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Fuel cells for automotive powertrains—A techno-economic assessment

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ABSTRACT

With the objective of identifying the hurdles currently preventing a widespread application of fuel cell technology in passenger cars an assessment of technical and economic parameters is carried out. Patent and publication analysis is used to assess current status of fuel cell technology regarding its position on technology life cycle. S-curve methodology leads to the conclusion that further scientific activity is to be expected but for today's low-temperature PEM fuel cell technology might level by 2015. Technical analysis identifies power density and platinum loading as parameters for which further improvements are necessary in order to satisfy future customer needs. A detailed cost evaluation suggests that in future for high production volumes (approx. 1 million vehicles cumulative) significantly lower costs for fuel cell stacks (12–40$ kW^{-1}) and systems (35–83$ kW^{-1}) will be viable. Reducing costs to such a level will have to be the main focus for upcoming research activities in order to make fuel cell driven road vehicles a competitive alternative.

1. Introduction

Fuels cells have been used as a propulsion system for passenger vehicles since General Motors first presented a fuel cell powered minivan in 1966. Especially during the 1990s and the beginning of the new millennium fuel cell vehicles did experience significant research activity and public attention.

One main reason for striving towards fuel cell driven passenger cars is the relatively high efficiency of this type of propulsion system. In combination with renewably produced hydrogen it offers the possibility to drive with close to zero emissions and at the same time to save precious fossil resources. In view of upcoming CO_2 restrictions and potentially further increasing prices for oil these arguments become even more striking than in the past.

The objective of this paper is to evaluate recent developments in the field of fuel cells for transportation and to use methods from technology analysis in order to discuss possible future developments. The analysis consists of three parts: (1) a review of research activities using patent and publication analysis, (2) a summary of current status regarding important technical parameters and (3) a cost estimate for producing fuel cell stacks and systems today and in future.

2. Patent and publication analysis

Patents as well as publications are commonly regarded as early indicators for changes of technological structure. Whereas publications are linked with scientific progress, patents additionally include suggestions on possible economic impacts of an invention. Together, and in combination with other methods pertaining to the domain of techno-economic assessments, an analysis of patent and publication statistics can help to draw a picture of future progress in a field of technology [1].

2.1. Patent analysis

Filing an application for a patent usually causes significant cost for the applicant. Although the 'culture' of applying for patents might differ for each country it can be expected that in most cases only inventions which are promising an economic added value for the applicant are being filed. Therefore patents are an indicator for the economic importance of an invention [2].

The total number of patent applications is increasing every year[1] lately showing an average growth rate of approx. 4.75% per year according to the Worlds Intellectual Property Organization. Applications for the area of fuel cells in general experienced a strong growth beginning in the mid 1990s. Up to the year 1996 annual

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[1] Following patent databases have been used for this analysis: Derwent Innovations Index^{SM}, Scopus and DEPATISnet. A combination of relevant key words and IPC-classes was used for filtering patent application files.

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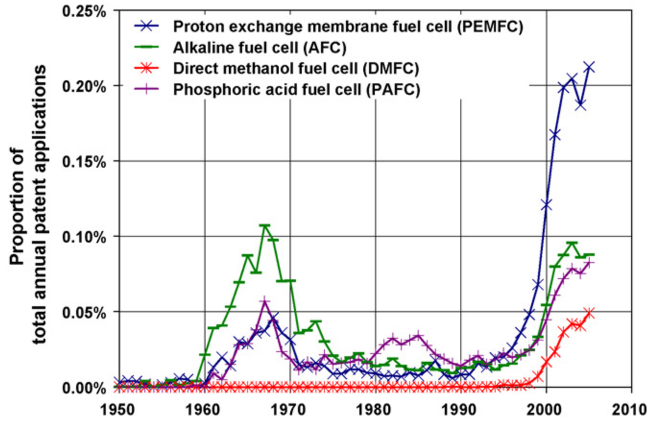

Fig. 1. Historical analysis of worldwide annual patent application numbers for various fuel cell types. To account for generally increasing annual patent application numbers, values are given as a proportion of relevant applications in comparison to the sum of patents for all topics.

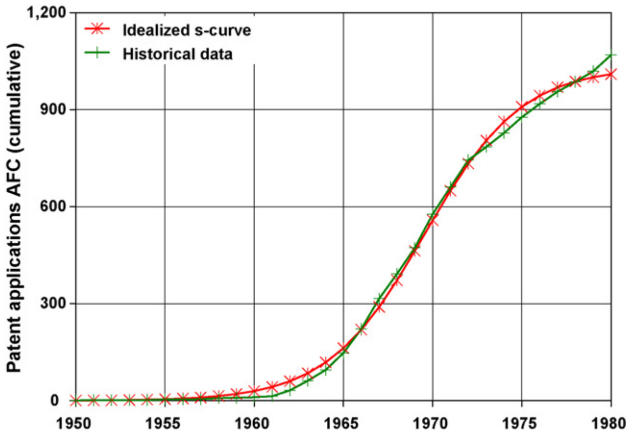

Fig. 2. Historical cumulative patent application numbers for alkaline fuel cell (AFC) type. An idealized mathematical S-curve was fitted to the data points given.

new applications were below 1000 but increased nearly tenfold during the next years. This fits well with the fuel cell boom experienced during the end of the 1990s, which led to increased research activities and was followed by a number of new inventions. At least for the patent applications, which can be analysed today,[2] no end of this trend is to be observed. Annual new applications continue increasing.

