements. At high load the energy efficiency is often above 40%. But the diesel engine is also used today to power auxiliary systems, when the truck is idle and the engine load is outside its optimal operating range. The net result is less than optimal, for the main engine, which has been developed and optimized to run at 250+ kW to haul a loaded 40-ton vehicle, can simply be powering an air conditioner and a light bulb. By supplying power to the vehicle by means other than idling the diesel engine, it is possible to increase performance and lower emissions. The use of Auxiliary Power Units, based upon small diesel engines, is today the preferred alternative in the automotive industry. These generators are however limited by low fuel economy and high emissions, both of which can be resolved by replacing the small diesel engine with a fuel cell. [3]. American studies show that the engine is idling 20-40% of the time [4]. The reason for this increased demand for comfort for the driver and utilization of just-in-time production increasing the time the drivers spend in the truck. An average of 6 hours of idling per day has been reported [4]. A lot of fuel is used this way and considerable amounts of nitrogen oxides, hydrocarbons, carbon oxides, and particulates are emitted. Furthermore, the energy efficiency when generating electricity via the alternator at standstill can be as low as a few percent [5].

Another benefit of using an APU is the reduced used of the main engine. The potential benefit of reduced idling is less use of fuel, less engine overhaul and less motor oil use. In Table 96 a summary of the cost of idling is summarised.

Table 96: Cost of idling per truck and year US market [6]

	EUR (2006) Cost per year
Diesel fuel used (1)	2 820
Oil change (2)	31
Engine overhaul (3)	125
TOTAL	2 975

(1) 3 litre diesel/hour, 2000 hours/year, diesel €0.47/diesel
(2) 48 000 km between oil changes, €100/oil change, km of idling 15 616 (2.6 km/litre), €0.002/km
(3) €6 666/engine overhaul, 800 000 km/overhaul, €0.008/km

20.3 Description of the market

The main market chosen is the market for trucks in North America. The potential market for FC APUs for long-haul trucks is 100,000 / year for new trucks, bur retrofit is also possible for long-haul trucks [3]. Therefore the potential market is larger. The European situation is also shown since this report target audience is European communities. In this study an assumptions is made about the number of heavy-duty trucks that can use fuel cell APU and the number of idling hours per year in Europe. The guess is 100,000 trucks and number of idling hours is 500 hours per year.

20.4 Description of FC/H2 technology for the application

The requirement for fuel cells for trucks are summarised in Table 97.

Table 97: Fuel cell based APUs: truck requirements [/]

	Units	
Voltage	V DC	12-42
Power	kW	1-5
Power density	> 0,1 kW/kg	0,1
Fuel	-	Gasoline, diesel, LPG, alcohol fuel
Duty Cycles	-	Continuous, load following, cycling
Operating life	Hours	5000 - 40000

The following parties are developing or demonstrating the combination of fuel cell systems with Fuel Cell APU for trucks [8]:

- Protonex + Cummins (SOFC). Sub-kilowatt diesel fuelled APU for trucks. Protonex as sub-contractor for Cummins (SECA). SOFC, CPOX reforming, desulphurization from Protonex.
- Ricardo & Technology Management Inc. (SOFC). 2 kW multi-fuel APU for heavy-duty trucks. Sulphur-tolerant, integrated hot assembly vaporizer-reformer-stack) SOFC from TMI. Ricardo designs and packages the systems.
- Staxera (HC Starck, Webasto & IKTS) researches APUs with SOFC. The targets for the unit include: Electric Efficiency: 1-2 kW (at market entry) Thermal Power: 2-5 kW. Mass / Volume: <35 kg / <70 liter. Start up time (cold): <60 minutes. Lifetime: >6000 hours
- Daimler Chrysler & Frightliner (PEMFC) Hydrogen fuelled PEM APU 1.4 kWe-No update from 2003.
- Delphi + Battelle (SOFC) On-board APU in vehicles for variety of fuels Delphi teamed with Battelle under SECA program Battelle works on basic cell and stack technology Delphi is working on system integration, system packaging and assembly, fuel reformer and powerconditioning and control electronics.
- Volvo and Powercell (PEMFC) Diesel reformer and 5 kW PEMFC PowerCell, a joint venture between Volvo and StatoilHydro, was established in 2005 for development and commercialization of PEM fuel cell systems based on Volvo technology in the range of 5-10 kW for Auxiliary Power Unit (APU) applications for heavy-duty trucks and other high-tech niche markets. The primary sectors for PowerCell are the European and North American truck market, with a focus on trucks larger than 20 tons.

Both SOFC and PEMFC are used as fuel system technology. The fuel options are hydrogen, methanol, gasoline, diesel and other hydrocarbons.

If PEMFC systems and hydrocarbons are used there is a need for on-board reforming. Methanol reforming is often performed by steam- or autothermal reforming and CO clean-up equipment. For other hydrocarbons a POx reformer, LT or HT shift equipment and CO clean-up equipment is used.

The main option is diesel in short –term. The challenges to reform diesel fuel are:

- High boiling point
- Multi-component mixture
- Long-chain hydrocarbons
- Aromatics
- Poly-aromatics
- Sulphur
- Additives

The advantages and negative aspects of different technology options for APUs for trucks are presented in Table 98.

Table 98: The advantages and negative aspects of different technology options for APUs

Technology option	Advantages	Negative aspects
SOFC	Light, compact, low start-up, low temperature	*High tolerance to poisons No noble-metals*
PEM	Sensitive to poisons	*Long start-up, thermal cycling, low response, heavy*
Diesel engine	Proven technologies, already available, technology infrastructure on place	*Lower efficiency, noisy*

Provided electrodes become less sensitive to poisons, PEM fuel cells are promising choice.

Table 99: The characteristics of the envisaged fuel cell APU (PEMFC using diesel)

Application	Unit	PEMFC APU
Power level	kW	*5*
Efficiency; energy use	MJ/hour	*20 (diesel) [9]*
Lifetime	year	*10*
Type of “fuel”	-	*Diesel*
Type of “fuel” supply	-	*Filling station*
Type of “fuel” storage	-	*Tank*
Typical storage capacity	MJ	--
Availability	%/yr	*Approx. 99%*

20.5 Economic boundary conditions for FC/H2 technology

The main market for fuel cell APU is North America, but since this report is looking for opportunities for European regions the economic boundary conditions both for the North American and European situation is shown.

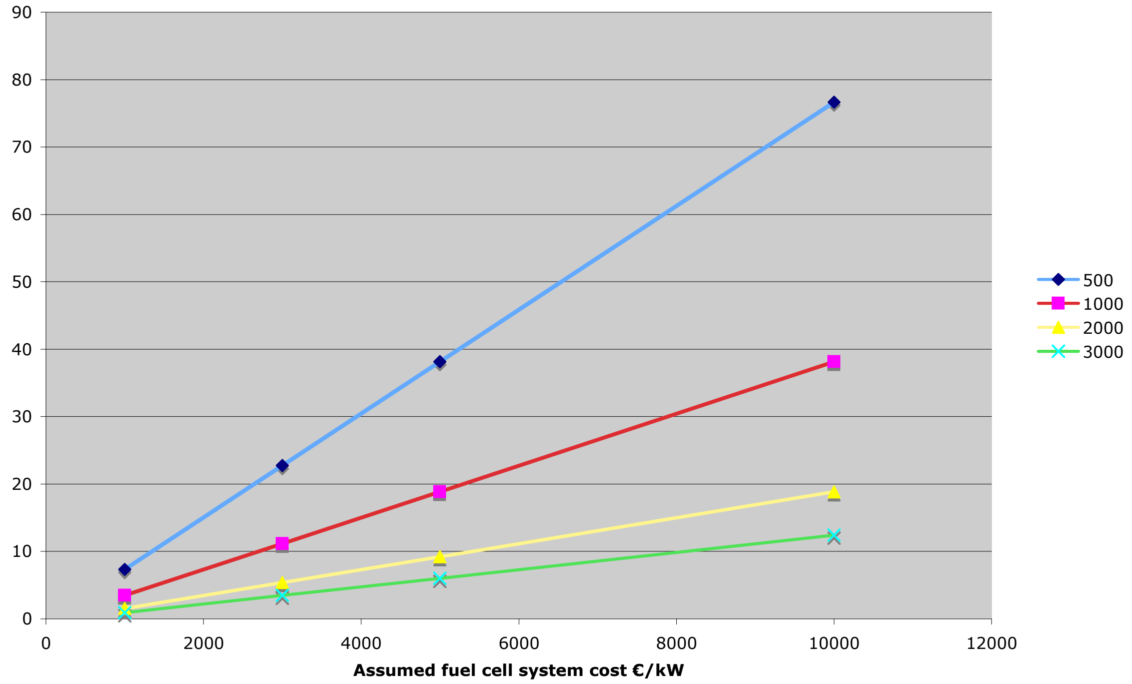


Figure 116: Allowable cost of diesel fuel (€/GJ) for the North American market, at the same cost per year as for diesel heavy duty truck idling using main engine 500, 1000 2000 and 3000 hours per year and a diesel consumption of 3,8 litre/hour, as a function of the assumed fuel cell APU system (using diesel as fuel) cost (incl. inverter and reformer). Life time of fuel cell system 10 years

The idling time is an important factor and also the lifetime of the fuel cell system. Since the diesel cost is approximately 10 €/GJ the fuel cell system could be competitive at a cost of 300-10000 €/kW depending on the idling time and lifetime of the fuel cell system. Compared with fuel cell cars the fuel cell system can be more expensive and still be competitive. But if the payback time needs to be 2-3 years then the max cost of the fuel cell system is approximately 1000 €/kWe per total system.

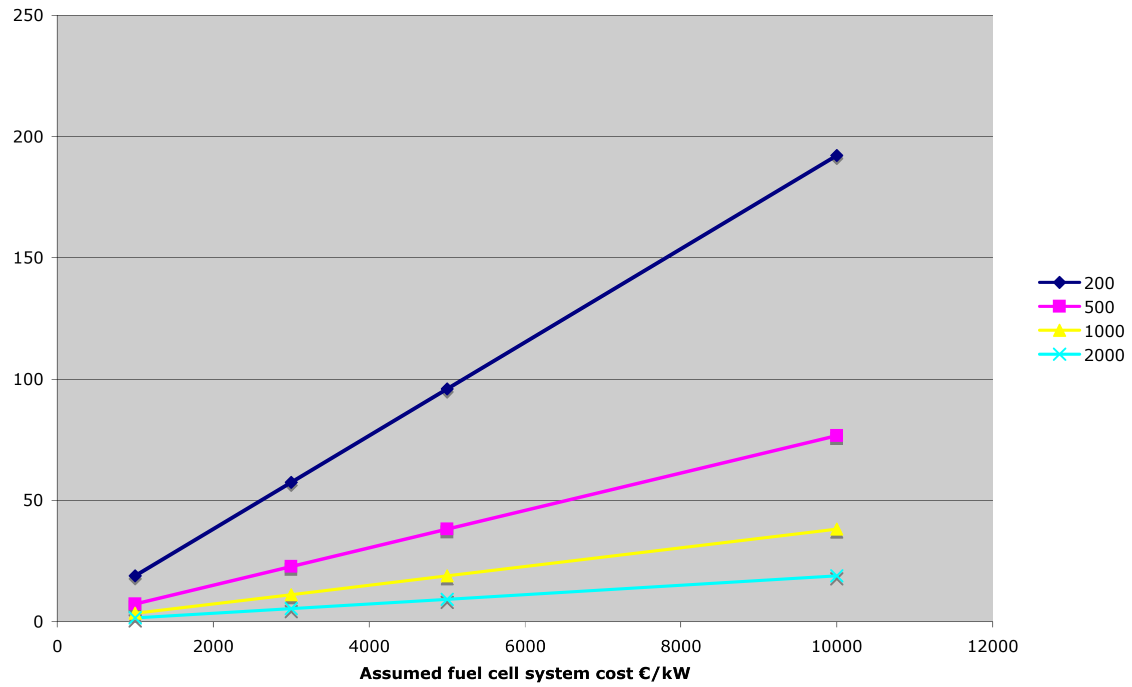


Figure 117: Allowable cost of diesel fuel (€/GJ) for the European market, at the same cost per year as for diesel heavy duty truck idling using main engine 200, 500, 1000 and 2000 hours per year and a diesel consumption of 3,8 litre/hour, as a function of the assumed fuel cell APU system (using diesel as fuel) cost (incl. inverter and reformer). Life time of fuel cell system 10 years

The two differences between the European situation and the North America situation are the number of hours idling and the cost of diesel. In Figure 117 the European the typical situation is around 1000-2000 hours, but in Europe the number of hours idling is around 200-1000 hours.

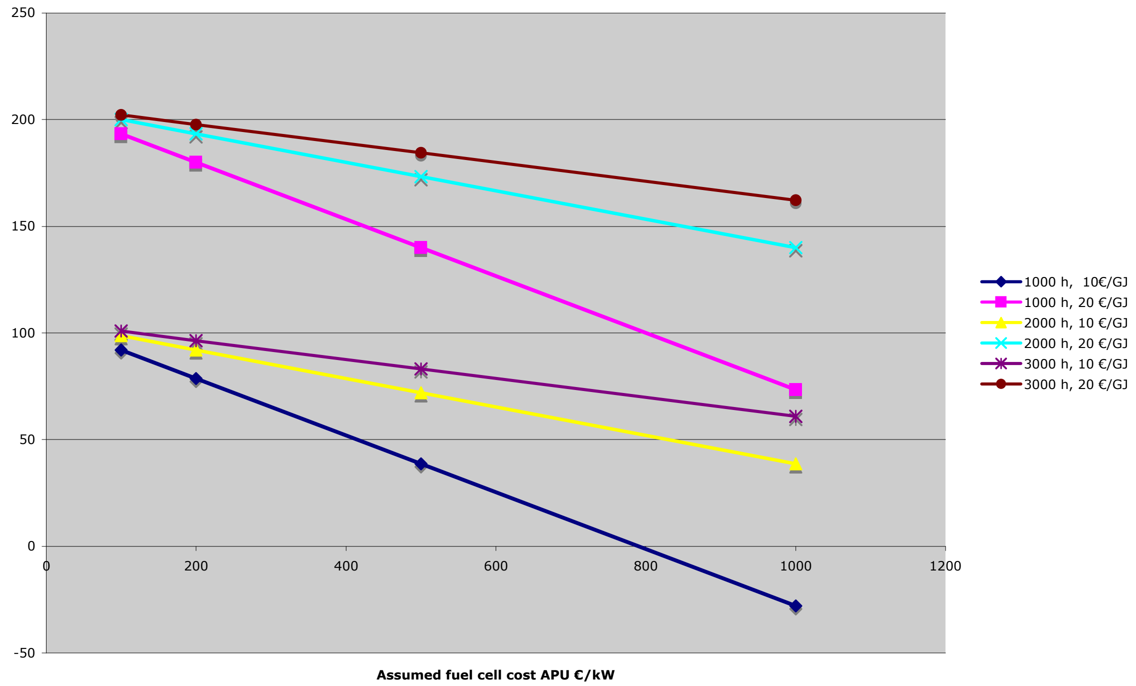


Figure 118: Allowable cost of hydrogen (€/GJ) for the North American market, at the same cost per year as for diesel heavy duty truck idling using main engine 1000, 2000 and 3000 hours per year and a diesel consumption of 3,8 litre/hour, as a function of the assumed fuel cell APU system cost (using hydrogen as fuel). Life time of fuel cell system 10 years. Diesel cost is 10 €/GJ or 20 €/GJ

The yearly use of idling is an important factor for the allowed fuel cell cost. Another important issue is the lifetime of the fuel cell system. Assuming the lifetime will only be 2000 h instead of 20 000 then the cost allowed cost will be 10% of the values in Figure 118.

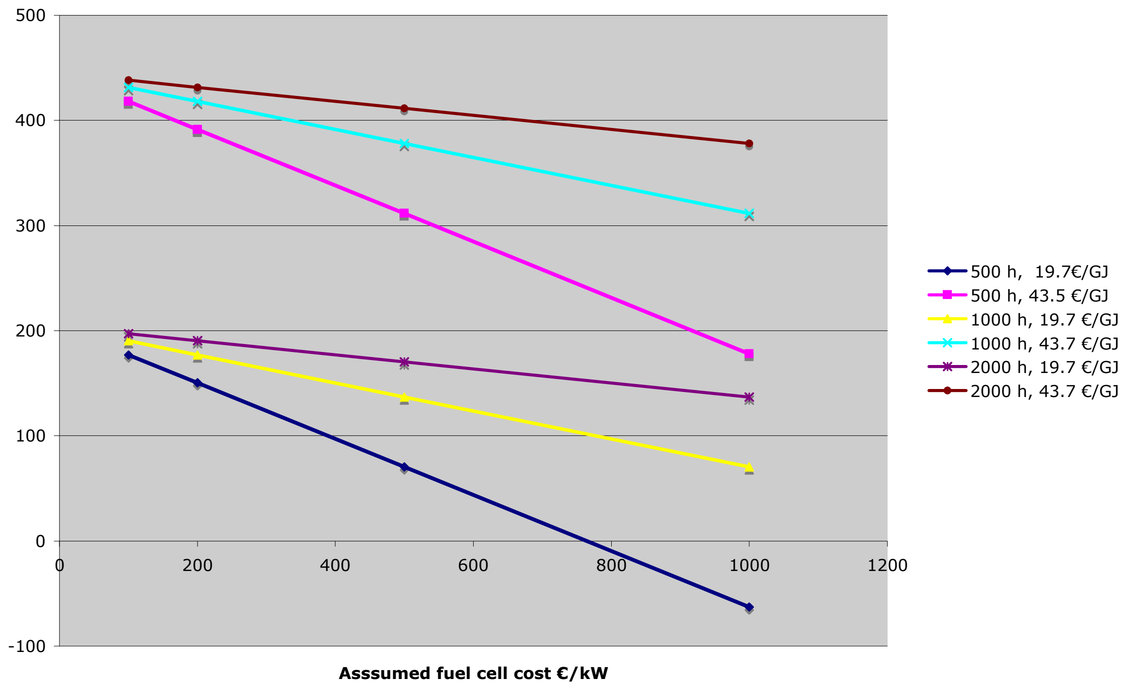


Figure 119: Allowable cost of hydrogen (€/GJ) for the European market, at the same cost per year as for diesel heavy duty truck idling using main engine 500, 1000 and 2000 hours per year and a diesel consumption of 3,8 litre/hour, as a function of the assumed fuel cell APU system cost (using hydrogen as fuel). Life time of fuel cell system 10 years. Diesel cost is 19.7 €/GJ or 43.7 €/GJ

The cost of the hydrogen can be higher in the European situation, because the diesel price is higher than in the US, but if the idling time is lower than 500 hours per year, the diesel price is 19.7 €/GJ then the cost of APU fuel cell system must be lower 800 €/kW to be competitive.

Table 100: Background table for calculation for the North American situation (Based upon [9]). The European situation differences are that the idling time is 500 hours

Reference system		Diesel Engine idling	PEMFC APU with reformer	PEMFC APU using H_2
Idling	hours/years	2000	2000	2000
Fuel consumption idling (diesel)	GJ/hour	0,152	0	0
Oil change	€/hours	0.05	0	0
Engine overhaul	€/hours	0.05	0	0
Fuel cost	€//GJ	10	0	0
Fuel cost idling	€/hours	1.52	0	0
Total cost	€/hours	1.62	0	0
FC system				
Max Power	kW	-	5	5
Lifetime FC system	years	10	10	10
Fuel used (hydrogen)	GJ/hours			0.015
Fuel used (diesel)	GJ/hours	0	0.022	0
Fuel cost (diesel, US market)	€/GJ	10	10	10
Engine maintenance cost	€/hours	0.04	0.05	0.04

20.6 CO2 reduction potential emission of reference and fuel cell technology Source-to-User

The CO_2 emission from idling the main diesel engine is calculated by using a diesel emission factor from the CONCAWE study [10] of 87 g CO_2/MJ. The CO_2 emissions from the main engine is 13 kg CO_2 /hour if 3,8 litre diesel per hour is used. If using reformed diesel in a PEM FC fuel cell APU the CO_2 emissions per hour is 1,9 kg/hour. If using a Fuel cell APU instead of a idling the main engine and the idling hours/years is 2000 hour there is a reduction of 22 tonne CO_2/year.

Table 101: CO_2 emission in relation to the source for the hydrogen

Concawe (WTW) [10]	Mean
Compresssed H_2	gCO_2/MJ
Onsite SMR	110
Waste wood	13
Offshore wind	11
Coal gasification + CCS	45

The reduction of using hydrogen in fuel cell APU will depend on the production of hydrogen. In Table 116 different CO_2 emission factors for different fuel options is shown.

Table 102: CO_2 emission reduction of using a fuel cell APU and hydrogen instead of idling main engine (2000 hours, 3,8 litres/hour) in relation to the different source

Concawe (WTW) [10]	CO_2 Ton/year
Source of hydrogen	Reduction
Onsite SMR	22,7
Waste wood	25,6
Offshore wind	25,7
Coal gasification + CCS	24,6

CO_2 reduction potential per service and for the potential market
The maximum CO_2 reduction for the US market of heavy duty trucks if average idling time is 2000 hours/year is calculated by multiplying the maximum reduction potential of 22 ton/year times the number of heavy duty trucks using fuel cell APU's (100.000). The maximum CO_2 reduction is then 2.2 Mton CO_2/yr.

The maximum CO_2 reduction for the European market of heavy duty trucks if average idling time is 500 hours/year is calculated by multiplying the maximum reduction potential of 5.5 ton/year times the number of heavy duty trucks using fuel cell APU's (100.000). The maximum CO_2 reduction is then 0.55 Mton CO_2/yr.

