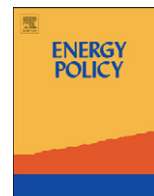




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Technology learning for fuel cells: An assessment of past and potential cost reductions

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ABSTRACT

Fuel cells have gained considerable interest as a means to efficiently convert the energy stored in gases like hydrogen and methane into electricity. Further developing fuel cells in order to reach cost, safety and reliability levels at which their widespread use becomes feasible is an essential prerequisite for the potential establishment of a 'hydrogen economy'. A major factor currently obviating the extensive use of fuel cells is their relatively high costs. At present we estimate these at about 1100 €(2005)/kW for an 80 kW fuel cell system but notice that specific costs vary markedly with fuel cell system power capacity. We analyze past fuel cell cost reductions for both individual manufacturers and the global market. We determine learning curves, with fairly high uncertainty ranges, for three different types of fuel cell technology – AFC, PAFC and PEMFC – each manufactured by a different producer. For PEMFC technology we also calculate a global learning curve, characterised by a learning rate of 21% with an error margin of 4%. Given their respective uncertainties, this global learning rate value is in agreement with those we find for different manufacturers. In contrast to some other new energy technologies, R&D still plays a major role in today's fuel cell improvement process and hence probably explains a substantial part of our observed cost reductions. The remaining share of these cost reductions derives from learning-by-doing proper. Since learning-by-doing usually involves a learning rate of typically 20%, the residual value for pure learning we find for fuel cells is relatively low. In an ideal scenario for fuel cell technology we estimate a bottom-line for specific (80 kW system) manufacturing costs of 95 €(2005)/kW. Although learning curves observed in the past constitute no guarantee for sustained cost reductions in the future, when we assume global total learning at the pace calculated here as the only cost reduction mechanism, this ultimate cost figure is reached after a large-scale deployment about 10 times doubled with respect to the cumulative installed fuel cell capacity to date.

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1. Introduction

Fuel cells are considered a promising candidate for efficiently converting the energy stored in several kinds of gases, among which hydrogen and methane, into electricity, especially in small-scale applications. They can be utilized to power e.g. electric motors in cars and appliances in buildings and households. Fuel cells can also replace batteries in a variety of portable consumer products such as laptops. Although the principle of fuel cells was already discovered in 1839 by William Grove, their first development only preliminarily started in 1932 through Francis Bacon's exploratory work and really took off in the early 1960s when

NASA appointed them as the principal replacement of batteries in spacecraft (Bacon, 1969). The primary energy storage used for extended manned spaceflight requires high power levels sustained during long (discharge) times, which the batteries of that time were unable to provide.

Table 1 shows a schematic selection of the most common fuel cell types currently produced and their main field of application. Also indicated is whether and how they are analyzed in this article. Today, most fuel cell technologies are still essentially in the demonstration phase. Although the focus is at present mainly on their application in transportation (OECD/IEA, 2005), also their use for stationary power generation purposes receives attention, even in the sphere of commercialization.

Across the spectrum of different types, high costs pose a problem for the deployment of fuel cells. Especially in the case of fuel cells that run on hydrogen, such as the most commonly used PEMFCs, this may well hamper their widespread application,

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Table 1
Main fuel cell types, their application and analysis in this article.

Type	Acronym	Main application			Our analysis	
		Stationary	Mobile	Portable	Manufacturer	Global
Proton exchange membrane fuel cell	PEMFC	x	x	x	x	x
Alkaline fuel cell	AFC	x	x		x	
Phosphoric acid fuel cell	PAFC	x			x	
Solid oxide fuel cell	SOFC	x	x			
Molten carbonate fuel cell	MCFC	x	x			
Direct methanol fuel cell	DMFC		x	x		

as these fuel cells have to compete with the significantly cheaper internal combustion engine. Elevated costs may continue obstructing the establishment of a viable fully fledged hydrogen economy, i.e. an economic infrastructure with hydrogen as principle energy carrier. In this article we present an analysis of the evolution of fuel cell manufacturing costs since their early deployment, in view of increasing our understanding of the potential for further cost reductions. Of the six fuel cell types listed in Table 1, we focus on PEMFC, AFC and PAFC, since these technologies (unlike the other three) were first developed already decades ago. Correspondingly, significant manufacturing experience has been accumulated, and, consequently, longer time series are available for the cost evolution of these three fuel cell types and more is known already today about their long-term cost breakdown. Our choice for these three fuel cell types does not reflect their current market segment: at present (2007), the volumetric market share for MCFCs is about 40%, for PAFCs and PEMFCs each a little over 20%, and for SOFCs approximately 15%, while those for AFCs and DMFCs are negligible. We reserve cost analyses for fuel cell types other than the three of choice in the present paper for future work (see e.g. the study by Rivera-Tinoco et al. (2010) on SOFCs that, like MCFCs, receive increasing deployment, R&D and patenting attention today).

We analyze observed cost reductions in two ways, at a global level and as applied to different manufacturers, and employ the learning curve methodology (see e.g. OECD/IEA, 2000). We assess learning phenomena at the manufacturer's level by analyzing each of the three different fuel cell types AFC, PAFC and PEMFC. Production cost developments of PEMFCs are also determined globally, in which case we do not discriminate by manufacturer. In neither of these two approaches the costs associated with the actual use of fuel cells are taken into account, hence we do not inspect cost categories related to fuel, operation and maintenance. For cost (reduction) data of hydrogen production and their trends we refer to our prior publication (Schoots et al., 2008). The purpose of this study is to construct learning curves for fuel cell manufacturing, which we hope enables us to better evaluate the potential for cost improvements in the future. While we recognize that the demand side has a crucial role to play in reducing the costs of fuel cells – as their actual use constitutes in the end the fundamental driver behind activating cost improvement mechanisms in the manufacturing process – we focus in this paper only on the supply (i.e. production) side. In practice stimulation and analysis of the demand and supply side must take place in concert, in order to realize technological innovation.

For decades learning curves have been used as a suitable visualization of learning-by-doing. Learning curves express the hypothesis that the costs of a technology decrease by a constant fraction with every doubling of cumulative installed capacity or exercised activity. Hence, on a double-logarithmic scale the relation between technology costs and cumulated manufacturing or usage involves a downward sloping straight line (see, for example: OECD/IEA, 2000; Ferioli et al., 2009). In other words,

technology costs follow the relation:

$$c_t = c_i \left(\frac{P_t}{P_i} \right)^{-\alpha} \quad (1)$$

in which c_t is the cost of the technology at time t , c_i its initial cost (in principle per item of the first batch of production), P_t the cumulative production at time t , P_i the initial cumulative number of produced items (normally but not necessarily in the first batch of production) and α the learning index. The learning index is related to the progress rate pr via the relation $pr=2^{-\alpha}$. The progress rate expresses the cost of a product that remains after a doubling of cumulative capacity (in relative terms, thus quantified as fraction and typically in percentages), so that the learning rate expresses the relative cost reduction (in percentages) after this accumulated increase in production. Hence, the progress rate plus the learning rate by definition equals 100%.

Fuel cell systems are produced with many different total capacities. For mutual comparability of our results, we follow the commonly used convention to express fuel cell costs per unit of kW, the so-called specific manufacturing costs. We use data available from the open literature, since in-house company information is often kept confidential. These data are normally biased towards the lower end, because their sources often only report commercial production costs and exclude relatively large R&D expenses.

In spite of extensive research efforts, the mechanisms behind cost-reducing learning phenomena are still poorly understood (see notably Argote and Epple, 1990; Arrow, 1962; Hirsch, 1956; Levitt and March, 1988; Muth, 1986), even while several studies point out the possible direction of search and other analyses have booked some progress in opening the black box of learning-by-doing (e.g. Grübler et al., 1999; Nemet, 2006; Sagar and van der Zwaan, 2006; Schoots et al., 2008). Learning curves can, by definition, only be determined for technologies that have matured sufficiently, that is, deployed to such an extent that has allowed a certain amount of commercialization. Learning curves by first principle cannot be determined for technologies that never reached this phase, but disappeared or were pushed out of the market before reaching the stage of significant diffusion.