When not only looking at absolute numbers of patent applications but normalising them by the number of patents filed in total for all areas of technology, one can observe a previous fuel cell boom during the 1960s/1970s. There has been a clear increase in patent applications on fuel cell technology from the early 1960s on with patents on fuel cells in general reaching nearly 0.4% of all patent applications in 1968. When differentiating between fuel cell types, it can be seen that patents specifically assigned to one of the four most prominent fuel cell types were in sum approx. 0.2% of all patent applications (Fig. 1). The alkaline fuel cell (AFC) was the technology with most patent applications during the 1960s/1970s. This is due mainly to aerospace research activities at that time, e.g. the NASA Apollo mission made use of an AFC on board [3].

Patent application numbers decreased in the years after but then revived in the 1990s mainly on the basis of research activities pertaining to the application of fuel cells for road transportation. These activities led to the second fuel cell boom, which is mainly driven by the proton exchange membrane (PEM) technology. If plotted cumulatively, the first fuel cell boom during the 1960s/1970s and the current activities since the 1990s form a clear double S-curve shape.

The curve of the cumulated newly filed patents for AFC-technology during the first fuel cell boom follows nearly perfectly an idealized S-curved shape[3] as it can be seen in Fig. 2. As patent numbers generally rise over time, when normalized by the number of all patents the function for AFC patents fits even better a S-curve shape.

Theory of S-curve methodology suggests that many technologies follow a S-curve shaped development with slow growth rates during the early stages of the technology life cycle and during maturity phase as well as a period of rapid growth in between these phases. According to literature patent analysis in combination with S-curve methodology in some cases can be used for estimating the current status of technology on its life cycle and for assessing its future potential [4]. It is important to differentiate between technology S-curves and market S-curves. Whereas technology S-curves focus on technological advancements, market S-curves describe the diffusion of a technology into the consumer market. Despite their similar shape both curves therefore express different evolutions.

In the case of the AFC-technology it would have been possible to predict future development of patent application numbers for the first boom as early as in 1966 using technology S-curve methodology. With the data available at that time the inflection point (1969) as well as the saturation level (approx. 1000 patents) could have been estimated correctly.[4] It should be noted that using less data points, this means using a data set not including the years up to 1966, would not have led to a correct result. Therefore, a certain number of data points has to be known before a correct prognosis using the S-curve analysis method is possible.

Given this situation the method of S-curve analysis is being applied to the PEMFC technology today during the second fuel cell boom. Using patent data available today and extrapolating this data using a S-curve function[5] leads to an inflection point for the application year 2004 as well as a saturation level of approx. 18,000 patents (see Fig. 3). These results are also stable when only using data material up to 2003.

So applying the S-curve method to patent statistic data leads to the conclusion that the current PEM fuel cell technology still is in the phase of rapid growth on the technology life cycle and will enter maturity phase by approx. 2015. The number of cumulative patent applications then will approach a plateau level.

It is important to realize that this does not mean there were no more technological advances for PEM-fuel cells feasible after 2015. In fact it is possible and likely that a new S-curve for a new technology type will start or has already started. An example could be the development of a high-temperature PEM fuel cell (HT-PEMFC), which would lead to a new S-curve as it is technologically rather different from the original low-temperature PEM fuel cell. Up to now patent application numbers on HT-PEMFC are still negligible.

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[2] As there is a time delay between patent application and patent publication of approx. two to three years it was only possible to evaluate patent applications including up to the year 2004.

[3] Function of S-curve used: $y = a/(1 + \exp(-k \times (x - xc)))$.

[4] Using data including 1966 and later leads to stable results giving a correct inflection point and saturation level.

[5] Function of S-curve used: $y = a/(1 + \exp(-k \times (x - xc)))$.

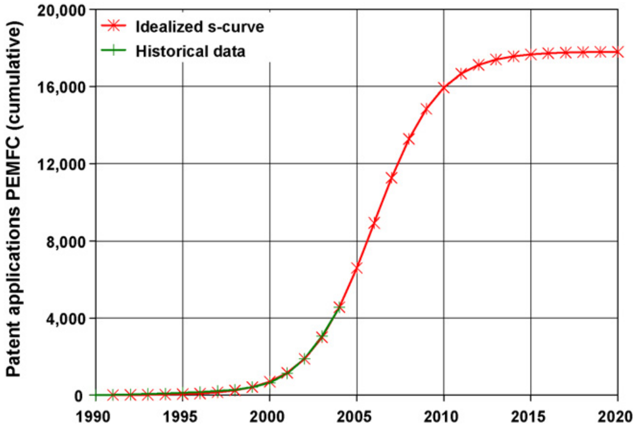

Fig. 3. Patent application numbers for proton exchange membrane fuel cell (PEMFC) type. An idealized mathematical S-curve was fitted to the data points known so far to estimate likely future progress.