20.7 Conclusions and recommendations

The following general conclusions can be taken:
- Using a fuel cell APU can be cost competitive at higher fuel cell cost than for a fuel cell for cars.
- Long "hotel load time" and long lifetime of the fuel cell system will increase cost benefits.
- The CO_2 reduction potential of using a fuel cell APU instead of using the main diesel engine can rather large.
- This main market for truck APUs will probably be in US.
- Both SOFC and PEMFC systems can be used as APUs.

Recommendations:
There is a huge potential for fuel cell APUs in trucks. Fuel cells can be cost competitive soon. In the short term diesel will probably be used as fuel. But when an hydrogen infrastructure is available then the option to use hydrogen will be interesting.

20.8 References

1. David Grupp, Matthew Forrest, Pippin Mader, CJ Brodrick, Marshall Miller, Harry Dwyer. 2004. Design Considerations for a PEM Fuel Cell Powered Truck APU. UCD-ITS-RR-04-16Institute of Transportation Studies, University of California – Davis
2. Nicholas Lutsey, Christie-Joy Brodrick, Daniel Sperling, Harry A. Dwyer.Markets for Fuel Cell Auxiliary Power Units in Vehicles:A Preliminary Assessment. TRB 2003 Annual meeting.
3. POWERCELL CORPORATE PRESENTATION. Available at www.powercell.se.
4. F. Stodolsky, L. Gaines, A. Vyas, Analysis of technology options to reduce the fuel consumption of idling trucks, ANL/ESD-43, Argonne.
5. C.J. Brodrick, T.E. Lipman, M. Farshchi, N.P. Lutsey, H.A. Dwyer, D. Sperling, S.W. Gouse, III, D.B. Harris, F.G. King Jr, Transportation Res. D: Transport and Environment 7(2002) 303-315.
6. L Gaines, 2006. How Much Could You Save by Idling Less? Argonne National Labor Excel-file.
7. Per Ekdunge. Presentation APU for trucks. A winter school on state of art & future of “Hydrogen & Fuel Cell Technologies”, Bardonecchia 21-26 January 2007. …
8. Andreas Bodén 2008. Olika bränslecellstekniker - teknikläget och framåtblick Traktionära tillämpningar Tunga fordon. (in Swedish). Different fuel cell technologies technology state-of-art and future possibilities. Tractionary. Heavy-Duty vehicles- Presentation.
9. Christie-Joy Brodrick,Timothy E. Lipman, Mohammad Farshchi, Nicholas, P. Lutsey, Harry A. Dwyer , Daniel Sperling,S. William Gouse, III , D. Bruce Harris , Foy G. King Jr. Evaluation of Fuel Cell Auxiliary Power Units for Heavy-Duty Diesel Trucks. 2002. Institute of Transportation Studies (University of California, Davis) Year 2002 Paper UCD-ITS-REP-02-13.
10. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)

21. Case study Pleasure boat APU

21.1 Description of application

Fuel cells can be used for marine applications and as APU for pleasure vessels [1]. Vessels include every description of watercraft, including non-displacement craft and seaplanes, used or capable of being used as a means of transportation over or on the water. A pleasure boat is a non-commercial vessel of any size designed for non-commercial use, intended to be operated by, and carry at least one person within the confines of a hull. Windsurfers, surfboards, rafts and tubes are not considered recreational boats.

There are approximately 6.0 million recreational marine craft in Europe. Of this total figure, approximately 1.1 million are sailing boats, 4.8 million motorboats and 0.1 million personal watercraft (such as jet skis) [2]. The use of recreational marine craft in Europe contributes to environmental costs with regard to both exhaust emissions and sound emissions. However, according to CORINAIR 94,4 the air emission inventory for Europe, emissions from recreational marine craft are minimal compared with other pollution sources such as energy industries, manufacturing industries, road transport, etc. In Europe recreational marine craft are estimated to contribute approximately 0.34% of total carbon monoxide emissions, 0.5% of total hydrocarbon emissions and 0.1% of total NOX emissions [2].

Although the aggregate emissions from recreational marine craft are low compared with other sources, they can lead to localised problems in areas that have a high concentration of recreational craft at certain times of peak activity (such as weekends). The implementation of the emission limits for carbon monoxide, hydrocarbons, nitrogen oxides and particulate matters specified in Directive 2003/44/EC will contribute substantially in reducing the amount of pollutants released into the air and water by recreational craft and as such contribute to the improvement of air and water quality in these areas as well [2].

Fuel Cell APU can reduce some of the environmental problems. Although there are cases of pleasure craft using fuel cells as propulsive power, they are mainly being researched and targeted as APUs, providing the power to the battery bank which in turn powers the electrical equipment. This chapter will focus upon fuel cell APU for sailing yachts, because it is considered an early target market.

Sailing yachts are mainly used for short trips, but also long trips, that last several weeks, are used. For the long trips there is a need to recharge the batteries, but also on other occasions when there is no grid available. A fuel cell APU can be used to recharge the batteries. Table 103 summarizes the electric energy needed for a sailing yacht.

Table 103: Typical Yacht Electrical Power Consumption When Sailing [3]

	Consumption Watt	AMP	Time on (hrs/per day)	Consumption over 24 hours Ah(12V)
Navigation Instruments	2.4	*0.2*	*24*	*5*
GPS	2.4	*0.2*	*24*	*5*
VHF Standby	1.2	*0.1*	*24*	*2*
Transmitting	60	*5*	*0.2*	*1*
Refrigerator	50	*4.2*	*24*	*100*
Tricolour Navigation Light and anchor light	25	*2.1l*	*8*	*17*
Autopilot	60	*5*	*20*	*100*
Radio	12	*1*	*3*	*3*
Cabin Lighting	200		*0.6*	*10*
Other				*5*

The total consumption over the 24 hour period is approximately 1.5 kWh. Then the average consumption is 64 W. Therefore the fuel cell average power does not need to be particularly high. This helps to reduce cost and size of a fuel cell APU. A typical use of the sailing yachts is assumed to be 30 days per year.

21.2 Description of reference technology

Some yacht owners run their main engine, so that the alternator can charge the battery pack. A typical large yacht uses 4 x 100Ah (Amp Hour) batteries. Some yacht owners use smaller diesel generators that emit emissions and are noisy, see Table 104. Fuel cell APU's are silent and do not vibrate. Vibrations can be problematic, especially in an enclosed sailboat cabin. A diesel generator is often heavy especially when mounted on a 100 kg anti-vibration base plate. Typically a generator installation together with the anti-vibration plate weighs about 250kg [4]. The fuel cells APU system can weigh considerably less than this. A diesel generator requires maintenance. For example, oil change after 150 hours of use, and an oil filter change about every 300 hours of use. Another difference between a fuel cell system and using the main diesel engine is that the yachts needed to store power generated in a short period for use over the day if using the main engine, but the fuel cell is recharging the battery continuous.

Table 104: The characteristics of the reference technologies

Application	Unit	Diesel generator	Main engine
Power level		*2*	*30*
Efficiency; energy use(diesel)	MJ/kWh (el.)	*18*	*36*
Maintenance	€/hours	*0,5*	*0,5*
Availability	%/yr	*> 99%*	
Cost	€	*500*	*-*
Use when recharging batteries	h/day	*2*	*2*

21.3 Description of the market

An early target market for the APU is sailing yachts in the 40-49 ft class. According to the International Boat Industry (IBI) there were 4,621 new yachts commissioned in this class in 2005. The total number of sailing boats in Europe is 1.1 million, but the main market for fuel cell APU is the large sailing boat.

21.4 Description of FC/H2 technology for the application

The advantages of fuel cells in comparison with normal engines are [1]:

- High electric efficiency (40-50%) in respect to traditional engines;
- High global efficiency (50-65%), accounting for cogeneration system;
- Products of fuel cells during electric energy production:
    - Electric energy;
    - Heat;
    - Steam;
    - No pollutant emissions.
- Products of Fuel Processor unit:
    - Gases for fuelling Fuel Cells;
    - Heat;
- Possibility to produce electric energy in protected areas
- Environmental impact
    - Lowering total emissions of pollutant gases
    - Lowering specific fuel consumption;
- Comfort on board:
    - Lowering vibration levels
    - Lowering acoustic pollution.

The requirements and challenges for fuel cells on board ships [1] are:

- Weight and volume constraint coming from the limited dimensions available on-board ships;
- Need to cope with on-board electric network requirements;
- Need to cope with existing on-board environmental conditions:
    - Motions and vibrations;
    - Temperature and humidity;
    - Sea air.

The following parties are developing or demonstrating APU fuel cell systems with leisure boats:

- Haveblue. Fuel cell installed as APU on board a sailing boat. Including an on-board hydrogen production system (wind/solar) for autonomous refuelling.
- Voller Energy is testing a prototype of its environmentally friendly fuel cell generator onboard the company's Solent-based Bénéteau Oceanis 411 Emerald. Voller's 1kW fuel cell generator works by automatically monitoring battery voltage. When the battery voltage falls, it switches itself on and recharges the batteries. Once the batteries are fully charged the fuel cell switches itself off to conserve fuel. The remote diagnostic capability of the Emerald fuel cell generator allows the team of designers and engineers to constantly monitor every aspect of the product's onboard performance from the Voller HQ in Basingstoke, Hampshire.
- Max Power with EFOY methanol fuel cells sells a methanol fuel cell for yacht applications. Ultrapure methanol is used as a fuel.
- Truma is developing a 250 W fuel cell system using LPG as fuel.

- MTU Friedrichshafen demonstrated a 4,8 kW Ballard fuel cell stack on-board a yacht on Lake Constance in 2003.
- A.G.O. and Microsec R & D Inc. demonstrated the use of a Horizon M300 fuel cell on-board a yacht in 2007. The next step will include Palcan's newly developed fuel cell system of 1 kW.

21.5 Economic boundary conditions for FC/MeOH technology

Since Max Power has a commercial product for the yacht market, the properties of this product can be used as basis for the fuel cell system for this market, see Table 105.

Table 105: The characteristics of the envisaged APU fuel cell for sailing yachts

Application	Unit	MeOH APU system
Power level	W	*64*
Cost	€	*2900*
Efficiency; energy use	MJ/kWh	*17*
Lifetime	Year	*3 years guarantee*
Type of “fuel”	-	*Methanol*
Type of “fuel” supply	-	*Ultrapure methanol*
Type of “fuel” storage	-	*Fuel tank*
Typical storage capacity		*10 litres*
Range/fuel charge	Days	*9*
Cost of fuel	€/MJ	*0.14*

The cost comparison between the diesel genset APU and the fuel cell system is shown in Table 106.

Table 106: Cost comparison between diesel APU system and Fuel cell APU €/year

Application	Unit	MeOH APU system	Diesel APU
Background data			
Days used per year	days	*30*	*30*
Energy used per day	kWh	*1.5*	*1.5*
Methanol fuel	€/GJ	*140 €/GJ*	*140 €/GJ*
Diesel fuel”	€/GJ	*19.7*	*19.7*
Cost			
Diesel APU	€/year	-	*166*
Fuel cell APU	€/year	*967*	--
Diesel cost	€/year	-	*16*
Methanol cost	€/year	*107*	-
Maintenance	€/year	-	*30*
Total	€/year-	*1074*	*212*

As shown in table the MeOH fuel cell system cost almost five times more than a diesel APU system. However, there is premium paid for low noise and vibration.

21.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

The CO_2 emission from the diesel ICE using the main engine is calculated as 4,7 kg CO_2/day using a diesel emission factor from the CONCAWE study [5] of 87 gCO_2/MJ and an energy use of 36 MJ diesel/kWh (electricity) and an energy use of 1,5 kWh electricity per day. The CO_2 emissions from the use of methanol and methanol fuel cell is calculated as 2.0 kg CO_2/day using a methanol (natural gas based) emission factor from the CONCAWE study [4] of 80,8 (11,7 (production)+ 69,1(fuel)) gCO_2/MJ and an energy use of 17 MJ/kWh (el.) and electricity use of 1,5 kWh/day. The difference between main engine and fuel cell system is 2,7 kg CO_2 per day.

CO_2 reduction potential per service and for the potential market
The maximum CO_2 reduction for APU fuel cell market for sailing boats using methanol is calculated by multiplying the maximum reduction potential of the service (≈ 2,7 kg CO_2/day) times 30 days per year and 50 000 larger yachts in Europe. The maximum CO_2 reduction is then 0.004 Mton CO_2/yr.

21.7 Conclusions and recommendations

The following general conclusions can be taken:

- Sailing boat APU's are already a commercial product. The main benefits are not energy efficiency, but reduction of noise and vibration.
- The sailing boat market is a high profile market with a lot of purchase power.
- Only about 50-100 W is needed as average power output of the fuel cell system. . Therefore a fuel cell average power does not need to particularly high. This helps to reduce cost and size of a fuel cell APU
- Methanol fuel cell system is commercial available in this sector.
- The next step could be to use fuel cell system for the main propulsion.
- The environmental benefits are not large of the fuel cell system, because of the low use of energy.

Recommendations:
There is a market for green, noiseless, and low vibration APU for sailboats for which customers are prepared to pay a premium. The power level is approximately 60-100 W, which means that the fuel cell system costs are really low compared to most other fuel cell markets. The sailing boats are operated with large distances; therefore a fuel distribution system needs to build up. This makes the fuel choice an important factor.

21.8 References

1. G. Cusano.2007. Naval Applications of fuel cells: state of art. A Winter school of art & future of "Hydrogen & Fuel Cell Technologies". http://www.mega-electric.co.uk/pdf/datasheet_pickup.pdf
2. COMMISSION STAFF WORKING DOCUMENT accompanying the COMMUNICATION FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on the possibilities of further improving the environmental characteristics of recreational craft engines. IMPACT ASSESSMENT {COM(2007) 313} {SEC(2007) 819}.
3. Kerry-Ann Adamson, Fuel Cell Today – 2005. Fuel Cells and Marine Applications.
4. Voller 2006. Voller Energy Announces Major Fuel Cell Milestone-On Schedule. Voller Pressrelease.
5. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (*http://ies.jrc.cec.eu.int/wtw.html*)

22. Case study Yacht APU

22.1 Description of application

Today's conventional technology for auxiliary energy productions in ships has largely reached its potential for emission reductions. New and more energy efficient technologies are needed for a further decrease. One of these new technologies could be based on fuel cells.

This report evaluates the environmental and economical performance of a solid oxide fuel cell and a HT PEM fuel cell with a reformer both fuelled with methanol in comparison to an auxiliary power unit based on a diesel engine.

One electrical generator of the reference vessel is replaced by the fuel cell system. The power level and the type of current provided to the grid is similar to the one provided by the reference technology.

22.2 Description of reference technology

Figure 120: Luxury Yacht Alysia

Table 107: Specification Luxury Yacht Alysia [1]

Specification	Luxury Yacht Alysia	
Length	m	85,30
Beam (width)	m	14,44
Draft	m	4,15
Gross weight	t	2.990
Net tonnage	t	891
Max. speed	kn	18
Cruising speed	kn	16
Economic speed	kn	14
Range	nmiles	7.000
Number of Guests	-	36
Water capacity	l	110.213
Fuel capacity	l	234.455

Table 108: Machinery Data Luxury Yacht Alysia [1]

Machinery	Luxury Yacht Alysia		
Main engines	2x Caterpillar 3606	kW	2022
Auxiliary	Caterpillar 3406	kW	400
Generators	**3x Caterpillar 3412**	**kW**	**500**

The reference vessel has an electrical generation system based on three of these Caterpillar generators. The fuel cell system replaces one generator and supplies a constant level of energy – basic load. The other two generators supply the dynamic load. It is estimated that the fuel cell runs 3000h per year. Mega Yachts spend more time in the harbour than on the sea and are not operated 24 hours. Especially for the harbour and coastal regions, the fuel cell system supplies the ship with energy.

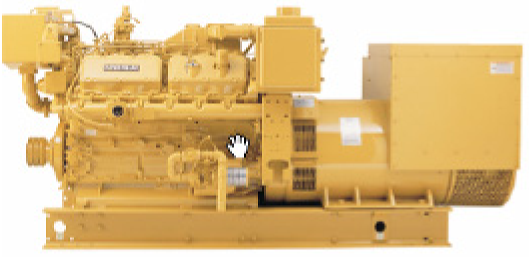


Figure 121: Generator from Caterpillar

22.3 Description of the market

This category of vessels was chosen for following under following requirements

i. The fuel cell should represent a technology in the bigger segment.
ii. The application and integration should be in a realistic range.
iii. The operation should be attractive to the operator/owner.

Several categories of ships have been reviewed and discussed with experts of this branch. A selection of the category and application has been performed by engineering judgment.

Category	Typical (kWel)	Operation	Comment	Selection
Big Container	15 /container req.	permanent	APU power req. out of range. Very little effect to be expected	No
Small Container	10.000	permanent	Very little effect to be expected. Not attractive for the operator.	No
Fishing vessel	Depending on the size	permanent	Not attractive for the operator because it can be expected that two fuels have to be serviced.	Possible
Motor Yachts	Depending on the size and the onboard consumers	on purpose	Range of size could be met. An attractive phase of operation could be the time of mooring due to low emissions and noise to low noise levels.	Yes

We have found up to now no official numbers of yachts of the selected size under operation or produced per year in Europe. Consequently we could not conclude on fleet level.

22.4 Description of FC technology for the application

Analyzing the characteristics of the different technologies, the current applications and the technology suitable to this kind of maritime application lead to following discussion for the technology selection:

LT PEM: (Low Temperature <80°C): This technology requires very clean hydrogen. On board reforming hydrocarbons is found not practical due to complicated desulphurization (if applicable) and cleaning processes.
SELECTION: Possible, but not applicable for this study. Solutions may exist only in applications where pure hydrogen is available. On board reforming of hydrocarbon fuels for LT PEM is not mature today,

AFC: This technology requires clean hydrogen and oxygen. From the infrastructure point of view this technology is not suitable for such an application.
SELECTION: Negative.

DMFC: Today this technology is commercially developed for small scale products. Especially for potable applications like mobile phones and laptops DMFC have good potential. A large scale application of several hundred kW's is not developed.
SELECTION: Possible, but not applicable for this study. In general the technology contains a certain potential, but today the application and the sizing would be on a very speculative basis.

PAFC: This technology is indicated to be most mature for large scale applications. Maritime projects are not identified yet. PAFC are due to the operating temperature of around 180°C applicable for reformed hydrogen.
SELECTION: Positive, but not chosen for this study. PAFC and HT PEM is a quite similar technology. The decision for this study fell to HT PEM.

SOFC: Besides the PEM technology, SOFC's are in developing for mobile applications. Furthermore SOFC's are a promising technology for large stationary systems. A big advantage for SOFC is the reduction of overall system size, since SOFC's can be fueled directly with hydrocarbons. In opposite to the PEM technology, which requires very clean H_2 gas, the SOFCs runs with H_2 from a reformation process and with some hydrocarbons like methanol or natural gas without reforming.
SELECTION: Positive, due to the flexibility of different fuels. Although the maturity level is a concern, SOFC is selected as a technology for yacht application.

MCFC: This technology is selected by some projects for maritime applications in Europe, which are still in the proposal phase.
SELECTION: Positive, but not chosen for this study.

HT PEM: (High Temperature >120°C). This technology offers good advantages for maritime application because it is more resistant to impurities and contaminations like CO compared to the LT PEM. Today the maturity on system level is not as developed as for the LT PEM, but the technological outlook for this technology is promising.
SELECTION: Positive, due to the fact that it can run on hydrogen that is reformed out of methanol.

The fuel cell type the most likely to replace the diesel generator is decided to be SOFC and HT PEM. The fuel for both technologies is methanol. For the HT PEM system layout,

methanol is reformed to H_2 and CO_2 via steam reforming. Steam reforming is a mature technology and further purification is not necessary due to the higher operating temperature of HT PEM compared to LT PEM. This technology is mature and more applicable as methane reforming.
For the SOFC system layout, reforming of methanol is not necessary. It is reformed directly at the anode side of the SOFC fuel cell. This leads to a higher efficiency of the system. (Table 109)

Some special conditions for the fuel cell system and the balance of plant components should be considered:

- The system needs a rigid housing and vibration dampers.
- Yachts operate world wide in all kind of climatic conditions. In general fuel cells should not be stored below 0°C. Although this topic is already solved by the automobile industry, a good water management is required for the stack and for the periphery to avoid freezing inside the system.
- The salt content in the air requires good filtration to avoid negative effects for the flow fields and for the periphery components.

Table 109: Data of the reference diesel engine for 2007 and 2030 and the corresponding SOFC and HTPEM system [3],[4],[7]

Reference system		**ALYSIA diesel 2007**	**ALYSIA diesel 2030**	**ALYSIA diesel 2007**	**ALYSIA diesel 2030**
Energy Source		Diesel	Diesel	Diesel	Diesel
Engine cost	€/kW	400	300	400	300
Power	kW	500	500	500	500
Lifetime	yr	12	12	12	12
Operating	hr/yr	3000	3000	3000	3000
Specific investment cost	€/hr	5,556	4,167	5,556	4,167
Fuel cost	€/GJ	23,5	33,4	23,5	33,4
Fuel use	MJ/hr	4883	4883,00	4883	4883,00
Specific fuel cost	€/hr	115	163	115	163
Engine maintenance cost	€/hr	2,44	2,44	2,44	2,44
Total cost	€/hr	123	170	123	170
FC system		**SOFC 2007**	**SOFC 2030**	**HT PEM 2007**	**HT PEM 2030**
Energy Source		Methanol	Methanol	Methanol	Methanol
Overall Efficiency /Ref.&FC	%	45	55	25	35
Power	kW	500	500	500	500
Lifetime	yr	12	12	12	12
Operating	hr/yr	3000	3000	3000	3000
Fuel use	MJ/hr	4000,00	3272,73	7200,00	5142,86
Maintenance cost	€/hr	2,00	2,00	2,00	2,00

The assumption of the operating hours is based on the special conditions for Mega Yachts. The fuel cell system with 500 kW generates a basic supply for the electrical grid on board. Since SOFC systems and also HT PEM system with reformer are not quite dynamic and a load profile is not available, it is assumed that the system runs on full power. Efficiency is assumed to be on the highest level at full power.

