LIPMAN

Universität Stuttgart
Institut für Energiewirtschaft und Rationelle Energieanwendung
IER

Forschungsbericht

Experience Curves for Policy Making - The Case of Energy Technologies -

C.-O. Wene, A. Voß, T. Fried (eds.)

Band 67

Experience Curves for Policy Making
- The Case of Energy Technologies -

Proceedings of the
IEA International Workshop at Stuttgart, Germany
10 - 11 May 1999
organized by the IER
in cooperation with the IEA
sponsored by
the Swedish Government and
Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie,
Germany

C.-O. Wene, A. Voß, T. Fried (eds.)

April 2000

Institut für Energiewirtschaft und Rationelle Energieanwendung, Stuttgart
Prof. Dr.-Ing. A. Voß
Abteilung Energiewirtschaft und Systemtechnische Analysen (ESA)
Dr. U. Fahl

ISSN 0938-1228

10 Forecasting the Costs of Automotive PEM Fuel Cell Systems - Using Bounded Manufacturing Progress Functions

Timothy E. Lipman
Daniel Sperling
Institute of Transportation Studies - Davis
University of California, Davis, CA 95616
phone / fax: 530-758-4680/6572
e-mail: telipman@ucdavis.edu

Abstract

The future manufacturing costs of emerging technologies are difficult to assess because of the complex dynamics of both product and process innovation, and because cost data often are proprietary and difficult to obtain. One method of forecasting potential future technology costs uses the concept of manufacturing progress functions, which are closely related to manufacturing experience curves. Manufacturing cost is related to cumulative production volume for a specific firm in an industry, using relatively simple relationships that have been observed for a wide range of products. Progress functions and experience curves take into account scale economies, technological improvements in production processes, improvements in product design, and improved efficiency of workers and production management. Here we analyze the future manufacturing cost of an innovative new technology – the automotive PEM fuel cell system - using a manufacturing progress function analysis. Based on manufacturing progress function theory and the assumptions used in the analysis, we trace the manufacturing costs of fuel cells systems from present levels of $1,500 - 2,500 per kW to less than $50 per kW. For products such as PEM fuel cells that may reach high levels of accumulated production, we suggest methods for bounding forecasts in order to guard against eventually forecasting unrealistically low costs.

10.1 Introduction

The surge in interest in electric vehicles (EVs) during the past decade has resulted in much technological advancement, and the recent introduction of advanced, purpose-built, and high quality EVs. These vehicles use advanced battery power systems, based primarily on lead-acid, nickel-metal hydride, and lithium-ion battery chemistry. The use of battery-based power systems results in quiet and pollution-free vehicle operation, but such vehicles face important limitations including vehicle ranges of only 100 - 150 km, and long recharge times of several hours. A rapidly emerging alternative EV power system is the proton-exchange membrane

(PEM) fuel cell stack. Vehicles that use PEM fuel cells would have low or no operational emissions, and they could be fueled with hydrogen, methanol, or possibly reformulated gasoline. They could have driving ranges and refueling times comparable to today's conventional vehicles.

The challenge of integrating fuel cell systems into future generations of EVs is increasingly becoming one of cost, rather than technology. While there certainly are some technical hurdles left to overcome, PEM fuel cell stacks for automotive applications are rapidly becoming a proven technology. However, these stacks are currently produced in pilot-scale volumes, at very high cost. Recent cost studies by Directed Technologies, Inc. (DTI) suggest that in high volume production, PEM fuel cell systems could cost $35 - 90/kW, depending on system size (Lomax et al. (1997). Thomas et al. (1998a)). However, it is clear that significant product and process development will be required for these costs to be realized, and in any event it will be many years before such high volume production is possible. An interesting question is how PEM fuel cell system manufacturing costs might evolve from those in today's pilot-scale production, to the costs in mature, high-volume production level assessed in the DTI study. This paper forecasts the potential manufacturing costs of PEM fuel cells systems using a manufacturing progress function framework, and demonstrates how high-volume manufacturing cost estimates can be used in conjunction with manufacturing progress function analysis to forecast complete "cost paths" while at the same time preventing overly-optimistic cost forecasts.

