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**ANALYSIS OF OPPORTUNITIES AND SYNERGIES IN FUEL CELL
AND HYDROGEN TECHNOLOGIES**

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The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org



ANALYSIS OF OPPORTUNITIES AND SYNERGIES IN FUEL CELL AND HYDROGEN TECHNOLOGIES

EXECUTIVE SUMMARY

This report is a deliverable of the Roads2HyCom project, 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 CO₂ 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 CO₂ 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/H₂ technologies to gain ground.



ANALYSIS OF OPPORTUNITIES AND SYNERGIES IN FUEL CELL AND HYDROGEN TECHNOLOGIES

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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/H₂) technologies
- Potential CO₂ reductions when using FC/H₂ technologies
- Insight into near- and mid-term opportunities for FC/H₂ 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 CO₂ emission parameters used throughout this task are presented.

In Chapter 4, the results of the case studies are combined and the metrics cost and CO₂ 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 CO₂ 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/H₂ 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/H₂ 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 CO₂ emissions through usage of FC/H₂ technologies for the applications considered.



3. Methodology

3.1 General Approach

First, 23 potential FC/H₂ 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/H₂ 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/H₂ technology are equal.

Third, the costs of the applications using SOTA (state-of-the-art) or evaluated 2020 - 2025 FC/H₂ 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/H₂ 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/H₂ 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/H₂ 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/H₂ technology suitable for the application
- Economic boundary conditions for FC/H₂ technology
- CO₂ reduction potential Source-to-User
- Conclusions and recommendations
- References



3.4 Economics

In the comparison of FC/H₂ 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/H₂ 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:

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

C_{DT}	Cost of the reference drivetrain	[€/kW]
C_{Fuel}	Fuel cost including excise duties	[€/GJ]
t_{Ref}	Lifetime of the reference drivetrain	[years]
U_{Ref}	Annual use of the reference drivetrain	[km/year or hr/year]
$C_{Ref-maint.}$	Maintenance cost of the reference drivetrain	[€/km or €/hr]
P_{Ref}	Power of the reference drivetrain	[kW]
Eff_{Ref}	Efficiency/Energy consumption of the reference drivetrain	[MJ/km or MJ/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/H₂ drivetrain costs, is calculated (see equation below). This linear correlation of allowable hydrogen costs to assumed FC/H₂ 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/H₂ technology is equal to the reference technology in the considered case.



$$\text{Allowed Cost of H}_2 \text{ [€/GJ]} = \frac{(C_{\text{ref}} - C_{\text{H}_2\text{-Sys-maint.}}) \cdot t_{\text{H}_2\text{-Sys}} \cdot U_{\text{H}_2\text{-Sys}} - C_{\text{H}_2\text{-Sys}} \cdot P_{\text{H}_2\text{-Sys}}}{t_{\text{H}_2\text{-Sys}} \cdot U_{\text{H}_2\text{-Sys}} \cdot \frac{\text{Eff}_{\text{H}_2\text{-Sys}}}{1000}}$$

C_{ref}	Total cost of reference system	[€/km or €/hr]
$C_{\text{H}_2\text{-Sys-maint.}}$	Cost of Maintenance of FC/H ₂ system	[€/km or €/hr]
$t_{\text{H}_2\text{-Sys}}$	Lifetime of the FC/H ₂ system	[years]
$U_{\text{H}_2\text{-Sys}}$	Annual use of FC/H ₂ system	[km/year or hr/year]
$C_{\text{H}_2\text{-Sys}}$	Assumed cost of FC/H ₂ system (Values used: 0, 200, 500, 1000, 2000, 4000)	[€/kW]
$P_{\text{H}_2\text{-Sys}}$	Power of FC/H ₂ system	[kW]
$\text{Eff}_{\text{H}_2\text{-Sys}}$	Efficiency/Energy consumption of the FC/H ₂ system	[MJ/km or MJ/hr]

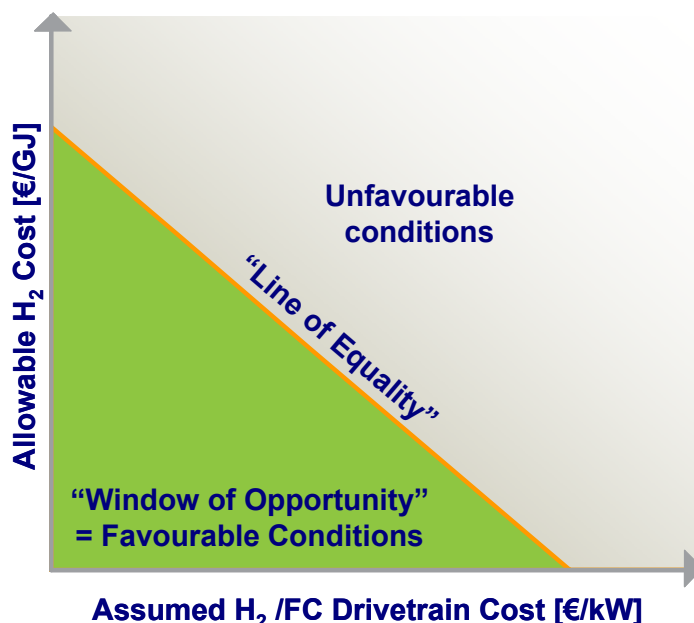


Figure 1: “Line of Equality” – Methodology for economical comparison of applications on an equal cost per unit service basis

For the evaluation of the cost-competitiveness, the calculated, assumed and targeted costs of SOTA and future FC/H₂ 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/H₂ system cost lies within the “Window of Opportunity” (see Figure 2, situation A), the conditions for the FC/H₂ 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/H₂ 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/H₂ drivetrain would stay the same. If the cost of hydrogen stays the same, the horizontal distance reflects necessary FC/H₂ 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.

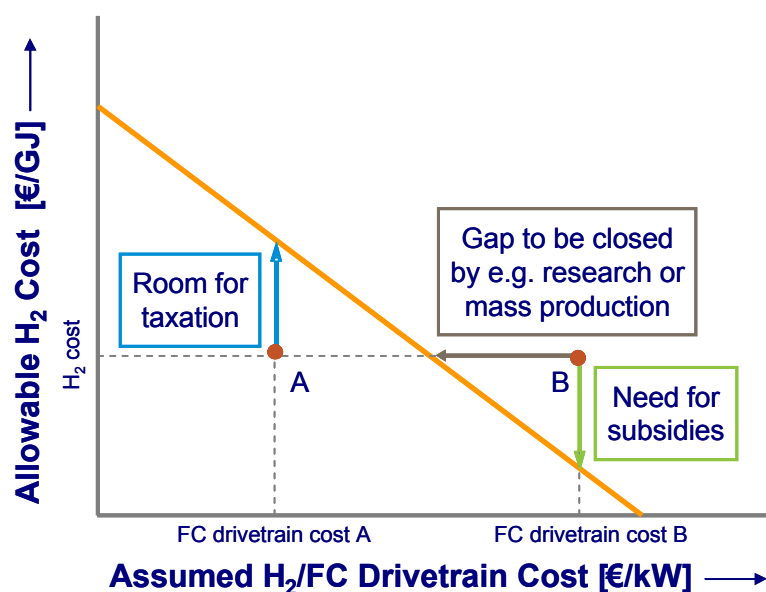


Figure 2: Plotting assumed/evaluated/targeted costs of hydrogen to FC/H₂ drivetrain costs

In this graph, necessities or possibilities of the application using FC/H₂ 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: $oil_{2007} = 60 \text{ \$/barrel}$ or $7,1 \text{ €}_{2000}/\text{GJ}$
($0,7575 \text{ €} = 1 \text{ \$}$; 159 L/barrel ; $34,8 \text{ MJ/L}$; $\text{€}_{2000} = \text{€}_{2007}/1,164$)
- Price of crude oil in 2030: $oil_{2030} = 14 \text{ €}_{2000}/\text{GJ}$ (= 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/H₂ 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. This parameter affects the slope of the “Line of Equality” towards favouring the use of FC/H₂ technologies in applications with higher annual usage, i.e. driven kilometres or hours of operation.

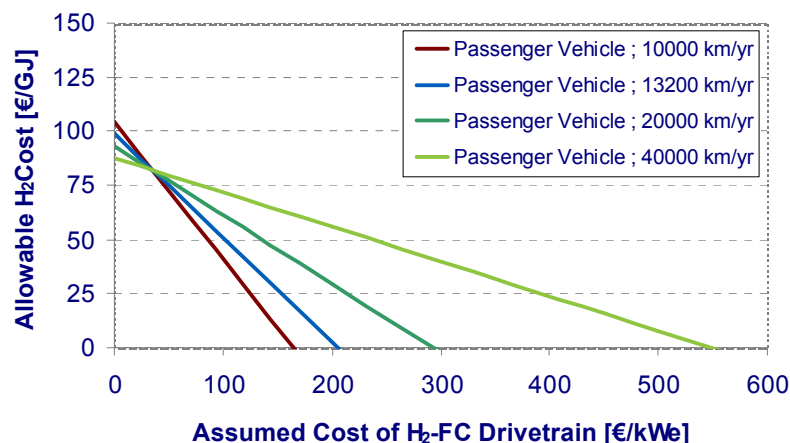


Figure 3: Sensitivity of the calculation of the Window of Opportunity towards different annual usage

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.

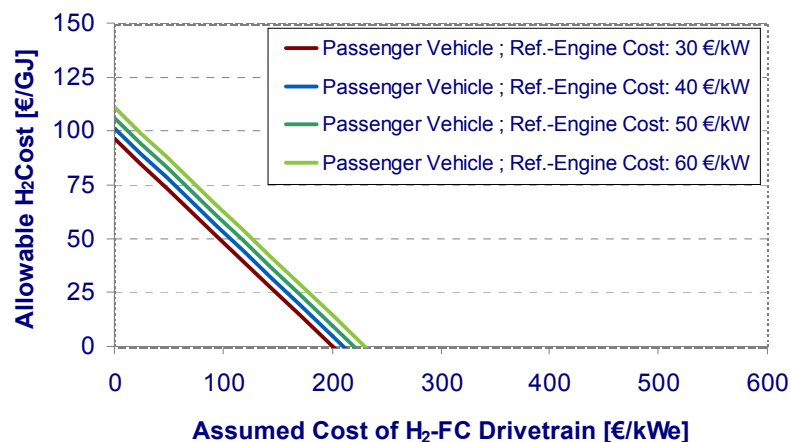


Figure 4: Sensitivity of the calculation of the Window of Opportunity towards different engine costs for reference technology

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).

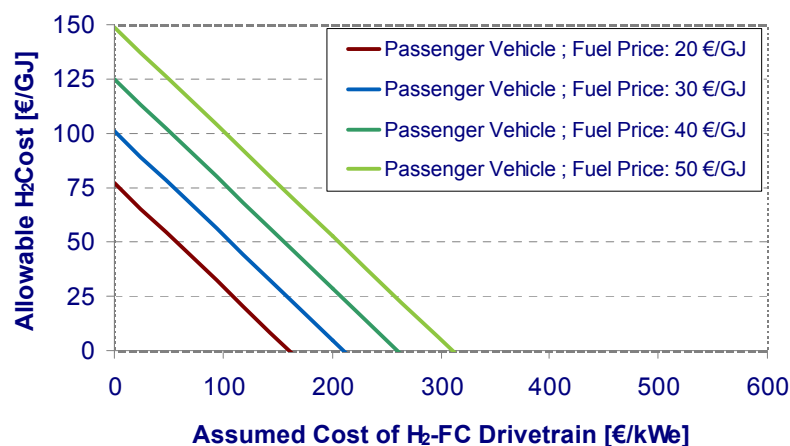


Figure 5: Sensitivity of the calculation of the Window of Opportunity towards different cost of fuel used by reference technologies

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.

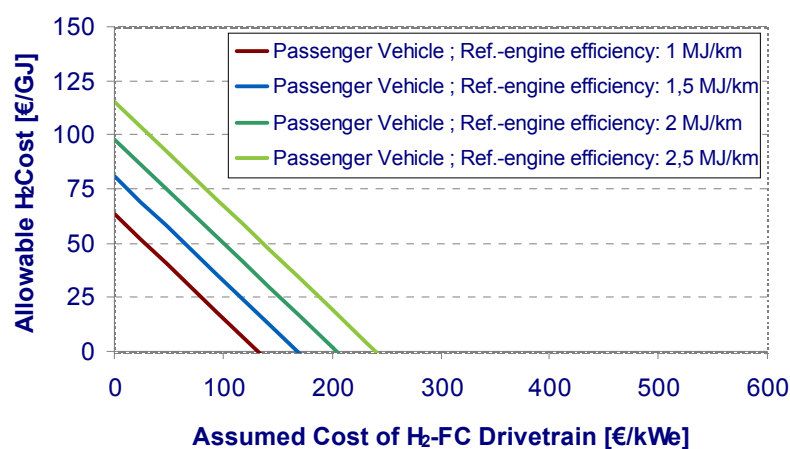


Figure 6: Sensitivity of the calculation of the Window of Opportunity towards different engine efficiencies of the reference technology

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/H₂ technology.

3.4.2.3 Energy Efficiency of the FC/H₂ technology

The chosen values reflecting different energy efficiencies of the FC/H₂ 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.