22.5 Economic boundary conditions for FC technology

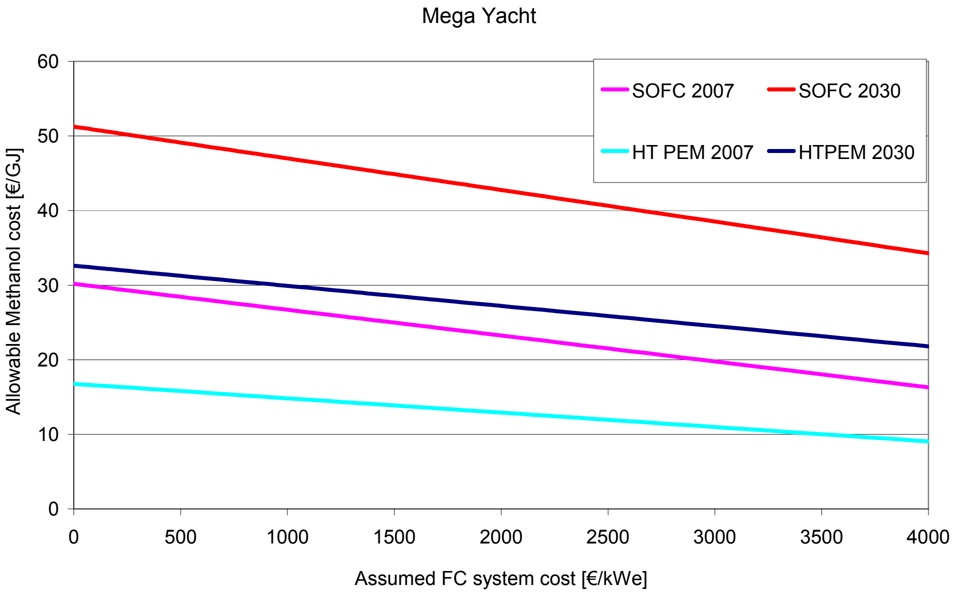


Figure 122: Boundary conditions for the SOFC and HTPEM system for 2007 and 2030

The SOFC technology is due to its high electrical efficiency, more attractive in comparison to a diesel engine. An assumed fuel cell system price of 2000 €/kW of SOFC can tolerate a methanol price up to 23 € per GJ to be competitive to a diesel fuelled engine in 2007. In 2030 the price can go up 43 €/GJ. This is due to an even higher efficiency of 55% methanol to electrical power in 2030.
The HT PEM system that runs with reformer technology is less competitive to the diesel engine compared to the SOFC. An assumed price of 2000 €/kW of system costs requires methanol costs of less than 13 €/GJ to be competitive to a diesel engine. Higher efficiencies in 2030 increase that boundary up to 27 €/GJ.

22.6 CO2 Emissions

A calculation of the CO_2 emissions of the different technologies is given in [3], [4]:

Diesel engine Caterpillar 3412:
Energy content diesel: 43,1MJ/kg
Emission factor diesel: 0,087 $kgCO_2/MJ$
Emission factor diesel per hour: 4883MJ/h *0,087 $kgCO_2/MJ$

➢ **425 kg CO_2 / h**

Methanol CO_2 missions depends strongly on the way it is produced, as it can also be produced in renewable way. Here it is estimated that 1 kg of methanol generates 1,375 kg of CO_2 at the point where it is used.

SOFC Methanol fuelled, 2007:

CO_2 emissions are simply calculated with the fact that 1 mole methanol produces 1 mol CO_2. Average methanol consumption is approximately 450g/kWh. With the molar mass of methanol (32 g/mol) and of CO_2 (44 g/mol) the emission is to be calculated:
Energy content methanol: 19,69MJ/kg
Emission factor methanol: One molar mass of methanol (32g/mol) generates one molar mass of CO_2 (44g/mol). (44/32) = 1,375 kg CO_2/kg methanol.
Emission factor methanol per hour: (4000MJ/h / 19,69MJ/kg) * 1,375kg CO_2/ kg methanol

- **279 kg CO_2 / h**

SOFC Methanol fuelled, 2030:
Emission factor methanol per hour: (5142MJ/h / 19,69MJ/kg) * 1,375kg CO_2/ kg methanol

- **228 kg CO_2 / h**

HT PEM Methanol fuelled, 2007:
Energy content methanol: 19,69MJ/kg
Emission factor methanol: One molar mass of methanol (32g/mol) generates one molar mass of CO_2 (44g/mol). (44/32) = 1,375 kg CO_2/kg methanol.
Emission factor methanol per hour: (7200MJ/h / 19,69MJ/kg) * 1,375kg CO_2/ kg methanol

- **502 kg CO_2 / h**

HT PEM Methanol fuelled, 2030:
Emission factor methanol per hour: (5142MJ/h / 19,69MJ/kg) * 1,375kg CO_2/ kg methanol

- **360 kg CO_2 / h**

A reduction of CO_2 emissions can only be reached with a technology that offers a higher efficiency. This cannot be stated for fuel cells in general. SOFC's that are directly fuelled with methanol can reduce CO_2 emissions by more than 20% today. In comparison to HT PEM technology that, due to its lower efficiency including the reformer, even increases the CO_2 footprint. More development in the technology of HT PEM's could lead to a reduction of emissions compared to a diesel engine in 2030. A demand perspective of the Mega Yacht market can not be given, but it is assumed that it is a growing market especially in the regions of China and India. [8]

22.7 Conclusions and recommendations

A more detailed cost analysis should be performed, taking more economic categories into account. The data quality should also be improved; fuel prices, which indeed influence the results, are due to problems gathering data based on many different sources. Better fuel data will give a better picture. The technological stage of the fuel cell technology makes the cost estimates for the fuel cell difficult to estimate. Long term test results are needed to make the fuel cell costs more credible.

Concept HT PEM and reformer, methanol fuelled.
This concept looks very promising from a technical and economical point of view. The concept uses methanol as fuel. This fuel is mixed with water and relatively easy reformed in a hydrogen rich gas. After CO-removal, the gas is ready to be used in the HT PEM. The concept has the potential to be very flexible in operation. Load changes and starting/stopping would not represent major problems.
Disadvantages of the system are related to the dangers of methanol. Proven technical solutions are readily available to reduce risks to acceptable levels. A major disadvantage of the system is the amount of CO_2 emission due to its low electrical efficiency from the fuel to the grid.

Concept SOFC, methanol fuelled

Main advantages of SOFC are the high fuel efficiency and the flexibility with regard to fuel choice. The efficiency results in a significant CO_2 emission reduction of more than 20% compared to diesel engines.

Major problems can be seen in the development status of the technology and in complications that are caused by the high operating temperature, approximately over 700°C. This high temperature is the reason for the good efficiency and fuel flexibility but it also makes that SOFC systems are difficult to start and stop. Besides that, it makes the technology more expensive compared to the HT PEM.

22.8 References

1. Data sheet of the Yacht “Alysia”
2. Data sheet of Caterpillar marine 3412C
3. Marte Reenaas; SOFC with gas turbine versus diesel engine as APU
4. M.J.A.J. Couwenberg; Fuel Cells on Containerships for Electric Supply
5. Hzwei – Das Magazin für Wasserstoff und Brennstoffzelle, April 2008, Seite 14, “Wärtsilä erprobt die WFC20”
6. M.Krumbeck, C. Bruch, H. Merkat, C. Jansen, RWE Fuel Cells, Essen, publication at the dh2e conference 2003.
7. J. Thormann, H.Walter. W.Winkler; Hamburg University of Applied Siences, Berliner Tor 21; 20099 Hamburg “Entwicklung und Systemintegration von hocheffizienten Gasturbinen-Brennstoffzellen-Kombianlagen (SOFC-GT) an Bord von Seeschiffen”
8. Blohm+Voss Engineering Office

23. Case study Aircraft APU

23.1 Description of application

Fuel Cell Systems as a main part of the electrical power generation in an aircraft becomes more and more attractive due to several reasons. The Fuel Cell System gives potential to substitute the APU and batteries. Moreover it can reduce the fresh water tank, provide humidity for cabin air and inerting for the kerosene tanks. All those advantages can be achieved in a very “green” way, because the Fuel Cell System has no climate critical emissions such as CO_2 and works with a negligible noise level.

23.2 Description of reference technology

Today various power systems are installed on the aircraft:

- Electrical power,
- Hydraulic power,
- Pneumatic power and
- Thermal power systems

Projects have been launched to optimise, reduce or even eliminate existing power systems. The overall trend goes to a higher electrical power demand.
At the same time environmental friendliness becomes an important role in the air framers strategy.
The use of H_2 fuelled fuel cell technology gives a new opportunity to cope with future challenges. The objective is to save weight and operational costs by finding high-integrated system architecture and to make best use of water generation, electrical and thermal power and inert gas generation.

The reference electrical power system is based on the electrical generators of the turbines and on the APU in the rear end of the airplane.

Table 110: Characteristics of an aircraft APU

Application	Unit	APU
Design total power at shaft	kW	*300*
Electrical power	kW	*83*
Bleed extraction	kg/min	*70*
Weight	kg	*160*
Fuel demand	Kg/hr	*88*
Type of fuel	-	*Kerosene*

Table 111: Characteristics of an electrical engine generator

Application	Unit	APU
Electrical power	kW	*225*
Frequency	Hz	*360-700*
Overload / 5min	%	*125*
Overload / 5sec	%	*175*
Weight	kg	*71*
MTBF	h	*30.000*

APU's and electrical generators have been developed over decades. For the future only small steps of further weight reduction and higher efficiency are expected for these systems.

The comparison of fuel cell systems with APU's and generators only, results in a major disadvantage for the fuel cell system in terms of weight and reliability. Taking a highly integrated fuel cell system into account, that not only benchmarks against energy generation but also against the fresh water tank – fuel cell systems are getting more attractive.

Fresh water tanks:
Fresh water tank size in a small single aisle aircraft starts at ~100l and goes up to 2000l for a very large aircraft.

The fuel cell system produces water according to the electrical demand. In general the water system is divided in three different water quality classifications – potable water, grey water and black water.
The water coming from the fuel cell covers potable and grey water. In contrast to the conventional grey water the "grey water" produced by the fuel cell has the quality of distillate water (very clean; without minerals). This quality of water could be used for cabin humidification and toilet flush. According to its quality it can be assumed that toilet maintenance will decrease.

A further application that can be covered by an Aircraft APU fuel cell system is the inerting of the kerosene tanks by using the cathode exhaust of the fuel cell. Reference systems for inerting currently not exist.

23.3 Description of the market

The market chosen is the market for airplanes over 100 passengers.

Air traffic has experienced strong growth over a long time, and it is predicted that such growth will continue at rates of 4 - 5 % p.a. over the next decades. Traffic losses in the aftermath of September 11th 2001 were only temporary. Assuming continuing worldwide economic growth, saturation of air traffic is not yet in sight. For the aircraft manufacturers, this is a highly welcome prospect, because only one third of their production is for replacement of old aircraft, two thirds of the production serves the needs of traffic growth. (ref. Airbus Global Market Forecast 2006-2025[3])

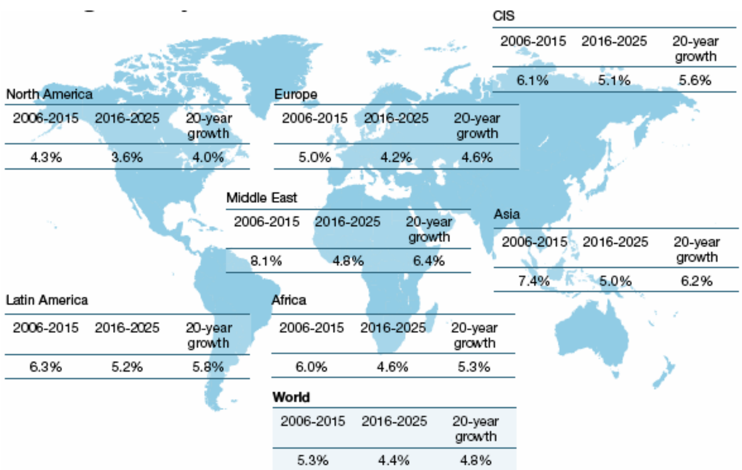


Figure 123: Air traffic growth by Airline domicile (2006-2025)

23.4 Description of FC/H2 technology for the application

A Fuel Cell System does not provide electrical energy only. The products of the chemical reaction can be used for various purposes in the aircraft system architecture. The high integration approach is a key enabler to create a new efficient aircraft system architecture making use of the advantages of a fuel cell.
Since a fuel cell system has not been installed as an APU today, only the opportunities can be described.
The power of the fuel cell systems depends on the integration level. Currently studies investigate systems with 20kW and up to several hundred kW. Weight, reliability and safety are the key drivers for the development rather than the significant price reduction needed by the automobile industry.

The main driver for the weight reduction potential is the usage of the water generated by the fuel cell system.
Water quality studies of fuel cell exhaust water found that inorganic, organic, physical and microbiological parameters were determined. Contaminations due to material erosion, fuel impurities and environmental influences were found in different ranges from negligible to critical. The source for most water contaminants was the system periphery as piping or heat exchangers. The microbiological quality of fuel cell water was found to be sufficient in a first approach. More representative and especially long term analysis need to be performed in future.

Table 112: The characteristics of an envisaged fuel cell system

Application	Unit	H_2 FC Airplane APU
Power level	kW	*20 – 500kW*
Electrical efficiency;	%	*> 50*
Lifetime	hr	*> 20.000*
Type of “fuel”	-	*H_2 possibly LH_2*
Type of “fuel” supply	-	*@ Turn Around*
Type of “fuel” storage	-	*Tank; pressurized or liquid*
FC system weight	kW/kg	*0,5*
Tank system weight	kg Tank/kg H_2	*<3*
Temp. range of environment	°C	*-40 - +50*
Availability	%/yr	*Approx. 99%*

23.5 Economic boundary conditions for FC/H2 technology

Economic system evaluation in the aircraft industry does consider lots of variables. For a rough analysis the following should be considered:

- Block fuel savings
- DMC “Direct Maintenance Cost”
- DOC “Direct Operating Cost”
- RC “Recurring Cost”
- Weight

To identify the effects, a cost estimation requires a reference Aircraft and an Aircraft with Fuel Cell System installed. For both, the following need to be defined:

- The size of the aircraft
    - E.g. Single Aisle Aircraft

- The operating conditions
  - E.g. Mission of 500 nm (910km)
- The integration level of the fuel cell system
  - E.g. 100 kW continuous power
  - E.g. Fresh water generation
- The properties of the fuel cell system and the fuel system itself
  - E.g. Operating temperature. 90 °C
  - E.g. Liquid hydrogen tank with 25 kg of H_2.

A typical economical analysis starts with a weight comparison of the reference and the fuel cell system aircraft. The weight analysis provides the comparison of the removed and replaced components, called out, and the new integrated fuel cell system and additional components, called in.
Consequently, the DMC's [$/per flight hour] can be calculated by the new system layout. Since experiences with maintenance costs for fuel cell systems have not been made so far, assumptions have to be given.
A benefit for fuel cell systems as an APU replacement for aircrafts is expected to be in the block fuel savings [%]. The APU is replaced and leads to a decrease in kerosene burn. The same can be expected with a decrease of generator size by the decrease of the mechanical power extraction at the engines. Contrary to the reduction of kerosene is the consumption of hydrogen for the fuel cell system.

E.g. with an LH_2 price of 2,6 $/kg the corresponding kerosene price is 0.8 $/gallon ($H_2$ price = Kerosene price * 3.25 related to the heating value).

It has to be considered, that fuel cell systems have a higher efficiency in the generation of electricity compared to engine generators.

23.6 CO2 reduction potential Source-to-User

An APU replacement by a fuel cell system is a great opportunity in terms of emission reduction. The fuel cell system has no climatic critical emissions and is nearly completely silent. Beside the direct effect of an APU replacement the fuel cell system can offer more opportunities such as the generation of water, which results in a weight reduction and therefore in a further reduction of kerosene, hence emissions. For ground operations of the aircraft, the fuel cell system also reduces emissions and noise. Also APU replacement improves the working conditions for the ground staff.

For in cruise operations, a blockfuel saving of 1kg, results in a reduction of ~3kg of CO_2 emissions.

In 2006 for instance, European skies welcomed almost 10 million flights and up to 33,000 flights on busiest days. With a saving of only 1kg of blockfuel per flight, up to 100t of CO_2 emissions can be reduced in Europe per day or 30 kton/yr.

23.7 Conclusions

The following general conclusions can be taken:

- A fuel cell system on board an aircraft has great opportunity with the integration of all products: Electrical Power, Thermal Power, Water and Inert Gas.

- An economic estimation cannot be assessed just by the replacement of the APU. A complete new aircraft system lay out needs evaluated.
- CO_2 and emission reduction offers great potential for the APU replacement on ground.

23.8 References

1. Cryoplane Final Report (http://www.aero-net.org/pdf-docs/20040202-final-technical-report-4-pv.pdf)
2. Airbus internal studies
3. Airbus Global Market forecast

24. Case study Back-up power for telecom

24.1 Description of application

Proton exchange membrane (PEM) fuel cell (FC) system can be used as a standby or emergency power source ensuring uninterrupted service in power critical applications. Backup power systems cover utility grid outages and are also used for improving utility power quality. Both the reliability and availability of the system are more critical than efficiency. The users of uninterruptible power sources (UPS) are willing to pay more for power supply for their critical applications. Nevertheless the sum of investment, maintenance and operation costs is a very important decision driver.

The application and power range of backup power sources is so large, that description of all applications would be out of scope of this study. This report will therefore focus on one currently mainly used technology, which is:

- a 48V DC (direct current) battery backup power system for base transmitter station (BTS) for mobile telecommunications

One of the most promising applications of fuel cells is a replacement of power backup batteries in base stations for mobile communication network as shown in Figure 124. This is a large market comprising both the civilian mobile phone networks and the special TETRA-nets that are currently being established worldwide[3].

Figure 124: Mobile base transceiver stations and antenna system

24.2 Description of reference technology

Generally backup power systems for uninterrupted service consist of two main components, UPS (uninterruptible power supply) and electric generator.
Most of UPS nowadays use lead acid batteries for accumulating electric energy. A single conversion battery UPS system is used (see Figure 125) for DC critical loads.

[3] (TETRA – Terrestrial Trunked RAdio) is a closed mobile radio network, designed for use by government agencies, emergency services, police forces, fire departments, ambulance, transport services and military forces.

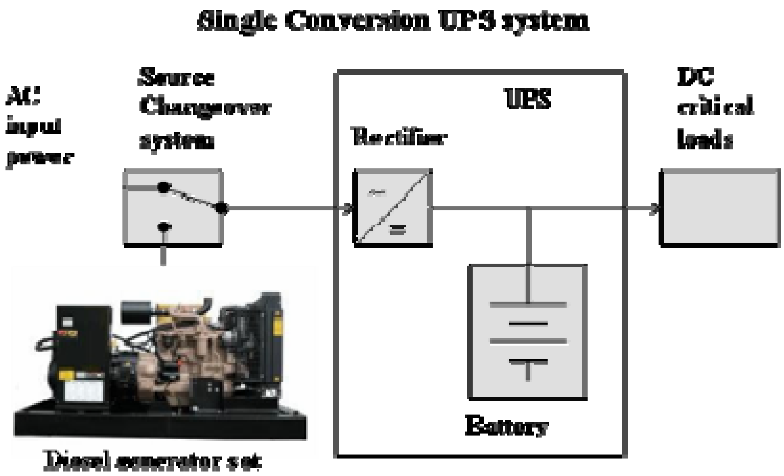


Figure 125: Schematic drawing of a single conversion UPS for DC critical load

“Standby state” efficiency of small DC systems varies between 80 to 90% depending on the load. For continuous 24 hours and 7 days a week operation the efficiency becomes very important figure in economy.

Backup time depends on in battery accumulated electric charge. Most of the UPS installations use only batteries for power supply of several minutes (usually up to several tens of minutes). For longer backup time the UPS must be coupled with a generator using diesel or gas fuelled internal combustion engine or microturbine as a prime mover. Typical diesel generators need several (around fifteen) seconds to start and take over the load. Therefore the UPS is used to bridge the power from net and generator and provide time to start the generator in case of power net outage.

Although energy can be accumulated in various forms:

- electrochemical in batteries
- kinetic energy in flywheel
- electric charge in capacitors/ultracapacitors
- superconducting magnetic energy storage
- pressurised air
- hydro power

The only first two means are mostly used nowadays in UPS systems. These systems cover power grid outages or faults from several seconds (flywheel systems) to several tens of minutes (battery pack systems). Ultracapacitors become the most promising system for replacement of batteries.
At least, UPS provides time needed to start diesel generator to take over the load. The diesel generator then supplies the whole critical load system and recharges the UPS for period of power outage. Maximum operating time of engine driven generator set is limited only by the amount of fuel in its fuel tank.

Network equipment
The most important parts of wireless networks for mobile phone services are following:

- Base Transceiver Stations (BTS) - many these stations are needed for direct connection to the users with handsets (mobile phones). Each BTS covers geographical area called cell and connects all users who are located in the cell to the wireless network. Many small cells are in urban areas. On the other hand far less cells cover large areas outside the urban zones.
- Base Station Controller (BSC) - are needed to control several Base Stations.