Fuel cell technology forms a challenging – but interesting – example, since so far limited deployment has materialized and the commercialization phase has only barely started. Progress in fuel cell development today for each type at least partly originates from R&D (learning-by-searching), in addition to effects associated with technology deployment (learning-by-doing) for several fuel cell categories. Deployment today mainly takes place through demonstration projects. The large-scale commercialization of fuel cell technology, as promoted by several companies, has not yet taken off. On the other hand, based on the high expectations of experts and the evident applicability of fuel cells in various niche markets, it is unlikely that this technology is abandoned anytime soon. In this paper we give insight into the feasibility of constructing a learning curve for fuel cell technology,

even while it has not entered the widespread deployment phase yet. Because much of the development of fuel cells still centers around R&D, one may expect that, if a reliable learning curve can be found, the observed cost reductions may at least to some extent originate from learning-by-searching rather than learning-by-doing. Note that while R&D expenses are usually omitted from production costs publicly reported by manufacturers, their effects are often visible in the data, for instance in the form of discrete cost reduction steps.

In Section 2 of this article we determine learning curves for three different manufacturers, each of another fuel cell type. In Section 3 we establish a global learning curve for PEMFCs and present a cost breakdown for this technology. In Section 4 we discuss our results and point out some caveats in our analysis. We here also determine the bottom-line to which fuel cell costs might eventually (but not certainly) drop. We conclude our study in Section 5.

2. Learning by manufacturers

Below learning curves are determined for AFCs produced by Pratt & Whitney Aircraft during the 1960s, PAFCs by UTC Power in the 1990s and PEMFCs by Ballard in the early 2000s.

2.1. Pratt & Whitney Aircraft

We analyze fuel cell cost developments using data for NASA's Apollo project from Rice and Bell (1972). Given the publication year of this source we assume that the reported data are all in US\$(1972). While for the Gemini project NASA had initiated R&D and deployment of PEMFCs, for the Apollo project it chose AFCs (Burke, 2003). For reasons such as their high efficiency, AFCs prove a particularly suitable fuel cell technology for spaceflight to date, as demonstrated by their use also in the Space Shuttle. Several developments that significantly improved the performance of fuel cells reduced AFC manufacturing costs from 98 kUS\$(1972)/kW in 1962 to 47 kUS\$(1972)/kW in 1970 (Rice and Bell, 1972).

For the period between 1964 and 1970 a total number of 90 AFC systems were produced for the Apollo project (see Table 2) (DeRonck, 2008). All were constructed by Pratt & Whitney Aircraft (today UTC Power) and were able to deliver a maximum power of 2.3 kW (Burke, 2003). For each Apollo vehicle the Command and Service Module (CSM), installed by spacecraft constructor North American Rockwell, contained three fuel cell systems. Although the exact breakdown of the cumulative AFC production number of

90 into annual figures is unknown, we were able to make a reasonable estimate based on qualitative knowledge on fuel cell demand for e.g. R&D purposes in 1964 and the estimated construction year of each CSM (DeRonck, 2008; NASA, 2000). It appears that the production of AFCs has not been uniform over the Apollo program. We summarize our estimates for the annual manufacturing of AFCs during the entire project in Table 2.

In the R&D phase we think about 4 systems were fabricated by Pratt & Whitney for the purpose of engineering and in-house testing. The moment the AFC system passed qualification and certification procedures (for which 1 system was required), production was paced up to meet systems integration testing requisites by NASA and North American Rockwell (2 systems) and usage needs for the first mission schedule (5 systems, consisting of 3 for the CSM and 2 spare units). This explains the number 12 in the first row of Table 2. In addition to the 3 fuel cell systems installed in each CSM, we know that numerous spare units were produced and stored for possible later use, presumably 1–2 systems per mission. Table 2 shows how we assume the construction of units has been distributed over the various Apollo missions. After Apollo 1 (constructed in 1965) accidentally took fire on the launch base in early 1967, the design of the AFC system was updated and some of the older units were retired. We suppose that consequently production temporarily paced up from the beginning of 1967 in order to replenish the spare unit stock, as indicated in Table 2. The overall cumulative production pattern over time accompanying the numbers of Table 2 is displayed in Fig. 1.

A learning curve for AFCs can be constructed by plotting and fitting the cost data from Rice and Bell (1972) against the associated cumulative production data from Fig. 1 on a double-logarithmic scale. From the result, shown in Fig. 2, we observe

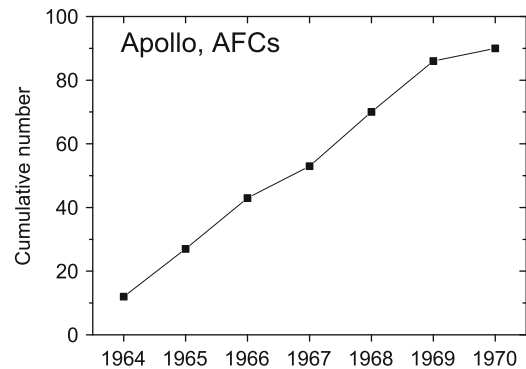


Fig. 1. Cumulative AFC production during the Apollo project.

Table 2

Annual AFC system production numbers during the Apollo project.

Construction year	Estimated number AFCs	Purpose and breakdown (Number AFCs between brackets)
1964	12	R&D (4), qualification (1), testing (2), Apollo AS201 (5)
1965	15	Apollo AS202, 1 and 4 (3 × 5) ^a
1966	16	Apollo 6–9 (4 × 4)
1967	10	Apollo 10–11 (2 × 5)
1968	17	Apollo 12–15 (5, 3 × 4)
1969	16	Apollo 16–19 (4 × 4) ^b
1970	4	Apollo 20 (4) ^b
Total	90	

^a Apollo missions AS203 and 5 carried a Lunar Module and only a nose cone instead of the CSM (NASA, 2000). No fuel cells were used for these missions. No missions or flights were ever designated Apollo 2 and 3.

^b Apollo vehicles 18–20 were initially contemplated but never actually flew. Yet, their fuel cells had already been produced before these flights were cancelled.

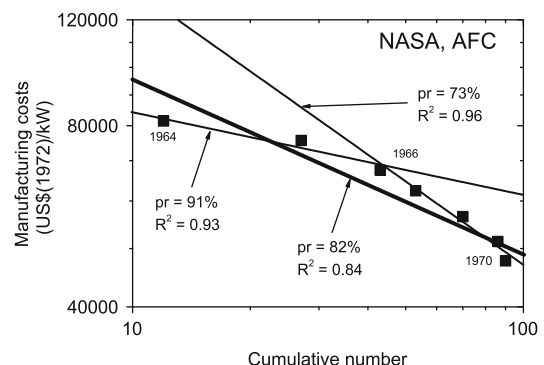


Fig. 2. Learning curves for AFCs between 1964 and 1970 (data from Rice and Bell, 1972; DeRonck, 2008; NASA, 2000).

that the downward sloping of the learning curve in early years further declines after the fuel cell system design update in 1967. We therefore split the learning curve in two parts: one for the period 1964–1966 and one for 1967–1970. Our least-squares fitting procedure yields distinct learning behavior with a progress rate of 91% and 73% (hence a learning rate of 9% and 27%), and relatively high correlation coefficient R^2 of 0.93 and 0.96, for these two periods, respectively (see the thin lines in Fig. 2).

A possible reason for the higher progress rate (i.e. lower learning rate) during the pre-1967 phase is that the emphasis may initially have been on making the concept work, rather than optimizing the fuel cell and its production process. After the system redesign the focus probably shifted to improving both fuel cell performance and manufacturing practice. This may have been at the origin of the sharper reduction of specific costs that materialized after 1967. Of course, both periods are part of the development process of the same basic AFC system, since there is no evidence for any fundamental change in technology, design or production philosophy. We therefore also present a result for the two periods combined and assume that the progress rate for the Apollo project AFCs on average lies between 73% and 91%. We correspondingly report as final central value their mean of $82 \pm 9\%$. A forced least-squares fit performed with this value for the progress rate, also shown in Fig. 2 (thick line), resulted in a lower R^2 of 0.84. One may argue that in this example AFC technology did not yet sufficiently reach the stage of commercialization: first, because R&D also still played a substantial role at this phase of AFC development, and second, since for the prestigious case of the aerospace industry monetary expenses were of second-order importance hence limiting an otherwise important stimulus for innovation. Both these factors should be considered when interpreting the learning-by-doing results depicted in Fig. 2.