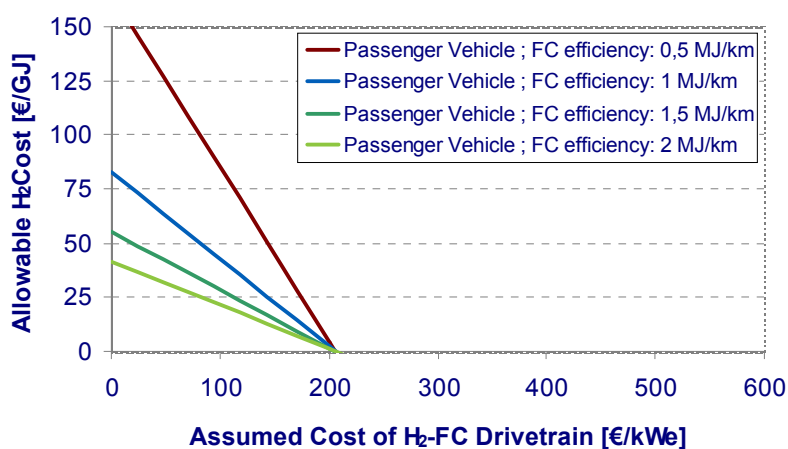


Figure 7: Sensitivity of the calculation of the Window of Opportunity towards different FC/H₂ system efficiencies

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 CO₂ 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 H₂, 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
C₀	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

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.

¹ See Chapter 3.4.3.4 for further explanation



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.

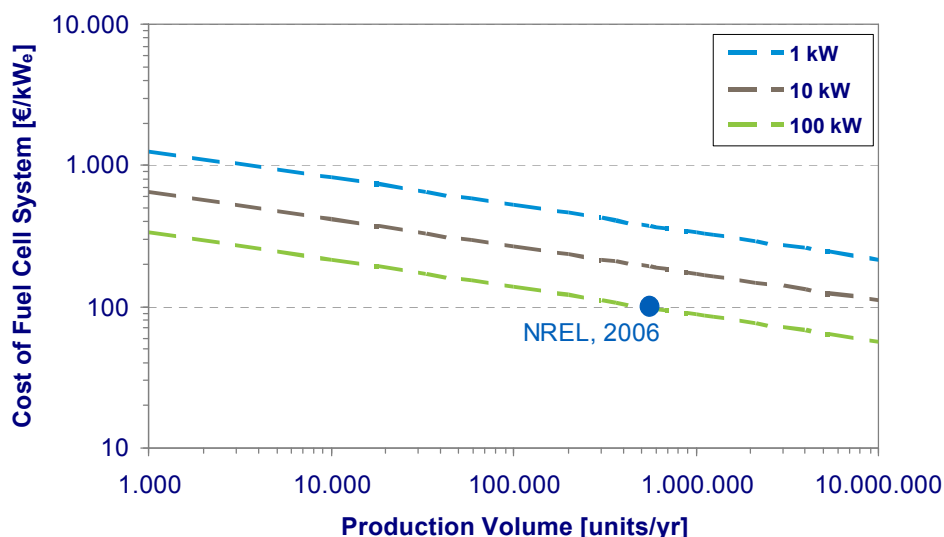


Figure 8: Economies of scale effects on drivetrain costs



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 H₂-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 H₂-FC technology in a certain field of application (e.g. passenger cars). It should not be confused with fleet penetrations!

All H₂-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 CO₂ emissions

For environmental comparison of different applications a common basis for the CO₂ 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 CO₂ emission factors for the electricity network in different countries [4] [5].

Table 5 provides the source-to-user emission factors for conventional fuels and H₂ from different sources, all used in the analysis. Furthermore, it provides a mean of taxing CO₂ emissions based on an assumed CO₂ tax of 50 €/ton CO₂ emitted.

Table 5: Source-to-user emission factors for conventional fuels and H₂

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 H₂		
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 CO₂ emission factors (see Figure 26), Table 5 does in this case not provide the means for CO₂ taxation. The HyWays production mix includes a CO₂ emissions factor of 56 g CO₂/MJ, which means that, based on a CO₂ tax of 50€/ton, 2,8 €/GJ have to be added to reflect CO₂ taxation. To illustrate a taxation of 100€/ton CO₂ 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 CO₂ emissions by replacing reference with FC/H₂ 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	30 000 km/yr	
Forklift (Electric 24/5)		2 MJ/km		
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 €/kW	Maintenance cost €/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/H₂ 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 H₂-FC/H₂-ICE (0,01 and 0,018 €/km) drivetrains is applied to the maintenance 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: H₂ 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%

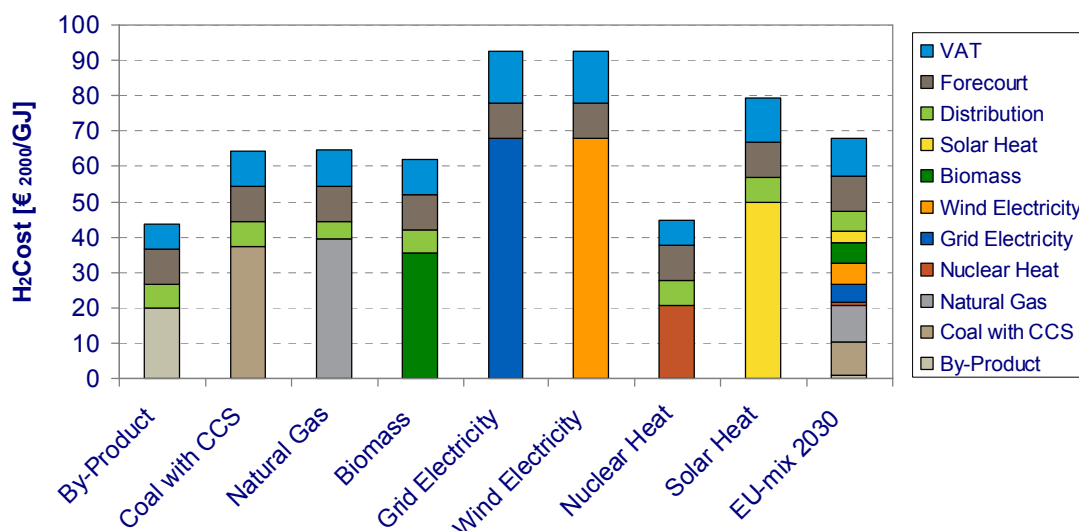


Figure 9: Cost of hydrogen (€₂₀₀₀/GJ) from different sources using WT4.3 and HyWays production mix for 2030 from member state review

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/H₂ applications including the Windows of Opportunities and corresponding specifications. This information can be used to:

- Analyse the position of FC/H₂ 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/H₂ 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/H₂ technologies that would lead to a positive business case (purely based on cost-competitiveness).

The next sub-chapters will evaluate the opportunities of FC/H₂ 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 H₂-ICE the Windows of Opportunity are much smaller. This is caused by the lower efficiency (see Chapter 3.4.2.3) of the H₂-ICE drivetrain compared to the H₂-FC and thus leads to lower allowable hydrogen costs.

In urban operation, it is expected that the efficiency of H₂-ICE drivetrains will stay significantly below that of the H₂-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, H₂-ICE technology is not further considered in the cost analysis.

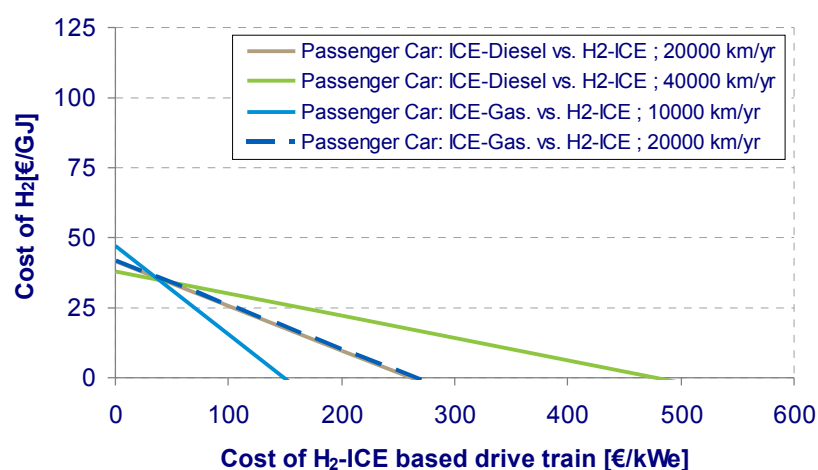


Figure 10: Windows of Opportunity for passenger cars using a H₂-ICE based drive train.

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

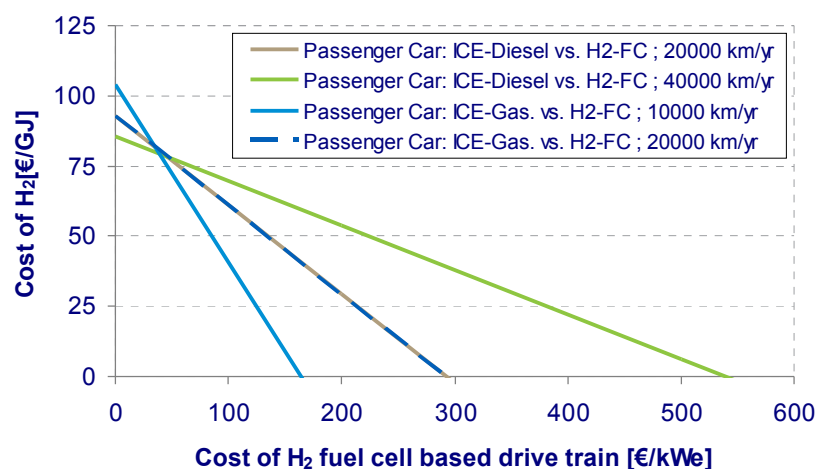


Figure 11: Windows of Opportunity for passenger cars using a H₂-FC based drive train. Considered reference technologies are internal combustion engines running on either diesel or gasoline for different annual mileage (km)

4.3.1.2 H₂-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) H₂-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 CO₂ 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%.

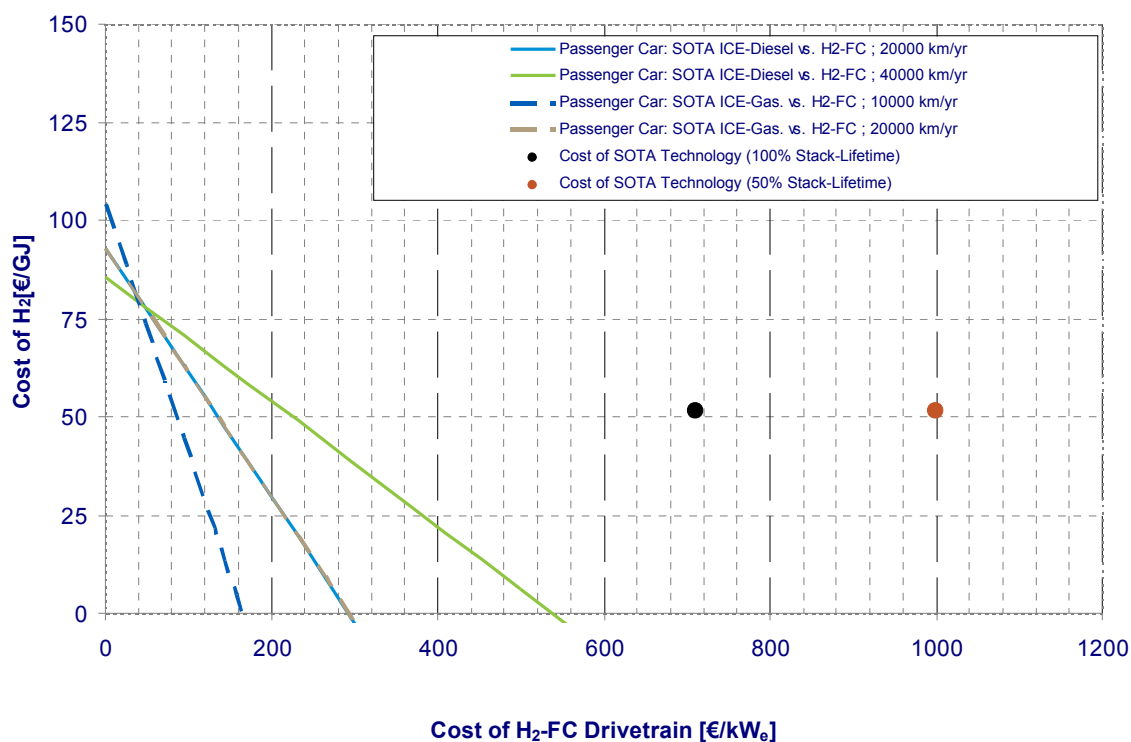


Figure 12: Windows of Opportunity for passenger cars based on SOTA technologies and 2007 prices and policies

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) H₂-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.