- Mobile Service Switching Centre (MSC) - connects users between wireless and wired network.

All mentioned components must be protected against grid outages.

48 V DC backup system for mobile telecommunications

NetSure 501 power supply from Emerson, of 48V DC with 4.9 kW coupled with 100Ah Valve Regulated Lead Acid (VRLA) battery pack (Table 113) has been chosen as a reference technology competing with FC/H_2 system. Two rectifiers with 1700W each have been considered for higher redundancy and availability. System cost includes one set of spare batteries, which need to be replaced during 10 years of system lifetime.

Table 113: The characteristics of 48V DC battery UPS

Application	Unit	NetSure 501 Emerson
Power level	kW_e	*4.9* *100A -48V DC*
Efficiency; energy use	MJ/kWh	*3.96 ie.* η*=90%*
Typical cost complete system	€	*9000*
Specific cost energy system	€/kW	*1837*
Lifetime	year	*10*
Type of “fuel”	-	*Electricity*
Type of “fuel” supply	-	*Elect. grid 230V/50 Hz*
Type of “fuel” storage	-	*VRLA battery pack 100Ah*
Typical storage capacity	MJ	*17*
Operation/fuel charge	hr	*1.5*
Availability	%/yr	*~ 99.98%*
Maintenance	*hr/ year*	2

24.3 Description of the market

Mobile Telecommunication Market

The number of mobile telecommunication network base stations worldwide was 2.7 million in 2006 and 3.1 million in 2007. More than 4.7 million cellular base stations will be in operation by 2011 1.

Estimations of mobile network equipment numbers in Europe in 2005 are presented in Table 114, according to 2. Also average power consumptions of each network component according to 3 are presented as well.

Table 114: Numbers of Network equipment in Western Europe in 2005

Component	BTS	BSC	MSC
Number of Units [-]	417000	5210	2605
Lifetime [yr]	7	8	10
Average consumption [W]	1100	475	4000

Price of lead

One of the drivers of H_2 FC deployment in backup power market could be a price of a base material for lead acid batteries. A trend of lead price from 04/1998 to 04/2008 and industrial consumption distribution taken from 4 are displayed in Figure 126. Current price of lead (04/2008) in US$ per ton is six times higher than that in 04/1998.

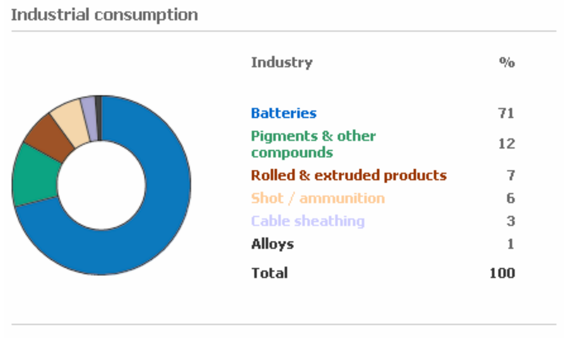


Figure 126: Price of lead in US$/ton graph from 04/1998 to 04/2008 (left) and lead industrial consumption (right)

24.4 Description of FC/H2 technology for the application

Due to large numbers and distribution of base transceiver stations (BTS) and no simple access to them especially in non-urban areas, the attendance free operation is a very important factor. Large costs of periodic checks and exercises for diesel and gasoline fuelled generators and other factors like high start-ability, low maintenance and remote control call for preferable use of fuel cells in wireless telecommunications.

Following companies already offer fuel cell backup power sources for base stations in mobile telecommunication networks:

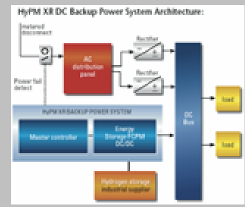
- P-21 GMBH (Germany) with Premion T 3000 PEM FC backup system coupled with integrated ultra-capacitors for immediate start at the power of 3 kW at -48 VDC 5
- Dantherm Power A/S (Denmark) offers IPSM-A1600 1600 W (-40 to -57V) power module which can be coupled with ultracapacitors 6
- PLUG POWER INC (USA) offers 5kW -48 to -55.5 V GenCore 5T48 FC system alternatively coupled with batteries or ultracapacitors to ambient temperature 7
- Hydrogenics (Canada) offers HyPM XTR Fuel Cell Power Module to OEMs and system integrators 8.
- IDaTech developed ElectraGen™ family PEM FC system as a replacement for VRLA battery backup system with more than ten years higher system reliability claimed 9.
- Axane (Fr) offers its CommPac™ in power range up to 5 kW optionally in AC 110/60Hz or 230/50Hz or 48V DC configuration 10.

Technical data for several of these systems are displayed in Table 115.

The advantages of using fuel cell solutions for emergency power supplies according to their manufacturers are:

- Reliability
- Long service life
- Outdoor operation capability
- Compact design
- Minimum maintenance
- Reduced environmental impact compared to current technologies
- Backup time of FC systems depends only on a number of hydrogen cylinders installed. Some manufacturers offer so called hot swapping ability that allows replacement of empty cylinders when FC is in operation.

Table 115: The characteristics H_2 PEM FC solutions for backup for mobile telecom networks

Application	Unit	IPSM-A1600	Premion T3000	ElectraGen™5	GenCore® 5T4 8	HyPM XR12	Comm Pac™ Backup/UPS
							
Manufacturer		Dantherm Power	P21 GmbH	IdaTech LCC	PLUG POWER INC.	Hydrogenics	Axane
Power level	kW	1.7	3	5	5	12.5	5
Nominal voltage	V	56	48	48	48	48	48
Efficiency; energy use	MJ / kWh	9.18 at 1.7 kW	*8.16 at 3 kW* *8.29 at 2 kW* *9.35 at 1 kW*	*9.07 at 5 kW*	*9.07 at 5 kW* *8.06 at 3 kW*	*7.5 at 12.5 kW* *6.5 at 5 kW*	*6.85 at 5kW* *6.85 at 2.5kW* *7.14 at 1kW*
Fuel consumption		*0.85 Nm^3/kWh at 100% output*		*75slpm at 100% output*	*40 slm at 3000W* *75 slm / 5000W*		
Start time	s	>1	*0 with ultra-cap.*	*0 with ultra-cap.*	*0 with ultra-cap.*	*0 with ultra-cap.*	-
Instalation		*indoor/outdoor*	*indoor/outdoor*	*indoor/outdoor*	*indoor/outdoor*	*indoor/outdoor*	*indoor/outdoor*
Lifetime	years	4000 op. hours	-	*10*	-	-	
Type of "fuel"	-		*Gaseous pressurized*	*Gaseous pressurized*	*Gaseous pressurized*	*Gaseous pressurized*	*Gaseous*
H_2 purity		*H_2 99.9%*	*H_2 99.9%*	*H2 99.9%*	*dry H_2 99.95%*	*H_2 99.95%*	-
Availability	%/yr	-	-	-	-	-	-
Dimensions		*420 x 420 x 600 (HxWxD)*	*800 x 483 x 470 mm (HxWxD)*	*648 x 997 x 1345 mm (WxDxH)*	*(117cm H x 91cm W x 81cm D)*	*37.8 x 19.7 x 12.6 (LxWxH)*	*115 x 170 x 210 cm (LxWxH)*
Weight w/o fuel	kg	45	*93*	*226*	*276*	*90*	*600*
Maintenance	-	-	-	-	-	-	*every 2000 hr*

24.5 Economic boundary conditions for FC/H2 technology

As a reference technology, 4.9 kW 48V DC battery UPS for telecommunication base station have been chosen for economic evaluation. The average European energy prices for small companies in 2007 are used for the evaluation. All prices in this study include taxes. Average power demand of base station 1.1 kW from the Table 114 has been considered. In this case the batteries allow 4 hours of continuous run for this load. The calculations have been carried out for yearly backup time 16, 56 and 106 hours.

In Figure 127, which is based on the input in Table 116, the allowable cost of H_2 as a function of the assumed FC system cost is shown at the same cost per kW as the UPS battery system. The H_2 FC system is economically attractive if the combination of cost of hydrogen and cost of fuel cell system are below the line for the reference technology.

High specific electricity cost (related to overall backup power) for battery UPS is a result of continuous power consumption of 250 W that is required to keep the batteries in good operating condition regarding temperature and charge.
The FC system consumes in standby operation only 20 W for and 100 W for heating when low ambient temperature (according to Dantherm Power). Only 20 W of average continuous standby consumption was assumed for the FC solution. Preheating of the FC system was neglected because the system can be installed in the same cabinet as a transmitter electronics sharing the same air conditioning and ventilation system. Also the energy for ultracapacitor needed for uninterrupted power supply at the short time when grid failure occurs and before FC system starts has been neglected.

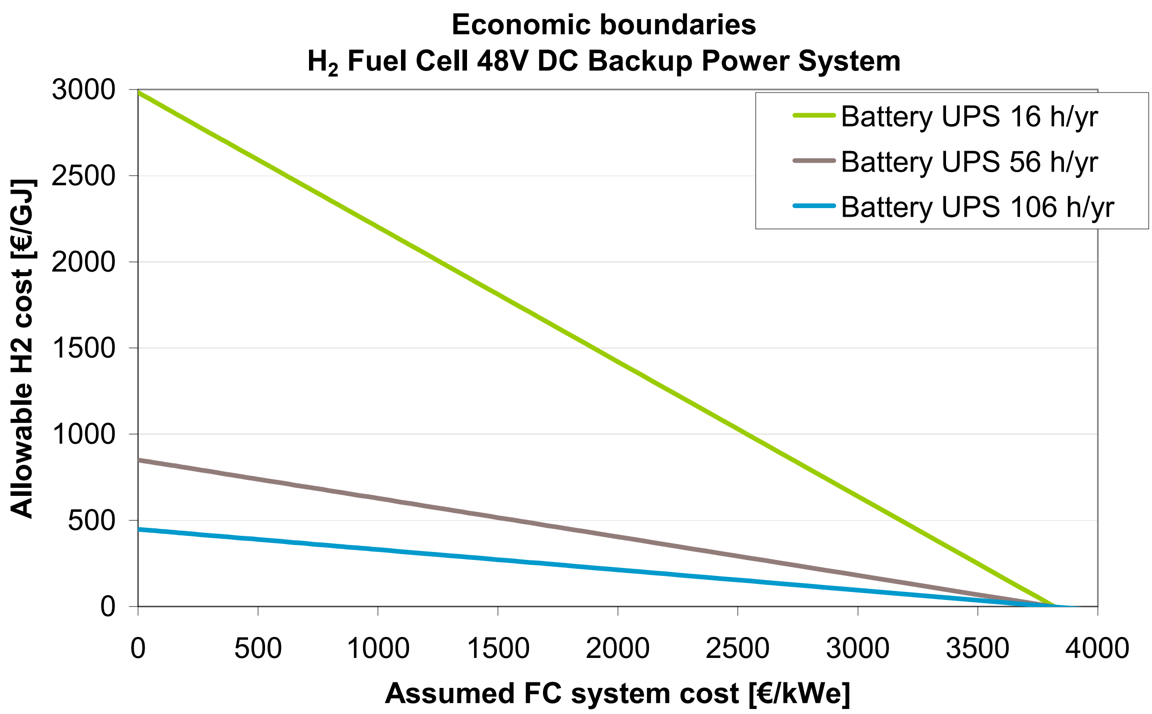


Figure 127: Allowable cost of H_2 as a function of the assumed two FC systems cost at the same cost per kW as for 48 V DC battery UPS for yearly run times of 16, 56 and 106 hours

An efficiency of 45% has been estimated for the FC system. Several other assumptions have been made for FC systems. Maintenance was expected to be equal to cost of

battery UPS annual preventive check. In case of a small FC system electricity cost of heating was neglected due to that this system can be installed in the same cabinet as a transmitter electronics sharing the same air conditioning and ventilation system.
The same 90% efficiency of rectifiers and filters needed to AC power conversion from the grid to DC current for both the fuel cell system and battery UPS was included in the calculations.
The need for replacement of batteries in UPS during its lifetime significantly increases the specific investment cost of battery UPS system. For this study only one battery replacement is expected for system lifetime 10 years, because a lifetime of 12V valve regulated lead acid batteries (VRLA) can be expected somewhere between 5 to 10 years according to their manufacturers[4].

Results of calculations are displayed in Figure 127. This figure is based on the input in Table 116. The cost of hydrogen does play a little role as an economic driver when compared to battery UPS for short backup runs. For longer backup times the importance of H_2 cost increases.

Table 116: Background table for the same cost in €/kWh for a DC battery UPS compared to fuel cell system

Reference system		**Battery UPS**		
Backup time		16 h/yr	56 h/yr	106 h/yr
System cost	€/kW	1837	1837	1837
Power	kW	1.1	1.1	1.1
Lifetime	yr	10	10	10
Operation	hr/yr	16	56	106
Operation	kWh/yr	17.6	61.6	116.6
Specific investment cost	€/kWh	11.48	3.28	1.73
Fuel cost	€/GJ			
Electricity cost	€/GJ	30.1	30.1	30.1
Fuel use	MJ/kWh			
Specific fuel cost	€/kWh			
Specific electricity cost	€/kWh	13.46	3.83	2.01
Spec. maintenance cost	€/kWh	27.05	7.73	4.08
Total cost	€/kWh	51.98	14.83	7.83
FC system				
Power	kW	1.1	1.1	1.1
Lifetime	yr	10	10	10
Operation	kWh/yr	17.6	61.6	116.6
Fuel use	MJ/kWh	8.00	8.00	8.00
FC specific electricity cost	€/kWh	1.08	0.31	0.16
FC specific maintenance cost	€/kWh	27.05	7.73	4.08
Assumed FC system cost €/kWe		Allowable H2 cost €/GJ	Allowable H2 cost €/GJ	Allowable H2 cost €/GJ
0		2983	850	448
200		2826	806	424
500		2592	739	389

[4] Batteries must be operated within limited temperature range. Operation beyond these limits both ways significantly reduces lifetime of batteries. Temperature conditioned cabinet is necessary for outdoor installation.

1000	2201	627	330
2000	1420	404	212
4000	-142	-43	-24

Fuel cost scenario

The effect of different fuel cost on the assumed fuel cell system cost and the allowed hydrogen costs is provided in Figure 128 for battery UPS.

For reference, the following average European electricity prices in €$_{2000}$ for small industries are considered:

- The low 2007 value with all taxes (14.2 €/GJ)
- The mean 2007 value with all taxes (30.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (52.7 €/GJ)

Figure shows that the effect of increasing electricity price on the economy of battery UPS system is significantly favourable to FC solution.

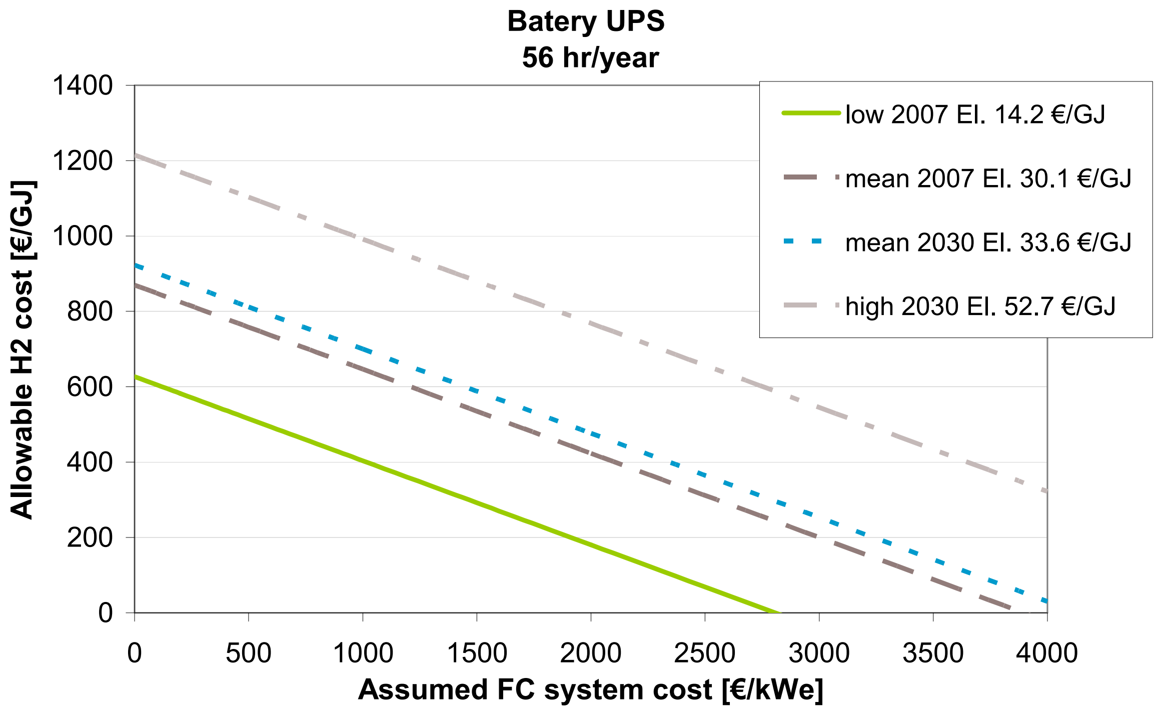


Figure 128: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of electricity with all taxes included

24.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

Effect of replacing battery UPS by fuel cell system on total production of CO_2 emissions has investigated for assumption of 56 hours a year backup operation and exercises for the both compared systems.

Potential of CO_2 reduction for fuel cell replacement of battery system is displayed in Figure 129. Hydrogen production by electrolysis is accounted and effect of various means of electricity production across Europe can be seen in the figure. Data was taken from 11. For battery UPS 70% efficiency of recharging has been accounted. The overall effect differs with a mean of electricity production in each country. For European Union (EU25) average for one replacement of battery system by fuel cell the reduction in CO_2 production is about 0.789 ton a year per one installation. Multiplying this figure by the number of base stations in Europe, the total reduction in CO_2 emissions would be 329 thousand tons CO_2 yearly.

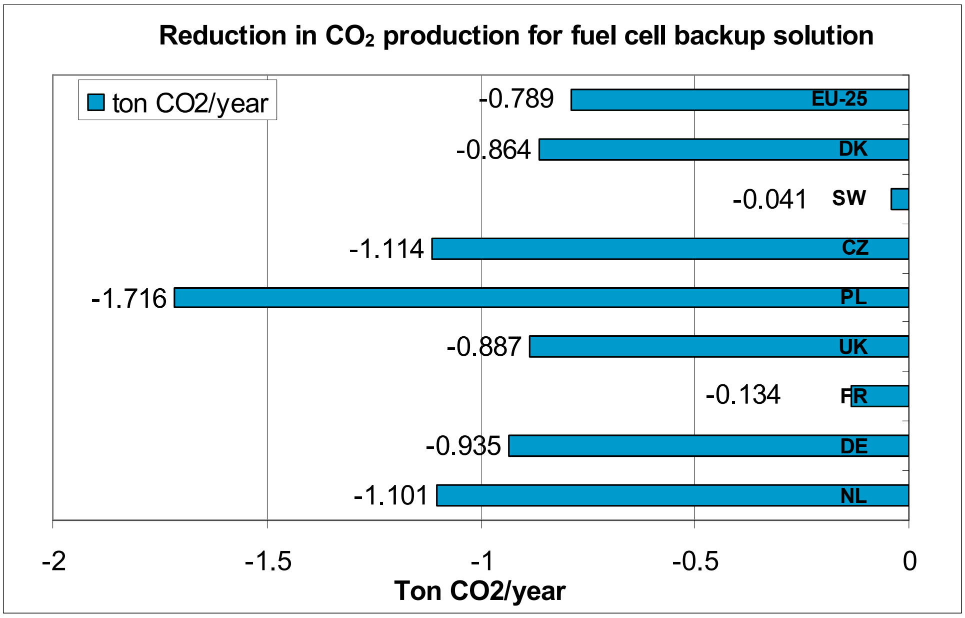


Figure 129: Yearly increase in CO_2 production by replacement battery UPS with fuel cell

24.7 Conclusions and recommendations

A replacement of power backup batteries in base stations for mobile communication network is one of the most promising applications for fuel cells. This is a large market comprising civilian and emergency services, government and military telecommunication networks.

The following general conclusions can be taken:

- The cost of hydrogen does play a little role as an economic driver when compared to battery UPS for short backup runs. For longer backup times the importance of H_2 cost increases. The most promising factor for economy of FC backup system is its standby state consumption that is roughly only one tenth of the battery UPS consumption.
- Large costs of periodic checks and exercises for diesel or gasoline fuelled generators and other factors like demanded high start-ability, low maintenance and remote control, call for preferable use of fuel cells in wireless telecommunications.
- Economic potential for fuel cells as a replacement of battery UPS is much higher than for diesel generator.
- Battery lifetime is significantly reduced if operated outside the strictly limited temperature range, which call for high energy-consuming conditioned cabinet.
- Manufacturers of fuel cell systems offer longer service life compared to lead-acid battery.
- Backup time of both the Diesel generator and fuel cell system depends on a quantity of fuel in its tanks and can be prolonged by supplying additional fuel, which is not possible for battery system.
- The effect of replacing battery UPS by fuel cell on CO_2 reduction is significant, caused by the higher standby state electric consumption.

- Diesel generator set features significant fixed cost to machinery room equipment and comparatively low cost proportional to engine power. Unlike it fuel cell features very high cost proportional to the power depending on the prices of Pt and hi-tech membranes. That is why powers higher less than 10 kW are not economical if covered by FC system.