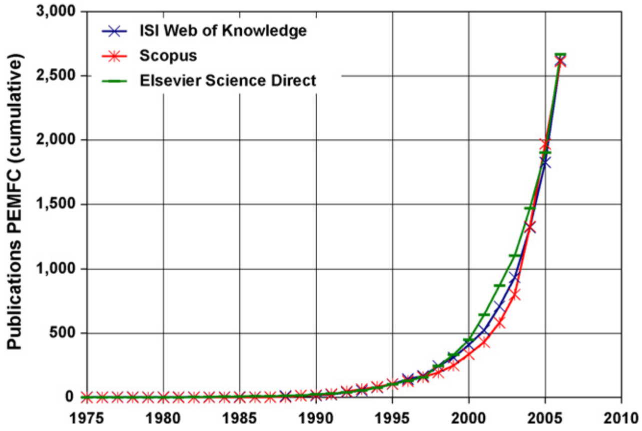

Fig. 4. Scientific publications on proton exchange membrane fuel cell (PEMFC).

2.2. *Publication analysis*

Like patent applications publications are regarded as an early indicator for technological advances. Due to the system of peer reviewing for many journals a certain level of quality and respectability of the articles can be expected [5].

Total number of scientific publications is slowly increasing every year.[6] From our analysis for fuel cells there is an increased publication activity starting in 1995. Publication numbers go up from approx. 200 per year in 1995 to more than 2000 in 2006. This is equivalent to a share of approx. 0.5% of all articles published in Elsevier Science Direct® today compared to 0.05% in 1995. From the data available to this day no end of the trend of increasing publication numbers for fuel cells can be observed. Analysis of publications therefore suggests that fuel cell technology still is in the phase of rapid growth of an S-curve, which started in approx. 1995. In contrast to patent application statistics there is no phase of rapid growth observable for publications on fuel cells during the 1960s/1970s.

When distinguishing between different fuel cell types it becomes apparent that today most articles are on PEM fuel cells. Direct methanol fuel cells (DMFC) as well as solid oxide fuel cells (SOFC) are mentioned less often, other types are regarded as not relevant.

Publication data on PEM fuel cells is shown in Fig. 4. Beginning in about 1993 the cumulative number of publications is strongly increasing from nearly zero to more than 2500 articles today. As for fuel cells in general, numbers of publications on PEM fuel cells are continuously increasing, therefore suggesting that PEM fuel cell technology still is in the phase of rapid growth of an S-curve.

An analysis of the geographical distribution of publications shows that there is an increasing share of publications from China and South Korea. The proportion of articles from the U.S. and Japan on the other hand is decreasing (Fig. 5).

3. Technical analysis

As patent and publication analyses have shown further scientific research and inventions for the area of fuel cell technology can be expected for the near-term future. The following section evaluates from a macroscopic point of view possible technological potentials that could be approached by these research activities in order to satisfy future customer expectations.

3.1. *Stack power*

Power output of fuel cell stacks has increased dramatically over time. One of the first fuel cell stacks of Ballard Power Systems Inc., Mk 3, had a power output of approx. 0.4 kW and was not at all suitable as a propulsion system for a car. Nowadays stack module, Mk 1100, has a net power of 110 kW.

When plotted over cumulated R&D expenditures of the company one can observe that output in terms of improved product performance is decreasing with increasing cumulative R&D expenditures (Fig. 6). This is in line with previous studies indicating that improvements in product performance are realized requiring lower expenditures at the beginning of research activities on a technology than they are later on as research activities continue [6].

Power output of a typical middle class passenger car nowadays is between 60 and 130 kW. However, internal combustion engines (ICE) are usually excessively motorized in order to be able to achieve short-term high power demand (e.g. when accelerating at a traffic light). Electric vehicles, like a fuel cell car, in contrast have excellent acceleration attributes. For this reason, a value of 110 kW is sufficient for everyday usage and a further significant increase in

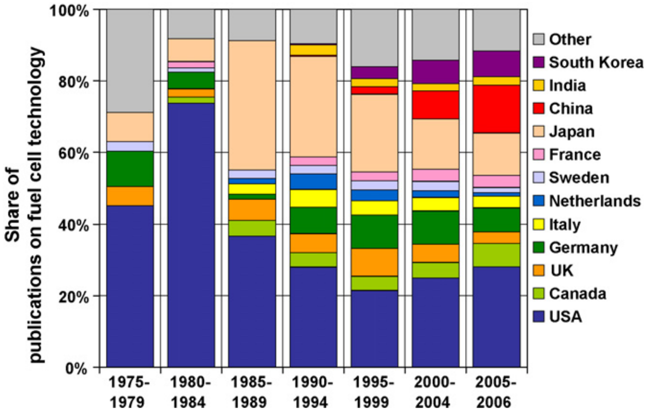

Fig. 5. Geographical distribution of the origin of the authors of scientific publications on fuel cells in general, differentiated by a set of time periods. Numbers are given as a proportion of publications for a specific country in comparison to the sum of publications for all countries.

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[6] Following scientific publication databases have been used for this analysis: Elsevier Science Direct®, ISI Web of Knowledge^{SM}, Scopus. Relevant key words were used for filtering publication statistics on fuel cells in general and specific fuel cell types. General publications (e.g. on fundamental electrochemistry) are included if they pertain to fuel cells in general or a specific fuel cell type.