10.2 Learning curves, experience curves and manufacturing progress functions

The concept of the learning curve has been applied to manufacturing settings since 1936, when T.P. Wright discovered a relationship between the labor hours needed to manufacture an airframe and the total number of airframes built. Wright found that each time the total quantity of airframes produced doubled, the labor hours required to assemble the airframe decreased by a stable percentage (Wright (1936)). Since this early work, thousands of studies have been conducted on the nature and variability of manufacturing cost reduction as a function of accumulated output, in industries as diverse as electric power, microchips, Japanese beer, consumer electronics, and automobiles (Argote and Epple (1990). Boston Consulting Group (1972). Dino (1985). Dutton and Thomas (1984). Ghemawat (1985) Yelle (1983). Among others). The term "learning curve" is often used generically to describe various types of cost decline and/or efficiency improvement, but many analysts prefer to reserve the term for labor efficiency improvement only, as in Wright's study of airframe production.

10.2.1 The Manufacturing Experience Curve

Thus, learning curves capture only a portion of the manufacturing cost reduction phenomena. They describe improvements in the efficiency of the labor component of total manufacturing cost, while the term that has come to be used to describe the curve that defines progress in the entire manufacturing cost is the "manufacturing experience curve". Learning curves can account for important sources of cost reduction for products in low-volume production, where assembly operations are often done by hand, and for products whose production is not amenable to automation. For most products, the production process becomes highly automated relatively rapidly, and learning curves become correspondingly less relevant.

In essence, the experience curve describes the cost path of a manufactured product, beginning with the first and continuing to the 'nth' unit produced. Cost reductions are typically due to four primary factors: scale economies, technological improvements in production processes, improvements in product design (i. e., reduced parts counts and design for manufacturability), and improved production worker and organizational efficiency. The progress of an industry along an experience curve for a new technology represents the steady decline in its inflation-corrected unit cost of manufacture.

In the seminal work on experience curves, the Boston Consulting Group suggested that experience curves could alternatively be construed to reflect the progress in the cost of adding value to a product (i. e., all manufacturing costs other than materials costs), rather than the entire manufacturing cost (Conley (1970)). They suggested that this distinction could be important for products where materials costs represented a large share of total manufacturing cost, and where cost declines in materials were likely to follow a different pattern than the overall unit cost decline. In practice, however, experience curves have almost always been analyzed in terms of total manufacturing costs, without regard for the materials cost/value added cost distinction.

10.2.2 The Manufacturing Progress Function

Manufacturing progress functions (MPFs) are similar to experience curves, except that MPFs describe the pattern of manufacturing costs for a particular firm in an industry, while experience curves describe industry-wide cost reductions. In principle, if market shares in an industry were stable over time, one could estimate an industry-wide experience curve by aggregating the MPFs of the firms in an industry and calculating a market share-weighted average of the progress function slopes. However, this would require analysis of the MPFs of all of the firms in an industry – a daunting task. In practice, experience curve analysis is used when the available data or the forecast of interest is for industry-wide production, and MPF analysis is used if an individual firm is the unit of analysis of interest.

Several different functional forms for MPFs and experience curves have been investigated, but the most commonly used expression is the simple log-linear form shown in Equation (1)[77].

$$C_N = C_I * V_N^{(\log\partial/\log 2)} \qquad (1)$$

where

C_N : Cost of manufacturing nth unit
C_I : Cost of manufacturing 1st unit
V_N : Cumulative production at nth unit
∂ : Experience curve slope

This relationship predicts that the constant dollar cost of manufacturing a product falls by a fixed percentage with each doubling of accumulated manufacturing experience. For example, an 80 % curve predicts that the constant dollar cost of a product will fall by 20 % with each doubling of cumulative production volume. Hence, cost reductions are relatively dramatic during the early stages of manufacture, as scale economies are captured and the production process is perfected, and then drop off as doublings in volume take longer to achieve.

10.2.3 Ex Post and Ex Ante Analyses

Experience curve and MPF analyses are often applied retrospectively, or *ex post*. One classic example, and one of the most often cited, is from the early history of the automobile industry. Figure 1 depicts the decline in the price of the Model-T Ford from 1909 to 1918. During this period, the price fell from over \$3,000 (in \$1958) to under \$1,000 (Abernathy and Wayne (1974)). Note that the data shows a good fit to the straight line of a log-linear MPF with an 85 % slope.