2.2. UTC Power

The first fuel cells ever fabricated and used commercially (apart from those employed in space industry) were PAFCs. In 1998 UTC Power (at that time called ONSI International Fuel Cells) published a learning curve for their 200 kW system, the PC25 model (Whitaker, 1998). In Fig. 3 we plot the UTC cost and cumulative production data as reported in this publication. These are 'real' data referring to individual years from 1993 to 1998 and two forecasts for 1999 and 2000 (the two points furthest to the right). We perform a least-squares fitting procedure, including and excluding these two forecasts, and find a progress rate of 68% ($R^2=0.79$) and 62% ($R^2=0.73$), respectively. The average progress rate for PAFCs amounts thus to $65 \pm 3\%$. This is a particularly low value in comparison to progress rates reported in the literature, whose median is typically around 80% (McDonald and Schratzenholzer, 2001).

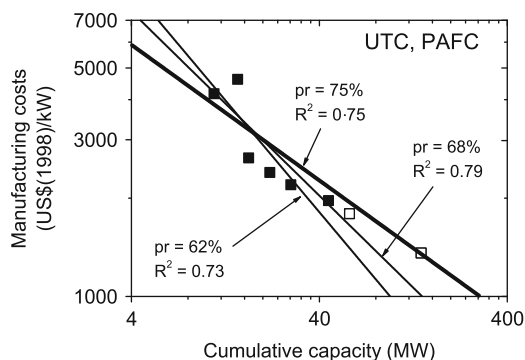


Fig. 3. Learning curves for PAFCs between 1993 and 2000 (data from Whitaker, 1998; open squares are forecasts).

Based on the same data set, Whitaker (1998) reports a progress rate of 75%. There may be at least two possible explanations for the difference between his and our progress rate calculations. First, between 1993 and 1998 UTC increased its fuel cell production capacity, which probably led to economies-of-scale benefits. Possibly, Whitaker has explicitly accounted for these effects and extracted them from his progress rate determination. This could rationalize part or whole of the discrepancy we observe. Second, PAFC technology is still subject to a moderate level of R&D. Whitaker may also have subtracted the corresponding learning-by-searching from the overall learning he determines (e.g. by leaving out the first two high-lying data points), in order to obtain learning-by-doing proper. We believe that accounting for these effects could well explain the 10% difference between our respective progress rate assessments. Unfortunately Whitaker (1998) reveals no details on his analysis: a lack of information on the precise composition and inclusion of the published cost data and the evolution of the production scale inhibits thus a conclusive explanation, and we can only guess. As we are predominantly interested in learning-by-doing and our two learning curve fits in Fig. 3 (thin lines) are likely to include cost reductions resulting from economies-of-scale and/or R&D, we adopt the central value reported by Whitaker. We match this figure with the error margin calculated by us and thus obtain $pr=75 \pm 3\%$. Fig. 3 also shows a forced fit through the data points based on this progress rate (thick line).

2.3. Ballard

Today PEMFCs are regarded the prime candidate for mobile applications in road vehicles and portable power generation because of their high power density and ability to quick-start in cold conditions. Ballard has annually published the development of its PEMFC manufacturing costs between 2002 and 2005 (Ballard Power Systems Inc., 2007). It does not, however, report the corresponding capacities of production. In this period, Ballard has mostly been active in the transportation sector. Given the lack of detail on Ballard's own production numbers, we use as proxy the global capacity figures of PEMFCs installed in cars and buses (see Section 3.1). We use the fact that the learning index is invariant under any multiplicative factor of cumulative capacity and assume that during the years under consideration Ballard has retained a constant market share. Because in reality the market share of Ballard may have changed between 2002 and 2005, we potentially introduce a systematic error with this assumption, but it allows us to determine a progress rate for Ballard's PEMFC.

Fig. 4 depicts the Ballard fuel cell learning curve determined by a least-squares fit of the cost data from Ballard Power Systems Inc. (2007) against the global cumulative capacity on a

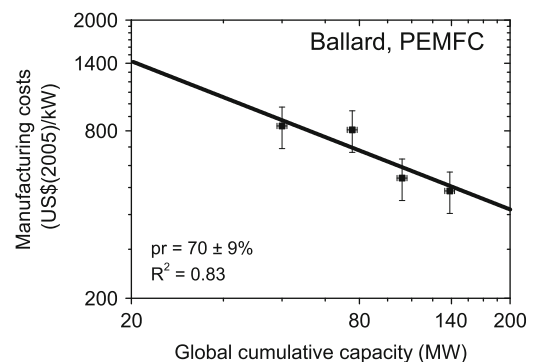


Fig. 4. Learning curve for PEMFCs in transportation between 2002 and 2005 (cost data from Ballard Power Systems Inc., 2007).

double-logarithmic scale. From the result we calculate a progress rate of 70%. The uncertainty ranges adopted in the cumulative capacity and specific manufacturing costs (the details of which are specified in Sections 3.1 and 3.2) enable us to determine an error margin for the progress rate through the Gauss propagation method (Bronshstein et al., 2002). This propagation method transmits the spread in the original data points and their individual error margins into an overall standard deviation for the progress rate, which we calculate to be 9%. The correlation coefficient $R^2=0.83$ indicates that our fit is imperfect but acceptable for our purposes: the Ballard PEMFC manufacturing costs prove to follow learning curve behavior with a rather low progress rate. A possible reason for finding such a low progress rate is that the global cumulative PEMFC capacity increased less rapidly than for Ballard alone. In other words, for Ballard the rate of fuel cell production may have gone up faster than we assumed here (but we have not been able to confirm this possibility, partly as a result of the restructuring of both Ballard and the sector at large).

3. Global learning

Having observed three examples of apparent learning for the production of fuel cells at the manufacturer's level, can we also determine a global learning curve? We here inspect the case of PEMFCs during 1995–2006. Because of the diversity in available PEMFC technologies, the determination of a global learning curve is not a trivial task. For example, the composition of the primary fuel one intends to feed into the PEMFC has important implications for its design. In particular the types and amounts of materials needed to fabricate the catalyst and membrane are sensitive to the kind of fuel used. The fuel cell's purpose also plays an important role, since each has a different cost target and drivers. For stationary applications, for instance, a cost level of 530 €(2005)/kW is sometimes acceptable, while for automotive purposes the target is typically set at 20 €(2005)/kW (US DOE, 2009). The reason for this difference in targets is that for stationary fuel cell system applications (small) niche markets exist for which one is willing to pay a high price (such as back-up power units in hospitals, residences and industrial plants), while for mobile applications one usually needs to compete with the current low-cost internal combustion engine (as in cars – back-up power requirements in trucks is a well-known exception). An additional complication is the fact that the costs of some parts of the fuel cell do not scale linearly with its capacity. The cost associated with the fabrication of the balance of plant constitutes a good example in case.

These factors render the costs of distinct PEMFC types and applications not readily comparable. Simple aggregation of different PEMFC types under a single denominator would cause undue scattering of data in learning curve plots. This scattering may overshadow otherwise discernable learning behavior and yield a signal-to-noise ratio too small to calculate a statistically meaningful progress rate. In order to avoid these sorts of intricacies we limit the boundaries of our learning system and assess only the specific manufacturing costs of those PEMFCs that are fuelled with pure hydrogen and used to power road vehicles.

3.1. Cumulative PEMFC capacity

PEMFCs can be arranged in five distinct categories: used in large or small stationary applications, for transit buses, cars and portable devices. Essentially all PEMFCs are employed in one of these categories, apart from some niche applications for fuel cells in e.g. spacecraft, trains, ships, forklifts and as auxiliary power

Table 3

PEMFC use and corresponding characteristic capacity (Adamson, 2004, 2006, 2007; Adamson and Crawley, 2006; Crawley, 2006).