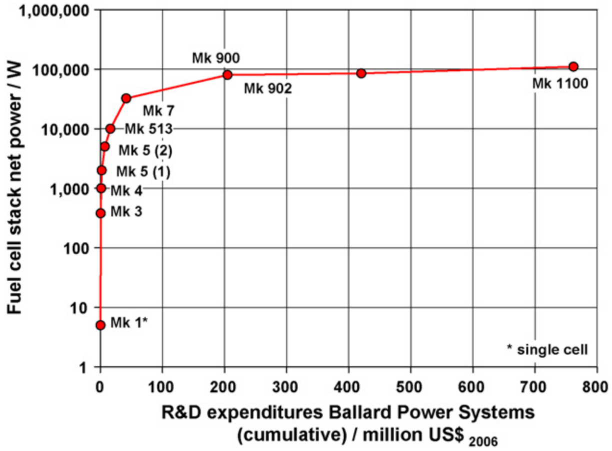

Fig. 6. Historic development of net power of Ballard Power Systems PEM fuel cell stacks versus cumulative research and development (R&D) expenditures of the company.

stack power for passenger car fuel cells is not to be expected for the future.

3.2. *Stack power density*

Volume in a passenger car engine bay is rare and the mass of the vehicle restricted due to performance reasons. Therefore volumetric as well as gravimetric power density should be as high as possible for a fuel cell stack to be used in a passenger car.

As Fig. 7 shows, there have been impressive improvements achieved over time. The first application of a PEM fuel cell stack was during NASA Gemini mission in the 1960s. Volumetric power density of the stack at this time was around 20 W l^{-1} [3]. In the 1980s/1990s Ballard Power Systems improved stack power density significantly to approx. 1300 W l^{-1}. Today the Mk 1100 module, which in contrast to the stack does include some auxiliary equipment, reaches approx. 1340 W l^{-1}. Honda claims to already have reached a value of approx. 1900 W l^{-1} for its newest stack. Ballard Power Systems' own target value for 2010 is at 2500 W l^{-1}, the official target set by the U.S. Department of Energy (DOE) is 2000 W l^{-1}.

Gravimetric power density improved similarly over time. It began with approx. 15 W kg^{-1} for NASA Gemini and now is at approx. 1000 W kg^{-1} for the Mk 1100 module, respectively 1500 W kg^{-1} for the current Honda stack. DOE goal for gravimetric power density of the stack is 2000 W kg^{-1}.

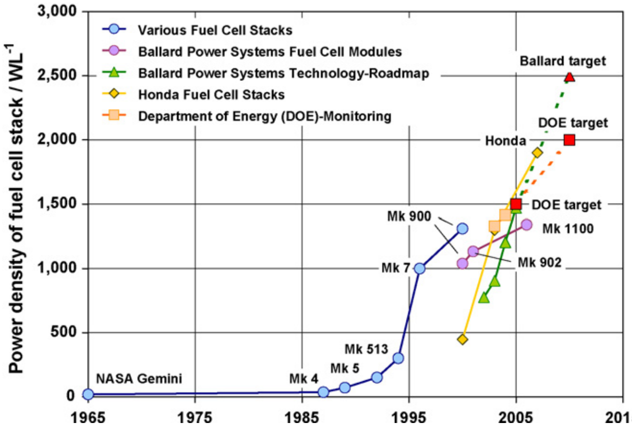

Fig. 7. Historic development of volumetric power density of PEM fuel cell stacks including various targets set for the future.

Different detail definitions for power density complicate a comparison of status values among manufacturers. Nevertheless, it seems reasonable that the DOE target values for 2010 for power density will be met. Further research activities and new materials, e.g. thin metallic bipolar plates, should enable further improvements in the mid-term future.

3.3. *Cell power density*

Power density improvements at the level of the fuel cell stack are pertained to improvements at the single cell level. Power density here is defined by the voltage of the cell as well as the current flow through the active area of the cell. While the NASA Gemini stack only reached a power density of approx. 30 mW $(cm^2)^{-1}$ more recent stacks like the Ballard Mk 900 have power densities of approx. 600 mW $(cm^2)^{-1}$. This is also the status reported by DOE for 2005. The target for 2010 and also for 2015 according to DOE is a value of 1000 mW $(cm^2)^{-1}$. Power densities of this magnitude and even higher have already been met in laboratory [7]. Hence, although there are opposed interdependencies between power density and catalyst loading it seems reasonable that a value of approx. 1000 mW $(cm^2)^{-1}$ could be reached in the mid-term future.

3.4. *Platinum loading*

To accelerate the chemical reaction of hydrogen and oxygen in the cell a catalyst material is needed for low-temperature PEM fuel cells. The materials commonly used are platinum and also to a lesser extend ruthenium and iridium. Because of the high economic value of these materials it has always been a target to reduce usage of them within the fuel cell.

The first PEM fuel cell stack in the NASA Gemini mission had a platinum loading of approx. 28 mg $(cm^2)^{-1}$ per electrode. Current loadings are 0.7 mg $(cm^2)^{-1}$ for both electrodes together according to DOE. This is going to be reduced to approx. 0.2 mg $(cm^2)^{-1}$ by 2015 according to the DOE target value.