Experience curves and MPFs are also commonly used *ex ante*, as a forecasting tool. The difficulty with conducting *ex ante* analyses is that it is impossible to know with certainty what experience curve or MPF slope is appropriate for the product in question. Even if some production cost data are available to estimate the initial part of the curve, experience curve and MPF slopes are not always stable for a given product, and simply extrapolating the entire

---

[77] There are some variations in how this equation is expressed mathematically. Such forms as $C_N = C_1 * V_n^{-b}$ and $Log\,C_N = \frac{Log\,A \times Log\,N}{Log\,2} + Log\,C_1$ are mathematically equivalent to Equation (1), although the value of "b" in the first formula is not directly equivalent to the value of the experience curve slope value in Equation (1).

curve from the initial portion may not be accurate. In order to contend with this issue, some form of probabilistic analysis is warranted. This could take the form of simply forecasting two or more different cases, with different corresponding curve slopes, or a more elaborate type of analysis such as Monte Carlo simulation (Lipman and Sperling (1997)).

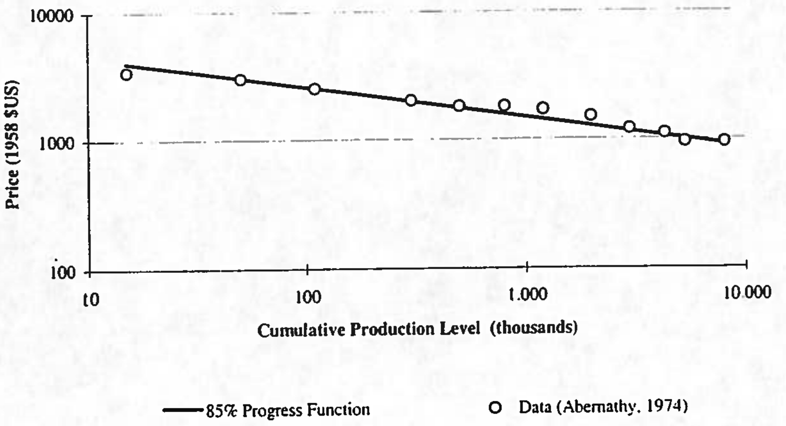

Figure 1: Price Path of Model-T Ford (1909-1918) Plotted on a Log-Log Scale (Abernathy and Wayne (1974))

An additional difficulty with *ex ante* MPF cost forecasts, and one that is rarely noted in the literature, is that if a forecast is extended far enough, it may be the case that at some point an unrealistically low cost will be forecast. The nature of the logarithmic function shown above is such that percentage reductions in manufacturing cost take longer and longer to achieve with higher levels of accumulated production, but the formula will continue to calculate reductions in manufacturing costs indefinitely if allowed to do so. *Ex post* analyses of some products provide evidence that technologies with very long product life cycles may eventually reach a plateau in manufacturing cost, even if they very closely followed a certain curve slope up until that point.

For example, consider the case of laser diodes produced by Sony starting in 1982. These devices have been produced in great numbers because they are components of a highly successful consumer product, the compact disc player. Figure 2 shows manufacturing cost data for this product from 1982 until 1994 (Wood (1998)), and a set of three manufacturing progress functions with different slopes, calculated by the authors. Three interesting features are apparent in this figure. First, the overall pattern of cost reduction is reasonably well approximated by an 80 % curve slope. Second, the data do not perfectly track any given curve slope, but rather "wander" considerably. The early production history of the product closely tracks a 75 % curve slope, but extending this would have yielded an unrealistically optimistic cost forecast. Third, there is clear evidence of a manufacturing cost plateau at cumulative production levels of over about 10 million units. The cost at this point of 140 Yen is equal to about 1 $US, and this apparently represents a lower bound on the manufacturing cost of this product. Thus, there is a danger to extending experience curve and MPF analysis too far, without regard for a potential lower limits on the manufacturing cost of the product. This point will be discussed further in a later section.

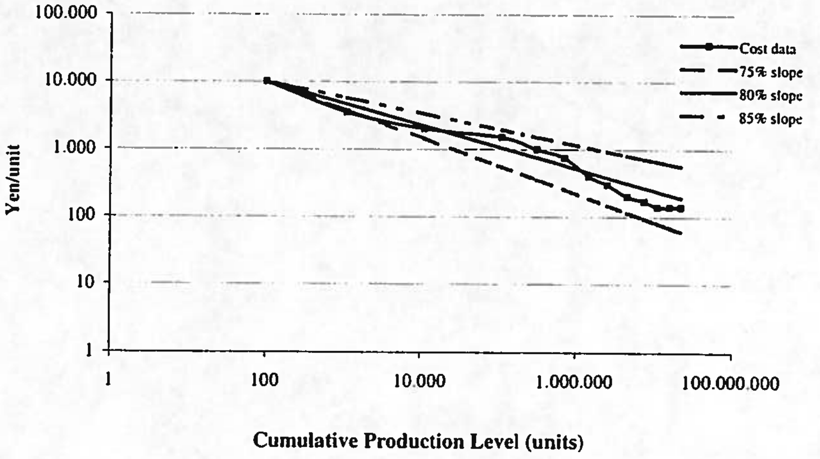

Figure 2: Sony Laser Diode Manufacturing Costs (1982 - 1994)