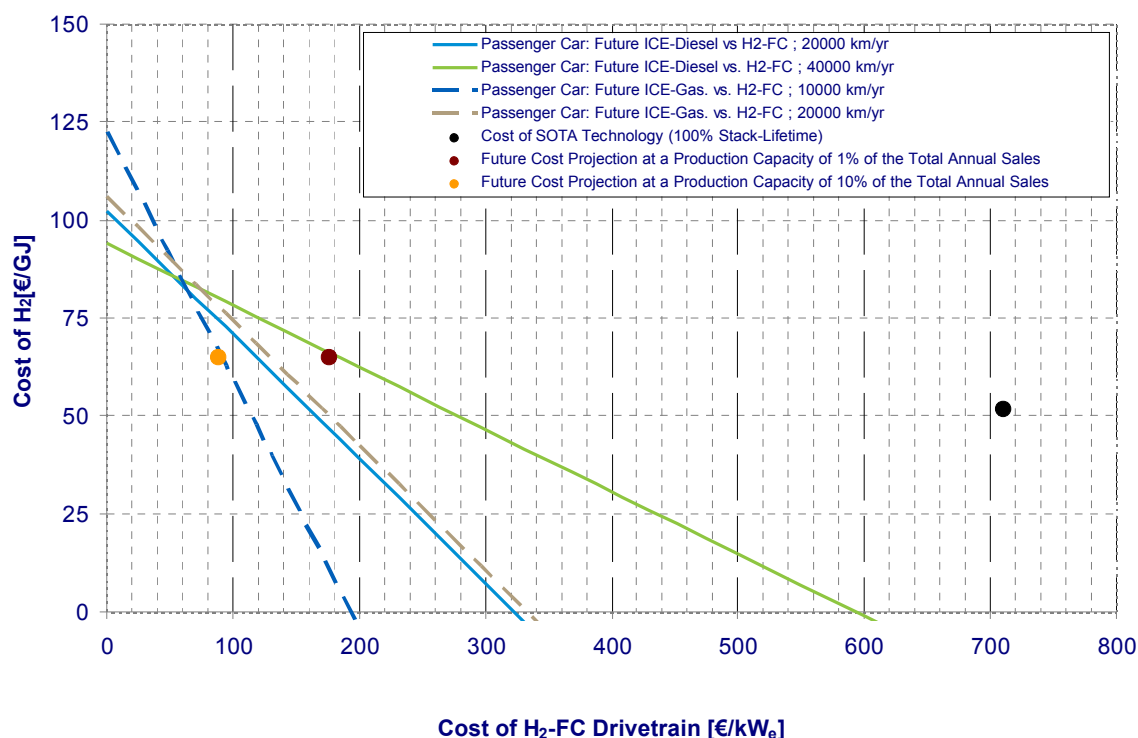


Figure 13: Windows of Opportunity for passenger cars based on SOTA FC and 2020 ICE technology, prices and policies

The black data point reflects SOTA H₂-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) H₂-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 CO₂ emissions. Therefore, Figure 14 and Figure 15 show the effect on both the cost of fossil fuels and hydrogen if a CO₂ 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 CO₂ 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.

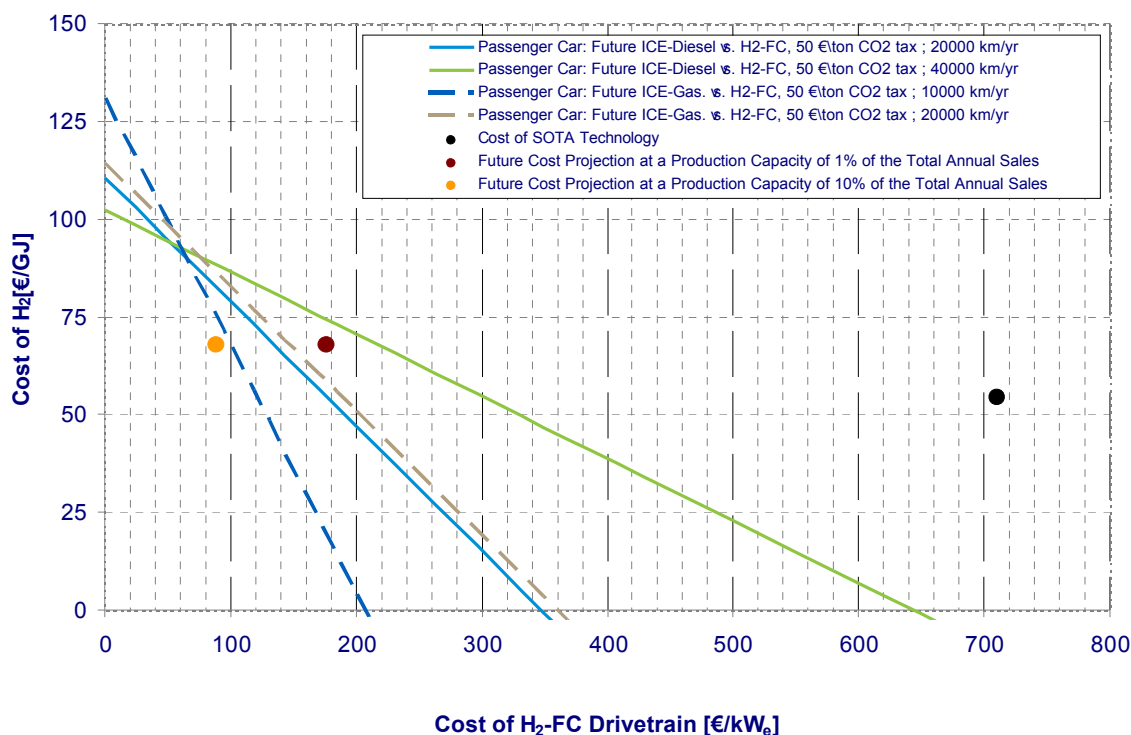


Figure 14: Windows of Opportunity for passenger cars based on SOTA FC technology and 2020 ICE technology, prices and policies including a CO₂ tax of 50 €/ton

The black data point reflects SOTA H₂-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR plus 2,8 €/GJ CO₂ tax. The red and yellow data points reflect future (2020-2025) H₂-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 CO₂ tax in 2030.

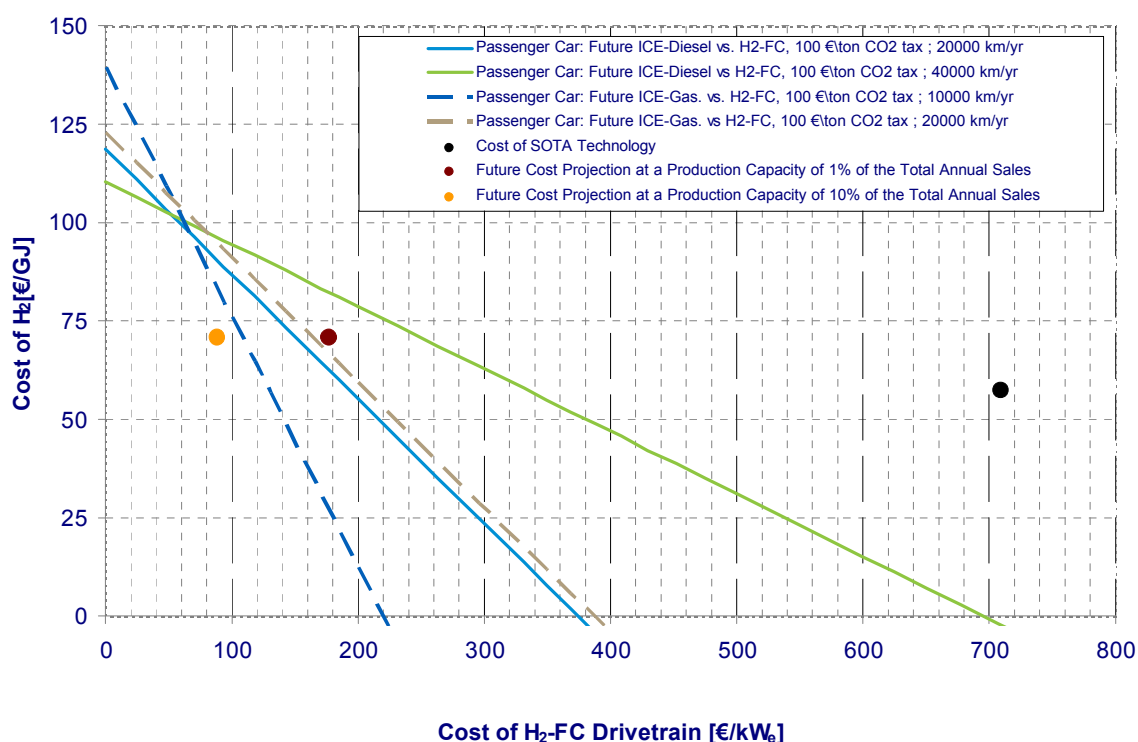


Figure 15: Windows of Opportunity for passenger cars based on SOTA FC technology and 2020 ICE technology, prices and policies including a CO₂ tax of 100 €/ton

The black data point reflects SOTA H₂-FC specs (100% stack-lifetime) and SOTA cost of hydrogen produced from NG (mean 2007 cost) via SMR plus 5,6 €/GJ CO₂ tax. The red and yellow data points reflect future (2020-2025) H₂-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 CO₂ tax in 2030.

4.3.1.3 H₂-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 led to a significant reduction in their cost, they might build an attractive business case for light duty trucks.

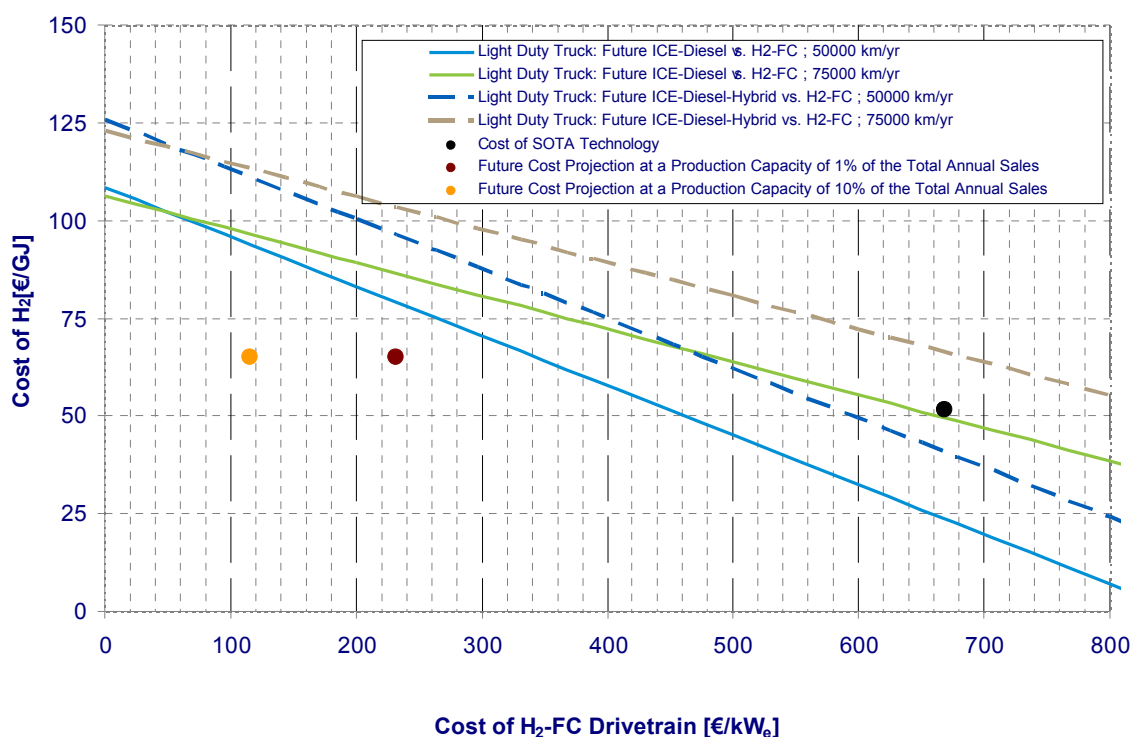


Figure 16: Windows of Opportunity for light duty trucks based on SOTA FC and 2020 ICE technology, prices and policies.

The black data point reflects SOTA H₂-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) H₂-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.

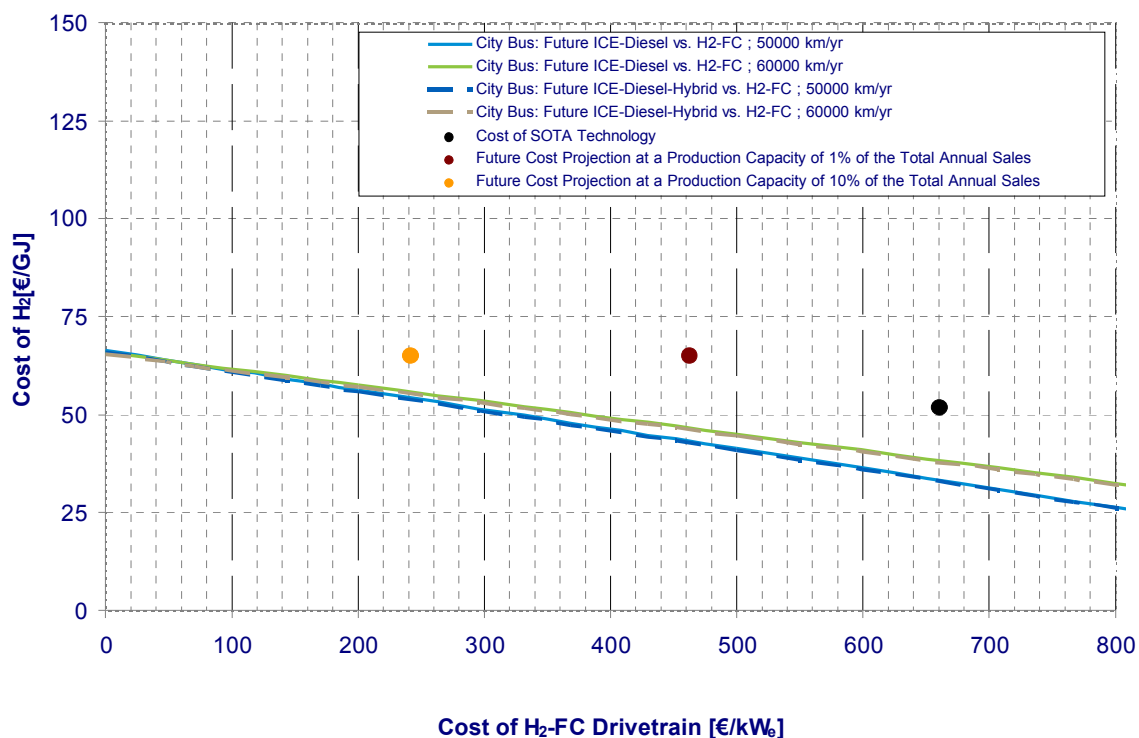


Figure 17: Windows of Opportunity for city buses based on SOTA FC and 2020 ICE technology, prices and policies

The black data point reflects SOTA H₂-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) H₂-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 H₂-FC Applications

To identify market opportunities of SOTA and future H₂-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 H₂-FC technologies.