Even lower loadings have been achieved in laboratory before, however often associated with poor power densities. According to recent studies only 10–20% of the catalytic material is chemically active, so there is still potential for improvement. A loading of 0.02 mg $(cm^2)^{-1}$ with high activities is being reported [8] and even ideas for platinum-free catalysts do exist [9]. Thus it seems likely that the current DOE target value of 0.2 mg $(cm^2)^{-1}$ will be met.

3.5. *Vehicle performance*

An important advantage of fuel cell vehicles when being compared with conventional ICE vehicles is their high efficiency of fuel conversion. The maximum efficiency of a modern Diesel engine for passenger cars is at approx. 40%. Maximum efficiency of the fuel cell system used in the Daimler Necar 4 vehicle in 1999 was 50%, for the F-Cell in 2002 it was almost 60%.

More important than maximum values is the overall result during a typical driving cycle. When analyzing a fuel cell system including an electric motor using the New European Driving Cycle (NEDC) (a test cycle with a duration of 20 min) the fuel cell system reaches an efficiency of 45–50% for both low and also high load demand. Applying the same test cycle the diesel engine is at approx. 15–25% efficiency for most of the time and only reaches values of 30–40% for high load demand. Fig. 8 illustrates this discrepancy, representing load demand by vehicle speed in km h^{-1}

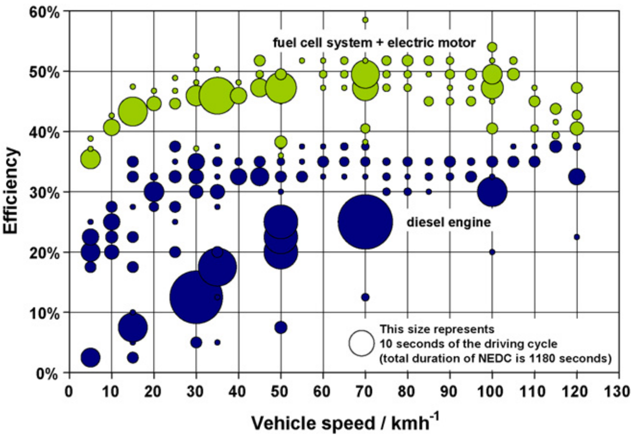

Fig. 8. Comparison of efficiency of a fuel cell system including electric motor and a conventional diesel engine during New European Driving Cycle (NEDC). The total duration of the NEDC is 1180 s, a bubble of the size indicated represents a condition occurring in sum during 10 s of the NEDC.

and frequency of occurrence of a certain condition by the size of a bubble.

This advantage of the fuel cell in respect to system efficiency might increase even more as technological advancements like a start–stop system and software optimization are going to further improve efficiency of the fuel cell system.

In terms of many other parameters fuel cell vehicles have already reached the technical level of conventional engines. For example during the 1990s top speed of fuel cell driven prototype vehicles usually was below 100 km h^{-1} but increased to more than 150 km h^{-1} for current models.

Furthermore, the power-to-weight ratio which is the ratio between power output of the vehicle and its curb weight (and therefore also includes the fuel storage system) improved from approx. 10 W kg^{-1} in 1994 to approx. 50 W kg^{-1} today. Current values for diesel cars are at approx. 70 W kg^{-1} and for gasoline cars at approx. 90 W kg^{-1}.

Cold start ability improved significantly over the years. Honda's latest model FCX Clarity supposedly is able to start at temperatures as low as −30 °C (DOE target for 2010 is −40 °C). However, this might negatively affect long-term durability, which for transportation fuel cells currently is at 2000 h (stack)/1000 h (system) according to DOE. A value of approx. 5000 h (equivalent to approx. 250,000 km of driving) has to be met in order to ensure a proper lifetime for the needs of a future private customer. For this reason manufacturers are focusing research activities to this issue. Durability of steady-state fuel cell stacks, for example for application in a private home heater system, today is at approx. 20,000 h according to DOE.

3.6. Hydrogen storage

Between 1995 and 2001 many of the fuel cell vehicle models presented to public used fuel storage systems other than compressed hydrogen. In 2000 for example only half of the newly presented models used compressed hydrogen, whereas the rest was using liquid hydrogen, methanol, gasoline or a hydride storage system.

From 2002 on this situation changed and nowadays nearly all models on the market are powered by compressed hydrogen from a 350 or 700 bar storage system. These systems have energy densities of approx. 0.5–0.8 kW h l^{-1} and 1.6–1.9 kW h kg^{-1} which are significantly lower than the DOE target values for 2010 (1.5 kW h l^{-1} and 2.0 kW h kg^{-1}) and 2015 (2.7 kW h l^{-1} and 3.0 kW h kg^{-1}) [10] and nearly ten times lower than the values for a conventional gasoline fuel storage system.

Other hydrogen storage systems, like metal-hydrides, promise higher energy densities for the future but still are in an early research phase.