Application	PEMFC share in 2006 (%)	Characteristic capacity (kW)
Large stationary	18	180–540
Small stationary	96	2–4
Buses	100	200–250
Cars	100	50–80
Portable	46	0.05–0.10

units (APUs), 98% of which are PEMFCs (Adamson, 2006). In 2005 the cumulative amount of fuel cells produced for these latter purposes was 700 units of 1–2 kW each, that is, less than a percent of the 136 MW of PEMFCs manufactured for the five main categories. Since 2005 some of these niche applications expanded rapidly in absolute terms, for instance in forklifts.

A fuel cell system usually consists of a series of cells arranged in a stack. The number of cells varies depending on the power demanded, which in turn is related to its particular use (see Table 3). PEMFC systems are utilized for essentially all purposes and are therefore manufactured in a broad range of capacities. Because of their large differences in power output, simply counting the number of manufactured systems would give too heterogeneous a sample and thus does not suffice for our purposes. Producing a large-capacity fuel cell system requires many more cells – and thus involves more learning-by-doing – than when a small fuel cell system is fabricated. We therefore take cumulative capacity as basis for our learning curve analysis.

This approach has two disadvantages, of which we address one and neglect the other. First, different fuel cell system parts show different cost-scaling behavior. As a result, the specific costs of a 3 kW stationary system are higher than those of an 80 kW system used in cars. Such scaling effects ought to be eliminated when determining learning curves, which we do by investigating one particular field of application. We thereby focus on only a narrow range of fuel cell capacities. Second, even then the capacity of individual cells may vary. Their number per level of total capacity may thus depend on the particular fuel cell design. We expect this effect has only minor influence on the specific costs. Indeed, we may safely assume that at any point in time all manufacturers produce fuel cells with approximately the same state-of-the-art technology and similar power density, and thus use more or less the same amounts of stack materials per unit of capacity. The material costs for the stack scale with capacity and account for 92% of the total stack costs (see also Section 3.2), so that this effect can basically be neglected.

For each of the five categories, Adamson (2004, 2006, 2007, 2009), Adamson and Crawley (2006), Butler (2009), Callaghan Jerram (2008, 2009) and Crawley (2006) report the evolution over time of the cumulative number of fuel cell units, the share of PEMFCs and their respective characteristic power (see Table 3). We multiply these figures in order to find for each category the cumulative PEMFC capacity as function of time, and assume that the PEMFC share in each of these categories has remained roughly unchanged between 1990 and 2006.¹ Fig. 5 shows the resulting breakdown of the total cumulative PEMFC capacity. In order to get a feeling for the uncertainties governing capacity data reported in the literature, we have compared the data as plotted in Fig. 5 with those from other independent sources. For example, the increase

¹ The cumulative deployment of large stationary power plants was reported explicitly in MW (Adamson, 2007). These capacity figures could thus directly be multiplied by the PEMFC share to obtain the PEMFC capacity. For small stationary, buses and cars we use the typical capacities of 3, 250 and 50 kW, respectively, in our calculations. Portable applications contribute negligibly to overall capacity.

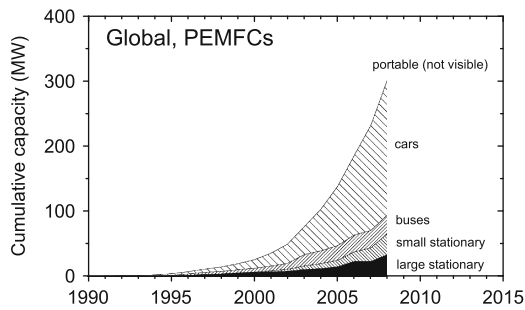


Fig. 5. Cumulative PEMFC capacity per category (data from Adamson, 2004, 2006, 2007, 2009; Adamson and Crawley, 2006; Butler, 2009; Callaghan Jerram, 2008, 2009; Crawley, 2006).

Table 4

Breakdown of the manufacturing costs of PEMFCs in 2007 with a production scale of 500 units/year.

Component	Specific costs (€(2005)/kW)				
	5 kW	50 kW	80 kW	200 kW	250 kW
Membrane electrode assembly					
Catalyst (1.25 gPt/kW)	105	105	105	105	105
Gas diffusion layer	58	58	58	58	58
Membrane	30	30	30	30	30
Electrode	8	8	8	8	8
Flow plates	139	133	132	132	132
Balance of plant					
Hydrogen management	2183	559	468	358	340
Air management	752	168	140	109	104
Temperature management	180	58	49	35	33
Peripherals	448	45	28	11	9
Stack assembly (MEA+plates)	22	22	22	22	22
Remaining assembly	174	34	27	20	18
Total PEMFC system cost	4099	1220	1067	888	859

in cumulative production of 46 MW between 2006 and 2007 shown in Fig. 5 agrees within an error margin of 3% with the 2007 figure for new fuel cell capacity from Middelman (2008). PEMFC constitutes a clear example of a technology, like many others, that grows exponentially in the early phase of its lifetime (Ferioli and van der Zwaan, 2009).

3.2. PEMFC cost breakdown

The costs of PEMFC manufacturing can be broken down in four major categories: membrane electrode assembly (MEA), flow plates, balance of plant (BoP) and assembly costs. The MEA and BoP costs can be subdivided further, each in four different components, as shown in Table 4. The production costs in this table are based on a detailed investigation and cross-checking of the 5 kW PEMFC system built in the experimental vehicle HydroGEM at the main premises of the Energy research Centre of the Netherlands (ECN) in Petten (van den Oosterkamp et al., 2007; van den Oosterkamp, 2008; Makkus, 2008; Gebert, 2004). We assume this fuel cell system is produced in series at a production rate of 500 units/year, has a power density of 0.60 W/cm² and a platinum (Pt) loading of 0.75 mg/cm² (Carlson et al., 2005a; hence we abstain from recent R&D results that seem to promise a reduction of the Pt loading e.g. through a variety of spraying techniques). The 5 kW stack is composed of cells with an active area of 400 cm² (van den Oosterkamp et al., 2007). We obtained the total costs of this system by assessing the costs of each of its individual components – as far down as the sub-

component (nut and bolt) level – grouping these under each of the main categories and subsequently summing them up. The fuel cell application primarily considered in this article is transportation.²

Increasing the power of the stack simply means in principle to proportionally increase the number of cells. The total MEA material therefore scales linearly with capacity – the only way to reduce specific costs would be to reduce the amount of materials used per unit of capacity (involving e.g. thinner fuel cell layers and less catalyst). In other words, without such material reductions the specific MEA costs remain the same, regardless of the fuel cell system capacity, as indicated in Table 4. Similarly, we assume that the specific costs of the flow plates remain (essentially) independent of the fuel cell capacity. Hence, likewise the specific stack costs do not depend on the fuel cell power. With increasing stack capacity the BoP also needs to be scaled up. This up-sizing is realized by enlarging the many BoP parts so as to appropriately deal with e.g. larger gas flows, rather than by multiplying the number of parts. For each BoP sub-component, per unit of stack capacity (and thus internal volume) increase, the material use only increases per associated unit of surface. Therefore, the material costs for each of these BoP sub-components increases as a function of the fuel cell system capacity to the power 2/3 (Tribe and Alpine, 1986). To find the material costs for each of the four listed BoP components the costs of its associated sub-components are summed.

The stack assembly costs (associated with putting together all cells, thus MEA and flow plates) were estimated based on labor costs for semi-automatic production. Like the stack itself, its assembly costs scale linearly with capacity so that the specific stack assembly costs are constant with regard to the fuel cell power. The remaining assembly costs consist of labor costs for the procurement of parts, system assembly and testing. Their cost dynamics therefore differs from that of the stack assembly. We assume that the remaining specific system assembly costs scale linearly with the specific BoP material costs. In contrast, we suppose that the costs associated with the purchase of parts and system testing do not scale with the fuel cell capacity: a good approximation is that the corresponding specific costs linearly inversely decrease with capacity. All parts that are produced outside the plant are designed to fit directly into the overall fuel cell arrangement. This arrangement is optimized so as to aid an efficient production process. Note that the total assembly costs only represent operating costs: maintenance and investment costs for the component production facilities are not taken into account.