Considering the cases, where electrical reference technologies are involved, the H₂-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 H₂-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 H₂-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.

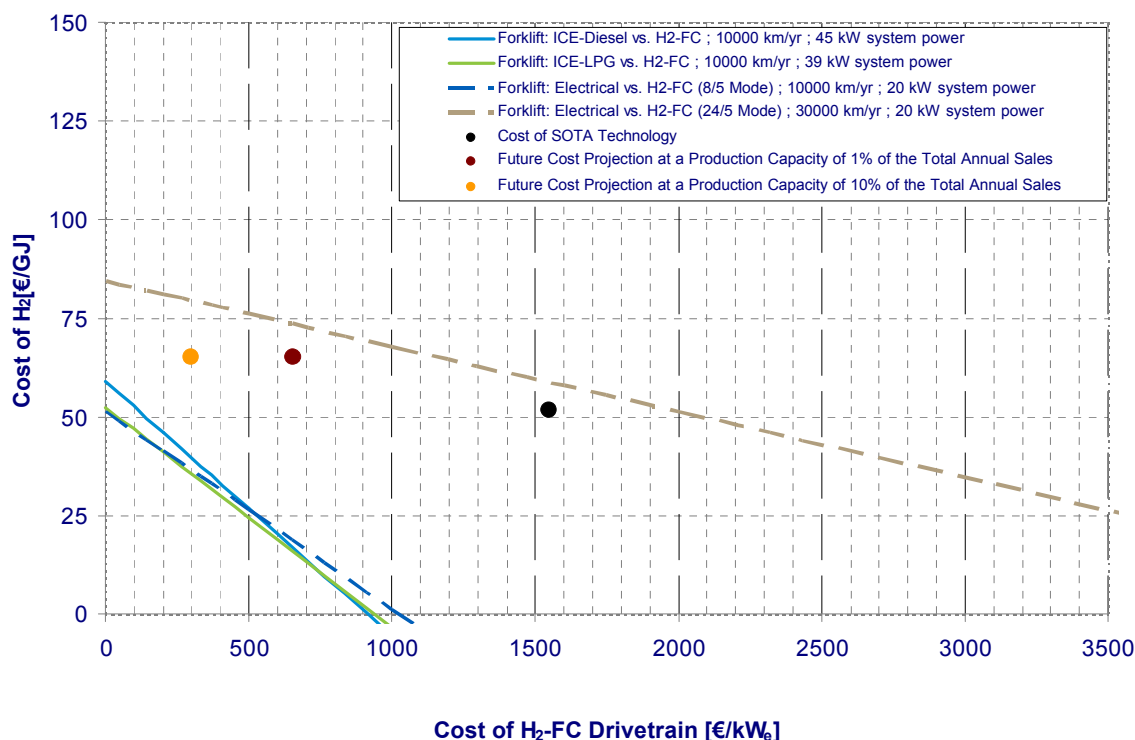


Figure 18: Windows of Opportunity for forklifts based on SOTA FC and reference technologies, prices and policies.

The black data point reflects SOTA H₂-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) H₂-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, H₂-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 H₂-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.

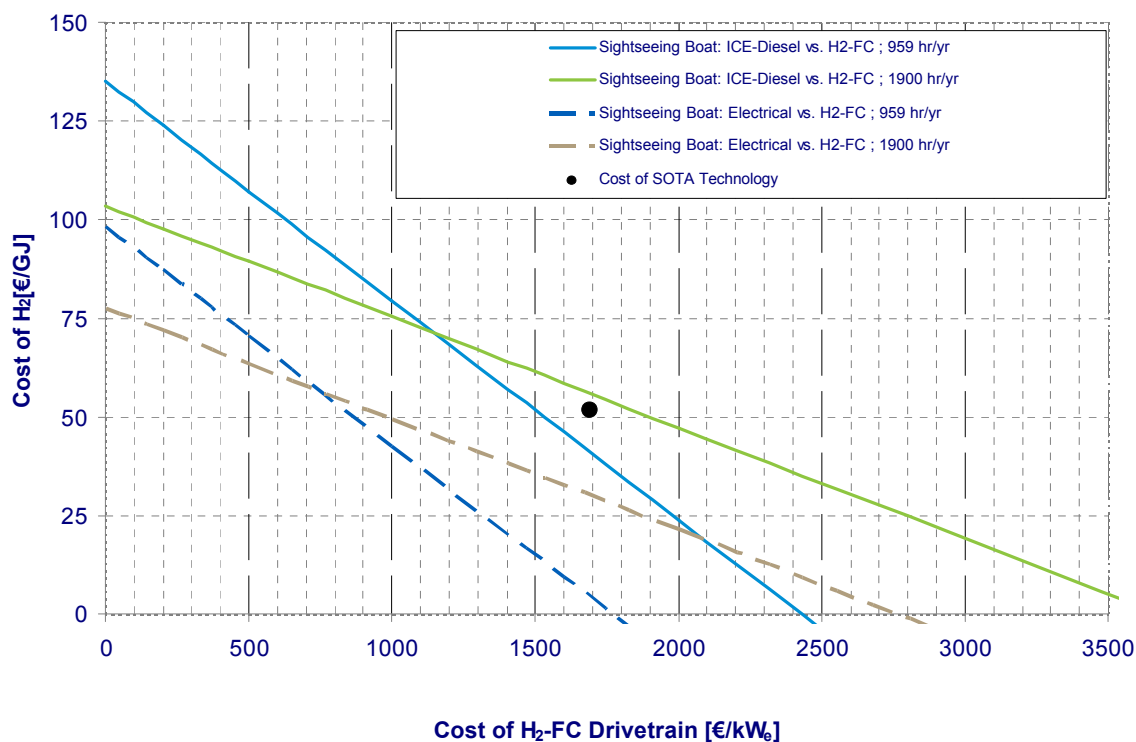


Figure 19: Windows of Opportunity for sightseeing boats based on SOTA FC and reference technologies, prices and policies

The black data point reflects SOTA H₂-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.

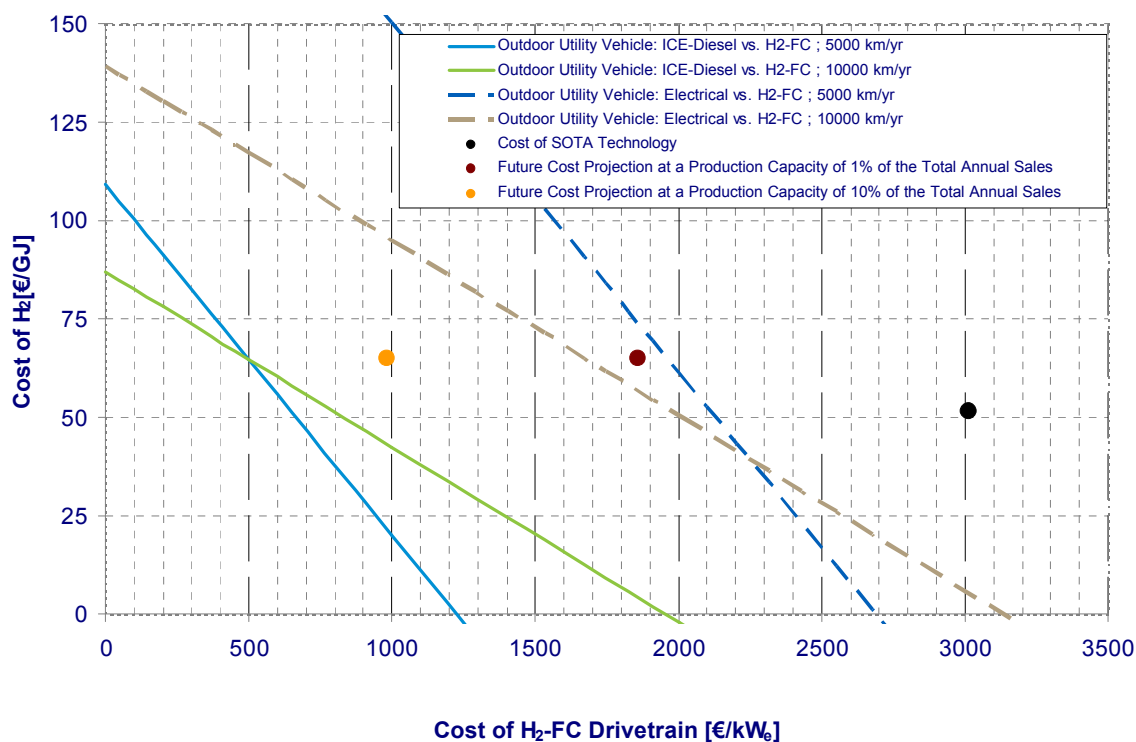


Figure 20: Windows of Opportunity for outdoor utility vehicles based on SOTA FC and reference technologies, prices and policies

The black data point reflects SOTA H₂-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) H₂-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 H₂-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.

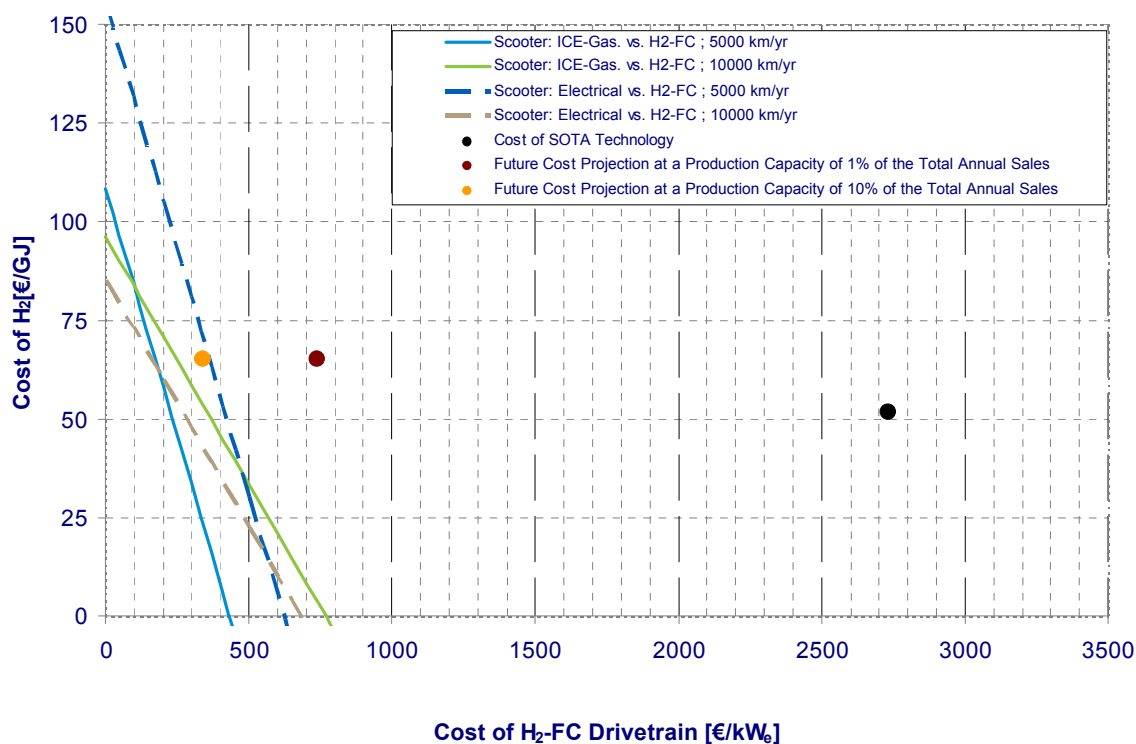


Figure 21: Windows of Opportunity for scooters based on SOTA FC and reference technologies, prices and policies

The black data point reflects SOTA H₂-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) H₂-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.