10.2.4 Experience Curve and MPF Slope Variation

Returning to the first caveat discussed above with regard to performing *ex ante* cost forecasts, care must be taken in applying MPFs and experience curves due to variations in curve slopes within and between industries. According to one study of about 100 experience curves, slopes do vary significantly across industries, as figure 3 illustrates, but they are typically between 70 % and 85 % (implying cost reductions of 30 % to 15 % with each doubling of accumulated output). While in some cases a curve of a certain slope seems to describe the cost path for most firms in an industry - a 70 % curve for dynamic RAM chips is one example - experience curve slopes often vary within an industry (Ghemawat (1985)). MPF slopes also vary, and the nature of the variation (shown in figure 4) is quite similar to that observed for experience curve slopes (Dutton and Thomas (1984)).

Many explanations are possible for these variations in experience curve and MPF slopes. Variation between industries might be explained by such factors as the degree of product complexity, market structure, and industry maturity. Variation among individual firms in the same industry can occur for many reasons, including relative levels of vertical integration, corporate work ethics, research and development expenditures, and access to technical information.

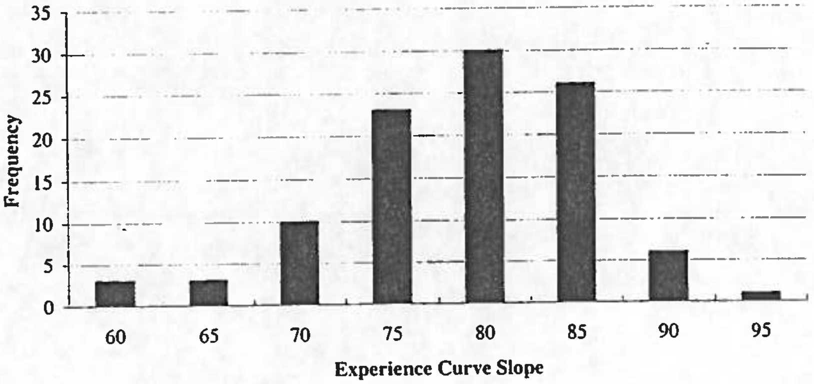

Figure 3: Variation in Experience Curve Slope (Ghemawat (1985))

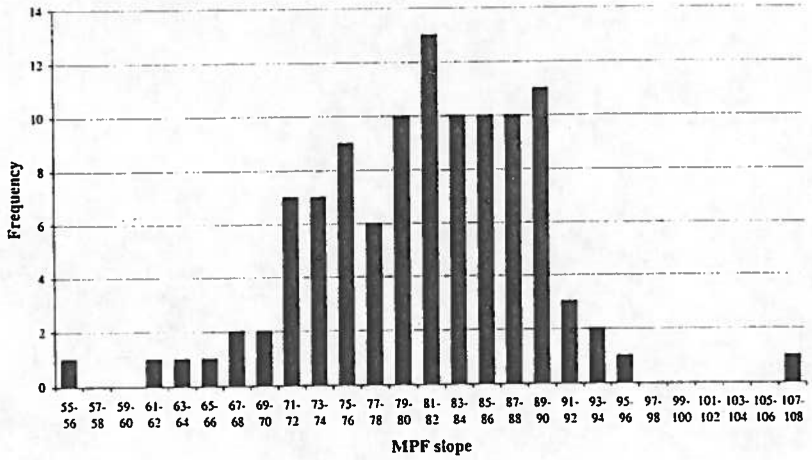

Figure 4: Variation in Manufacturing Progress Function Slope (Dutton and Thomas (1984))

