

# Market Opportunities for PEM FC Vehicles

## – A Distance-to-Market Analysis –

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| Revisions                    |                               |                                        |
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## COM34a-4 Market Opportunities for PEM FC Technologies

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### 1 Introduction

Within the EU project Roads2HyCom [1], we analysed market opportunities for PEM FC (proton exchange membrane fuel cell) applications. The aim of this paper is to indicate the near- and mid-term market potentials of different transport applications. The research is based on a cost analysis, taking into account the cost of the FC drivetrain, the cost of hydrogen and the cost of the reference drivetrain for each particular vehicle. This could help stakeholders, who are committed to develop hydrogen activities in choosing promising applications for further research and development of business cases.

Costs of transport applications are often compared by their cost per driven kilometre. The cost of fuel and investment costs are usually the main contributors. In case of mature technologies, these and other influential factors such as the vehicle's lifetime, the average fuel consumption and annually driven distance are known. In case of PEM FC vehicles a different approach is demanded due to two main unknowns: the cost of the FC drivetrain and the cost of hydrogen.

### 2 Methodology

Three steps are undertaken to estimate the cost-competitiveness of PEM FC vehicles:

- 1) Evaluation of FC drivetrain and hydrogen cost combinations leading to equal costs of the PEM FC vehicle and reference vehicle per driven kilometre. They form the economic "Window of Opportunity" describing all favourable conditions for FC vehicles (section 2.1)
- 2) Projection of current and future costs of FC drivetrains and hydrogen (fuel) (section 2.2)
- 3) Current and future costs of FC drivetrains and hydrogen are compared to the economic "Windows of Opportunities" (section 2.3)

Cost data from various sources have been used in this study. In order to allow comparison, all cost values are inflation-adjusted to year-2000-based Euros, if not stated differently. The used exchange rate from €<sub>2000</sub> to US\$<sub>2009</sub> is 0,93 €/€; from €<sub>2009</sub> to US\$<sub>2009</sub> it is 0,75 €/€.

#### 2.1 Evaluating Economic Windows of Opportunities

First of all, the cost of the reference vehicle per driven kilometre (see equation (1)) is evaluated. Table 1 lists all necessary characteristics including also operational factors such as fuel consumption and cost of fuel. The reference vehicle's cost per driven kilometre represents the limit for the cost of a PEM FC vehicle to be cost-competitive.

**Table 1: Characteristics of vehicles (using reference drivetrains) [3]**

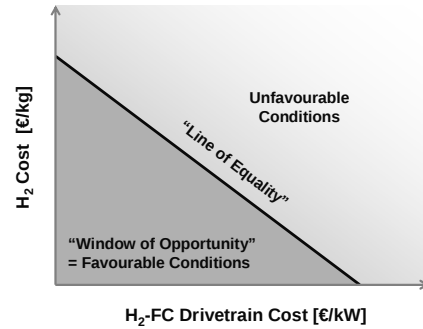
|                                                      | P <sub>Ref</sub> | C <sub>DT,Ref</sub>        | t <sub>Ref</sub> | U <sub>Ref</sub> | Con <sub>Ref</sub> | C <sub>Fuel,Ref</sub> | C <sub>Ref-maint.</sub> |
|------------------------------------------------------|------------------|----------------------------|------------------|------------------|--------------------|-----------------------|-------------------------|
|                                                      | Power            | Drivetrain Investment Cost | Lifetime         | Annual Usage     | Fuel Consumption   | Cost of Fuel          | Cost of Maintenance     |
| Vehicle (Drivetrain)                                 | kW               | €/kW                       | years            | km/year          | MJ/km              | €/GJ                  | €/km                    |
| <b>Mass Market Applications</b>                      |                  |                            |                  |                  |                    |                       |                         |
| Light Duty Truck (2006-SOTA ICE-Diesel)              | 95               | 45,6                       | 10               | 30 000 - 50 000  | 3,24               | 23,5                  | 0,07                    |
| Light Duty Truck (Future ICE-Diesel)                 |                  | 52,5                       |                  |                  | 2,59               | 33,4                  |                         |
| Passenger Car (Future ICE-Gasoline)                  | 80               | 51,9                       | 15               | 20 000           | 1,67               | 39,0                  | 0,02                    |
| Passenger Car (Future ICE-Diesel)                    |                  | 52,5                       |                  | 40 000           | 1,56               | 33,4                  | 0,03                    |
| City Bus (Future ICE-Diesel)                         | 220              | 780                        | 12               | 50 000 - 75 000  | 12,67              | 33,4                  | 0,11                    |
| <b>Niche Market Applications</b>                     |                  |                            |                  |                  |                    |                       |                         |
| Outdoor Utility Vehicle (Future ICE-Diesel)          | 4                | 576                        | 15               | 5 000            | 0,99               | 33,4                  | 0,07                    |
| Outdoor Utility Vehicle (2006-SOTA Battery-Electric) |                  | 2250                       |                  |                  | 0,31               | 30,1                  |                         |
| Scooter (Future ICE-Gasoline)                        | 7                | 104                        | 10               | 5 000 - 10 000   | 0,67               | 39,0                  | 0,02                    |
| Forklift (Future ICE-Diesel)                         | 45               | 92                         | 10               | 10 000           | 10,40              | 33,4                  | 0,12                    |
| Forklift (2006-SOTA Battery-Electric 24/5)           | 20               | 1000                       |                  | 30 000           | 2,00               | 30,1                  | 0,27                    |