Expressing costs per kW is somewhat misleading because of the two different relations by which costs depend on the capacity of the fuel cell system. We have therefore determined the specific costs for a 5 kW system and the characteristic capacities used for passenger cars (50 and 80 kW) and transit buses (200 and 250 kW). The overall result listed in Table 4 shows that the specific costs decrease considerably as the fuel cell capacity increases. Different choices for the fuel cell capacity may explain much of the large differences in cost estimates observed in the literature.

3.3. Global PEMFC cost development

We analyze the specific manufacturing costs of PEMFCs between 1995 and 2006 by collecting data from a variety of

² As indicated, the fuel cell capacity in cars ranges from 50 to 80 kW and in buses from 200 to 250 kW. The HydroGEM cost data apply to a fuel cell 10–50 times smaller. Its specific costs are therefore scaled up to match the larger fuel cell capacities used in transportation.

sources that report costs in US dollar (Ballard Power Systems Inc., 2007; Tsuchiya and Kobayashi, 2004; TIAX, 2002; Ronne, 1995; Lipman et al., 2004; Carlson et al., 2005b; Alhluwalia and Garland, 2007; James and Kalinoski, 2007). Fig. 6 shows the results expressed in *nominal* US dollar terms. We next correct for inflation with respect to the base year 2005 by using the US producers price index (PPI) for hardware manufacturing from the US DOL (2009) (see Fig. 8). Table 4, however, expresses total fuel cell system costs in euros. We thus apply a second transformation by converting the inflation corrected literature data from US\$(2005)/kW to €(2005)/kW with an exchange rate of 1.25 US\$/€, the 3-year-average of the exchange rates over the period 2004–2006 (De Nederlandsche Bank, 2007). Fig. 7(a) shows the result of these two corrections on our collected data set, from which it can be seen that the effect is rather limited. (data from Ballard Power Systems Inc., 2007; Tsuchiya and Kobayashi, 2004; TIAX, 2002; Ronne, 1995; Lipman et al., 2004; Carlson et al., 2005b; Alhluwalia and Garland, 2007; James and Kalinoski, 2007).

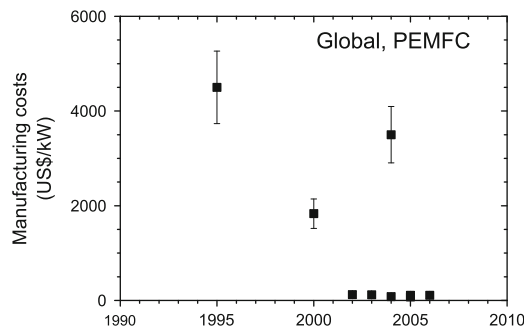


Fig. 6. Nominal manufacturing costs of PEMFCs between 1995 and 2006.

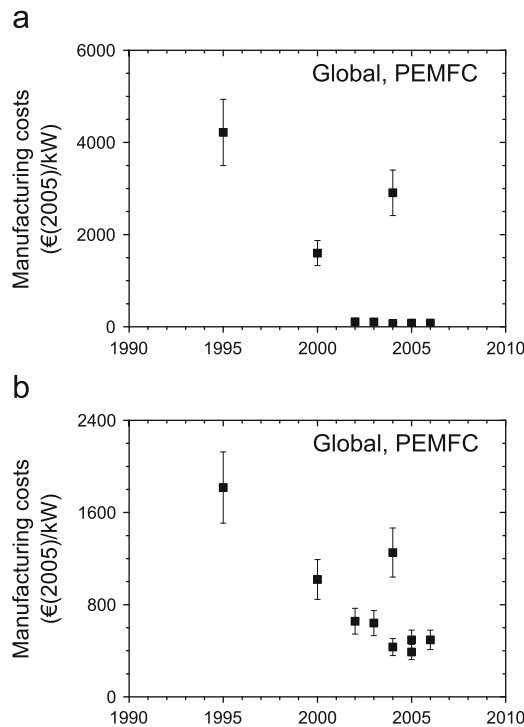


Fig. 7. Real manufacturing costs of PEMFCs between 1995 and 2006 before (a) and after (b) the economies-of-scale correction (data from Ballard Power Systems Inc., 2007; Tsuchiya and Kobayashi, 2004; TIAX, 2002; Ronne, 1995; Lipman et al., 2004; Carlson et al., 2005b; Alhluwalia and Garland, 2007; James and Kalinoski, 2007).

Within the transportation sector different fuel cell capacities are used ranging from 50 to 250 kW. The (normal) average of the specific manufacturing costs of the 50 and 250 kW fuel cell in Table 4 is 1040 €(2005)/kW. As this is close to the specific costs of an 80 kW fuel cell (see also Table 4), we use this fuel cell capacity as reference for further cost evaluation. Because we do not know the fuel cell capacity behind each data point in Fig. 6, we use an error margin on the specific manufacturing costs of 17%, i.e. half the difference between the specific costs for a 50 and 250 kW system.

The spread in the data of Fig. 6 is strikingly high, most of which can be explained by the fact that manufacturing costs are reported for different production scales. To make cost data mutually comparable we perform an economies-of-scale correction by converting manufacturing costs to a production scale of 500 fuel cells per year. We perform this conversion with the relation:

$$C_{500} = C_{lit} \left(\frac{S_{lit}}{500} \right)^{1-\lambda} \quad (2)$$

In Eq. (2), C_{500} are the specific manufacturing costs at a production scale of 500 fuel cells per year, C_{lit} the costs reported in the literature and S_{lit} the corresponding plant capacity (production scale) in terms of the number of fuel cells fabricated per year. In another source (McLean et al., 2002), PEMFC costs are reported for both small-scale manufacturing and high-volume production. Solving Eq. (2) with the data from Fig. 7a and a value for the scale factor λ of 69%. (McLean et al., 2002), we derive the data corrected for economies-of-scale shown in Fig. 7b. Technology learning is implicitly time-dependent while economies-of-scale are not. Therefore, filtering out economies-of-scale is what in our view should be done in order to determine learning-by-doing proper. Unfortunately, this is often erroneously omitted in practice, for which we here correct. The result is shown in Fig. 7 where the real costs are shown before (a) and after (b) the economies-of-scale correction. We followed a similar procedure with a different value for λ for the case of hydrogen production (Schoots et al., 2008).

In a PEMFC platinum plays an important but expensive role as catalyst. In contrast to many of the other components, the price of platinum is essentially only subject to supply and demand effects rather than to learning (Feroli et al., 2009). Fig. 8 shows the nominal market price of platinum normalized to its value in 2005. The resulting “platinum price index” evolves differently from the PPI for hardware manufacturing (also shown in Fig. 8). Fluctuations in the price for platinum cannot be compensated for with the PPI for hardware manufacturing, because the evolution of these two indices is too different. Between 1998 and 2007 the platinum market price rose sharply from 12 US\$(1998)/g to 42 US\$(2007)/g (Kitco Inc. (2009)).³ The sensitivity of PEMFC manufacturing costs for the increasing platinum market price may overshadow possible learning effects. This could especially apply to larger capacity systems for which BoP costs take a relatively low share. To increase the mutual comparability of cost data from different years we compensate for platinum market price fluctuations, which allows us to better extract a potential learning signal.

For all PEMFC manufacturing cost data we assess the amount of platinum per kW fabricated of the respective fuel cell. Over the years, the quantity of platinum required per kW has significantly decreased (which, incidentally, constitutes also a form of learning, with a progress rate of 91%). We assume a linear decrease over

³ Customarily the troy ounce (ozt) is the unit of mass used for precious metals: 1 ozt \approx 31 g.