The main advantages of FC systems according their manufacturers are:
- Reliability
- Long service life due to low operating times
- Outdoor operation capability
- Minimum maintenance
- Reduced environmental impact compared to current technologies

24.8 References

1. http://www.3g.co.uk
2. Scharnhorst W., Lorenz Hilty L. M., Jolliet O., Life cycle assessment of second generation (2G) and third generation (3G) mobile phone networks, Elsevier 2006
3. Schaefer C., Weber C., Voss A., Energy Usage of mobile services in Germany, Elsevier 2003
4. London metal exchange http://www.lme.com
5. http://www.p-21.de
6. http://www.dantherm.com/
7. http://www.plugpower.com
8. http://hydrogenics.com
9. http://www.idatech.com
10. http://axane.com/
11. http://www.concawe.be

25. Case study Back-up power for hospitals

25.1 Description of application

Proton exchange membrane (PEM) fuel cell (FC) system can be used as a standby or emergency power source ensuring uninterrupted service in power critical applications. Backup power systems cover utility grid outages and are also used for improving utility power quality. Both the reliability and availability of the system are more critical than efficiency. The users of uninterruptible power sources (UPS) are willing to pay more for power supply for their critical applications. Nevertheless the sum of investment, maintenance and operation costs is a very important decision driver.

Range of applications of backup power is very large. Following areas need to be protected against power grid outages.

- Health care - hospitals
- Emergency services - ambulance, police, fire protection
- Financial sector – banks, stock exchange
- Power industry – nuclear power stations
- Industrial plants
- Petroleum refineries
- Chemical plants
- Mines
- Pharmaceutical industry
- Food manufacturing and storage
- Transport – airports
- State agencies
- Military services
- Market malls
- IT sector - datacenters
- Water treatment
- Telecommunications
- Amusement and sport centers
- Hotels
- Office buildings
- Universities & research facilities

Description of all applications would be out of scope of this study. This report will focus on one mainly used technology which is a stand-by diesel generator usable as backup power source for datacenters or hospitals.

25.2 Description of reference technology

Generally backup power system for uninterrupted service consists of two main components, UPS (uninterruptible power supply) and electric generator.
Most of UPS nowadays use lead acid batteries for accumulating electric energy. The most common system for AC power backup uses dual conversion system (with one AC/DC conversion and one DC/AC conversion) in Figure 130.

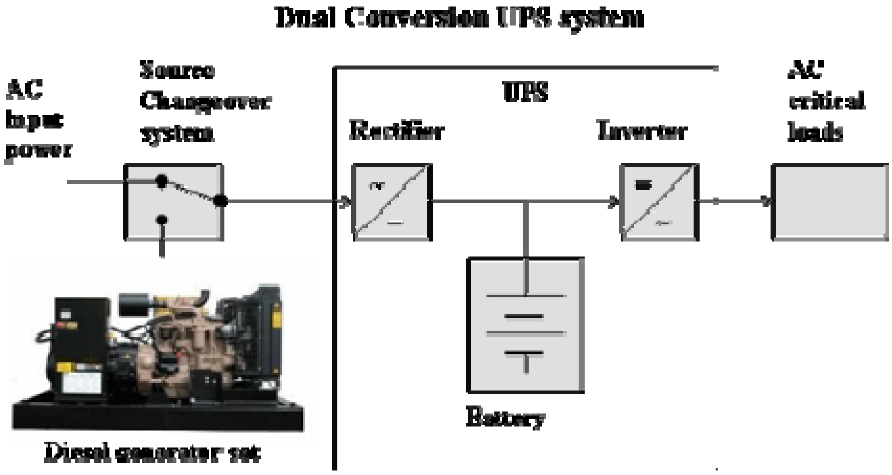


Figure 130: Schematic drawing of dual conversion UPS system for AC critical load coupled with diesel generator

“Standby state” efficiency of dual conversion UPS usually reaches 93 percent at maximum load, with lower load the efficiency decreases.
Most of the UPS installations use only batteries for power supply of several minutes (usually up to several tens of minutes). For longer backup time the UPS must be coupled with a generator using diesel or gas fuelled internal combustion engine or microturbine as a prime mover. Typical diesel generator needs several (around fifteen) seconds to start and take over the load. Therefore the UPS is used to bridge the time between the power from the grid and the generator and thus provide time to start the generator in case of power net outage.

Although energy can be accumulated in various forms:

- electrochemical in batteries
- kinetic energy in flywheel
- electric charge in capacitors/ultracapacitors
- superconducting magnetic energy storage
- pressurised air
- hydro power

only the first two means are mostly used nowadays in UPS systems. These systems cover power grid outages or faults from several seconds (non-break generator sets with flywheel) to several tens of minutes (battery pack systems). Ultracapacitors become the most promising system for replacement of batteries.
At least, UPS provides time needed to start diesel generator to take over the load. The diesel generator then supplies the whole critical load system and recharges the UPS for period of power outage. Maximum operating time of engine driven generator is limited only by the amount of fuel in its fuel tank.

The only competitive current technologies in backup systems within the power range of several kW to several hundreds kW for H_2 fuel cells are diesel or gas fuelled generator sets based on reciprocating internal combustion engines. For higher power output the diesel or gas fuelled turbines could be also considered.

There are many manufacturers worldwide producing diesel Generators. The top manufacturers are:

- Caterpillar
- Cummins
- Detroit Diesel

- Kohler
- Generac
- Mitsubishi

Three phase 400 V AC diesel generator
For the purpose of this study a three phase 400V Caterpillar Olympian GEH-250 diesel generator set has been chosen as a reference technology Figure 131 [2].

Figure 131: Reference technology - Caterpillar Olympian GEH250 200 kW, 3-phase AC 400 V diesel generator

Table 113 displays basic technical and typical economic data of the reference system.

Table 117: The characteristics of three phase 400V AC diesel generator set and 48V DC battery UPS

Application	Unit	Caterpillar GEH-250
Power level	kW_e	*250kVA, 200kW 3x400VAC, 50Hz diesel generator*
Efficiency; energy use	MJ/kWh	*9.5(100%), 10.5(75%)*
Typical cost complete system	€	*56000*
Specific cost energy system	€/kW	*278*
Lifetime	year	*15*
Type of “fuel”	-	*diesel*
Type of “fuel” supply	-	*Trucked diesel*
Type of “fuel” storage	-	*350 l fuel tank*
Typical storage capacity	MJ	*12460*
Operation time/fuel charge	hr	*7(100%), 8(75%)*
Availability	%/yr	*> 99.1%*
Maintenance	*hr/ year*	*80*

25.3 Description of the market

Hospitals
Operation rooms, intensive care units, emergency care, facilities with diagnostic equipment, laboratories, elevators and lighting need to be supplied by uninterruptible power in hospitals. In 2006 there were 14.9 thousand of hospitals in the countries of EU27 [1]. All hospitals must be equipped by backup power system. Power range of diesel generators used in hospitals varies from tens of kW up to several MW for large

hospitals. According to backup power systems suppliers a typical system for hospital is about 200 kW of electric power output.

25.4 Description of FC/H2 technology for the application

Although PEM fuel cells of power output around 200 kW are nowadays being tested in city buses (EU project HyFleet:CUTE), there are also several standby stationary commercial application for PEM fuel cell for lower power range.

APC offers InfraStruXure 30 kW DC 200V FC standby power system using gaseous pressurized hydrogen [4], which uses HyPM XR PEM FCs from Hydrogenics Corp.

Nuvera's 125kW Forza™ PEM Fuel Cell power system has been installed at Sacre-Devey Innovations in North Vancouver within the framework of the Integrated Waste Hydrogen Utilization Project (IWHUP). The fuel cell uses waste hydrogen, which is produced by local electro-chemical plant.

Medium and High temperature fuel cells like the Solid oxides fuel cell (SOFC), phosporic acid fuel cells (PAFC) or molten carbonate fuel cells (MCFC) are used for stationary applications for the power range from several hundred kW up to several MW. Due to the high temperature of exhaust gases there is heat available, which enables combining these FC with reformers for more readily available fuels as natural gas. The high temperature nature eliminates these fuel cells from standby operation, these fuel cell systems are used in CHP (combined heat and power) applications parallel to the electric grid.
One example of such system is a HotModule MCFC based system from MTU CFC Solutions producing 250 kW electric and 180 kW of heat and has been installed in several locations in Germany [5].

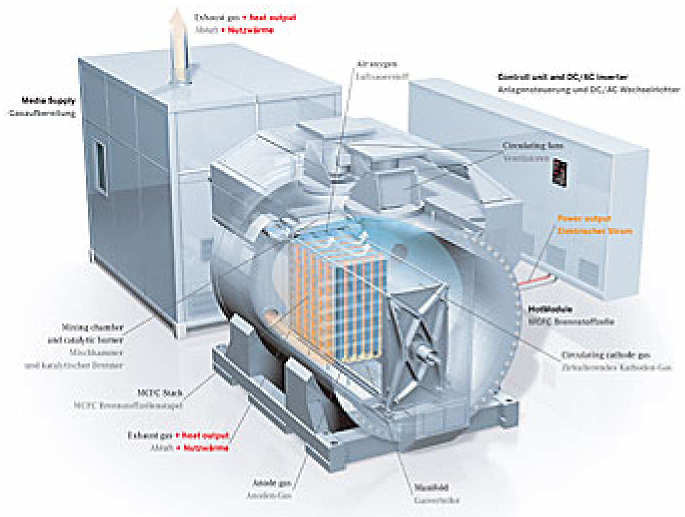


Figure 132: HotModule from MTU CFC Solutions offers 250 kW electric and 180 kW heat power from natural gas

Another example of high temperature system is a PureCell™ 200 Power System from UTC (A United Technologies Company) [6]. The system uses natural gas as a fuel for producing 200 kW of AC electric power, backup power and exhaust heat for cooling and heating.

A DFC300™ power plant from FuelCell Energy [7], Inc delivers 300 kW 333 kVA, 50 or 60 Hz and 237 kW of heat power from natural gas. This system offers 47% efficiency in continuous operation and 444 g/kWh or 236 to 308 g/kWh of CO_2 emissions.

Complete list of all applications worldwide can be found at [8].

25.5 Economic boundary conditions for FC/H2 technology

A three phase 400V standby diesel generator of nominal power output 200 kW for hospital has been considered as a reference technology for economic evaluation. The average European energy prices for small companies in 2007 are used for evaluation. All prices in this study include taxes.
In Figure 133, which is based on the input in Table 116, the allowable cost of H_2 as a function of the assumed FC system cost is shown at the same cost per kW as the diesel generator. The H_2 FC system is economically attractive if the combination of cost of hydrogen and cost of fuel cell system are below the line for the reference technology.

Investment cost, cost of fuel for operation and cost of monthly preventive exercise have been accounted for. Both the material and labour cost of (daily/weekly/monthly/yearly) preventive checks and maintenance procedures (needed to achieve high system reliability) according to generator set manufacturer recommendations have been estimated. Yearly operation at 16, 56 and 106 hours (from that 6 hours fall to monthly 30 minutes preventive exercise run) at 75% load have been considered for diesel generator and corresponding H_2 FC system in this study. Electricity cost of diesel generator has been enforced by a need of continuous engine lubricating oil and coolant preheating that is needed for instant load take over. Electricity needed for charging a start-battery has been neglected.

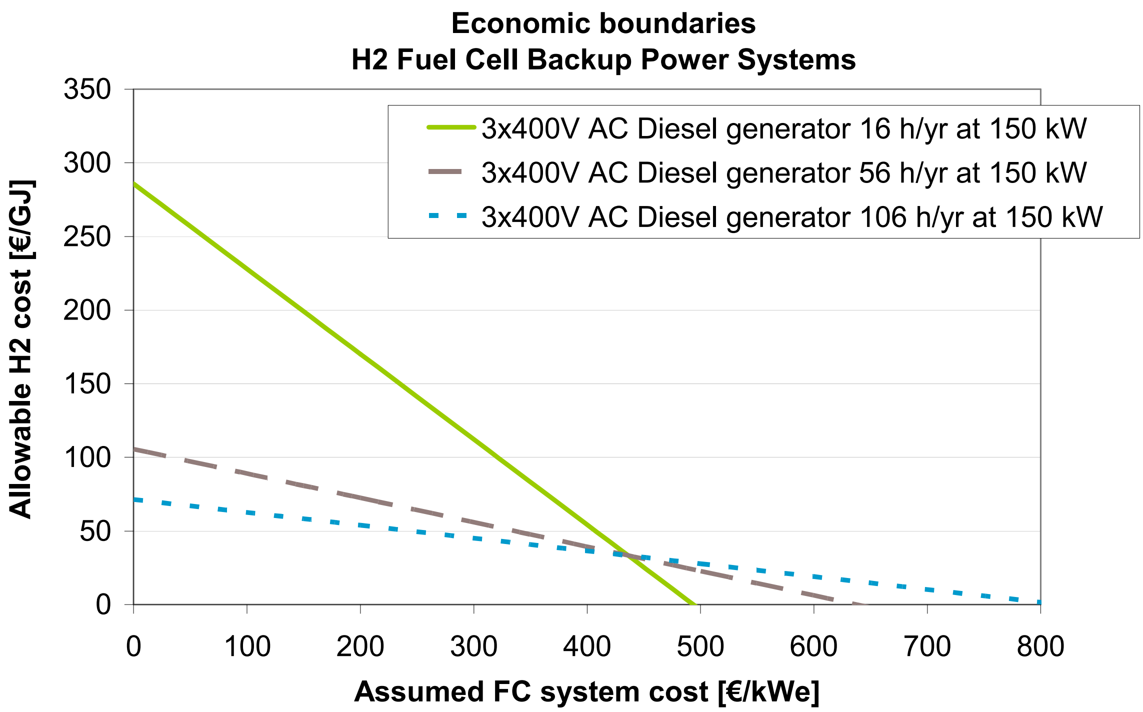


Figure 133: Allowable cost of H_2 as a function of the assumed FC system cost at the same cost per kW as for standby diesel generator for yearly run times 16, 56 and 106 hours

Total efficiency of 50% has been estimated for the FC system. Several other assumptions have been made for FC systems. Maintenance was expected to be half the yearly preventive check of a diesel system. Electricity for continuous preheating the coolant system for the FC system was omitted.

FC system competitiveness to diesel generator significantly increases with short yearly run hours when fuel cost does not pay any role.

Table 118: Background table for the same cost in €/kWh for a three phase AC diesel generator and DC battery UPS compared to alternative fuel cell systems

Reference system		**3x400V AC Diesel generator**		
Run time and load		16 h/yr at 150 kW	56 h/yr at 150 kW	106 h/yr at 150 kW
Gen set cost	€/kW	278	278	278
Power	kW	150	150	150
Lifetime	yr	15	15	15
Operation	hr/yr	16	56	106
Operation	kWh/yr	2400	8400	15900
Specific investment cost	€/kWh	1.158	0.331	0.175
Fuel cost	€/GJ	23.5	23.5	23.5
Electricity cost	€/GJ	30.1	30.1	30.1
Fuel use	MJ/kWh	10.22	10.22	10.22
Specific fuel cost	€/kWh	0.240	0.240	0.240
Specific electricity cost	€/kWh	0.237	0.067	0.035
Spec. maintenance cost	€/kWh	0.739	0.211	0.112
Total cost	€/kWh	2.374	0.850	0.562
FC system				
Power	kW	150	150	150
Lifetime	yr	15	15	15
Operation	kWh/yr	2400	8400	15900
Fuel use	MJ/kWh	7.20	7.20	7.20
FC electricity cost	€/kWh	0.118	0.034	0.018
FC maintenance cost	€/kWh	0.198	0.057	0.030
Assumed FC system cost €/kWe		Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ	Allowable H_2 cost €/GJ
0		286	105	71
200		170	72	54
500		-4	23	28
1000		-293	-60	-16
2000		-872	-225	-103
4000		-2029	-556	-278

Fuel cost scenario

The effect of different fuel cost on the assumed fuel cell system cost and the allowed hydrogen costs is provided in Figure 128 for diesel Generator.

For reference, the following average European electricity prices in $€_{2000}$ for small industries are considered:

- The low 2007 value with all taxes (14.2 €/GJ)
- The mean 2007 value with all taxes (30.1 €/GJ)
- The mean 2030 value with all taxes (33.6 €/GJ)
- The high 2030 value with all taxes (52.7 €/GJ)

Calculations for the diesel generator are presented in Figure 128 show a large spread due to the lower dependency of diesel on both the electricity and fuel price.

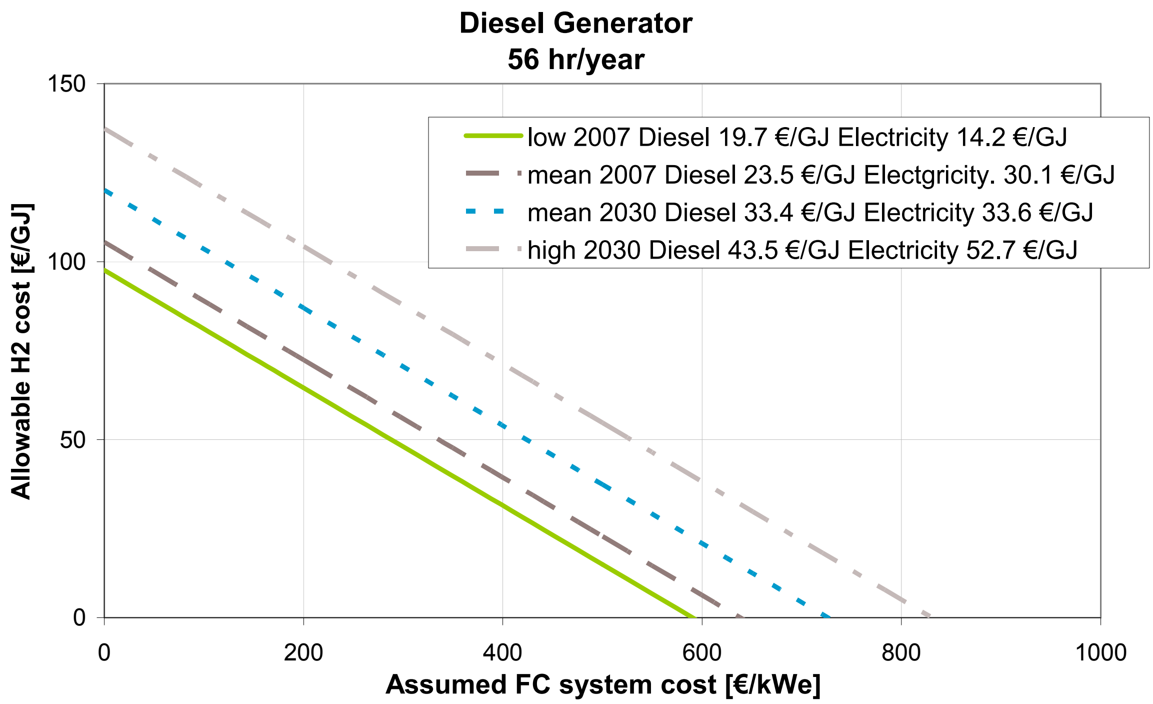


Figure 134: Allowable hydrogen costs vs. assumed FC system cost of 4 different energy prices of diesel fuel and electricity with all taxes included

25.6 CO2 reduction potential Source-to-User

CO_2 emission of reference and fuel cell technology

For a consumption of 44l/h and electric power output of 150 kW and for assumption of ideal combustion the diesel generator produces 115.6 kg CO_2 per hour. That corresponds to 934 gCO_2/kWh or 259 gCO_2/MJ.

Effect of replacing diesel generators by fuel cell system on total production of CO_2 emissions has been carried out for assumption of 56 hours a year backup operation and exercises for the both compared systems. Potential of CO_2 reduction for fuel cell replacement of diesel generator is displayed in Figure 135. Hydrogen production by electrolysis is accounted and effect of various means of electricity production across

Europe can be seen in the figure. Data has been taken from [9]. The overall effect depends on the mean of electricity production in each country, can be either positive or negative. For European Union EU25 average is positive but very low. For one installation it is about 520 kg of CO_2 a year per one installation. Using wind energy and electrolysis, the reduction is approximately 6.06 ton CO_2/yr. Multiplying it by the number of European hospitals, the total reduction in CO_2 emissions would count 86 thousand ton CO_2/yr.