**Table 2: Characteristics of vehicles (using PEM FC drivetrains) [3]**

|                                     | P <sub>FC</sub> | C <sub>DT,FC</sub>         | t <sub>FC</sub> | U <sub>FC</sub> | Con <sub>FC</sub> | C <sub>H2,a</sub> | C <sub>FC-maint.</sub> |
|-------------------------------------|-----------------|----------------------------|-----------------|-----------------|-------------------|-------------------|------------------------|
|                                     | Power           | Drivetrain Investment Cost | Lifetime        | Annual Usage    | Fuel Consumption  | Cost of Hydrogen  | Cost of Maintenance    |
| Vehicle (Drivetrain)                | kW              | €/kW                       | years           | km/year         | MJ/km             | €/GJ              | €/km                   |
| Mass Market Applications            |                 | ?                          |                 |                 |                   | ?                 |                        |
| Light Duty Truck (2006-SOTA PEM FC) | 95              |                            | 10              | 30 000 - 50 000 | 1,58              |                   | 0,02                   |
| Light Duty Truck (Future PEM FC)    | 95              |                            |                 |                 | 1,30              |                   | 0,02                   |
| Passenger Car (Future PEM FC)       | 80              |                            | 15              | 20 000 - 40 000 | 0,84              |                   | 0,01                   |
| City Bus (Future PEM FC)            | 220             |                            | 12              | 50 000 - 75 000 | 9,60              |                   | 0,16                   |
| Niche Market Applications           |                 | ?                          |                 |                 |                   | ?                 |                        |
| Outdoor Utility Vehicle (PEM FC)    | 4               |                            | 15              | 5 000           | 0,60              |                   | 0,06                   |
| Scooter (PEM FC)                    | 5               |                            | 10              | 5 000 - 10 000  | 0,40              |                   | 0,01                   |
| Forklift (PEM FC)                   | 20 - 45         |                            | 10              | 10 000 - 30 000 | 4 - 7 MJ/km       |                   | 0,05 - 0,06            |

As shown in Table 2, both the FC drivetrain and hydrogen costs are uncertain. However, the reference vehicle's total cost per driven km is used to derive one while assuming the other (equation (2)).

Figure 1 illustrates equal costs of the reference and FC vehicle along the "Line of Equality". Below the "Line of Equality" lies the "Window of Opportunity". It represents all combinations of FC drivetrain to hydrogen costs that represent favourable economic conditions for the FC vehicle. Windows of opportunities are evaluated not only for different types of vehicles but also for different drivetrains and modes of operation (e.g. annual distance driven). Amongst these, 2006-state-of-the-art (2006-SOTA) and future (within two decades) internal combustion engines running on diesel (ICE-Diesel) or gasoline (ICE-Gas.) and 2006-SOTA battery-electric engines (Battery-Electric) are considered.