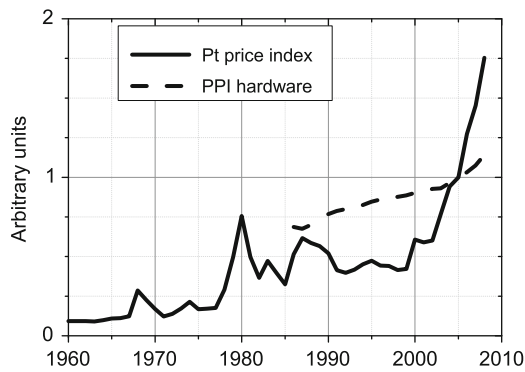


Fig. 8. Nominal Pt price and PPI, normalized to their value in 2005 (based on annual average data from Kitco Inc., 2009; US DOL, 2009).

time for the platinum use between the 2.6 gPt/kW quoted by Ticianelli et al. (1988) and the 1.25 gPt/kW in Carlson et al. (2005a). The platinum cost share for 2007 calculated with this linear function (of 13.2%) deviates somewhat from the share calculated from the 2007 cost breakdown shown in Table 4 (9.8% for the 80 kW system). These platinum cost shares are made consistent by calibrating the evolution of the platinum use with a factor 0.75, so that the cost share from the platinum usage function corresponds to the share determined for 2007 in Table 4. The resulting platinum load function enables us to estimate the amount of platinum used in PEMFCs between 1995 and 2006, the period for which we obtained manufacturing cost data. Fuel cell costs can be corrected for platinum market price fluctuations by following a straightforward procedure applied to each data point.

We calculate the platinum costs per kW at time t , c_t^{Pt} , by multiplying the platinum market price, p_t^{Pt} , with the corresponding amount of platinum per kW, a_t^{Pt} :

$$c_t^{Pt} = p_t^{Pt} a_t^{Pt}. \quad (3)$$

We then determine $c_{t,Pt2005}^{Pt}$, the platinum costs per kW at time t , based on the platinum market price of 2005:

$$c_{t,Pt2005}^{Pt} = p_{2005}^{Pt} a_t^{Pt}. \quad (4)$$

We can thus compensate the overall fuel cell costs at time t for fluctuations in the platinum market price by

$$c_{t,Pt2005}^{FC} = c_t^{FC} - c_t^{Pt} + c_{t,Pt2005}^{Pt}, \quad (5)$$

in which $c_{t,Pt2005}^{FC}$ is the specific fuel cell cost at t based on the platinum price in 2005, and c_t^{FC} the specific fuel cell cost at t based on the platinum price at t . The PEMFC manufacturing costs resulting from this additional platinum market price correction are shown in Fig. 9. The platinum market price effect proves to be negligible in perspective of the economies-of-scale correction for all data over the period considered, as can be seen from a comparison between Figs. 7 and 9. This effect is smaller than one may have anticipated (and proves to be also independent of which year is taken as Pt reference point). The explanation is that during the first several years we analyzed (when platinum prices were considerably lower than today's) the price of platinum still only accounted for a relatively small share of the total PEMFC production cost, while during 2004–2006 (when the platinum cost share grew to approximately 10% of the total fuel cell cost) the average annual platinum market price deviated by less than 10% from the figure in reference year 2005. (data from Ballard Power Systems Inc., 2007; Tsuchiya and Kobayashi, 2004; TIAX, 2002; Ronne, 1995; Lipman et al., 2004; Carlson et al., 2005b; Alhluwalia and Garland, 2007; James and Kalinoski, 2007).

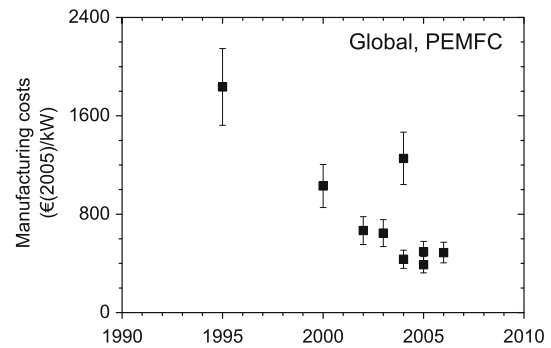


Fig. 9. Manufacturing costs of PEMFCs between 1995 and 2006 after corrections for inflation, economies-of-scale and platinum market price.

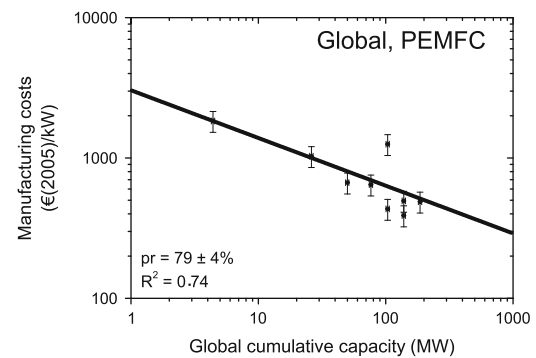


Fig. 10. Learning curve for PEMFCs in transportation between 1995 and 2006.

The PEMFC cumulated capacity from Fig. 5 can be combined with the cost data from Fig. 9, the result of which is plotted on a double-logarithmic scale in Fig. 10. The horizontal and vertical error bars correspond, respectively, to the error margins determined in Sections 3.1 and 3.3. The solid straight line through the data points in Fig. 10 is the result of a least-squares fitting procedure. Although there is still some scattering present in the cost data, they clearly show correlation with a power law. This is confirmed by a reasonable value for the correlation coefficient, $R^2=0.74$, which is imperfect but acceptable for our purposes. The calculated progress rate is $79 \pm 4\%$. The uncertainty ranges for cumulative capacity and specific manufacturing costs provide the input for the determination of the error margin for the progress rate by using the Gauss propagation method (Bronshstein et al., 2002). Although one data point is clearly an outlier, its deviation proves not to have a significant effect on the progress rate. Performing the analysis without this point gives a progress rate of 76%, i.e. within the error margin we calculate.

Note that we have plotted the costs of PEMFCs used in transportation against the cumulative capacity of *all* uses of PEMFCs, that is, not just in transportation. We think this is the correct comparison, as we believe that all deployment of PEMFCs, irrespective of their application, contributed to the observed cost reductions. From Fig. 5, we obtain a figure for the capacity of about 46 MW installed in 2007. From Fig. 10 we see that this additional power should ideally generate a cost reduction down to some 500 €(2005)/kW. This figure substantially deviates from the value we found for the 80 kW fuel cell in Table 4 (approximately 1100 €(2005)/kW). A possible explanation is that the two corrections we applied, both aimed at excluding non-learning effects and thus obtaining a 'purer' progress rate, shifted the learning curve in Fig. 10 downwards, and more so than justified according to the sources used for our calculations of the numbers listed in Table 4.

Table 5
Summary of the results of our fuel cell learning curve analysis.

Fuel cell type	Development start	Period investigated	Progress rate	R ²
<i>Manufacturer</i>				
AFC	1952	1964–1970	82 ± 9%	0.84
PAFC	1965	1993–2000	75 ± 3%	0.75
PEMFC	1959	2002–2005	70 ± 9%	0.83
<i>Global</i>				
PEMFC	1959	1995–2006	79 ± 4%	0.73

4. Discussion

In Sections 2 and 3 we have shown that learning curves can be constructed for fuel cells both for individual manufacturers and globally. In Table 5 we summarize our results for the types of fuel cell technology we analyzed. Indicated are the years in which the development of the respective fuel cell technologies started, the periods over which we investigated their cost evolution, and the progress rates we calculated along with their error margins and correlation coefficients.

The overlap between the error margins listed in Table 5 indicates that these progress rate values mutually agree. The most deviating progress rate of 70% is found for PEMFC manufacturer learning. This may be caused by a systematic error in our assumption regarding the definition of cumulative production. We observe better correlation with a power law for individual manufacturers than for the global case, in spite of the corrections performed for the latter by removing cost effects like inflation, economies-of-scale and platinum market price volatilities. We identify four reasons for which (global and manufacturing) learning curves remain characterized by a scattering of cost data and hence a relatively low correlation factor R².