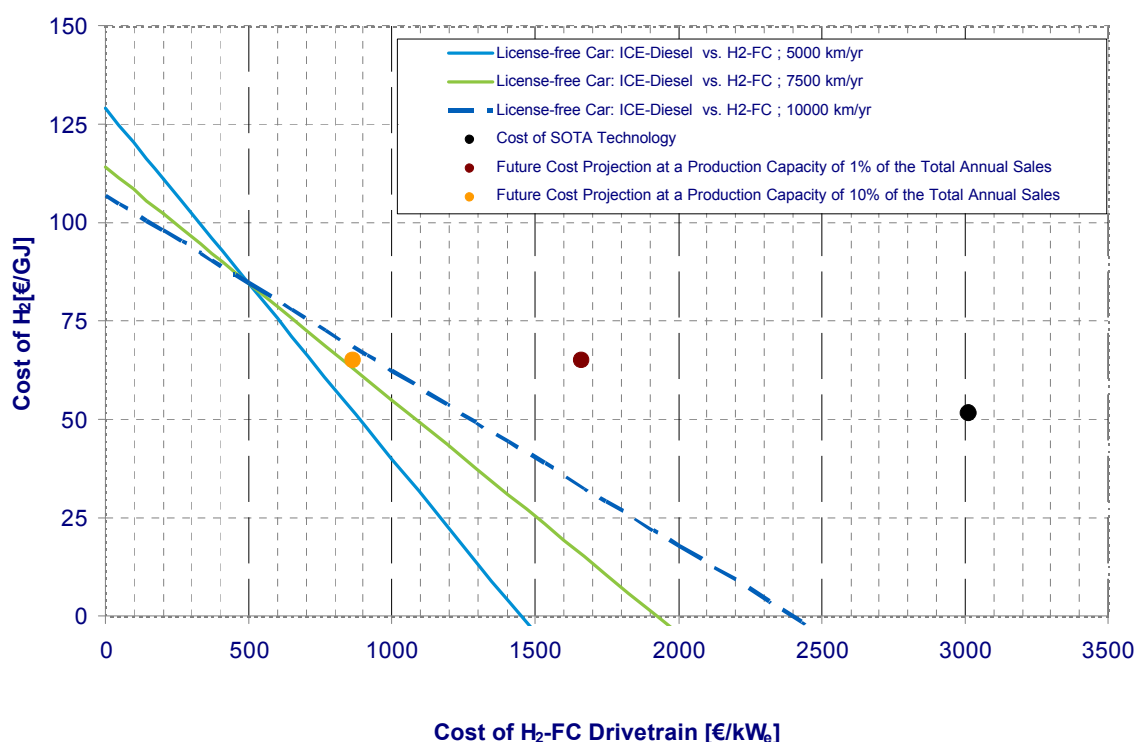


Figure 22: Windows of Opportunity for license-free cars based on SOTA FC and reference technologies, prices and policies.

The black data point reflects SOTA H₂-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) H₂-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).

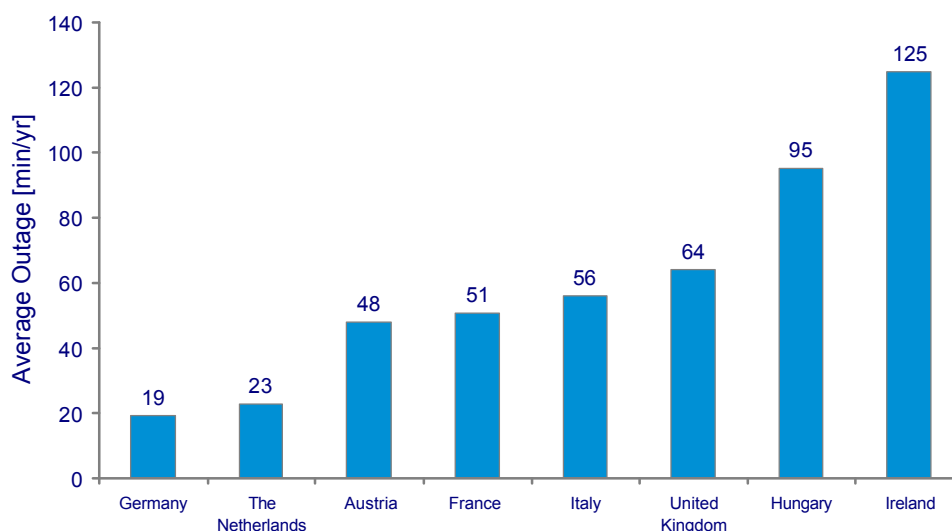
CHP (Central Heat and Power) applications provide both electricity and heat. Consequently their success on the market for continuous operating applications is influenced by both demand for heating systems and electricity. In this case of high annual usage, CHP systems compete with electricity from the 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 need to be conditioned and 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 H₂ 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.



Source: Energie-Kontrol

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)

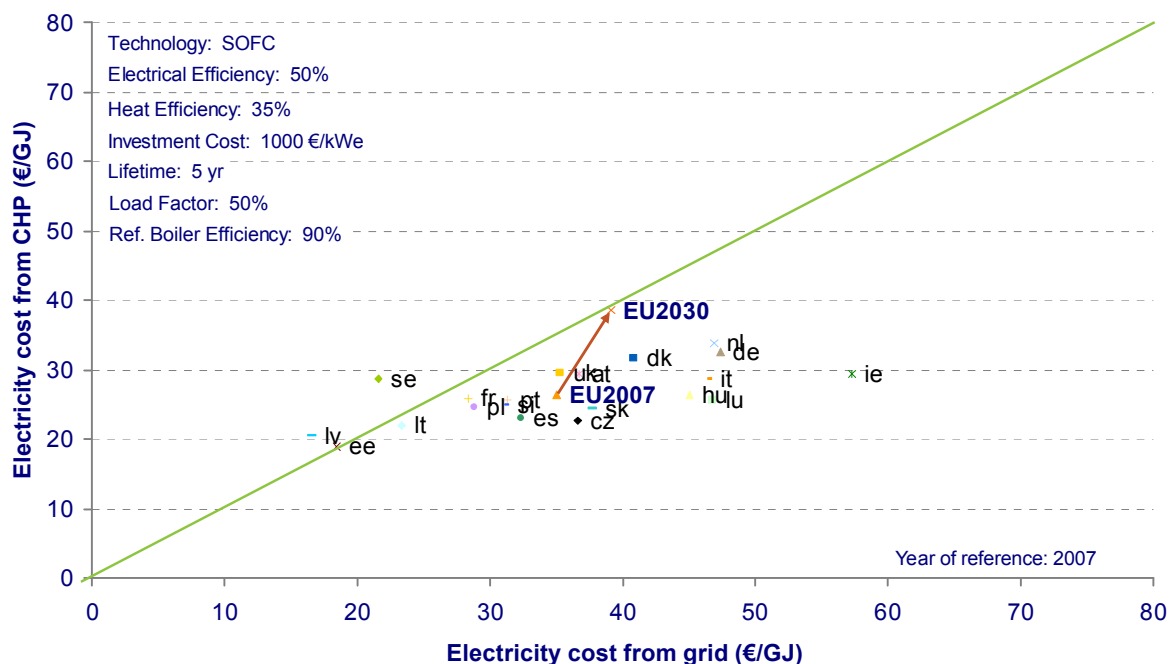


Figure 24: Economy of INDUSTRIAL CHP applications on NG in different countries



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 cost 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).

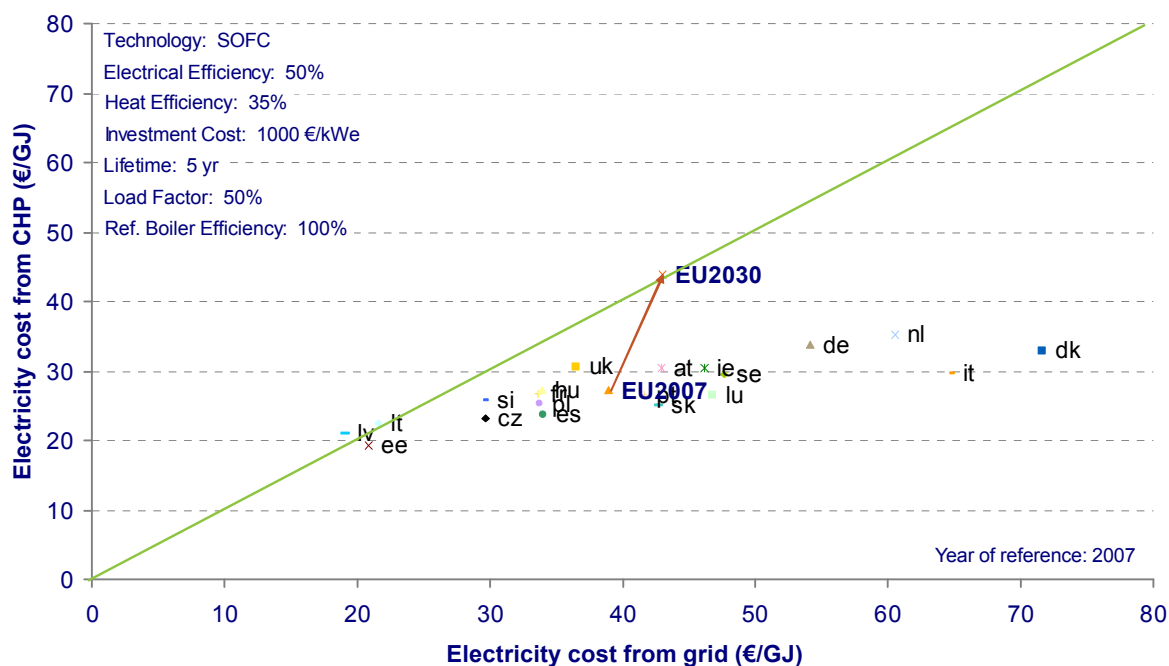


Figure 25: Economy of RESIDENTIAL CHP applications on NG in different countries



4.4 CO₂ Emissions

The CO₂ emissions from the different production pathways and the EU-mix for 2030 from Table 9 are presented in Figure 26. The CO₂ 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.

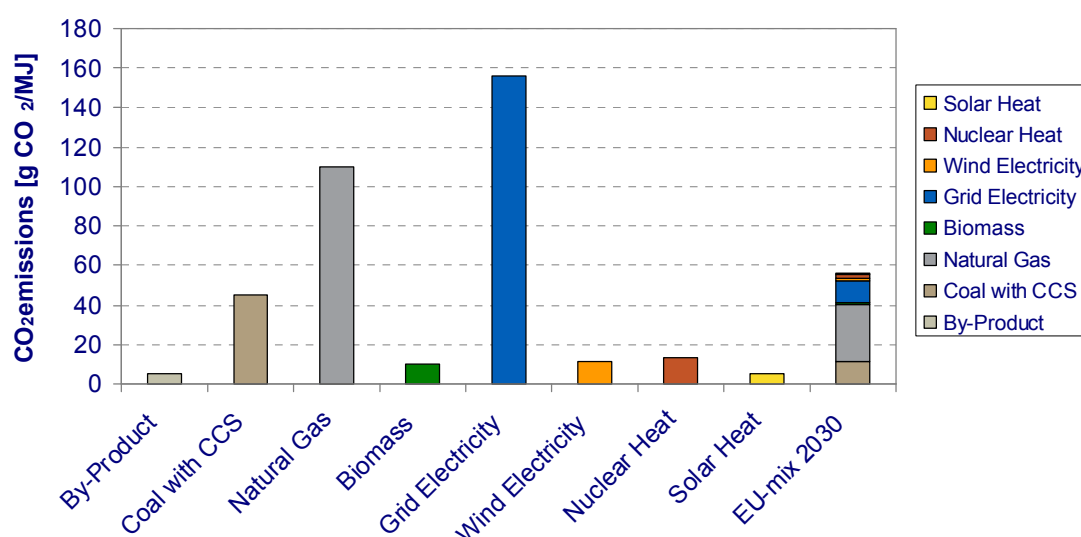


Figure 26: CO₂ emissions for the different pathways in the hydrogen production mix for 2030 from the Concawe project

4.4.1 Transport applications

The use of hydrogen in transport applications can reduce CO₂ 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 CO₂ 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 H₂-ICE are used, the CO₂ emission factor for the hydrogen should be much lower in order to obtain the same CO₂ emission reduction compared to the same application using fuel cells.

In Figure 27 the CO₂ emission of 3 reference vehicles and their fuel cell vehicles are compared for hydrogen from different sources. With a CO₂ emission factor for hydrogen production between 150 and 180 gCO₂/MJ the effect on total CO₂ 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 CO₂ reduction.

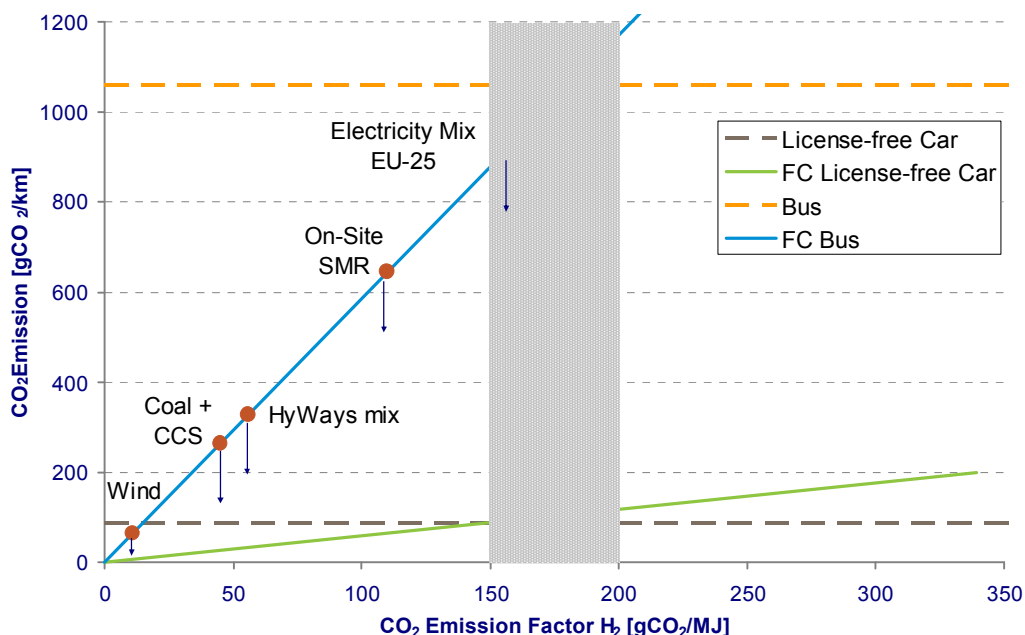


Figure 27: CO₂ emission of the reference vehicle running on diesel and FC vehicle using hydrogen from different sources

The bar shows the range of CO₂ emission factors for H₂ for which the WTW CO₂ 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 CO₂ reduction for Europe, which is presented in Figure 28. For the calculation the present number of vehicles are used and the assumption that the H₂-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 H₂-ICE operated passenger cars, the potential is practically halved. The buses and forklifts CO₂ 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.