**Figure 1: Window of Opportunity: Economical comparison of applications on an equal cost per unit service basis**

$$C_{Ref} = \frac{C_{DT,Ref} \cdot P_{Ref}}{t_{Ref} \cdot U_{Ref}} + \frac{C_{Fuel,Ref} \cdot Con_{Ref}}{1000} + C_{Ref-maint.} \quad (1)$$

$$C_{H_2,a} = \frac{(C_{Ref} - C_{FC-maint.}) \cdot t_{FC} \cdot U_{FC} - C_{DT,FC} \cdot P_{FC}}{t_{FC} \cdot U_{FC} \cdot Con_{FC} \cdot 0,001} \quad (2)$$

## 2.2 Evaluating PEM FC Drivetrain and Hydrogen Costs

In comparing reference to FC vehicles, solely the main parts that differ are taken into account and referred to as "drivetrain". Other characteristics or parts of the vehicle such as the weight or the body of a car are assumed equal and therefore need not be considered. Thus, a PEM FC drivetrain comprises the fuel cell system, the hydrogen (compressed at 350 bar) tank, the battery and the electromotor. By summing up the components' projected cost values, the total drivetrain cost is estimated. Table 3 shows the cost basis of PEM FC drivetrain components in general, which are used to evaluate 2006-SOTA and future PEM FC drivetrain costs as explained in [2]. Summarised, this is done by:

- Adjusting the cost basis of the PEM FC system and H<sub>2</sub> storage tank (by using economies-of-scale indices) to the annual production capacities in year 2006
- Scaling the component's basic costs to the required power (by using power laws)
- Projecting future cost values by applying learning curves (progress ratios) to assumed cumulative numbers of applications produced [2]

**Table 3: General input parameters and cost bases [3]**

|                                                   | PEM FC System<br>(Pt: 1200 US\$/ozt) | H <sub>2</sub> Storage Tank<br>(5,6 kg gas. H <sub>2</sub> , 350 bar) | Electromotor<br>(plus Controller) | Battery<br>(6 kWh Capacity) |
|---------------------------------------------------|--------------------------------------|-----------------------------------------------------------------------|-----------------------------------|-----------------------------|
| Cost Basis [€]                                    | 1000                                 | 1350                                                                  | 2160                              | 6240                        |
| Power of Reference System [kW]                    | 100                                  | 100                                                                   | 80                                | 80                          |
| Annual Production Capacity given in the Reference | 500 000                              | 500 000                                                               | > 50 000                          | > 50 000                    |
| Reference                                         | [6]                                  | [7]                                                                   | [5]                               | [5]                         |
| Learning Curve Progress Ratio [4]                 | 0,80                                 | 0,85                                                                  | 0,90                              | 0,90                        |

Annual production capacities of different PEM FC applications are combined to account for the effect that one vehicle segment can profit from developments in another segment. Thus, two markets are distinguished: A mass market consisting of the combined markets for passenger cars, light duty trucks and city buses (drivetrains with high power) and a niche market consisting of the combined markets for applications such as forklifts, small in- and outdoor utility vehicles and scooters (see table 4).

**Table 4: European (EU-15) annual production capacities and cumulative numbers of PEM FC vehicles produced in 2006 [3]**

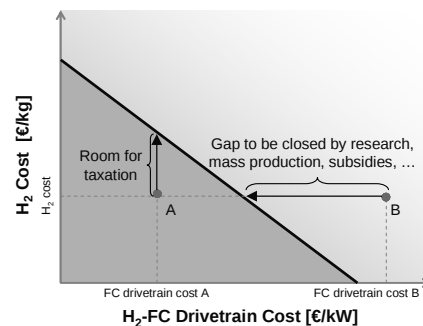
|                                                                | PEM FC Mass Market Applications |                |            | PEM FC Niche Market Applications |         |           |
|----------------------------------------------------------------|---------------------------------|----------------|------------|----------------------------------|---------|-----------|
|                                                                | Light Duty Trucks               | Passenger Cars | City Buses | Outdoor Utility Veh.             | Scooter | Forklifts |
| Annual Production Capacities of PEM FC Vehicles (in 2006)      | 40                              | 60             | 15         | 20                               | 70      | 140       |
| Cumulative Number of produced PEM FC Vehicles (until end 2006) | 240                             | 360            | 110        | 30                               | 115     | 235       |

The projected price of hydrogen at the filling station is either 6,2 €/kg (51,8 €/GJ) for hydrogen produced from natural gas via steam methane reforming (mean 2007 price of NG at 12,1 €/GJ) or 8,2 €/kg (68 €/GJ) for hydrogen in 2030 based on the HyWays production mix and using feedstock

prices based on IEA (high price scenarios, see [2]). All hydrogen costs are total supply chain costs, including cost of production, storage, transportation to the filling station, VAT and forecourt costs. Other duties like excise taxes are neglected. It should be noted that these cost levels hold for a well established and utilised hydrogen refuelling infrastructure. In the initial phase – as long as the hydrogen demand is still low – the cost may be higher.