From a potential customer point of view most important parameters with regard to the energy storage system are easy fueling and everyday usage, safety and maximum driving range. As the first two requirements are already fulfilled by modern fuel cell driven passenger car prototypes and a maximum cruising range of 600 km could also be realized using today's 700 bar compressed hydrogen storage systems, the hydrogen storage system of the vehicle seems to be no major hurdle for mass market introduction.

4. Economic analysis

Patent and publication analyses suggest that there will be further research activity in the area of fuel cells for transportation. Technical analysis has furthermore shown past developments and potentials for future technical performance. The following economic evaluation combines this information gathered to derive future cost estimates for fuel cell stacks and systems using a bottom-up cost-model as well as learning curve methodology.

4.1. Cost estimation for high production volumes

Information gathered from a recent report of TIAX LLC [11] was used to build up a detailed bottom-up cost-model for the production of fuel cells for transportation at high production rates (approx. 0.5 million vehicles per year).

Analysing cost structure revealed that approx. 90% of production costs at high rates is for material. According to TIAX LLC data costs for the electrodes would make up more than 80% of total production costs of the fuel cell stack at high volumes.

Costs for the electrodes are strongly influenced by platinum loading and market price for platinum. Furthermore, a higher power density of the fuel cell stack allows reducing stack size while ensuring sufficient power output, therefore resulting in less material needed and lower costs for the fuel cell stack.

Cost estimates were recalculated using updated assumptions for future values of these identified key factors based on the information from patent and publication as well as technical analyses. Other parameters were not changed from the original TIAX LLC assumptions.

For power density of the stack TIAX LLC assumes a value of 600 mW $(cm^2)^{-1}$. As it has been shown in chapter 3 this is approx. the status value already achieved today. Significantly higher values have been met in laboratory. For the point of time when high annual production rates could be achieved it can be expected that power density will be higher than today while ensuring a high efficiency of the system and a low platinum loading at the same time. So for power density a Gaussian distribution with a mean of 1.000 mW $(cm^2)^{-1}$ and a standard deviation of 400 is assumed. The lower boundary is set at 800 mW $(cm^2)^{-1}$.

For platinum loading of the electrodes TIAX LLC assumes 0.75 mg $(cm^2)^{-1}$ for the sum of both electrodes. This is approx. the value achieved today. Future targets include significantly lower values as shown in chapter 3. For platinum loading a Gaussian distribution with a mean of 0.10 mg $(cm^2)^{-1}$ for each electrode and a standard deviation of 0.08 with a lower boundary of 0.05 mg $(cm^2)^{-1}$ is set.

Platinum market price has reached an all-time high of approx. 70.000$ kg^{-1} and is currently decreasing. Today's high price is not due to a shortage of the element as reserves currently are esti-

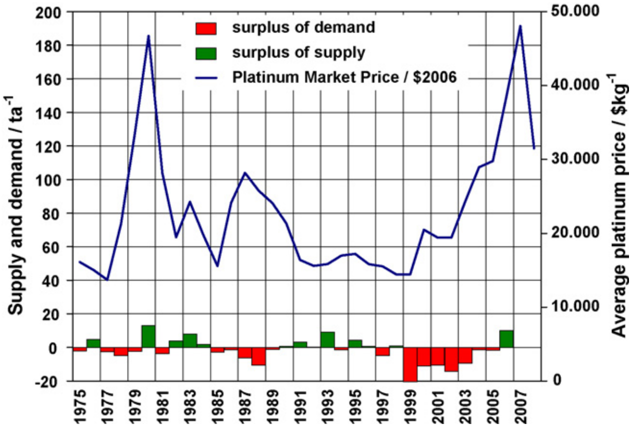

Fig. 9. Platinum supply/demand surplus and market price.

mated at 70,000 tons of platinum group metals, whereas the annual production of platinum is only approx. 200 tons and of palladium approx. 240 tons [12]. Origin of the metal is mostly South Africa (approx. 80%) and Russia (approx. 15%).

Most important usage nowadays is for catalytic converters in gasoline and diesel engines (approx. 50%) and jewellery (approx. 25%) [13]. During the introduction of the three-way catalytic converter in the 1980s relatively high platinum loading was necessary. Nowadays loadings are lower and platinum can be recovered from scrap cars. Today already approx. 20% of the metal needed for new catalysts is being recovered from old vehicles. A 100% recycling quote however is not likely as some of the metal is lost to the environment during usage phase.

Platinum loading of a current ICE catalytic converter might rise to approx. 8 g per vehicle in future [14] whereas for a 90 kW fuel cell vehicle with 0.2 mg $(cm^2)^{-1}$ and 1000 mW $(cm^2)^{-1}$ a total loading of 18 g would be necessary. Hence for market introduction the platinum amount necessary for a fuel cell vehicle will be in the same range than the values of an ICE catalytic converter.

As Fig. 9 shows the recent price top was due to an excess demand relative to supply. During the 1990s Russian platinum-reserves have partly been sold which led to a decreasing price at this time [15]. As a result investments in exploration were temporarily cut which caused a shortage of supply a few years later. This shortage is becoming smaller and for the future it is expected that platinum price will decrease again and possibly return to its past mean value of approx. 20,000$ kW^{-1}. For calculation purposes a Gaussian distribution with a mean of 20,000$ kg^{-1} and a standard deviation of 6000 and a lower boundary of 12,000$ kg^{-1} is applied.