First, there may be more components like platinum of which the costs are not subject to learning, but merely depend on fluctuating market prices. The number of parts a manufacturer chooses buying from external suppliers instead of producing in-house, the volatility of the market price of these parts and their share in total fuel cell costs may exacerbate the size of this effect. The comparability of global cost data may be further reduced by price differences between local markets. Individual manufacturers only deal with the suppliers they select and mostly operate within local or regional markets. This may increase the variability of cost data across different manufacturers.

Second, discrepancies may exist between sources in the literature regarding the definition of which elements are included in manufacturing costs, and whether specific costs are defined in terms of net or gross output power.⁴ Cost data for the global learning curve were extracted from various references, whereas for manufacturers each cost data set was extracted from a single source only. The chance of finding different cost definitions across manufacturers is larger than for individual ones. This may partly explain the larger spread in global figures.

Third, one may question whether it is allowed to perform an economies-of-scale correction over the total manufacturing costs of a fuel cell as we do. A more justified approach could be to apply this correction only to those costs expected to reduce as the production scale increases, like assembly costs and the purchase price of standard parts (e.g. pumps and valves). The platinum

catalyst is an example of a cost category to which the economies-of-scale correction should probably not be applied. Unless a way is found to avoid altogether the use of platinum in fuel cells, an increase in production by a fuel cell construction plant logically and linearly would lead to a correspondingly higher platinum demand. Perhaps losses of platinum in manufacturing tails could be reduced at larger production scales thus incurring some cost reductions. Often, however, instead of cost reductions, the (temporarily) limited availability of platinum may under these circumstances push the market price of platinum up instead of lowering it, e.g. due to the inertia in expanding mining and processing activities. In some of our sources fuel cell manufacturing costs for large-scale production are reported below the costs of their supposed platinum content. Most likely, in these cases the scale benefits have been (erroneously) accounted for over the total fuel cell system rather than applied to only a few components. Since we lack more detailed information on the economies-of-scale correction, we are unable to substantiate this claim or correct for the induced error. For all PEMFC cost data we have performed the economies-of-scale correction over the total fuel cell system. By choosing this approach, we avoid the introduction of further differences between individual cost data, which could lead to more scattering in the learning curve plot. This is at the expense, however, of the introduction of a new systematic error. Again, the global learning curve may suffer most from this effect, because within the global data set there may be individual cost figures for which the economies-of-scale correction was performed correctly. Within each manufacturer's source all data are presumably reported for one distinct production scale only.

Fourth, on a technological level slight differences may exist between the PEMFC systems produced by different manufacturers. We do not, however, expect these differences to alter the cost data within individual companies, unless a system design change has been introduced during the years considered. This effect only may play a role for the data underlying the global learning curve.

The learning curves we determined cannot continue indefinitely. At some stage a lower limit will be reached for fuel cell manufacturing costs (Ferioli et al. 2009). This lower limit may partly originate from the costs of raw materials (such as platinum, steel and plastics). What are the possibilities for future cost reductions of fuel cells? First, we estimate the amount of platinum used per kW may reduce further (Qi and Kaufman, 2003). Second, integrating passive regulation of gas flows in future system designs may provide an intrinsic humidity control that keeps the membrane at the right moisture level during operation and makes an additional (costly) active humidity management system redundant. Third, *in extremis* one may assume that the costs of the membrane, gas diffusion layer and balance of plant will ultimately reduce to the costs of their raw materials (Gebert, 2004).⁵ Taking these three improvements into account, we think ideally a lower limit for the material costs of fuel cells at 95 €(2005)/kW (which excludes assembly costs) may once be reached. This value is calculated independently from the learning curves we determine. The mechanism by which this 95 €(2005)/kW may be reached (probably in a time frame of decades rather than years) is therefore not necessarily only through continuous gradual cost reductions from learning effects, but also by discontinuous steps (such as when an active humidity control system is omitted). In support of the hypothesis of

⁴ The net electric power of a fuel cell is the gross electric power (maximum stack power) minus the 'parasitic' load from BoP components like pumps, valves, sensors and control electronics.

⁵ Gas diffusion layer costs are assumed to reduce down to the membrane costs reported by Gebert (2004). The lower limit for the balance of plant costs is determined from an estimate of the weight of a BoP system for an 80 kW fuel cell system (21 kg) multiplied with a steel price of 240 US\$/ton.

component-learning, 95 €(2005)/kW constitutes the cost of the non-learning part of the total technology, implying that the initial non-learning cost share, as in Ferioli et al. (2009), would be approximately $\alpha=0.10$.

The feasibility of reaching the 95 €(2005)/kW cost level also depends on the importance of cost reductions with respect to other drivers for developments in fuel cells. Other such factors may be reliability improvements and decreased start-up time. Their relevance depends on the demand of dominant players in the fuel cell market. For example, for the rapid response back-up power generation market, populated by companies like semiconductor manufacturers, credit card operators and brokerage firms, cost reduction is not necessarily the most important driver. With these sorts of companies a loss of power even for a short period of time may lead to significant economic damage, even to such an extent that the current high price of fuel cells is outweighed by the cost of power interruptions (Sammes et al., 2004). Hence, reliability improvements and faster start-up times could well be more important for the fuel cell market than cost reductions. On the other hand, if the market for fuel cells is going to be dominated by private consumers and individuals, cost reduction is likely to become a main focus for future fuel cell development.

5. Conclusion

It has been demonstrated that technologies yielding cost reductions via learning behavior are typically characterized by a progress rate of 80% (with a fairly large error margin) (see notably Ferioli et al., 2009; McDonald and Schrattenholzer, 2001; Dutton and Thomas, 1984). Similar progress rates are observed for the cases investigated in this article. The summary of our results listed in Table 5 shows that the progress rates we determine have been sustained over a period of over 40 years. For an 80 kW system we calculate the value for PEMFC manufacturing costs at 1067 €(2005)/kW in 2007, i.e. well above our estimated absolute lower limit of 95 €(2005)/kW. Although we are unable to conclude whether this cost gap will ever be breached, we conclude that, if the current speed of cost reductions is sustained, the lower bound will be reached after the cumulative capacity is multiplied by a factor of 1340, i.e. after about 10 doublings of installed power. Using the traditional learning curve methodology we derive that the learning investment involved amounts to 41 G€. This derivation holds if we assume that the learning phenomenon we observe is the only available cost reduction mechanism. Given recent and probably future price levels for raw materials (that are significantly higher than those experienced during the decades prior), and because charges for e.g. investments in production facilities and fuel cell assembly are not included in our derivation of the 'rock-bottom' level of 95 €(2005)/kW, one may question whether this value can be reached in the foreseeable future.

Since the work on fuel cells initiated in 1932 by Francis Thomas Bacon (1969) led to the construction and performance testing of the first AFC in 1952 (US DOE, 2000) and the first demonstration in real applications in 1959, R&D has played a dominant role in the improvement of fuel cells. Over the past 50 years, fuel cells have essentially only been used in niche applications and demonstration projects, which has strongly limited the build-up of cumulative capacity. It is likely that a possible future accumulation of capacity induces learning-by-doing and correspondingly leads to further improvement and deployment-related cost reductions. From the many expert elicitations performed for our study we conclude that R&D efforts will continue to yield fuel cell cost reductions. We

therefore expect that for fuel cell technology the dynamics of learning-by-searching remains important, at least in the short to medium term, and thus continues to complement those cost reductions anticipated on the sole basis of pure learning-by-doing.