### 2.3 Comparing Reference and FC Vehicle Costs

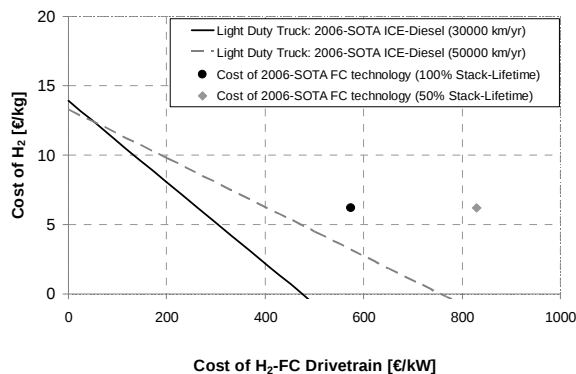
After evaluating the windows of opportunities (section 2.1), the estimated data points showing costs of PEM FC drivetrains to hydrogen costs (section 2.2) are plotted against the windows of opportunities. This allows indicating market potentials and identifying influences for various vehicle segments. Both 2006-state-of-the-art and future costs are projected. Figure 2 illustrates how the resulting graphs can be read: If the data point reflecting hydrogen cost to the FC drivetrain cost lies within the window of opportunity (data point A), the economic conditions are in favour of the FC vehicle. 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, but excluding any excise duties on hydrogen. If the data point reflecting hydrogen cost to FC drivetrain cost lies outside the “Window of Opportunity” (data point B), the economic conditions for the FC vehicle are unfavourable in comparison to the reference vehicle – even when excise duties on hydrogen are excluded. The horizontal distance to the “Line of Equality” reflects necessary cost reductions on the FC drivetrain. This could be achieved for instance through further research and development, through mass production or by subsidies on the purchase price of the FC vehicle, assuming that the cost of hydrogen for a certain market and delivered amount is a given.



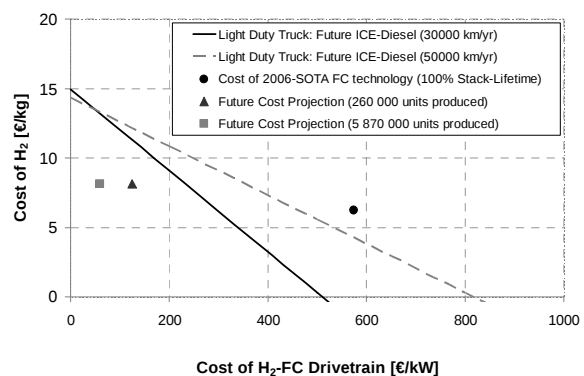
**Figure 2: The FC vehicle is cost-competitive compared to the reference vehicle, if the data point (here A or B) lies within the window of opportunity**

## 3 Results

Figure 3 and Figure 4 both show economic windows of opportunities for light duty trucks (max. weight of 3500 kg) driving 30 000 and 50 000 kilometres per year. Figure 3 compares the cost of 2006-SOTA FC technology with different stack-lifetimes (data points) to 2006-SOTA ICE-Diesel technology. It illustrates the cost-impact of current uncertainties in the durability of fuel cells. If the FC stack had the same lifetime as the vehicle, the cost of the FC drivetrain might decrease from 830 to 580 €/kW. Figure 4 compares 2006-SOTA and future FC technology (data points) to future ICE-Diesel technology (windows of opportunities). The future cost projections are based on different cost reductions, which are related to – by using learning curves – cumulative numbers of 260 000 and 5 870 000 produced mass market applications. Following the HyWays penetration curve (see section 2.2), these numbers could be reached when 1% or 10% (respectively) of all mass market application sales are FC vehicles.



**Figure 3: Windows of Opportunities for 2006-SOTA Light Duty Trucks; data points illustrate differences in FC drivetrain lifetimes**



**Figure 4: Windows of Opportunities for future Light Duty Trucks; data points illustrate differences in 2006-SOTA and potential future FC drivetrain cost**

Table 5 lists the most promising vehicles including the considered drivetrain and annual usage. For each vehicle segment, the table gives the cumulative number of units that need to be produced to enter its window of opportunity, assuming a price of hydrogen of 6,2 €/kg. By applying the penetration curve “High Learning Scenario” given in the EU-project HyWays [4] to the cumulative number of units produced, the market size, i.e. the corresponding annual production capacity can be evaluated.