Calculation of future fuel cell stack production cost at high volumes then results in an average value of 17$ kW^{-1} (Table 1). According to a Monte-Carlo analysis probability for production cost being between approx. 10 and 27$ kW^{-1} will be around 90% (Fig. 10).

4.2. Dynamic cost estimation using learning curves

Cost estimates calculated in Section 3.1 are only valid for high production rates at approx. 0.5 million vehicles per year. Assuming an exponential growth with a factor of approx. 0.9 this would correspond to approx. 1 million cumulative vehicles being produced.

For comparison with other vehicle propulsion concepts production cost estimates for lower production numbers have to be known. From literature costs for fuel cell vehicles for very low production rates around the end of the 1990s (corresponds to approx. 40 cumulated vehicles) is known. Together with the values for 1 million vehicles this information can be used to derive necessary learning curve rates. Table 2 summarizes the used sources and the derived learning curve rates.

Table 1
Comparison of cost estimates for fuel cell stacks at high production volumes.

	Cost analysis		TIAX LLC [11]	
Assumptions				
Production volume	500,000 vehicles/a		500,000 vehicles/a	
Net power	80 kW		80 kW	
Power density of stack	1000 mW cm^{-2}		600 mW cm^{-2}	
Platinum loading	0.20 mg cm^{-2}		0.75 mg cm^{-2}	
Market price platinum	20,000$ kg^{-1}		29,000$ kg^{-1}	
	Production costs			
	[$ kW^{-1}]	[%]	[$ kW^{-1}]	[%]
Membrane	3	5	4	4
Electrodes	10	17	56	52
Bipolar plates	2	3	3	3
Peripheral parts	<1	1	2	2
Assembly	2	3	2	2
Sum FC-stack	17	29	67	62
System components	41	71	41	38
Sum FC-system	58	100	108	100

Learning curve rates found in our analysis are between 74 and 90%, which is within the range normally found in literature [16]. Bipolar plates have the highest derived learning rate.

Besides learning curve effects for each of the component parts, improvement of power density will occur. This can also be summarized in a learning curve rate (92%) and leads to the effect that less of the now improved material is needed to obtain a certain level of power. Thus the overall learning curve rate for the stack is 74%.

According to the collected data a fuel cell stack at the end of the 1990s would have caused production costs of approx. 1300$ kW^{-1}. This fits well with the values in other studies, if power density is normalized [17,18].

System costs are at approx. 1700$ kW^{-1}. This corresponds with the values of other assessments [19,20]. Overall learning rate of the fuel cell system is at 79%. For the commercially available stationary system “PC25” a rate of 75% has been found empirically [19].

Using the start values for low production numbers and the derived learning curve rates cost curves for the fuel cell stack and system now can be plotted (Figs. 11 and 12).

Fuel cell stack costs start at approx. 1000$ kW^{-1} for 100 vehicles and decrease to approx. 12–40$ kW^{-1} for 1 million vehicles produced. Values tend to be lower than in previous studies [11,18,21].

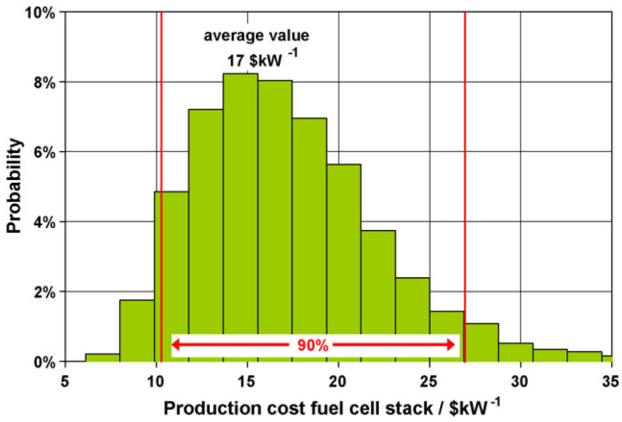

Fig. 10. Cost estimate for fuel cell stack production cost at high volumes.

Table 2
Deriving learning curve rates for mass production of fuel cell stacks/systems. Platinum price was set at 15,000$ kg^{-1} to represent the level of the 1990s.

	Cost estimate for cumulative number of produced vehicles			Learning curve rate
	Approx. 40	Source	1 million	[%]
Membrane	500–600$ m^{-2}	[17,18,23]	23$ m^{-2}	80
MEA (w/o platinum)	Approx. 2000$ m^{-2}	[18]	60$ m^{-2}	79
Platinum loading	1 g cm^{-2}	[24,25]	0.2 g cm^{-2}	90
Bipolar plates	1200–1600$ m^{-2}	[18,23]	17$ m^{-2}	74
Peripheral parts	Approx. 40$ m^{-2}	[18]	2$ m^{-2}	80
Power density of stack	0.3 W cm^{-2}	[18,23]	1.0 W cm^{-2}	92
Assembly	Approx. 8$ kW^{-1}	[18]	2$ kW^{-1}	95
Sum FC stack	1300$ kW^{-1}		15$ kW^{-1}	74
System components	400$ kW^{-1}	[19,20]	35$ kW^{-1}	85
Sum FC system	1700$ kW^{-1}		50$ kW^{-1}	79