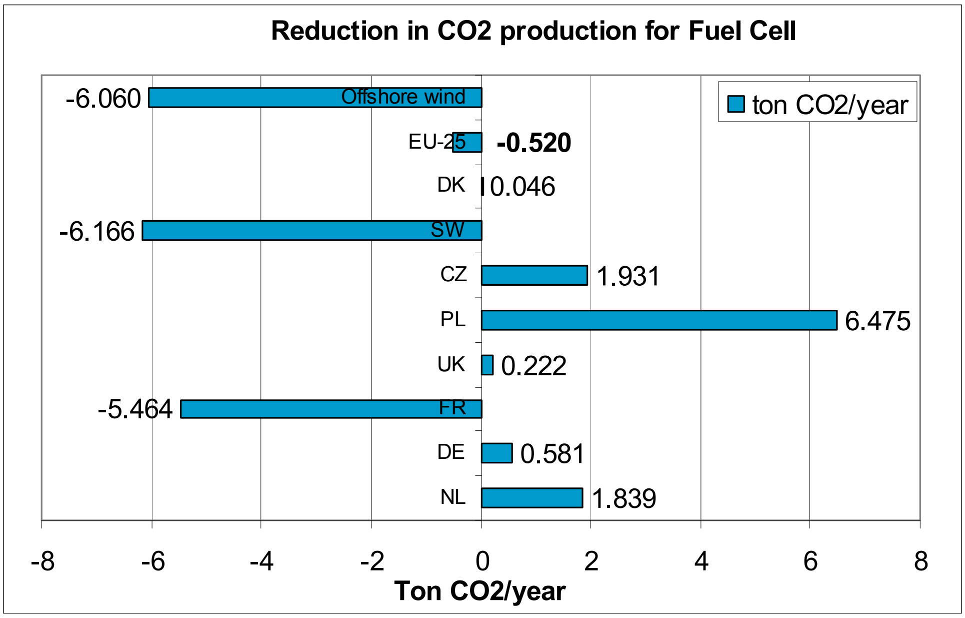


Figure 135: Potential CO_2 reduction for fuel cell replacement of diesel generator. Comparison for various means of electricity (across Europe) and consequent H_2 production by electrolysis

25.7 Conclusions and recommendations

A potential of fuel cell as a replacement of diesel generator for standby power backup system in hospitals has been evaluated in this study. This is very small part of the whole market comprising public and private sectors (see the list in chapter 25.1).
The following general conclusions can be taken:

- The cost of hydrogen does play a little role as an economic measure when compared with diesel for short backup runs. For longer backup times the importance of H_2 cost increases. The most important factor of economy of backup system together with investment cost is a maintenance cost, which can be significantly lower for FC systems than for diesel generators.
- The electricity consumed by continuous diesel engine preheating must be accounted for (especially for CO_2 emissions consideration). Continuous preheating can be omitted in case of PEM fuel cells.
- Expected availability of FC would be much better due to less maintenance than for a diesel generator.
- Backup time of both the diesel generator and fuel cell system depends on a quantity of fuel in its tanks and can be prolonged by supplying additional fuel.
- Potential of reduction of CO_2 emissions by replacing diesel generators by fuel cells for all European Union hospitals is small.
- Diesel generator set features significant fixed cost to machinery room equipment and comparatively low cost proportional to engine power. Unlike it

fuel cell features very high cost proportional to the power depending the prices of Pt and hi-tech membranes. That is why powers higher than 10 kW are not economical if covered by FC system.

- Because of short operation time, emissions and noise of standby diesel generators are not significant in comparison with other sources of pollution.

The main advantages of FC systems according their manufacturers are:

- Reliability
- Long service life
- Outdoor operation capability
- Minimum maintenance
- Reduced environmental impact compared to current technologies but not significant

25.8 References

[1] European health for all database (HFA-DB)
[2] http://www.p-z.cz
[3] Larminie J., Dicks A., Fuel Cell Systems Explained, second Edition, Wiley 2003 ISBN: 10-0-470-84857-X
[4] http://www.apc.com
[5] http://www.mtu-friedrichshafen.com/cfc
[6] http://www.utcpower.com
[7] http://www.fuelcellenergy.com
[8] http://www.fuelcells.org/db/project.php
[9] http://www.concawe.be
[10] http://www.energy.eu
[11] http://www.carma.org

26. Case study power plant/commercial CHP

26.1 Description of application

Technologies for combined heat and power (CHP) production are characterised by fast and complex development, in order to meet increasing buildings and environment demands. The ability to produce electrical power and heat in an environmentally friendly fashion assure future success on the global market. Application of fuel cell based cogeneration systems is being described in this report. Market and technology penetration was done till 2030. The system should provide electrical energy and heat 24 hours per day. Although the system operates continuous, peak and low demands are observed during each day. It depends on time, period of year, localisation and many others parameters. In case of energy consumption, weather data and building characteristics, such as a construction materials, should also be taken into consideration, in order to evaluate building hourly heating and cooling demands. It is worth to point out the most important demand is reliability. In XXI century life without stable electrical energy is simple impossible.

26.2 Description of reference technology

Presently, the majority of end users are connected to electrical grid. Current grid infrastructure in Europe results from long-year evolution both in technology and organisational areas. A characteristic solution predominating by now is generation of electric energy in large centralized sources and distributing it through the highest voltage transmission systems. End users are supplied via local high-, medium- and low-voltage distribution networks. Such model assumes a unidirectional energy flow from central sources via electric power network to customers. Liberalization of electric energy sector and its commercialisation have led to decentralization of management structures (operators of transmission and distribution networks) to implement the rules of transparency and non-discrimination under supervision of regulating body. Distributed generation will play in future key part in this new conception of the energetic sector by using a wide range of technologies and bringing small scale generating sources closer the customers. Pretty large dynamics is observed for highly effective combined heat and power sources as well as reserve and peak load systems.
Even presently, some consumers have to use own, independent source of energy. A generator set is one of the most attractive technological solutions in such situations. In this case study the overall electric efficiency for the engine is 37%. There are significant uncertainties connected with the fuel price market development. Fluctuation in the oil market influences the oil based fuel prices, and has also some influence on the LNG prices. Developers are aware of this fact. It motivates them to develop new generations of generators with better efficiencies and for different types of fuel: diesel, gasoline, gas, or biogas. Such trend is being observed in all technologies, which serve the stationary application. Reference technology: generator refers to natural gas as a source of fuel.

Table 119: Description of 250 kW Generator System natural gas fuelled

Reference System - Generator		
Power	250	kW
Lifetime or full load hours	5	yr
Maintenance	0.0055	€/kWh
	16%	
Operation cost	0.0055	€/kWh
Investment cost	0.0034	€/kWh
Specific investment cost	**0.0145**	**€/kWh**
Eflectric efficiency	40	%
Fuel net caloric value	45	MJ/kg
Fuel cost	9.6	€/GJ
Fuel use	9	MJ/kWh
Specific fuel cost	0.086	€/kWh
Specific cost	**0.101**	**€/kWh**

The reference generator has 250 kW power. The generator lifetime was assumed to be 5 years. The engines and ancillary system, except smaller parts, are not replaced. The operating time of an engine is obviously dependent on the maintenance quality and frequency. Generator fuelled by natural gas was reference technology to all CHP fuel cells systems. Two types of fuel were analyzed for the fuel cell system.

26.3 Description of market

The engine investment cost is a result of negotiations between buyer and supplier of the engines, of this reason there is, even if this is a mature technology, no identical market price available. However price difference is quite small so in this calculation generator specific investment cost is set to 0.0145 EUR/kWh.

Cogeneration (simultaneous production of electricity and heat), offers significantly higher fuel efficiency compared with conventional ways of generating electricity from fossil fuel. The expanded EU is now home to the world’s largest cogeneration industry, with ~104 GWe installed capacity. This is more than Russia and US, with ~80 GWe each. Figure 136 presents percentage of gross electricity generation within the EU-25, plus Bulgaria, Romania and Turkey. Table 120 shows total CHP electricity generation by type of CHP unit, along with the proportions generated by power stations for public supply and by autoproducers. 325.2 TWh of CHP electricity was generated within the EU-25. This corresponded to 10.2% of total gross electricity generation. In absolute terms Germany was the largest producer with 56.65 TWh followed by Denmark, Spain, France Italy, Netherland, Poland, Finland, and UK, all around 20÷30 TWh. Of more relevance is the share of CHP in total gross generation: here, Denmark stood out with a share of 50%, well ahead of Latvia (32%), Finland (34%) and Netherlands (29.5%). Whereas in Spain, Ireland, and UK, CHP electricity generation was largely or completely in the hands of autoproducers, the opposite was true in Estonia, Lithuania, Latvia, Luxemburg, Hungary, Poland, where public supply plants were responsible for at 93% of total. In the other Members States, the picture is more balanced.

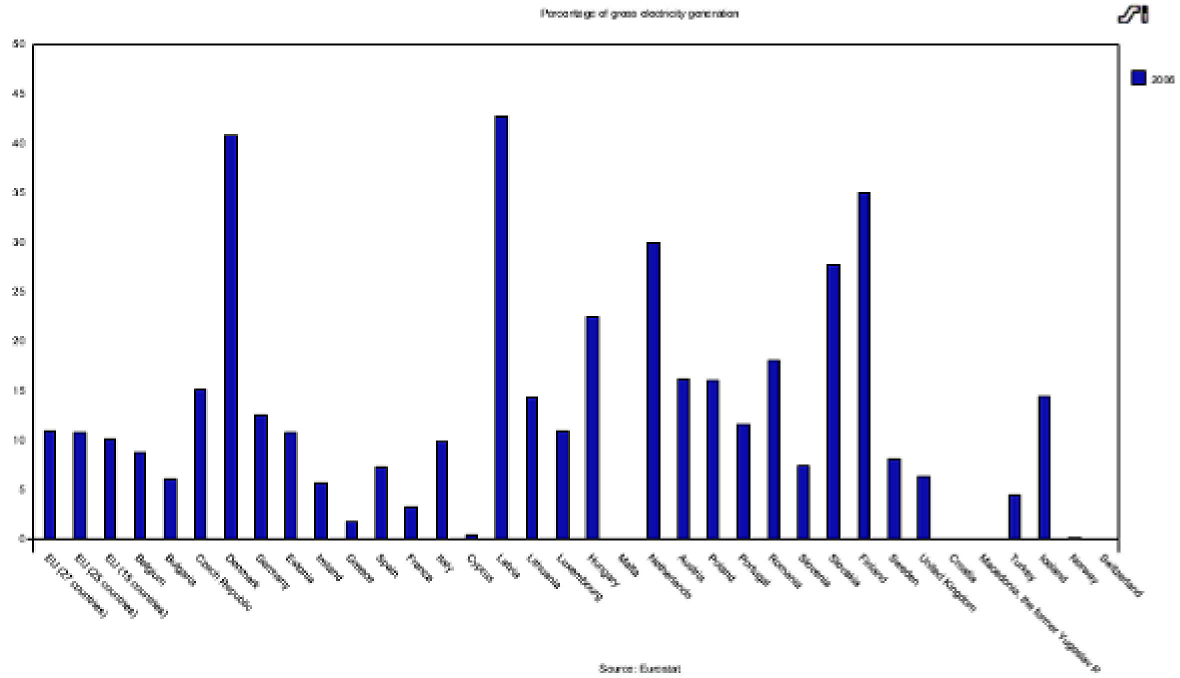


Figure 136: Combined heat and power generation in 2006. Source: EURSTAT [1]

Table 120: Combined Heat & Power (CHP) in the EU, Bulgaria, Romania and Turkey – 2004. Source EUROSTAT [2]

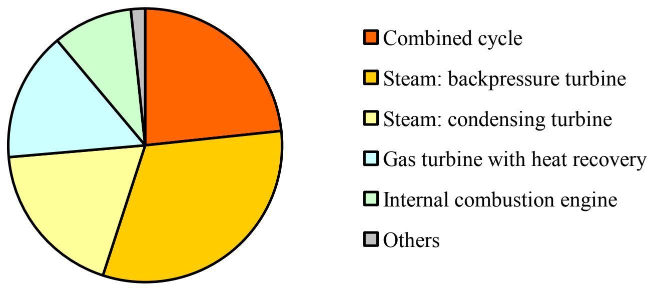
	CHP electricity generation, TWh	Public supply	Auto-producers	Share of CHP in total electricity generation	CHP Electrical capacity, GW	CHP Heat production, PJ	Public supply	Auto-producers
EU-25	325.2	:	:	10.2%	88.42	2783.7	:	:
BE	7.18	86.2%	13.8%	8.4%	1.36	21.0	:	:
CZ	13.87	71.1%	28.9%	16.5%	5.28	152.9	67.5%	32.5%
DK	20.22	:	:	50.0%	5.74	121.8	:	:
DE	56.65	59.6%	40.4%	9.3%	20.83	534.3	48.0%	52.0%
EE	1.02	87.8%	12.2%	9.9%	0.42	11.9	80.9%	19.1%
EL	0.87	16.9%	83.1%	1.5%	0.22	8.8	21.6%	78.4%
ES	22.05	0.0%	100.0%	7.9%	3.71	170.2	0.0%	100.0%
FR	23.66	45.5%	54.5%	4.1%	6.19	199.9	29.9%	70.1%
IE	0.66	0.0%	100.0%	2.6%	0.13	4.3	0.0%	100.0%
IT	24.68	:	:	8.1%	5.11	189.6	:	:
CY	-	-	-	0.0%	0.00	-	-	-
LV	1.50	95.6%	4.4%	32.0%	0.59	12.5	93.1%	6.9%
LT	2.24	92.6%	7.4%	11.6%	1.04	18.3	91.8%	8.2%
LU	0.44	100.0%	0.0%	10.7%	0.10	2.2	100.0%	0.0%
HU	6.14	89.0%	11.0%	18.2%	1.77	42.3	77.3%	22.7%
MT	0.00	-	-	0.0%	0.00	0.0	-	-
NL	29.70	68.5%	31.5%	29.5%	6.98	215.0	53.5%	46.5%
AT	9.78	47.5%	52.5%	15.2%	3.21	94.6	32.1%	67.9%
PL	26.20	76.6%	23.4%	17.0%	8.21	280.6	61.6%	38.4%
PT	4.95	59.6%	40.4%	11.0%	1.06	55.9	43.2%	56.8%
SI	0.98	65.6%	34.4%	6.4%	0.34	14.8	45.1%	54.9%
SK	4.68	60.6%	39.4%	15.3%	1.12	24.2	82.5%	17.5%
FI	29.16	63.9%	36.1%	34.0%	5.93	270.7	42.5%	57.5%
SE	12.25	64.5%	35.5%	8.1%	3.42	138.9	48.5%	51.5%
UK	26.34	6.5%	93.5%	6.7%	5.65	199.2	5.2%	94.8%
BG	3.03	:	:	7.3%	1.31	49.0	:	:
RO	14.92	97.4%	2.6%	26.4%	5.51	126.3	84.4%	15.6%
TR	6.10	26.5%	73.5%	4.0%	0.79	90.2	6.8%	93.2%

Source: Eurostat

TWh = 1000 GWh
GW = 1000 MW
PJ = 1000 TJ = 1000/3.6 GWh
: data not available

The most common types of analysed CHP units are:
- Combined-cycle gas turbine
- Steam back pressure turbine
- Steam condensing extraction turbine
- Gas turbine with heat recovery
- Internal combustion engine

Figure 137 presents share of each technology in total CHP electricity generation. Worth to point out about these technologies: the internal combustion engine and the gas turbine suit in the best way the power range which is described in this report. Presently, gas turbine rivals with diesel generator set. Looking at CHP production share, characterised by economic activities (Figure 138), the reader can observe that both for electricity and heat, the paper and printing industry, the chemical industry and refineries held the largest shares. However, not only industrial autoproducers were involved: the services sector accounted for 4% of CHP electricity generation and 3% of CHP heat production.



– **Figure 137: CHP electricity generation in 2002, in GWh**

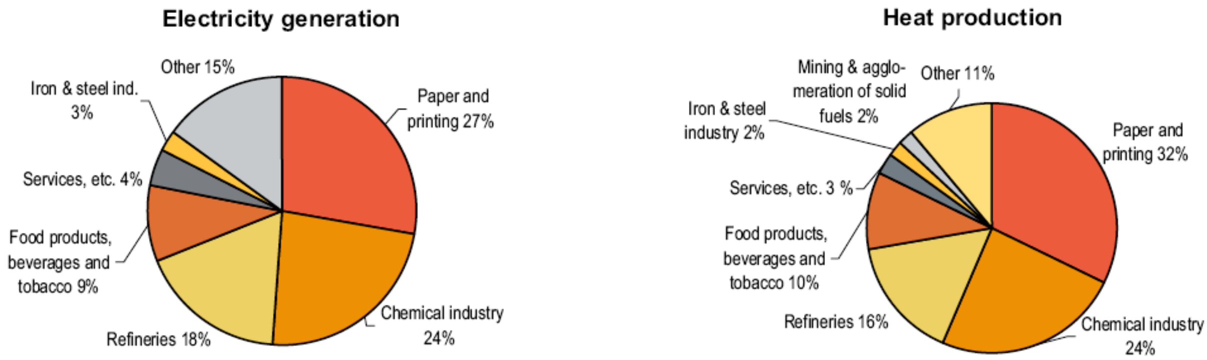


Figure 138: CHP production by autoproducers, EU-25, 2002: share by economic activities. Source: Eurostat [3]

Eastern Europe is emerging as the new growth hub for gen-sets in Europe. Low-cost countries such as Poland, the Czech Republic and Hungary are attracting new automotive, pharmaceuticals and healthcare manufacturing facilities and the region is witnessing a considerable increase in commercial infrastructure projects. Moreover, the retail industry is also in the growth stage in Eastern Europe, and as the number of retail outlets increase, the gen-set market is also expected to capitalise on the retail sector growth.

With regard to end-user segments, the industrial segment continues to be the major market for gen-sets, contributing to more than 40 per cent of the demand. However, the share of the industrial segment is expected to decrease moderately over the forecast period as the commercial and public/infrastructure segments gain greater share. Overall, gen-sets continue to be the mainstay of distributed power generation in Europe, especially for the stand–by application. Figure 139 shows potential for CHP capacity increase in Europe from 88 GWe to 230 GWe in 2020. Such scenario assumes net increase, some reinvestment in current stock, and proper energy policy.

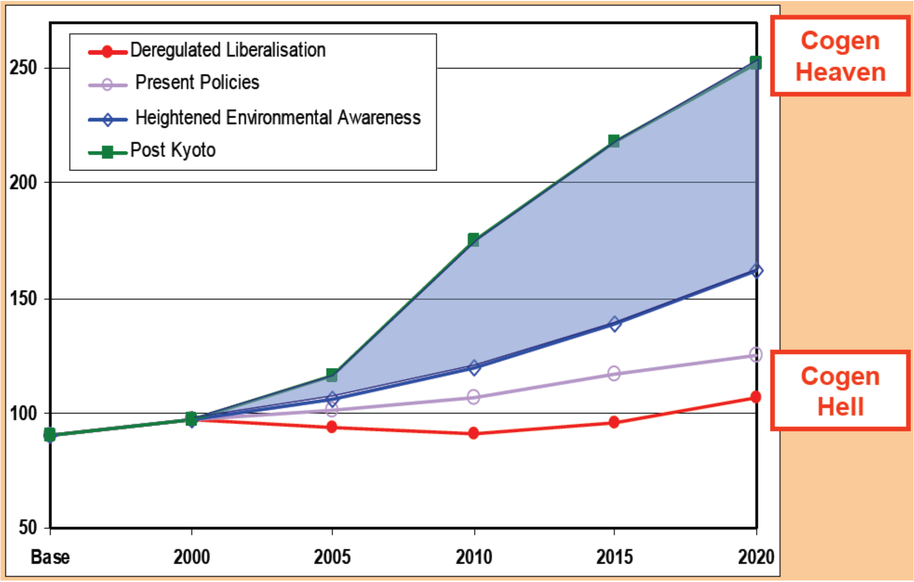


Figure 139: Four Scenarios for the development of CHP in Europe to 2020 (in GWe installed CHP capacity). Source: Future Cogen [4]

26.4 Description of fuel cell technology for the application

Stationary power fuel cells typically process natural gas, and release fewer environmentally harmful emissions than those produced by a combustion cogeneration plant. With a fuel cell, carbon dioxide emissions may be reduced by up to 49%, nitrogen oxide by 91%, carbon monoxide by 68%, and volatile organic compounds by 93%.

The major source of emissions is the fuel processing subsystem because of the heat required for reforming process. If temperature maintained below 1000^0C, this prevents the formation of oxides of nitrogen (NO_x). In addition, the temperature is sufficiently high for the oxidation of carbon monoxide (CO) and unburnt hydrocarbons. Absorbent beds help in removing other pollutants such as oxides of sulphur (SO_x). Table 121 illustrates emission characteristics of fuel cell system, which fulfilled current, the most rigorous environmental demands.

Table 121: Estimated fuel cell emission characteristics

Fuel cell type	PEMFC	PAFC	SOFC	MCFC
Nominal electricity capacity (kW)	200	200	100	250
Emissions				
NO_X (ppmv at 15% O_2)	1.8	1.0	2.0	2.0

The efficiencies mentioned below are based on HHV and the investment costs for the fuel cell system are target values for 2020.

26.4.1 Description of SOFC+GT technology for the application

Fuel cell technology is an emerging technology with potential for both electricity generation and cogeneration in an environmentally friendly fashion. One measure of a thermal-electric system's ability to provide both heat and electricity is its electric-to-thermal ratio. It has been stated that the characteristically high electric-to-thermal ratio of the SOFC makes them attractive for providing the electrical and thermal requirements of various end-use applications. The waste heat produced in a SOFC can be utilised for steam generation, space heating, and/or hot water demands. Total efficiency of SOFC+GT system equals 85% (HHV). Fuel cell's waste stream provides additional energy (heat) except electricity at no extra cost or investment. Such feature makes CHP fuel cells system economically more attractive.

Table 122: Description of SOFC+GT System

SOFC + GT System		
Power	250	kW
Lifetime or full load hours	5	yr
Maintenance	0.0037	€/kWh
	6%	
Operation cost	0.0040	€/kWh
Investment cost	0.0190	€/kWh
Specific investment cost	**0.0267**	**€/kWh**
Eflectric efficiency	60	%
Fuel use	6.0	MJ/kWh
Stack replacement	0.018	€/kWh

The SOFC were assumed to have a service life equivalent to 40000 full load hours, the Balance of Plant (BOP) about 45000 full load hours and Gas turbine have 60000 full load hours. For the Gas turbine it is assumed that the hot section components are changed, components of alloy, copper and steel.

Down time costs are directly related to reliability of the systems and is difficult to estimate, especially for the SOFC+GT system, where long term, large scale experience lacks. An auxiliary system usually runs part load, the SOFC+GT system runs well on part load while a generators' engine does not perform so well on such a load. This may lead to higher downtime costs for the gen-set. However, a problem for the fuel cell is a gradually decline in performance due to contamination of the stack, this may lead to lower reliability in the end of the stack lifetime. Eventually better reliability may be an important quality for the fuel cell system, but will not be evaluated in this report.