**Table 5: Overview of drivetrain costs leading to cost-competitiveness of listed applications [3]**

|                                                                     |                                                         | Competitive Drivetrain<br>Cost at 6,2 €/kg H <sub>2</sub> Cost | Cumulative Number of<br>Applications produced | Corresponding annual<br>Production Capacity |
|---------------------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------|-----------------------------------------------|---------------------------------------------|
| Fuel Cell Vehicles (replacing conventional Vehicles used x km/year) |                                                         | €/kW                                                           | # of units before competitive                 | units/year                                  |
| <b>Mass Market Applications</b>                                     |                                                         |                                                                |                                               |                                             |
| Light Duty Truck                                                    | (replacing future ICE-Diesel @ 30 000 km/year)          | 270                                                            | 15 000                                        | 12 000                                      |
|                                                                     | (replacing future ICE-Diesel @ 50 000 km/year)          | 410                                                            | 2 800                                         | 2 200                                       |
| Passenger Car                                                       | (replacing future ICE-Gasoline @ 20 000 km/year)        | 180                                                            | 95 000                                        | 60 000                                      |
|                                                                     | (replacing future ICE-Diesel @ 40 000 km/year)          | 270                                                            | 16 000                                        | 13 000                                      |
| City Bus                                                            | (replacing future ICE-Diesel @ 75 000 km/year)          | 500                                                            | 5 000                                         | 4 000                                       |
| <b>Niche Market Applications</b>                                    |                                                         |                                                                |                                               |                                             |
| Outdoor Utility Vehicle                                             | (replacing 2006-SOTA ICE-Diesel @ 5 000 km/year)        | 800                                                            | 20 000                                        | 40 000                                      |
|                                                                     | (replacing 2006-SOTA Battery-electric @ 5 000 km/year)  | 2100                                                           | already cost-competitive                      |                                             |
| Scooter                                                             | (replacing 2006-SOTA ICE-Gas. @ 5 000 km/year)          | 300                                                            | 500 000                                       | 110 000                                     |
|                                                                     | (replacing 2006-SOTA ICE-Gas. @ 10 000 km/year)         | 460                                                            | 80 000                                        | 34 000                                      |
| Forklift                                                            | (replacing 2006-SOTA ICE-Diesel @ 10 000 km/year)       | 230                                                            | 150 000                                       | 50 000                                      |
|                                                                     | (replacing 2006-SOTA Battery-electric @ 30 000 km/year) | 2000                                                           | already cost-competitive                      |                                             |

## 4 Discussion and Conclusions

It is of utmost importance to increase the durability of PEM fuel cells. Two extremes are compared: Replacing the whole PEM FC stack once during the lifetime of the vehicle – in this case a light duty truck – might increase the total cost per driven km by more than 40% compared to the case, when no FC replacement is necessary at all. If the durability of fuel cells could be increased to meet the vehicle's lifetime, FC light duty trucks might become cost-competitive to ICE-Diesel light duty trucks after 15 000 vehicles were produced. This corresponds to an annual production capacity of around 12 000 vehicles, being less than 1% of the European (EU-15) market [2] for light duty trucks.

Results indicate that the cumulative number of passenger cars to enter the window of opportunity lies within the order of 100 000. City buses even require a lower number, but the market for city buses is much smaller, thus requiring a higher penetration level before reaching cost-competitiveness.

In case of outdoor utility vehicles and forklifts with an annual usage of more than 5 000 km and 30 000 km respectively, 2006-state-of-the-art PEM FC drivetrains could already be cost-competitive to battery-electric drivetrains. It should be noted that in case of battery-electric drivetrains only 2006-SOTA technology and costs were considered. However, the case of forklifts in 24/5 (24 hours per day, 5 days per week) operation with 2006-SOTA battery-electric drivetrains is quite specific as multiple batteries and thus high investment costs are necessary to allow for such a sustained operation.

Based on current knowledge and the relative size of the markets, light duty trucks seem to be the most promising early market. However, as the vehicle's characteristics used in this study are mere generics influencing the results strongly, this study should be considered as first-order analysis (giving indications only). Highly potential and interesting applications deserve a more detailed analysis based on specifically interesting vehicle models. Furthermore, the methodology for cost-comparison presented in this paper can be used for a variety of applications and is not limited to transport applications only.

## 5 Acknowledgements

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## 6 References

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