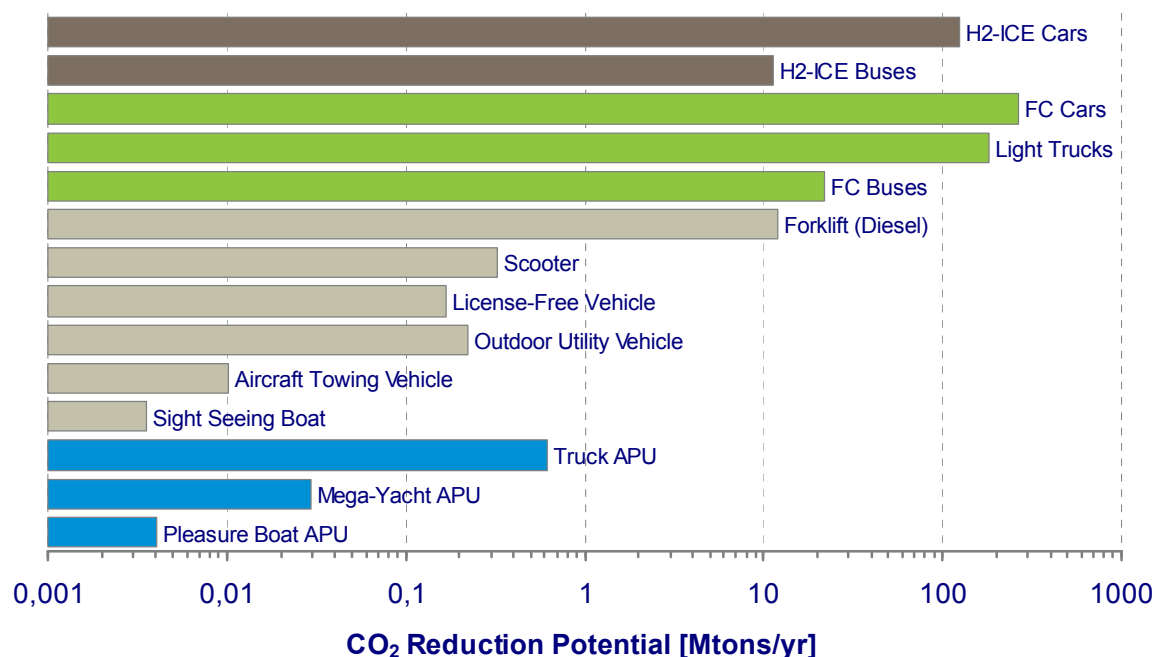


Figure 28: CO₂ reduction potential for Europe for the different applications using the H₂ production mix from HyWays

When the CO₂ 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 CO₂ 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.

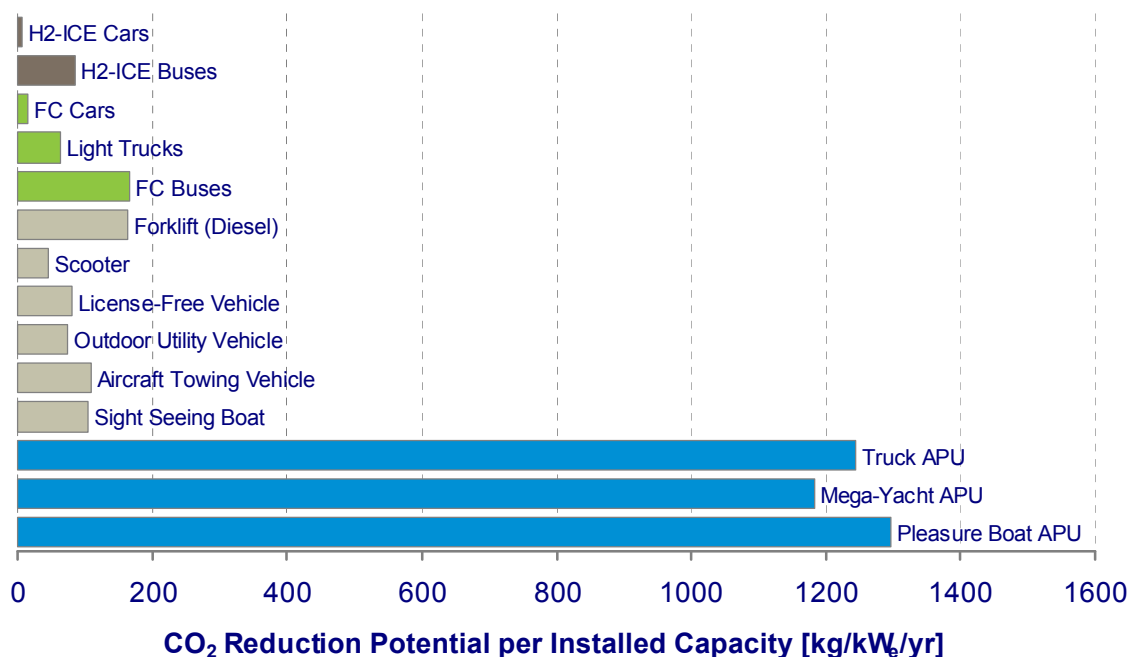


Figure 29: CO₂ reduction potential for different applications and per installed capacity of the conversion unit

In order to reach the maximum potential CO₂ 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 H₂-ICE passenger cars, the installed wind turbine capacity has to double once more due to the lower efficiency of the H₂ combustion engine compared to the fuel cell.

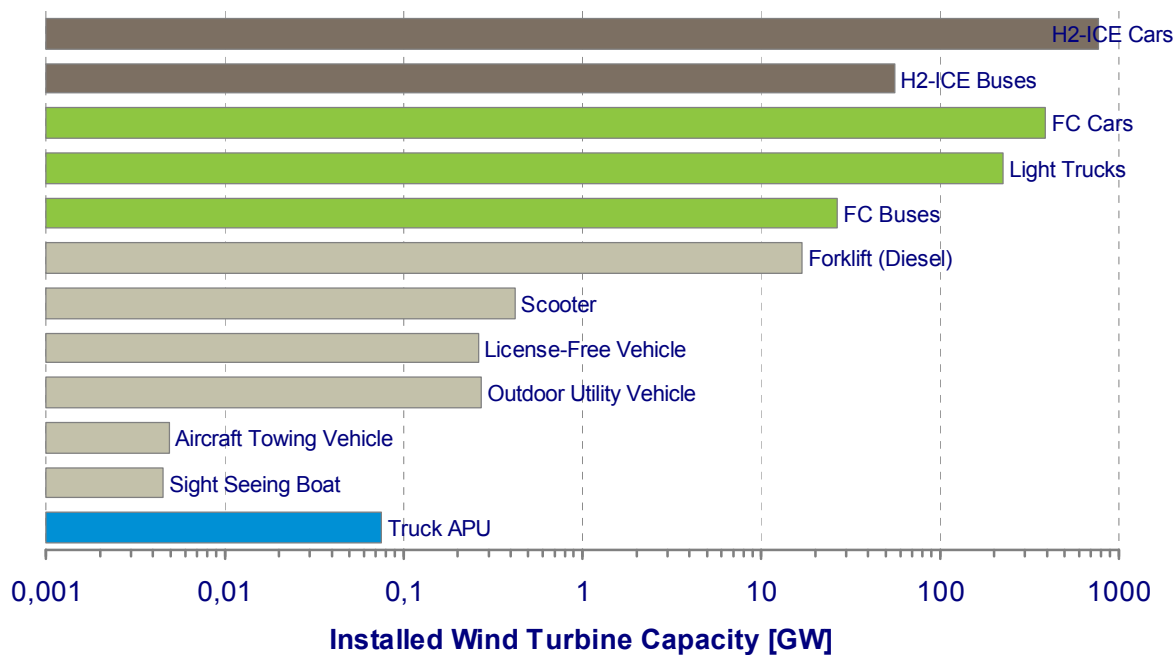


Figure 30: Estimated required capacity of wind turbines for the hydrogen production by electrolysis per application

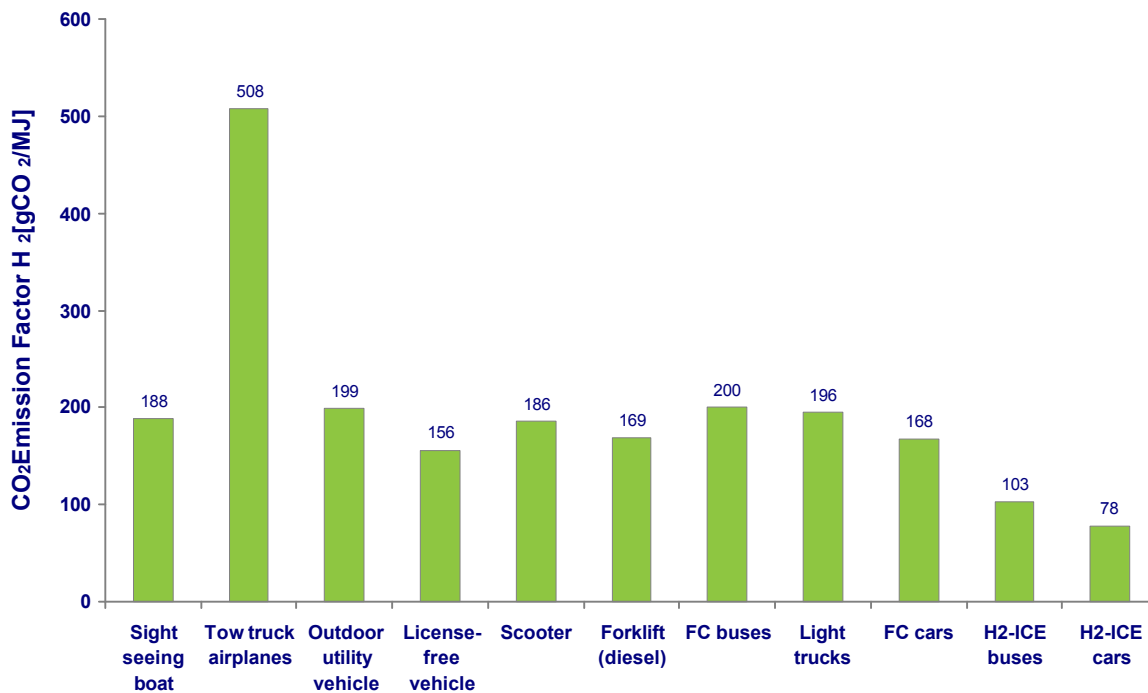


Figure 31: Maximum CO₂ emission factor for H₂ for the different applications using diesel or gasoline



4.4.2 Stationary applications

The CO₂ 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 CO₂ 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 CO₂ emission reduction potential for the CHP applications is substantial as shown in Figure 32. 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.

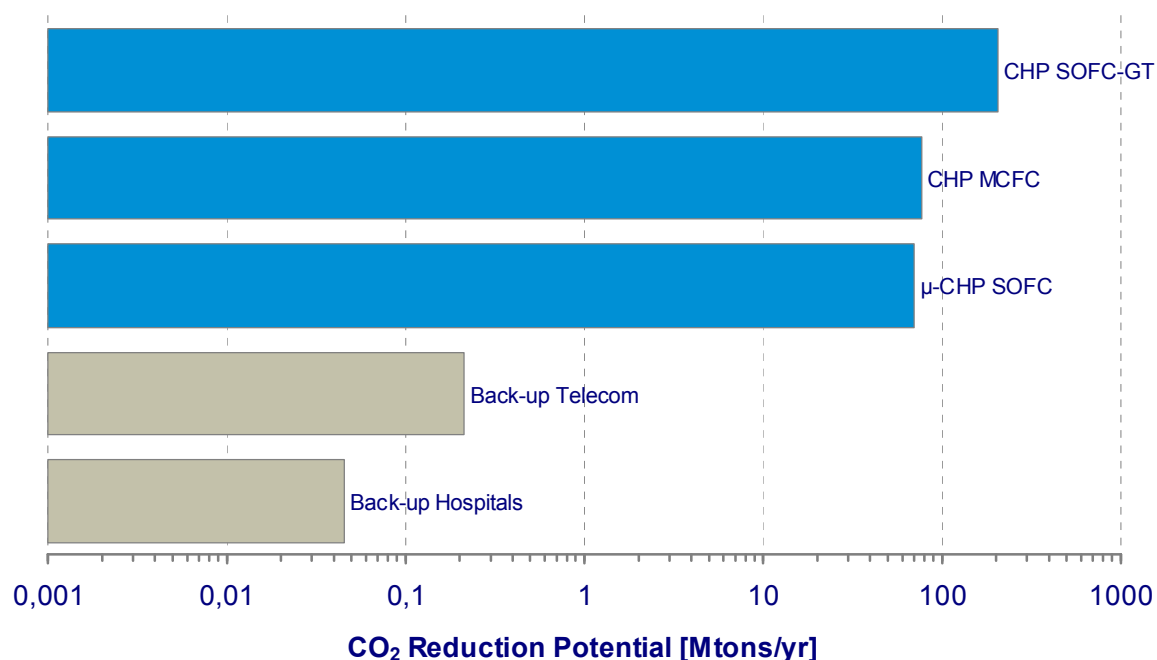


Figure 32: CO₂ reduction potential for stationary applications

The CO₂ 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 CO₂ reduction of 200 Mton CO₂/yr exist when CHP systems on the basis of SOFC +GT or 76 Mton CO₂/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 CO₂ reduction potential per installed kW is shown in Figure 33. For the back-up applications the CO₂ reduction is small due to the limited amount of operating hours. The SOFC + gas turbine provides the largest CO₂ 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.