Service time estimation is 40000 full load hours and such a lifetime target is reached most easily fuelled on natural gas. Stack replacement cost after 5 years must be accounted for along with maintenance requirements. In this report estimates were made for 5 years period but fuel cell system can live longer (several more stack replacement must be included).

In this case study the electric efficiency for SOFC+GT is 60%. Because a fuel cell has no moving parts, maintenance cost will be low compared to conventional engines. For generators' engines the maintenance cost will vary with the type of engine (speed/number of cylinders), fuel type and quality and the age of the engine. In case of fuel cells, the fuel supply systems and reformer system may need periodic inspection and maintenance.

List of fuel cells and systems manufacturers:

- Acumetrics (USA)
- Ballard (Canada)
- Bharat Heavy Electrical Limited – BHEL (India)

- CellTech Power
- Ceramic Fuel Cell (Australia and UK)
- Ceres Power (UK)
- Elcogen (Estonia)
- Fuel Cell Technologies (Canada)
- General Electric (USA)
- Kyocera and Osaka Gas (Japan)
- Mitsubishi Heavy Industries (Japan)
- Rolls Royce Fuel Cells (UK)
- Siemens Power Generation (USA)
- Sulzer Hexis
- Versa Power Systems (USA)

26.4.2 Description of PEMFC system for the application

Contrary to SOFC+GT technology description, the 250 kW PEMFC System was assumed to have a service life equivalent to 5000 full load hours [source: IEA], the Balance of Plant (BOP) about 45000 full load hours. Table 123 presents data for fuel cell cogeneration system based on PEMFC. Such comparison to the SOFC+GT systems allow to estimate the difference between them and share evaluation of each component and maintenance cost in fuel cell cogeneration system. The stack subsystem is estimated to represents 30-50% of equipment costs, the fuel processing subsystem represents 10-20% of equipment costs, the thermal management subsystem represents 5-15% of equipment costs.

Specific investment cost, which includes stack purchase, operating and maintenance cost, is higher compared to the SOFC+GT system. The PEMFC system is sensitive to carbon monoxide concentration, therefore it needs better service, which results in higher O & M Costs. Electric efficiency and total efficiency are lower and equals respectively 45% and 75% (HHV). System is also fuelled by natural gas and stack must be replaced after about 0.6 years. Extensive R&D on lifetime improvement is performed.

Table 123: Description of PEMFC System

PEMFC		
Power	250	kW
Lifetime or full load hours	5	yr
Maintenance	0.0041	€/kWh
	7%	
Operation cost	0.0051	€/kWh
Investment cost	0.0203	€/kWh
Specific investment cost	**0.0295**	**€/kWh**
Eflectric efficiency	45	%
Fuel use	8	MJ/kWh
Stack replacement	0.02	€/kWh

List of fuel cells manufacturers and systems:

- Altergy Freedom (USA)
- Arcotronics (Italy)
- Avista Labs (USA)
- Ballard (Canada)
- Cellkraft
- Dais Analytic (USA)
- Electrocell (Brazil)

- European Fuel Cells (Germany)
- Fuji (Japan)
- Hazeyama and Tottori Gas Industry (Japan)
- Hokkaido Gas (Japan)
- Hydrogenics (Canada)
- Ida tech (USA)
- IHI (Japan)
- Intelligent Energy (UK)
- Matsushita (Japan)
- Mitsubishi Heavy Industries (Japan)
- Ballard (Canada)
- Nedstack (the Netherlands)
- Nippon Oil (Japan)
- Nuvera Fuel Cell (USA/Italy)
- Osaka Gas (Japan)
- Sanyo Electric (Japan)
- Toshiba Fuel Cell Power Systems (Japan)
- Vaillant (Germany)

26.4.3 Description of MCFC (Biogas) technology

MCFC systems operate at high temperature (650^{o}C) with a high tolerance to air contamination and carbon monoxide. However, it is sensitive to sulphur compounds in hydrocarbons fuels. MCFC systems in principle may use a range of gaseous fuels, such as natural gas, biogas or coal gas. Similar to SOFC+GT technology description, the 250 kW MCFC system was assumed to have a service life equivalent to 40000 full load hours, the Balance of Plant (BOP) about 45000 full load hours. Table 124 presents data for fuel cell cogeneration system based on MCFC.

MCFC needs CO_2 circulation, which increases investment cost. Moreover, the electrolyte is very aggressive and can damage electrodes. Electric efficiency is lower compared to SOFC but higher than PEMFC and equals 50% (HHV). Depending on production technology and type of primary source, cost of syngas varies. In the same way like in previous systems, the stack must be replacement after 5 years.

Table 124: Description of MCFC System

MCFC		
Power	250	kW
Lifetime or full load hours	5	yr
Maintenance	0.0043	€/kWh
	8%	
Operation cost	0.0059	€/kWh
Investment cost	0.0236	€/kWh
Specific investment cost	**0.0338**	**€/kWh**
Eflectric efficiency	50	%
Fuel use	7	MJ/kWh
Stack replacement	0.023	€/kWh

List of fuel cells manufacturers and systems:

- Fuel Cell Energy
- GenCell Corporation Fuel Cell Generator Systems
- MTU Freidrichshafen Gmbh

26.5 Economic boundary conditions for SOFC+GT, PEMFC and MCFC systems

Cost is likely to be the major barrier to the widespread development of fuel cells. One of the main challenges for the developers of fuel cells is to reach feasible technical solutions that are not too expensive. In case of CHP fuel cells system, specific investment costs are higher compared to the reference system (compare Figure 140, Table 122, Table 123 and Table 124). Because the fuel cell technology is on an early development stage, it should have a potential for price drop in the next decades, while gen-set, which is a mature technology, probably will remain at the current price level.

Using the cost numbers the generator engine is the over all cheapest alternative as a result of lower investment and operation/maintenance cost. The potential for lower energy and operating costs is assumed to be the main cost advantage of fuel cells. Stack replacement is a major extra expense. In the following analysis the stack replacement cost is separated from the other maintenance costs. In future a leasing system for the stack, where they are replaced after their service life, and parts that can be reused are overhauled, may be good solution and may probably reduce the replacement cost.

Below is presented Figure 140, which describes 250 kW CHP system cost versus fuel cost. In these calculations the mean price for gas equals 9.6 EUR/GJ (2007 yr). Cost of SOFC+GT system is the highest one from all here presented technologies. Due to the coupling between SOFC and gas turbine, the systems' total efficiency reaches 80% and electrical 60%. Additional investment cost of gas turbine, increased the overall system cost. Differences between described systems reach maximum 800 EUR/kWe. Cost of MCFC system fuelled by biogas equals 1168 EUR/kWe. Since MCFC technology requires CO_2 in the system and biogas contains more CO_2 than natural gas, the extra CO_2 is an advantage. During the process of fuel preparation, biogas needs to be cleaned from sulphur components. It is clearly seen that lowest investment cost has PEMFC technology: 861 EUR/kWe. Presented prices of all FC CHP technologies make these technologies commercially competitive to reference CHP system.

All fuel cells CHP systems have similar advantages and disadvantages:

- Low noise level,
- Potential for low maintenance,
- Excellent part load management,
- Low emissions,
- Potential to achieve an overall efficiency of 90% even with small units,
- Relatively short lifetime of fuel cell systems,
- High cost.

However depending on type of used fuel, system configuration, auxiliary components like gas turbine together with SOFC and many other processes' parameters (described in previous chapters), price difference between them is being observed. Optimisation of system configuration should result in further decrease of CHP system's cost, where fuel cell in just one component from the whole. In fact, often the most expensive but not the only one.

Table 125: Commercially competitive to reference systems, cost of fuel cell 250kW technologies

Type of CHP system	FC system cost €/kWe	Nat. gas cost €/GJ
SOFC+GT	1716	9.6
PEMFC	861	9.6
MCFC	1168	9.6
Reference	633	9.6

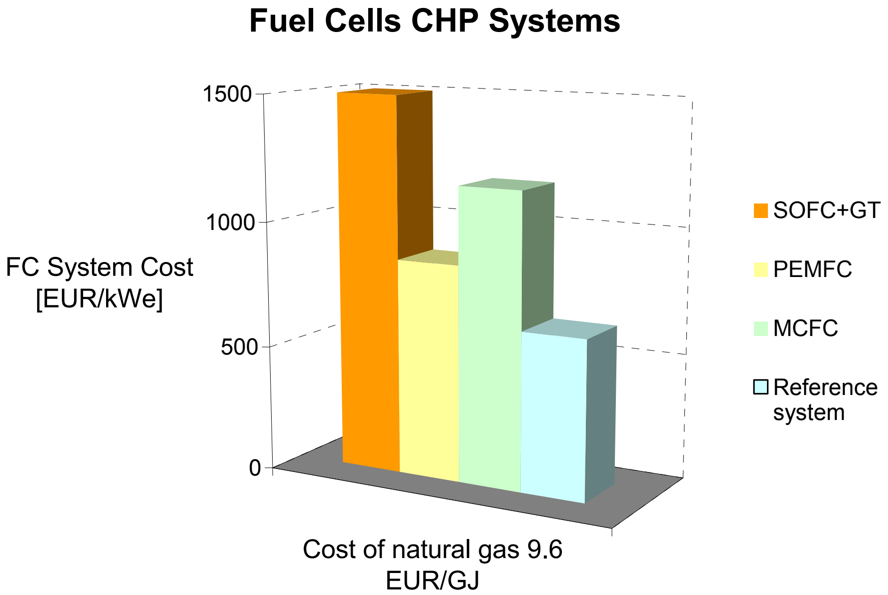


Figure 140: System cost comparison between fuel cells and reference technology

Figure 141 and Table 126 present results concerning fuel cost scenario for fuel cell CHP systems. Figure 141 describes the relation between the investment cost of the fuel cell system and the natural gas cost which has the same cost/kWhe as the reference technology. There is uncertainty connected with the numbers used in this analysis, e.g. for fuel price market development, fluctuation in the oil market, O&M costs and for the fuel cell prices. The energy prices are shown in this report with all taxes included and provided in $€_{2000}$ currency. Different values are used to calculate in a final overview the room for duty taxes or required subsidies for small industry. The 2007 energy prices are taken from Eurostat. It was assumed that the taxation on the different energy carriers will not change in the future. This procedure was used in order to calculate price in 2030. Different energy prices of natural gas with all taxes were used in calculations of FC system cost.

Table 126: Fuel cell system cost vs. natural gas cost at equal electricity cost.

NG cost €/GJ	SOFC+GT system cost €/kWe	MCFC system cost €/kWe	PEMFC system cost €/kWe
4.3	862	560	454
9.6	1558	978	686
18.2	2683	1656	1061
23.4	3368	2066	1289

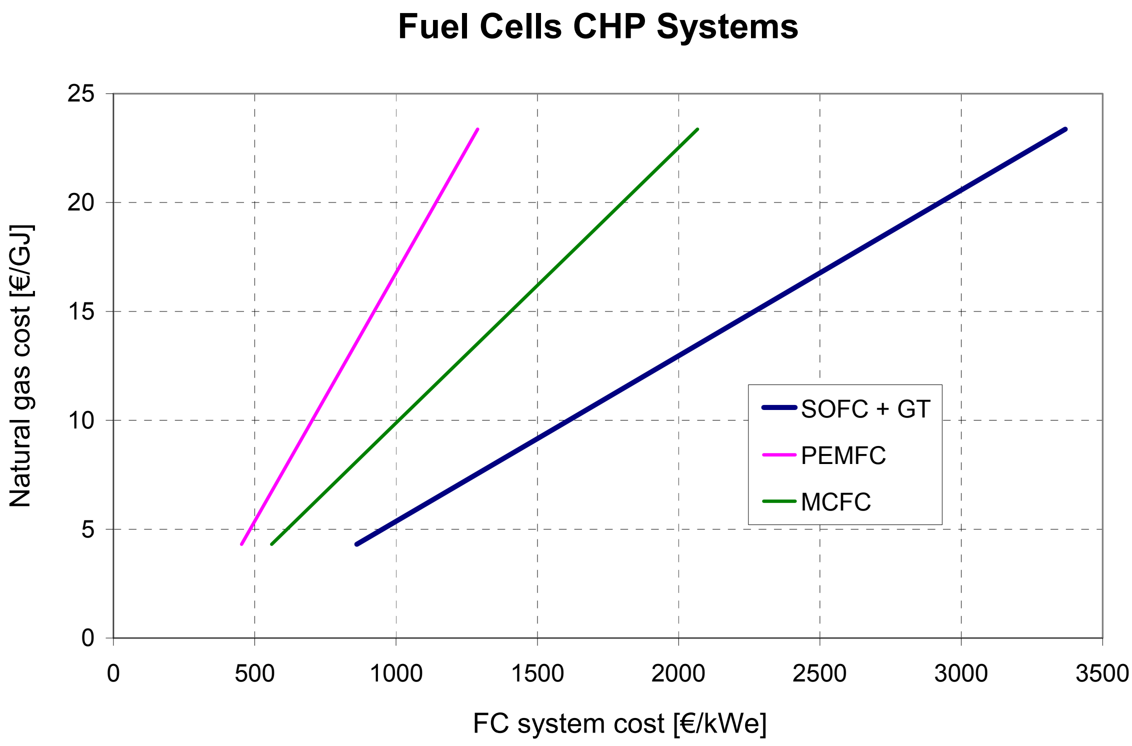


Figure 141: Interdependency between natural gas cost and commercially competitive FC CHP system cost

Figure 141 shows that the effect of different fuel prices on the economy is rather big and is characterised by high possibility of fluctuation in the oil market. FC CHP systems behave in a similar way. Investment cost rises with fuel price just to preserve system price [cost/kWe] which equals to reference technology. In this way more money is available and this is extra profit of FC technologies. Configuration of the system, type of used fuel, lifetime: these parameters influence also on economic competitiveness of fuel cells CHP systems.

26.6 CO2 reduction potential Source-to-User

For the fuel cell system potential income is also expected from emission trading according to very low emissions. However, the potential incomes depend on emission component considered and the area of operation, as well as time horizon.

In case of engine formation of NO from oxidation of atmospheric nitrogen in the combustion chamber depends on the conditions in the combustion chamber. During the passage through the exhaust system a proportion of NO, typically 5-10% will be converted to nitrogen dioxide NO_2, and a limited proportion to nitrous oxide N_2O. The engine in this report is a LowNOx engine, and will have a rather low NO_x emission compared to conventional engines of the same size. The pollution from the engine depends on variations in electricity need.

In Table 127 the WTW emission factors are provided for conventional fuels. The value for biogas is negative since use of biogas will prevent emission of methane into the air, which has a much larger GHG factor. These values were used in order to calculate CO_2 emission of reference technology.

Table 127: Well to electricity emission factor (Sources: Concawe)

Concawe (WTW)	8.0 MJ/kWh
Compressed H_2	gCO2/kWh
Diesel	695
Gasoline	681
Natural gas	503
Biogas	-534

Cogen Europe states that by the year 2020 in Europe, CHP capacity will reach 230 GWe. Investment over next 15÷20 years in CHP technologies should result in:

- CO_2 reductions 280 Mton per year,
- Value of CO_2 savings 5÷10 billions EUR per year,
- Value of energy savings ~30 billions EUR per year.

This data concerns CHP technologies in general. Additional benefits will be achieved be introducing to the market FC CHP systems. The CO_2 reduction potential depends strongly on the source from which the hydrogen comes. Technologies used to produce hydrogen from natural gas have a positive impact on global warming. Below are shown simple calculations which reflect positive impact of FC CHP systems on environment. Such quick evaluation allows calculating CO_2 reduction for the potential market, different scale and number of units. Apart from ecological benefits, additional energy and money will be saved. Scale of this tendency will depend of course of market scale and share of fuel cells technology in this market.

- Energy content natural gas: 45 MJ/kg
- Conversion MJ-kWh: 1kWh = 3.6 MJ
- Emission factor natural gas: 2.75 kg CO_2/kg nat.gas
- CO_2 emissions natural gas fuelled fuel cell systems (SOFC, PEMFC, MCFC), 50% (average) efficiency
- CO_2 emissions natural gas fuelled reference systems, 40% efficiency

Calculation of CO_2 emissions from CHP reference system:

$$\frac{2.75[kgCO_2 / kgNat.gas]}{45[MJ / kgNat.gas]} \times 3.6[MJ / kWh] \times \frac{1}{0.4} = 550[gCO_2 / kWh]$$

Calculation of CO_2 emissions from FC CHP system:

$$\frac{2.75[kgCO_2 / kgNat.gas]}{45[MJ / kgNat.gas]} \times 3.6[MJ / kWh] \times \frac{1}{0.5} = 440[gCO_2 / kWh]$$

Producing the same amount of heat as in 2004 by CHP units in the EU, shown in Table 120; 2783 PJ with fuel cell CHP with 50% electrical and 40% thermal efficiency instead of the reference technology with 40% electrical efficiency and 50% thermal efficiency reduces the CO_2 emissions with 77 Mton/year under the assumption that the electricity would otherwise be produced in natural gas power plants with 50% efficiency. If the fuel cell CHP has an electrical efficiency of 60% and a thermal efficiency of 30% (SOFC + GT) the CO_2 emission reduction will rise to 204 Mton/yr.

26.7 Conclusions and recommendations

The following general conclusion can be taken:

- Fuel cell technology is an emerging technology with potential for both electricity generation and cogeneration in an environmentally friendly fashion.
- Cost is the major barrier to widespread development of fuel cells.
- Fuel cell is on an early development stage, so it should have a potential for price drop in future.
- Low fuel cells O & M costs.
- Stack replacement is a major extra expense and research should be directed towards lifetime improvement.
- All CHP fuel cells systems have similar advantages and disadvantages. However depending on type of used fuel, system configuration and many other processes parameters, difference between them is being observed.
- The effect of different oil prices and connected to it natural gas prices on the economy is currently rather small but characterises by high possibility of fluctuation marketing future. Increase of oil price can fasten process of FC CHP commercialisation.
- Fuel cells system can have a potential income from emission trading according to very low emissions.

Recommendations:

- Better reliability may be an important quality for the fuel cell.
- Leasing system for the stack, where they are replaced after their service life, and parts that can be reused.
- Depending on local resources different fuel sources should be taken into consideration.

26.8 Literature

1. Combined heat and Power generation. EUROSTAT 2008.
2. Combined Heat & Power (CHP) in the EU, Bulgaria, Romania and Turkey – 2004 data.
3. Panorama of Energy, Energy statistics to support EU Policy and solutions. 2007 edition.
4. "Cogen – Clean, Clever, Competitive". COGEN Europe Annual Conference Brussels, 11 March 2005, Peter Lofler.
5. "Market share of the largest generator in the electricity market"; EUROSTAT
6. European Hydrogen & Fuel Cell Technology Platform, Deployment Strategy, August 2005, www.HFPeurope.org
7. "Assessment of Solid Oxide Fuel Cells in Buildings Applications", Phase 1: Modelling and Preliminary Analyses, Report Summary 207-R, Solar Energy Laboratory, University of Wisconsin-Madison, November 2001.
8. Dr. Ian Knight, Prof. Ismet Ugursal, "Residential Cogeneration Systems: A review of The Current Technologies", Annes 42 of the IEA Energy Conservation in Buildings and Community Systems Programme, April 2005.
9. Marte Reenaas, "Solid Oxide Fuel Cell combined with gas turbine versus diesel engine as auxiliary power producing unit onboard a passenger ferry", A comparative Life Cycle Assessment And Life Cycle Cost Assessment, 2005
10. www.energy .eu and carma.org

11. www.Hyways.de and Concawe
12. D.R. McIlveen-Wright, J.T. McMullan, D.J. Guiney; "Wood-fired fuel cells in selected buildings", Journal of Power Sources 2003.
13. S. Alkaner, P. Zhou; 'A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application", Journal of Power Sources 2006.
14. Charles-Emile Hubert, P. Achard, R. Metkemeijer, "Study of a small heat and power PEM fuel cell system generator", Journal of Power Sources 2006.
15. Dr. Kerry-Ann Adamson; Fuel Cell Today, "2006 Small Stationary Survey", "2007 Large Stationary Survey"
16. www.iea.org
17. "Development of Hydrogen and Fuel Cell Technologies in a Large-Scale Lighthouse Project", A study commissioned and guided by the European Commision, DG Energy and Transport, TREN/D4/23-254/2005
18. Anibal T. De Almeida, "Providing Energy Services with Fuel Cells in a Liberalised Energy Market", Fuel Cell Services, Berlin, 26 March 2004.

27. Case study µ-CHP (1-5 kW)

27.1 Description of application

Micro CHP (Combined Heat & Power) is the simultaneous production of useful heat and power within the home. It works very well like the modern condensing gas boiler in a central heating system and heats the home in just the same way. However, at the same time it generates electricity, some of which you will use in your own home; the remainder is exported to the grid to be used by your neighbours.

The technical and economic demands on such a system are onerous and it is important to mention that micro CHP is not simply a scaled-down version of conventional CHP. However, micro CHP offers significant opportunities to enhance the profitability of an energy company's supply business as well as providing substantial environmental benefits. These economic benefits may be passed on to the consumer in the form of reduced energy bills, whilst the environmental benefits are of value to all of us.

Natural gas is consumed in a Stirling engine (or other prime mover) to provide heat and electricity for use within the home (figure 1). A total of around 70-80% (Gross Calorific Value) of the energy value of the gas is converted into heat, principally in the form of hot water that is used for space heating and domestic hot water as in a normal central heating system. Between 10-25% is converted into electricity, and the remainder (5-15%) is lost in the flue gases. This compares with a conventional gas central heating boiler where around 90% of the energy in the gas is converted into heat and the remaining 10% is lost in the flue gases. Although the total "efficiency" of a micro CHP system is similar to a boiler system, the electricity produced has a much higher value than heat. It is the value of this electricity that covers the investment cost of the micro CHP unit and provides a net saving.