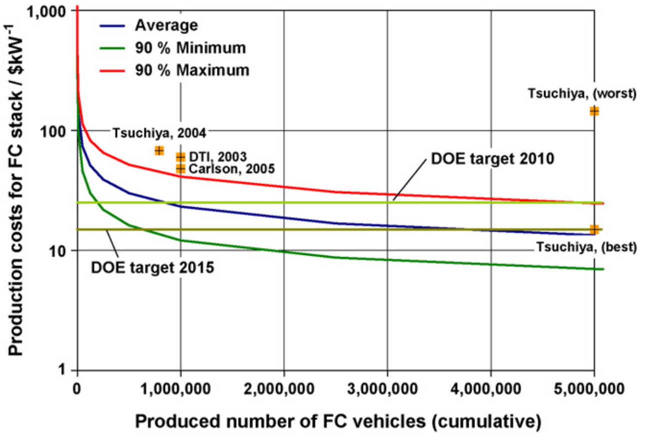

Fig. 11. Production cost estimate for fuel cell stacks. Values for comparison are from [11,18,21]. Cost estimate is for a platinum market price of 20,000$ kg^{-1}.

The DOE 2010 target value (which is for 0.5 million vehicles per year) would be achieved, however the 2015 target only in an optimistic case.

System cost start at approx. 1300$ kW^{-1} and decrease to approx. 35–83$ kW^{-1} for 1 million vehicles. According to these results DOE target values for 2010 and 2015 would be difficult to achieve.

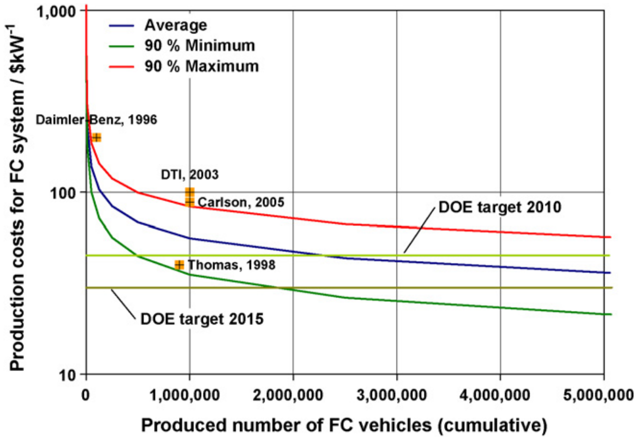

Fig. 12. Production cost estimate for fuel cell systems. Values for comparison are from [11,20–22]. Cost estimate is for a platinum market price of 20,000$ kg^{-1}.

5. Conclusion

Patent analysis has shown that scientific research on fuel cells has constantly been increasing since the 1990s. A trend reversal is not yet observable from patent application numbers. S-curve analysis suggests that patent applications for conventional PEM fuel cells will reach a saturation level by 2015. For the future further results of scientific research are to be expected, possibly more and more from China and South Korea as increasing publication numbers suggest. Approaching a saturation level for scientific activity on conventional PEM fuel cell technology leads to the assumption that research activity will refocus on a different type of technology, possibly high temperature PEM fuel cells, which will then start a new S-curve.

Technical analysis revealed that fuel cell vehicles in many respects have reached the level of conventional ICE driven passenger cars. Power, power-to-weight ratio, top speed and system efficiency are already satisfying. Power density on cell level and also on stack level have to be increased, however, some manufacturers already report relatively high values and DOE target values are likely to be met. While ensuring high power densities platinum loading of electrodes has to be decreased further. Promising laboratory work and past progress leads to the assumption that significantly lower values can be achieved. Cold start ability has improved impressively but may compromise long-term durability. Consequently, further improvements are necessary in this area. Regarding hydrogen storage nowadays storage systems do not meet the DOE target values. Nevertheless, using compressed hydrogen already allows a convenient driving range. In summary, significant technological improvements have been made for fuel cell vehicles and most targets for mass market introduction have already been met or will most likely be met in near- or mid-term future.

Cost analysis led to the conclusion that nowadays production costs for fuel cell stacks and systems are very high but could be reduced significantly for high production volumes. Mayor influencing factors for mass production cost are power density of the stack, platinum load of the electrodes and market price for platinum. Assuming that technical aspects will further improve and platinum price will return to its past mean value stack production cost of approx. 12–40$ kW^{-1} for 1 million cumulated vehicles could be achieved. Fuel cell system cost would be approx. 35–83$ kW^{-1}. These values correspond to a learning curve rate of approx. 74% for the stack and 79% for the fuel cell system. In addition to production costs for the fuel cell system other costs, e.g. for the hydrogen storage system and an electric motor, will apply.

A possible market success of fuel cell vehicles is furthermore dependent on an appropriate hydrogen production and distribution infrastructure. Additionally, competing propulsion systems, e.g. battery electric vehicles, might impede introduction at least for some vehicle segments and market niches. Production cost reduction will have to be the focus for fuel cell driven vehicles during the upcoming years in order to make them a competitive alternative.

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