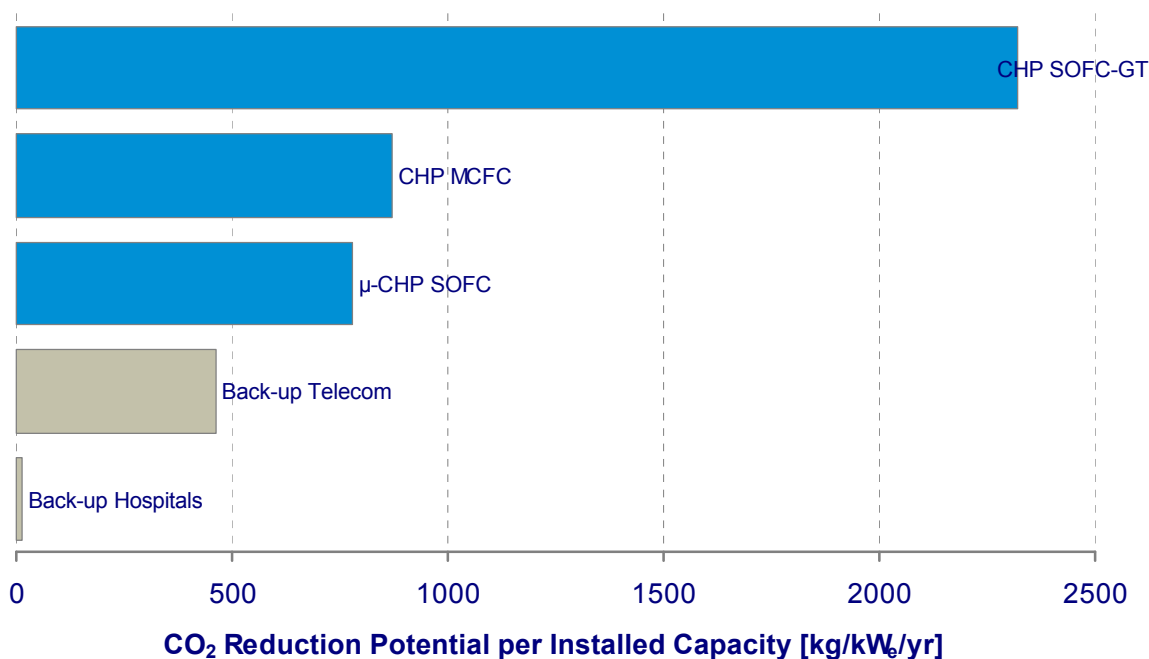


Figure 33: CO₂ reduction potential per installed kW for stationary applications



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
<ul style="list-style-type: none"> - Telecom. - Emergency response communications - Federal agencies – FAA, NOAA, USCG 	<ul style="list-style-type: none"> - Forklifts in distribution centres - Ground support equipment in airports 	<ul style="list-style-type: none"> - 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 	<ul style="list-style-type: none"> - 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/H₂ 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 CO₂ 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 CO₂ 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 H₂-FC drivetrain cost as shown in the Figure 34, Figure 35, Figure 36 and Figure 37 provide a mean for the analysis of potential cost reductions.

Figure 34 and Figure 36 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 35 and Figure 37.

Figure 34 and Figure 35 show cost breakdowns for a platinum price of 2000 \$/troz, which was used throughout this study, whereas Figure 36 and Figure 37 are based on a platinum price of 900 \$/troz as used in the TIAX study [10].

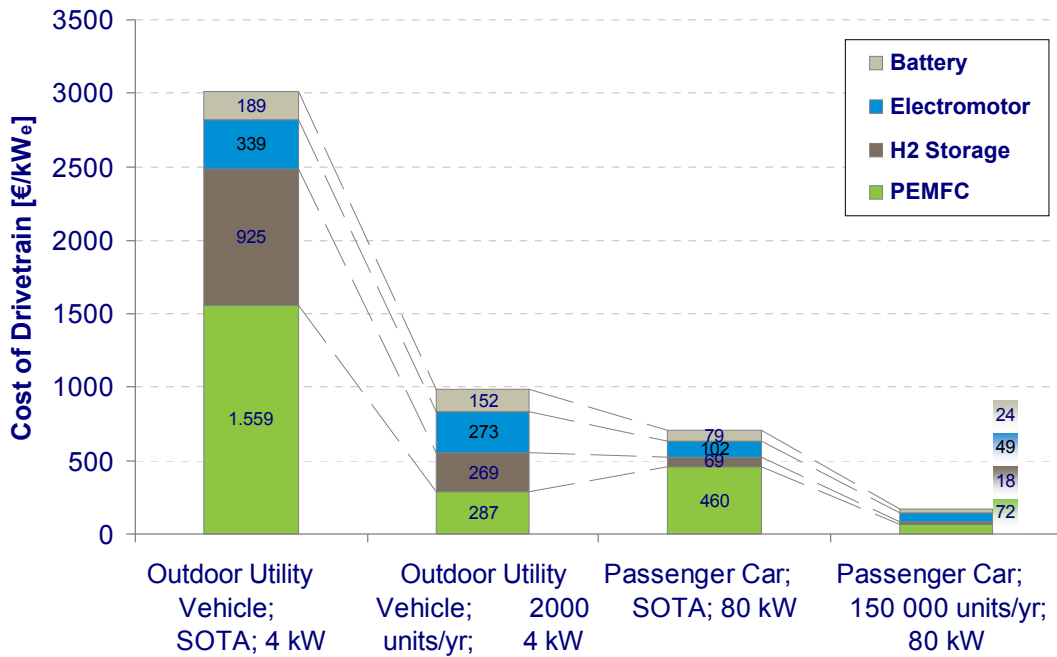


Figure 34: Breakdown of drivetrain cost for annual production capacities of 1000 and 500 000 units and system powers of 10 and 100 kW_e (Pt price of 2000 \$/troz)

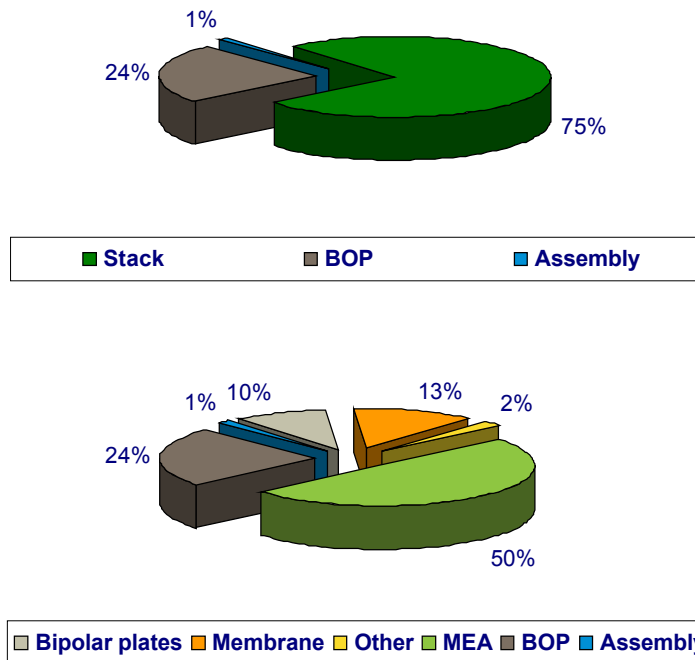


Figure 35: Breakdown of PEMFC cost into its components (Pt price of 2000 \$/troz)

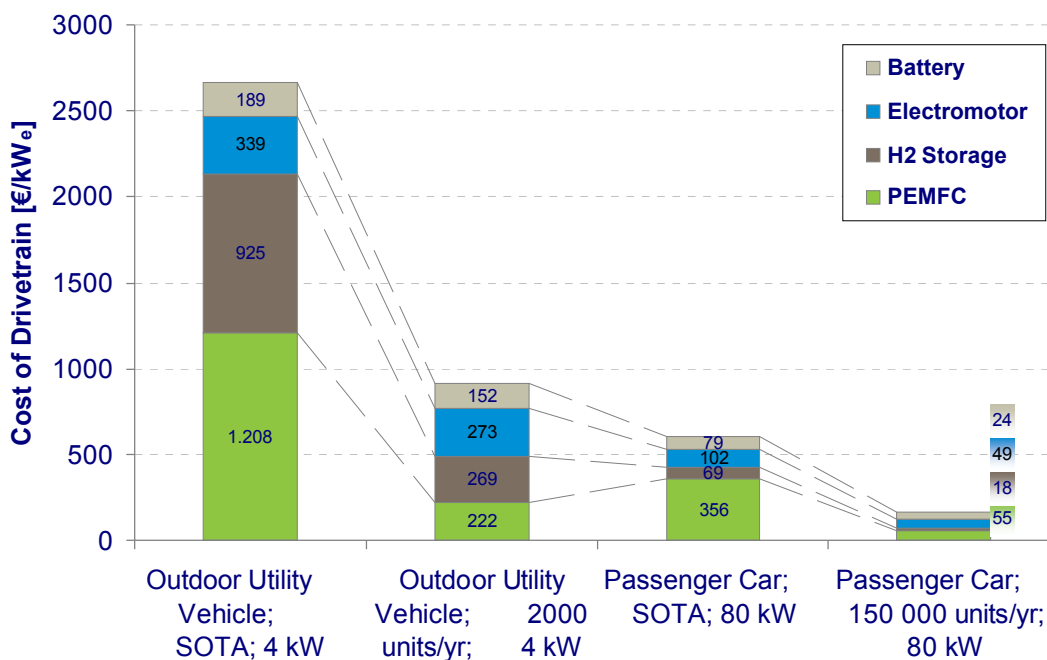


Figure 36: Breakdown of drivetrain cost for annual production capacities of 1000 and 500 000 units and system powers of 10 and 100 kW_e (Pt price of 900 \$/troz)

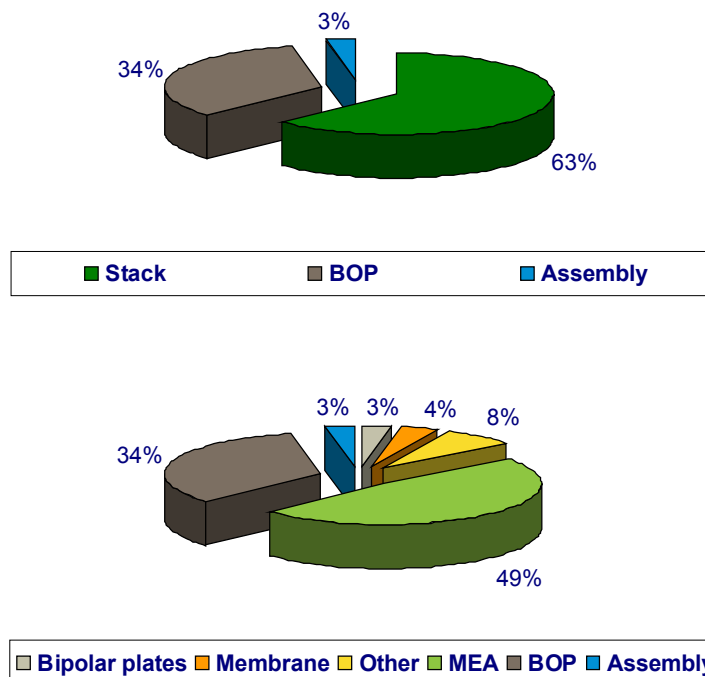


Figure 37: Breakdown of PEMFC cost into its components (Pt price of 900 \$/troz)



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 CO₂ 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 CO₂ reductions because of the large amount of vehicles being used.

The potential of CO₂ 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, CO₂ 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/H₂ technologies.

6.2 Gaps & Priorities

In the case of H₂-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 H₂-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 H₂-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 CO₂ 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.europa.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 H₂ 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 38. 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.