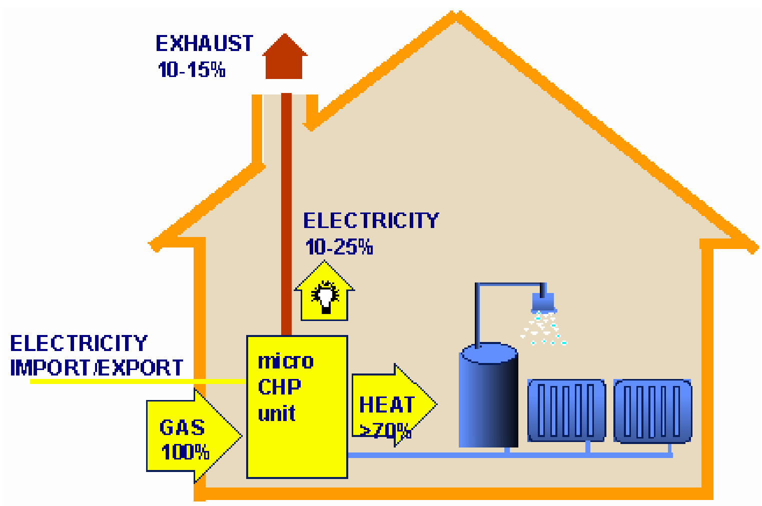


Figure 142: **Description and energy yields of a domestic combined heat and power system**

CHP systems have benefited the industrial sector since the energy crisis of the 1970s. For three decades, these larger CHP systems were more economically justifiable than micro-CHP, due to the economy of scale. After the year 2000, micro-CHP has become cost effective in many markets around the world, due to rising energy costs. The development of micro-CHP systems has also been facilitated by recent technological developments of small heat engines. This includes improved performance and/or cost-effectiveness of Stirling engines, steam engines, gas turbines, diesel engines and Otto engines.

The largest deployment of micro-CHP is in Japan at this time, where over 50,000 units are in place, with the vast majority being of the "ECO-WILL" type based on Honda's™ MCHP engine generator unit. It is estimated that about 1,000 micro-CHP systems are in operation in the UK as of 2002. These are primarily "Whispergen" Stirling engines, and Senertec Dachs™ reciprocating engines. In France, the energy company Gaz de France developed an efficient domestic cogeneration system (internal combustion) with De Dietrich™ and Vaillant-Viessmann™ and began to deploy these materials on the market.

27.2 Description of reference technology: domestic condensing boiler and electricity from CCGT

The condensing boiler is the currently most used technology for domestic heat generation in Europe. The boiler is a hot water heating device designed to recover energy normally discharged to the atmosphere through the flue. When a condensing boiler is working at peak efficiency the water vapour produced by the burning of gas or oil in the boiler condenses back into liquid water - hence the name "condensing boiler". The boiler uses a heat exchanger so that incoming air or water cools the exhaust, forcing the condensation of the water vapour it contains; this heats the incoming air (if an air-to-air heat exchanger is used) or pre-heats the water (if an air-to-water heat exchanger is used). A small proportion of the extra efficiency of the condensing boiler is due to the cooling of the exhaust gases, but the majority of the energy recovered is from the condensation of the water vapour in the exhaust gases.

Condensing boiler manufacturers claim that up to **98% thermal efficiency** of fuel conversion can be achieved in normal domestic use, compared to 70%-80% with a conventional design. Typical condensing boiler efficiencies are around 90%, which brings most brands of condensing gas boiler in to the highest categories for energy efficiency.

The condensing boiler is not designed to produce electricity, then the supply of power in the home is made from electrical grid.

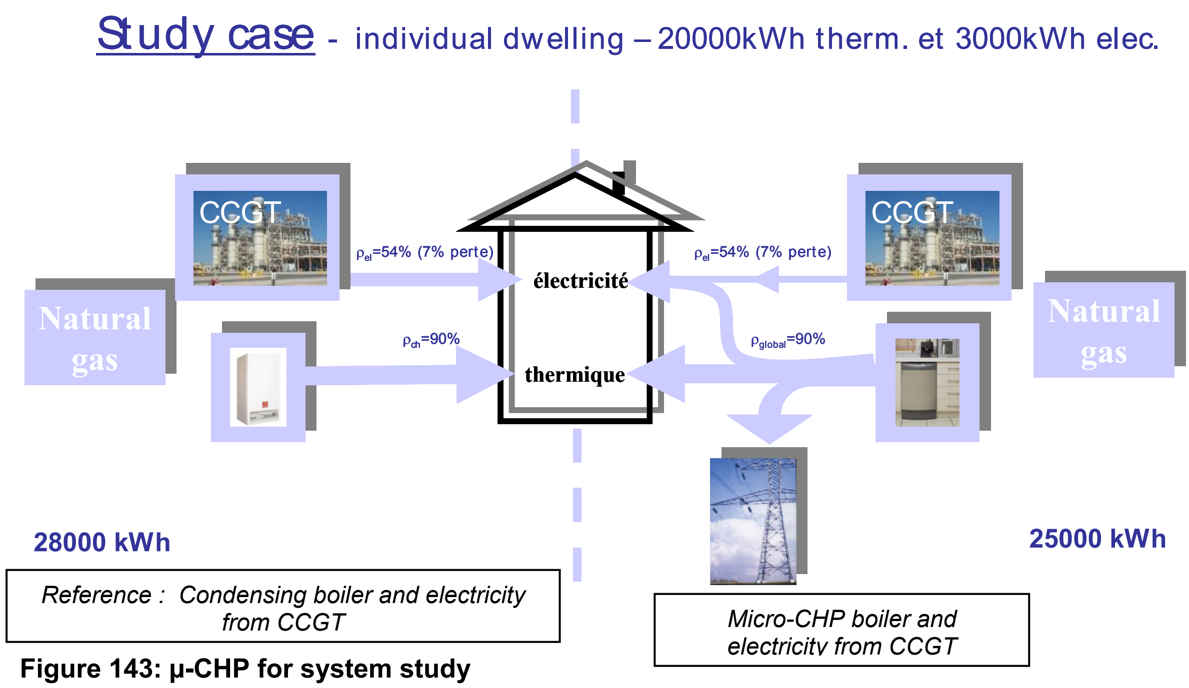


Figure 143: µ-CHP for system study

Description and characterisation of the technology used today for the considered application (Table 128 below):

Table 128: Description of the current reference technology: the condensing boiler

Application	Unit	Condensing Boiler
Thermal Power level	kW	5 – 20 kW
Efficiency; energy use	%	Annual efficiency 103% (NG LHV)
Typical cost complete system	€	4000 € installed
Specific cost energy system	€/kW	-
Running time	hours	Usually between 2000 and 3000h
Lifetime	year	15 years
Type of "fuel"	-	Natural Gas
Type of "fuel" supply	-	Natural gas grid
Type of "fuel" storage	-	No fuel storage
Typical storage capacity	-	*non applicable*
Range/fuel charge	-	*non applicable*
Availability	%/yr	Near 100%
Maintenance		Annual visit (150€/year)
Application	**Unit**	**NG Combined Cycle Power Plant**
Power level	MW	100 – 800MW
Efficiency; energy use	%	55% (NG LHV)
Type of "fuel"	-	Natural Gas

Major European developers of condensing boilers:

- Vaillant-Viessmann (Saunier Duval)
- Buderus
- MTS Merloni Thermo Sanitari
- De Dietrich

Developments and alternatives for 2020-2030 for the reference technology based on end-user needs and societal needs associated with the application.

The gas condensing boiler will not be a reference after 2015. The next reference heating system for the residential market could be condensing gas boiler associated with solar thermal panels; or heat pump (electrical or gas fired).

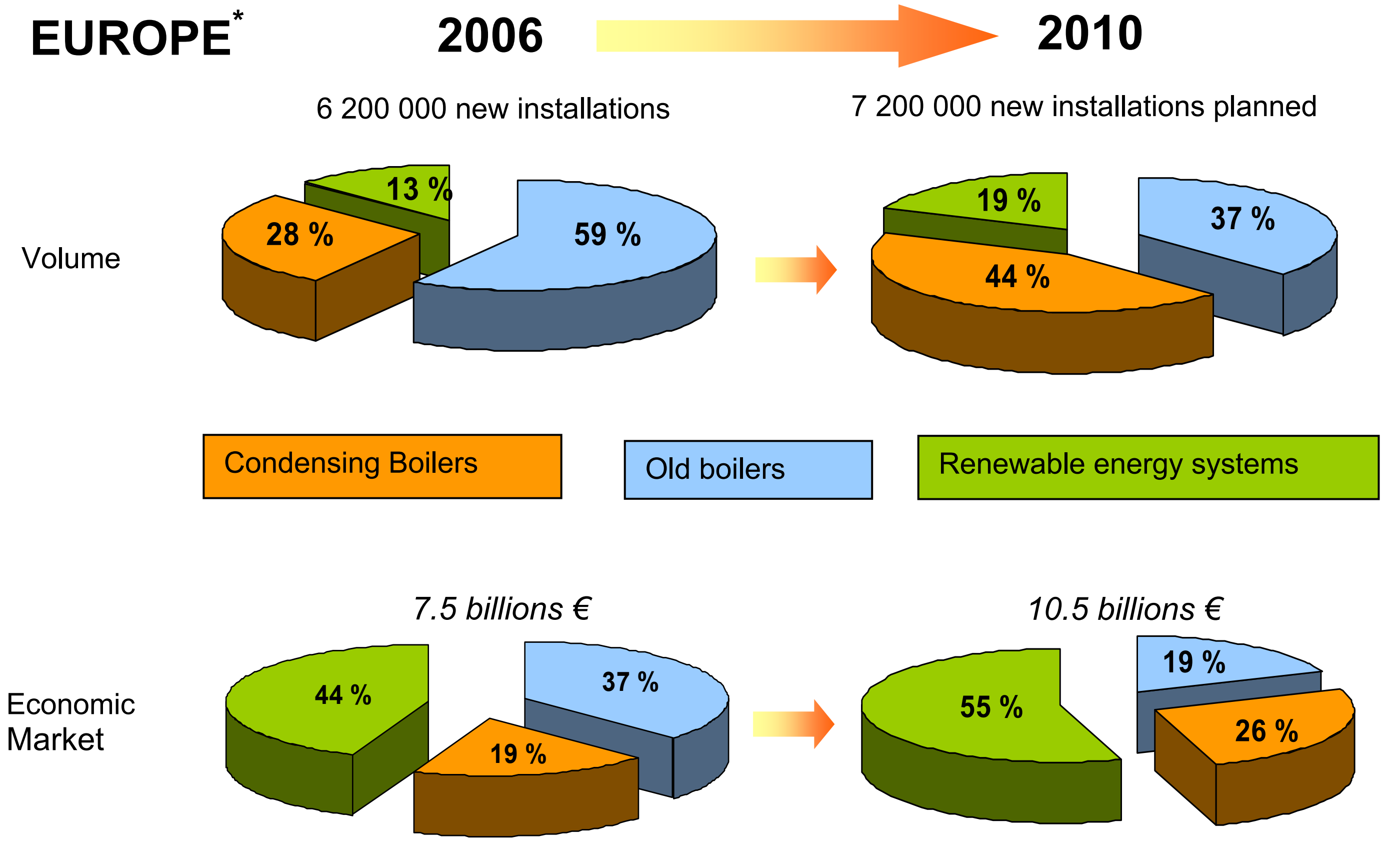
Table 129: µCHP unit in an average sized family home with annual heat demand of 18MWh (WhisperTech example)

Application	Unit	µCHP systems (Internal combustion or Stirling engine)
Power level	kWh	18 kWh (annual heat demand)
Efficiency; energy use	%	90 % (up to 98 % theoretically)
Electricity generated	kWh	2400 kWh
Typical cost complete system	€	6000 – 10000 €
Specific cost energy system	€/kW	-
Running time	hours	3000 h
Lifetime	year	-
Type of "fuel"	-	Natural Gas
Type of "fuel" supply	-	Natural gas grid
Type of "fuel" storage	-	No fuel storage
Typical storage capacity	-	*non applicable*
Range/fuel charge	-	*non applicable*
Availability	%/yr	99 %
Maintenance		-

27.3 Description of the market

The size of the EU[5] market of domestic micro-CHP (1 to 10 kW) could be evaluated approximately to 90 – 100 millions of units[6] and 6,2 millions of new installations per year (755 000 in France in 2005, of which 605 000 condensing boilers to natural gas, Table 129). The lack of information from the Eastern-European countries does not allow evaluating the real market of EU-25.
According to the last European policies (see next §) and with the future legislature, condensing boiler is becoming a benchmark for heating and regulation. The next thermal regulations this generator sets 2010 as a baseline minimum for a new home. The legislature has been able to recognize the condensing boiler equipment performance, he wants to see standardized.
The Directive will promote energy savings. Saving energy will help compliance with the emissions targets of the Kyoto Protocol. The EU recognised that energy efficiency is the single most cost-effective and publicly acceptable way of meeting our Kyoto objectives.
The European development plan for 2020 shows a quick evolution of micro-CHP solutions to a higher efficiency comparable to condensing boilers (Table 129).

[5] France, Germany, Netherlands, UK, Spain, Austria, Switzerland, Belgium, Italy.
[6] Data's from Gaz de France – hypothesis of a unit lifetime of 15 year.



* France, Germany, Netherlands, UK, Spain, Austria, Switzerland, Belgium, Italy.

Figure 144: Potential size of the micro-CHP market for 2010 (data's from GFCC7 and MTS)

The current European policy pathway on the energy savings (like the RT2005 and the future RT-2010[8] in France) will enhance and accelerate this evolution with the implementation of highly efficient systems like the PEMFC and SOFC.

European policies:
In parallel, the buildings sector accounts for 40% of the EU's energy requirements. It offers the largest single potential for energy efficiency. Research shows that more than one-fifth of the present energy consumption and up to 30-45Mton of CO_2/year could be saved by 2010 by applying more ambitious standards to new and refurbishing buildings – which represents a considerable contribution in order to meet the Kyoto targets
The aim of improved energy efficiency has been set out in earlier existing legal instruments. Among the main Community legislation for the sector are the Boiler Directive (92/42/EEC), the Construction Products Directive (89/106/EEC) and the buildings provisions in the SAVE Directive (93/76/EEC). The Directive on the energy performance of buildings in force since January 2003[9] builds on those measures with

[7] GFCC : « Groupement des Fabricants de matériels de Chauffage Central par l'eau chaude et de production d'eau chaude sanitaire »
[8] RT-2010 : see http://www.logement.gouv.fr/article.php3?id_article=5789
[9] DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings.

the aim to provide for an ambitious step-ahead to increase the energy performance of public, commercial and private buildings in all Member States. These decisions are currently transcribed in national policies to improve energy efficiency in all European union.
The rapid evolution of European regulation on the energetic performance of buildings will push towards a major modification of the micro-CHP market in order to reduce CO_2 emissions and to increase energy savings in the building sector.

27.4 Description of FC/H2 technology for µCHP: the SOFC (Solid Oxide Fuel Cell)

Fuel cells (SOFC and PEMFC), which convert fuel (Natural gas, hydrogen and gas mixtures) directly into heat and electricity, appear to offer very low emissions, high efficiency and very low noise levels. Heat is produced as a by-product of the electrochemical process, with water as a waste product. Firstly the natural gas needs to be reformed into hydrogen and CO, requiring additional components and implying parasitic energy consumption. The exhaust gas also needs to be treated to eliminate CO (only in the case of the PEFMC, the SOFC works very well with CO) and the gas supply may also need to be cleaned to remove sulphur. Although the electrical conversion itself may be quite efficient, the need to convert the DC output to AC requires power electronics and implies further costs and losses.
Current industrial prototypes are still too noisy, bulky, not enough efficient and expensive to be viable. Indeed, there is some product (Sulzer Hexis 1kWe) specifically targeted at individual homes and this is recognised as being several orders of magnitude too expensive (Diethelm et al., 1998). However, it is believed that continued development will enable them to compete within a ten year timescale.
Overview of developers of hydrogen/fuel cells for the application:

1. **SOFC :**
    - Hexis (CH)
    - CERES POWER (GB)
    - Ceramic Fuel Cells Ltd. (GB/AUS) and De Dietrich Thermique (REMEHA)
    - Acumentrics and MTS (USA/I)
    - Kyocera (JP)

2. **PEMFC :**
    - Plug Power
    - BAXI

Table 130: Description of the SOFC technology

Application	Unit	SOFC
Power level	kW	1kW
Efficiency; energy use	%	85% total efficiency (50% electrical, 35% thermal) on NG (LHV)
Lifetime	year	Minimal objective : 40 000h
Type of "fuel"	-	Natural Gas, Biogas, pure Hydrogen or Natural gas and Hydrogen mixtures (like Hythane®)
Type of "fuel" supply	-	Natural gas/hydrogen grid
Type of "fuel" storage	-	None
Typical storage capacity	-	*non applicable*
Range/fuel charge	-	*non applicable*
Availability	%/yr	Near 100%
Maintenance		Desulphurization and demineralisation cartridges

Micro-CHP technology main market is the residential market, with a typical product of a 1kW electrical power output, to fulfil a part of electrical, needs of the dwelling from natural gas. Micro-CHP technology can increase the natural gas share part within the residential market. Despite the important decrease of thermal needs in the residential market, micro-CHP can keep natural gas consumption in residential market while providing CO_2 savings.

27.5 Economic boundary conditions for the SOFC technology

A content case study of the economic boundary conditions of the SOFC for micro-CHP is summarized in the Table 131 below.

Table 131: Boundaries conditions estimated for the µCHP SOFC technology

Reference system		Existing house in 2007 (200kWh/m²/year)	Existing house in 2015 (100kWh/m²/year for heating)	New house in 2015 (30kWh/m²/year for heating)
Boiler cost	€	4 000	4 000	4 000
Heating demand	kWh	24 000	12 000	3 600
Domestic Hot Water demand	kWh	2 500	2 500	2 500
Electrical demand	kWh	2 500	2 500	2 500
Maintenance	€/year	150	150	150
Fuel cost	€/MWh	43.8	43.8	43.8
Electricity price	€/MWh	107	107	107
Electricity sell-back price	€/MWh	78.7	78.7	78.7
End-user’s annual energy bill	€/year		1120	725
End-user’s total bill over 15 years	€		19600	14200
FC system				
Power	kW	1	1	1
Lifetime	yr	5	5	5
Maintenance	€/year	250	250	250
FC system cost	€	6 000	6 000	6 000
FC stack cost	€/kW	1 000	1 000	1 000
End-user’s annual energy bill (w/ mCHP)	€/year		1 040	640
End-user’s total bill over 15 years (w/ mCHP)	€		25 300	21 700
End-user’s annual energy bill savings	€/year		80	85
End-user’s total bill over 15 years savings	€		- 5 700	- 7 500

***[Remark :** We are currently working on a second approach : evaluate the cost sensitivity of the SOFC technology]*

27.6 CO2 reduction potential Source-to-User

CO_2 content of electricity produced by micro-CHP: **295 g CO_2/kWhe**

Electricity produced by the micro-CHP: comparison with CO_2 content of several EU countries. Note that for France, the mean value of electricity CO_2 content must not be considered for micro-CHP, since electricity produced by a micro-CHP has to be compared with the marginal electricity, which in France is produced from coal and gas power plant. The marginal content is then 550 $gCO_2/kWhe$ according to RTE and ADEME in France.

Table 132: CO_2 emissions of µCHP and reduction potential

CO_2 reduction	*Electricity CO_2 content*	*CO_2 content of µCHP*	*Electricity produced by µCHP*	*CO_2 reduction per year per µCHP boiler installed*
	gCO_2/kWh	*gCO_2/kWh*	*kWhe*	*Tons of CO_2 per year and per boiler*
NL	598	295	5712	1.73
DE	508	295	5712	1.22
FR	550 (*)	295	5712	1.46
UK	482	295	5712	1.07
EU-25	429	295	5712	0.76

CO_2 reduction is calculated by comparison between grid electricity CO_2 content to µCHP electricity CO_2 content.

27.7 Conclusions and recommendations

According to the results of the state of the art and the content case study, we can conclude:

- Micro-CHP can be competitive with condensing boiler if their investment costs and maintenance are comparable,
- Micro-CHP with high electrical efficiency (up to 50%) is requested to reduce thermal power and then better fit with the reduction in residential dwellings thermal needs.
- SOFC technology can achieve higher efficiencies than PEMFC when running on natural gas. The low working temperature of PEMFC and their sensitivity to reformate products make this technology unadapted to residential micro-CHP applications.
- The CO_2 benefits provided by a micro-CHP have to be calculated considering marginal electricity, since electricity produced from a micro-CHP will substitute to the marginal electricity.
- The European policy on the energy performance of buildings will allow more efficient technologies to deploy on the market in short term.

27.8 References

1. Diethelm, R., Schmidt, M., Doggwiler, B., Gamper, T., Keller, M., Honegger, K. & Batawi, E. (1998). STATUS OF THE SULZER HEXIS SOLID OXIDE FUEL CELL(SOFC) SYSTEM DEVELOPMENT. Third European Solid Oxide Fuel Cell Forum Proc Oral Presentations, 87-93.
2. CO_2 emissions data from ADEME and RTE
3. HyWays, Roadmap, 2007 (www.Hyways.de)
4. Well-to-Wheels analysis for future automotive fuels and power trains in the European context, version 2b, 2006 (http://ies.jrc.cec.eu.int/wtw.html)
5. *www.energy.eu, last visited November 2007*
6. *carma.org, last visited November 2007*
7. Roland Diethelm, Sulzer Hexis, December 2001, “Promoting successful market entry of an SOFC system for residential applications”