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References

- Adamson, K.-A., 2004. Fuel Cell Market Survey: Buses. Fuel Cell Today, Royston, Hertfordshire.
- Adamson, K.-A., 2006. 2006 Small Stationary Survey. Fuel Cell Today, Royston, Hertfordshire.
- Adamson, K.-A., 2007. 2007 Large Stationary Survey. Fuel Cell Today, Royston, Hertfordshire.
- Adamson, K.-A., 2009. 2009 Small Stationary Survey. Fuel Cell Today, Royston, Hertfordshire.
- Adamson, K.-A., Crawley, G., 2006. 2006 Light Duty Vehicle Survey. Fuel Cell Today, Royston, Hertfordshire.
- Alhluwalia, R.K., Garland, N., 2007. Fuel Cell Systems Analysis. DOE Annual Progress Report, V.A.1, pp. 675–679.
- Argote, L., Epplé, D., 1990. Learning curves in manufacturing. *Science* 247 (4945), 920–924.
- Arrow, K.J., 1962. The economic implications of learning by doing. *The Review of Economic Studies* 29 (3), 155–173.
- Bacon, F.T., 1969. Fuel Cells, Past, Present and Future. *Electrochimica Acta* 14, 569–585.
- Ballard Power Systems Inc., 2007. <http://www.ballard.com/be_informed/fuel_cell_technology/roadmap> (Last checked 1 May 2007). Burnaby, BC.
- Bronshstein, I.N., Semendyayev, K.A., Musiol, G., Muehlig, H., 2002. *Handbook of Mathematics* fourth ed. Springer-Verlag, Berlin.
- Burke, K.A., 2003. Fuel Cells for Space Science Applications. NASA Glenn Research Center, Cleveland, OH.
- Butler, J., 2009. 2009 Portable Survey. Fuel Cell Today, Royston, Hertfordshire.
- Callaghan Jerram, L., 2008. 2008 Bus Survey. Fuel Cell Today, Royston, Hertfordshire.
- Callaghan Jerram, L., 2009. 2009 Light Duty Vehicle Survey. Fuel Cell Today, Royston, Hertfordshire.
- Carlson, E.J., Kopf, P., Sinha, J., Sriramulu, S., Yang, Y., 2005a. Cost Analysis for PEM Fuel Cell Systems for Transportation. National Renewable Energy Laboratory, Golden, CO.
- Carlson, E.J., Kopf, P., Sinha, J., Sriramulu, S., Yang, Y., 2005b. Cost Analysis of Fuel Cell Stack/Systems. DOE Annual Progress Report, VII.I.9, pp. 1067–1071.
- Crawley, G., 2006. 2006 Portable Survey. Fuel Cell Today, Royston, Hertfordshire.
- De Nederlandsche Bank, 2007. Exchange rates in euro. <<http://www.statistics.dnb.nl/index.cgi?lang=en&todo=Koersen>> (Last checked 21 November 2008). Amsterdam.
- DeRonck, H.J., 2008. Private Communication.
- Dutton, J.M., Thomas, A., 1984. Treating Progress Functions as a Managerial Opportunity. *Academy of Management Review* 9 (2), 235–247.
- Ferioli, F., Schoots, K., van der Zwaan, B.C.C., 2009. Use and Limitations of Learning Curves for Energy Technology Policy: A Component-Learning Hypothesis. *Energy Policy* 37, 2525–2535.
- Ferioli, F., van der Zwaan, B.C.C., 2009. Learning in Times of Change: A Dynamic Explanation for Technological Progress. *Environmental Science and Technology* 43 (11), 4002–4008.
- Gebert, M., 2004. Benchmarking method for components in polymer electrolyte fuel cells (Benchmarking-Methodik für Komponenten in Polymerelektrolyt-Brennstoffzellen). Schriften des Forschungszentrums Jülich Reihe Energietechnik, Forschungszentrums Jülich GmbH, Jülich.
- Grübler, A., Nakićenović, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. *Energy Policy* 27, 247–280.
- Hirsch, W.Z., 1956. Firm progress ratios. *Econometrica* 24 (2), 136–143.

- James, B.D., Kalinoski, J.A., 2007. Mass Production Cost Estimation for Direct H₂ PEM Fuel Cell Systems for Automotive Applications. DOE Annual Progress Report, V.A.6, pp. 700–704.
- Kitco Inc., 2009. London PM Fix. <http://www.kitco.com/scripts/hist_charts/yearly_graphs.plx> (Last checked 15 December 2009). Rouses Point, NY.
- Livitt, B., March, J.G., 1988. Organizational learning. *Annual Review of Sociology* 14, 319–340.
- Lipman, T., Edwards, J.L., Kammen, D.M., 2004. Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems. *Energy Policy* 32, 101–125.
- Makkus, R.C., 2008. Private Communication.
- McDonald, A., Schrattenholzer, L., 2001. Learning rates for energy technologies. *Energy Policy* 29, 255–261.
- McLean, G.F., Niet, T., Prince-Richard, S., Djilali, N., 2002. An assessment of alkaline fuel cell technology. *International Journal of Hydrogen Energy* 27, 507–526.
- Middelman, E., 2008. Private Communication.
- Muth, J.F., 1986. Search theory and the manufacturing progress function. *Management Science* 32 (8), 948–962.
- NASA, 2000. <<http://science.ksc.nasa.gov/history/apollo/apollo.html>> (Last checked 21 November 2008). Kennedy Space Center.
- Nemet, G.F., 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics. *Energy Policy* 34, 3218–3232.
- OECD/IEA, 2000. Experience Curves for Energy Technology Policy. Paris.
- OECD/IEA, 2005. Prospects for Hydrogen and Fuel Cells. Paris.
- Qi, Z., Kaufman, A., 2003. Low Pt loading high performance cathodes for PEM fuel cells. *Journal of Power Sources* 113, 37–43.
- Rice, W.E., Bell, D., 1972. Status of Shuttle Fuel Cell Technology Program. Proceedings of Seventh Intersociety Energy Conversion Engineering Conference, pp. 390–395.
- Rivera-Tinoco, R., Schoots, K., van der Zwaan, B.C.C., 2010. Learning Curves for Solid Oxide Fuel Cells. Working Paper.
- Ronne, J., 1995. An Integrated Cost Performance Model of a Transportation Fuel Cell System: Report for the Project Next Generation Fuel Cells for Transportation Applications. University of Victoria, Victoria, BC. Taken from Rogner, H.-H., 1998. Hydrogen technologies and the technology learning curve. *International Journal of Hydrogen Energy* 23, 833–840.
- Sagar, A.D., van der Zwaan, B.C.C., 2006. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. *Energy Policy* 34, 2601–2608.
- Sammes, N., Bove, R., Stahl, K., 2004. Phosphoric acid fuel cells: fundamentals and applications. *Current Opinion in Solid State and Material Science* 8, 372–378.
- Schoots, K., Ferioli, F., Kramer, G.J., van der Zwaan, B.C.C., 2008. Learning curves for hydrogen production technology: an assessment of observed cost reductions. *International Journal of Hydrogen Energy* 33, 2630–2645.
- TIAX LLC, 2002. Grid Independent Residential Fuel-Cell Conceptual Design and Cost Estimate. Cambridge, MA.
- Ticianelli, E.A., Derouin, C.R., Redondo, A., Srinivasan, S., 1988. Methods to advance technology of proton exchange membrane fuel cells. *Journal of the Electrochemical Society* 135 (9), 2209–2214.
- Tribe, M.A., Alpine, R.L.W., 1986. Scale economies and the “0.6 rule”. *Engineering Costs and Production Economics* 10 (1), 271–278.
- Tsuchiya, H., Kobayashi, O., 2004. Mass production cost of PEM fuel cell by learning curve. *International Journal of Hydrogen Energy* 29, 985–990.
- US DOE, 2000. Fuel Cell Handbook Fifth ed EG&G Services Parsons, Inc, Morgantown, WV.
- US DOE, 2009. Hydrogen Program Overview. Annual Merit Review Proceedings.
- US DOL, 2009. <<http://www.bls.gov/ppi/>> (Last checked 15 December 2009). Bureau of Labor Statistics, Washington, DC.
- van den Oosterkamp, P.F., de Bruijn, F.A., van der Laag, P.C., Mallant, R.K.A.M., 2007. Development & field trial of a hydrogen fuel cell vehicle. Presentation at the Fuel Cell Seminar, San Antonio, TX.
- van den Oosterkamp, P.F., 2008. Private Communication.
- Whitaker, R., 1998. Investment in volume building: the ‘virtuous cycle’ in PAFC. *Journal of Power Sources* 71, 71–74.