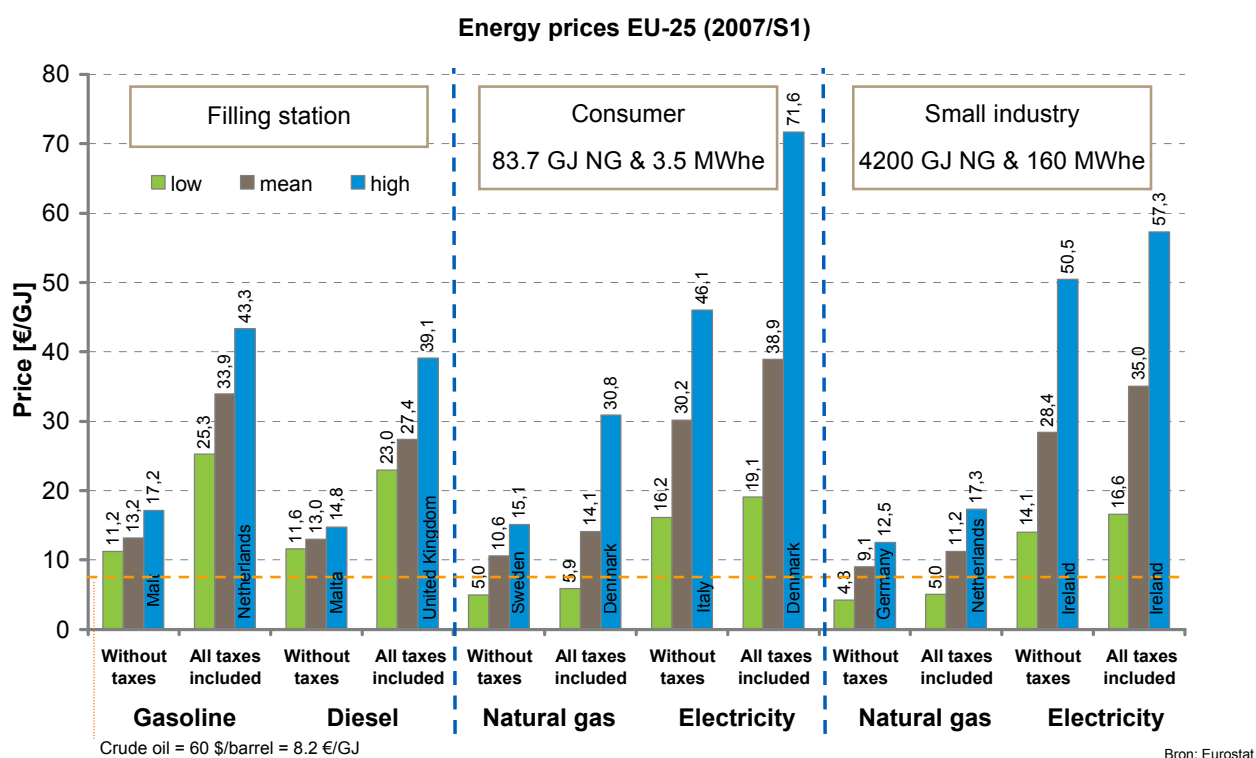


Figure 38: Minimum (low), mean and maximum (high) energy prices (€₂₀₀₇) within the EU-25 on 1st January 2007

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 39.

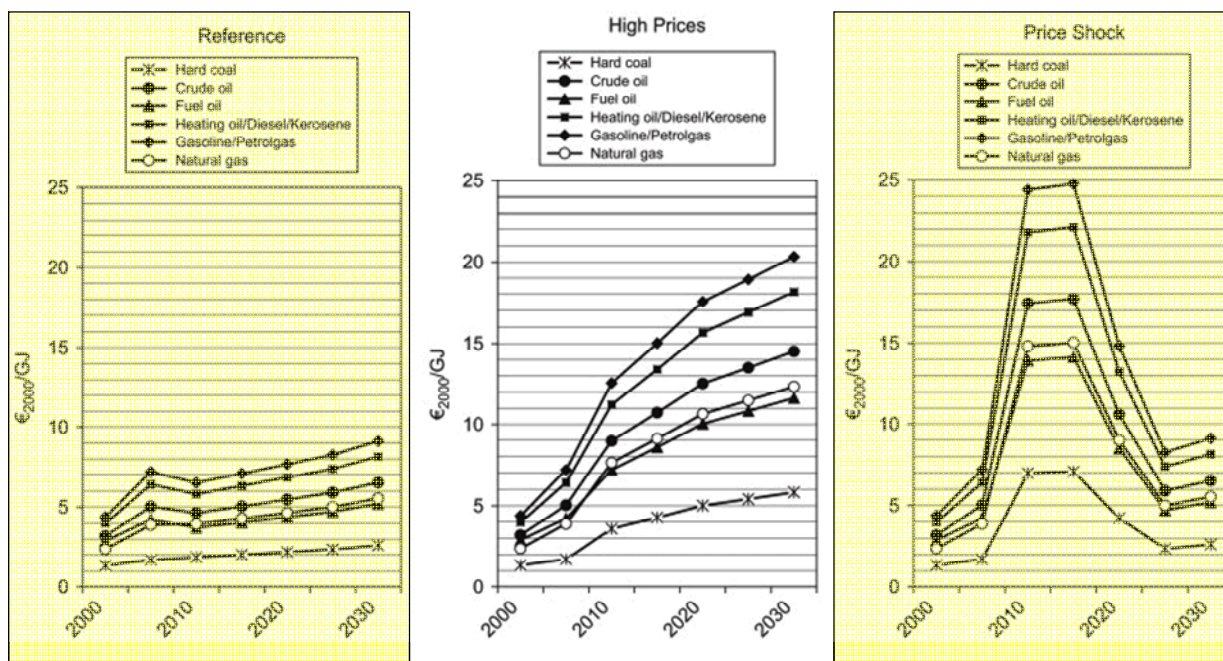


Figure 39: Price scenarios of imported energy carriers in €/2000/GJ. The high prices scenario will be used as a basis for the case study



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 38
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 ($\text{oil}_{2030} = 14 \text{ €}_{2000}/\text{GJ}$) and natural gas price ($\text{gas}_{2030} = 12 \text{ €}_{2000}/\text{GJ}$) from the **high prices scenario** of Figure 39.
2. The crude oil price in Jan 2007: $\text{oil}_{2007} = 7,1 \text{ €}_{2000}/\text{GJ}$.
 - (Using for oil 60 \$/barrel; 0,7575 € = 1 \$; 159 l/barrel; 0,835 kg/l; 41,7 MJ/kg; $\text{€}_{2000} = \text{€}_{2007}/1,164$)
3. Fuel price with taxes₂₀₃₀ = Fuel price with taxes₂₀₀₇ + 1,42*(oil₂₀₃₀-oil₂₀₀₇)
 - 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 40).
4. Fuel price without taxes₂₀₃₀ = Fuel price without taxes₂₀₀₇ + 1,2*(oil₂₀₃₀-oil₂₀₀₇)
 - 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 $\text{oil}_{2007} = 7,1 \text{ €}_{2000}/\text{GJ}$ the gas price $\text{gas}_{2007} = 6,0 \text{ €}_{2000}/\text{GJ}$ using Figure 39.
6. Repeat steps 4 and 5 for the gas price using the difference between $\text{gas}_{2030} - \text{gas}_{2007}$.
 - 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 $\text{oil}_{2030} - \text{oil}_{2007}$. 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 41.

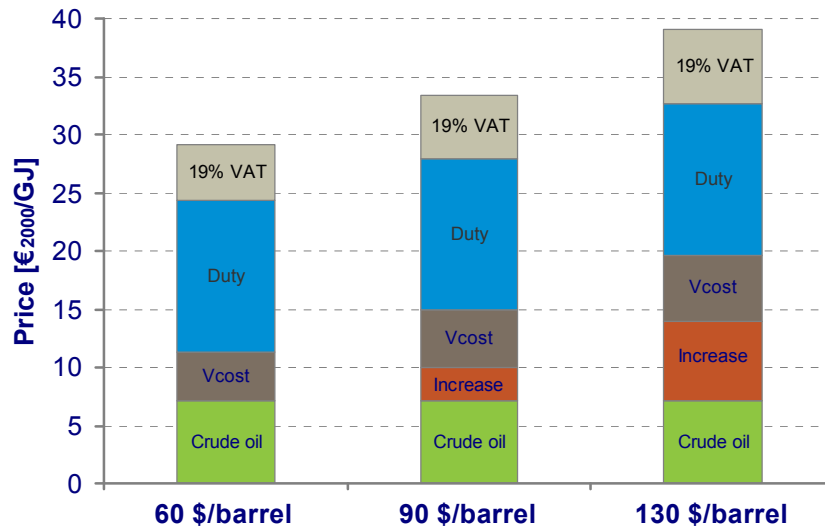


Figure 40: Relation between crude oil price increase and consumer price increase for the mean EU-25 price in 2007 and 2008 (prices in both cases on the 1st January)

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

Electricity prices households EU-15 1991-2007

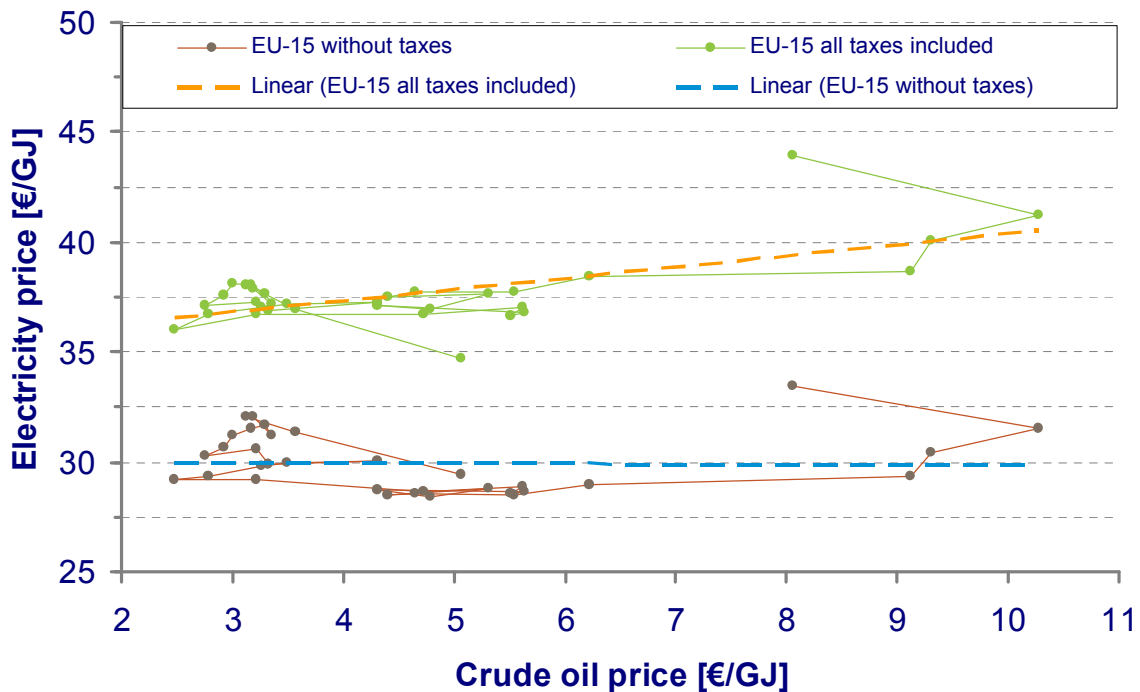


Figure 41: EU-15 household electricity prices vs crude oil price from 1991-2007



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 €/G J	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: CO₂ 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 gCO₂/km in the third column. For stationary applications the efficiency in (MJ/kWh) of the process is used for calculation of the emission in gCO₂/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]	<i>1,4 MJ/km</i> [gCO ₂ /km]	<i>9,0 MJ/kWh</i> [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 CO₂ emissions in gCO₂/km in the last but one column. For stationary applications use the efficiency in (MJ/kWh) for calculation of the emissions in gCO₂/kWh in the last column. The CO₂ emissions in gCO₂/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/kgH₂ and divided by the energy density of 120 MJ/kgH₂. In the HyWays study hydrogen is provided at 700 bar. The effect on the CO₂ 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 H₂ sources (Sources [www.HyWays.de](#)) and [Concawe](#)); FC car efficiency HyWays: 144 km/kgH₂

Concawe (WTW)	<i>Low</i>	<i>High</i>	<i>Mean</i>	Mean	<i>1,4 MJ/km</i>	<i>9,0 MJ/kWh</i>
Compressed H ₂	[gCO ₂ /km]	[gCO ₂ /km]	[gCO ₂ /km]	gCO ₂ /MJ	[gCO ₂ /km]	[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 hydrogen an electrolyser efficiency 65% (LHV) = 77% (HHV) is used to calculate the CO₂



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 gCO₂/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

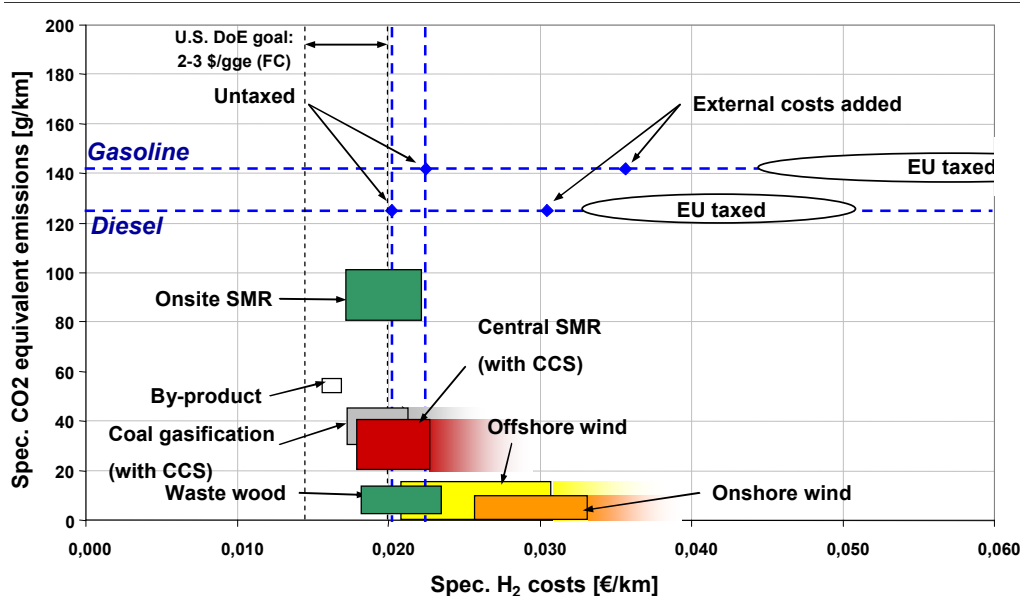


Figure 42: HyWays results on specific H₂ costs and CO₂ equivalent emissions for passenger cars



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