While some findings suggest that curve slopes are relatively stable throughout a product's life-cycle, it is worth noting that some research suggests that this may only be true through the duration of a development stage (e. g. introduction, take-off and growth, maturity, etc.) (Dino (1985)). However, even if stable, it is difficult to determine actual experience curves and MPFs precisely and accurately, and controlling for possible sources of variation between studies has been a persistent problem in interpreting the literature. For instance, the proprietary nature of cost data sometimes necessitates the use of product price data as a proxy for actual manufacturing costs. This can be problematic because the relationship between manufacturing cost and retail price is difficult to discern, and may not be stable. In research in which price data were analyzed, perhaps variations in the price-cost relationship that were observed, at least in part, rather than actual variations in the rate of decline of manufacturing cost. An additional complication with many studies is the difficulty in controlling for variations in product performance, durability, and quality over time. Experience curve analyses are most convincing, and probably have the most predictive power, where product design is relatively stable and where at least some manufacturing cost data are available. At any rate, while considerable efforts have been directed toward understanding these issues for a few industries, there remains insufficient evidence to warrant broad conclusions as to the causal factors for experience curve slope consistency or variation in different settings.

10.3 Costs of PEM fuel cell power systems for EVs

A few cost analyses for PEM fuel cell systems have been published. These tend to fall into two categories: experience curves, and production volume-based analyses. An experience curve analysis of PEM fuel cells was recently published by Rogner (1998). He estimated three different experience curves, with slopes of 0.76, 0.81, and 0.93, and initial costs for complete fuel cell systems of $2,500, $4,500, and $10,000 per kW, at 2 MW of cumulative production. After 100,000 MW of production, these three curves project widely differing costs of about $2,500 per kW (for initial cost of $10,000 per kW and slope of 0.93), $200 per kW (for initial cost of $4,500 per kW and slope of 0.81), and $25 per kW (for initial cost of $2,500 per kW and slope of 0.76). Also, Willand (1996) has presented a Daimler-Benz fuel cell system cost forecast that appears to be based on a MPF analysis, but is not explicitly identified as such. This forecast shows costs declining from 100,000 DM per kW initially (with 1 unit of cumulative production) to about 1,000 DM per kW at a cumulative production level of about 5,000 units, and then further to 300 - 500 DM per kW or 600 - 800 DM per kW after production of about 250,000 units (the curve forks into two branches beyond 5,000 units of cumulative production).

A detailed analysis of the manufacturing costs of PEM fuel cell stacks in high-volume production has recently been conducted by DTI, for the Ford Motor Company and U.S. DOE's Office of Transportation Technologies. This study examined four different approaches to manufacturing fuel cell stack mechanical parts, and considered a high volume production level of 300,000 - 500,000 units per year. This study concluded that a complete fuel cell stack manufacturing cost as low as about $20 per kW is possible for complete 70 kW (gross) fuel cell stacks, using either carbon-polymer composite or unitized metallic flowfield plate compositions (Lomax et al. (1997)). A subsequent study by DTI included cost estimates for additional fuel cell system components such as compressors, heat exchangers, a humidification system, safety devices, and a control system. Also produced in automotive volumes of 300,000 units per year, these additional system components would add about $14.35 per kW to the cost of the 70 kW system (Thomas et al. (1998a)).

Thus, at the present time, a detailed, high-volume PEM fuel cell system cost analysis has been conducted, but no detailed lower-volume manufacturing cost estimates are publicly available. In order to bridge the gap between today's pilot-scale PEM fuel cell manufacturing cost, and the manufacturing costs that are possible in high-volume production, a MPF analysis can be used. This analysis can then be fitted to assumptions of market penetration and component production in order to arrive at PEM fuel cell system manufacturing costs in a given year. By combining the MPF analysis with a high-volume cost analysis or cost target, some protection can be afforded against the problem of potentially forecasting unrealistically low $/kW costs at high levels of accumulated production.

10.3.1 Manufacturing Progress Function Assumptions

In order to apply the MPF cost analysis framework, it is necessary to assess the present cumulative production level and manufacturing cost of PEM fuel cell systems, for a specific manufacturer. At the present time, the world leader in producing PEM fuel cell systems for vehicle applications is Ballard Power Systems, of Vancouver, Canada. As of 1998, Ballard had produced a total of about 5 MW of PEM fuel cell stacks (Savoie (1998)). Estimating the manufacturing cost at the present time is more difficult, since data on the manufacturing costs or selling prices of Ballard stacks are not publicly available. DTI estimates a present manufacturing cost of about $1,500 per kW for complete fuel cell systems, depending somewhat on the power output of the stack. Using a formula that they provide, a 70 kW system would have a present cost of about $97,920, or $1,400 per kW, while a small, 30 kW system would have a present cost of about $64,960, or $2,165 per kW (Thomas et al. (1998a)). These estimates may be somewhat low, given that the present cost of stationary phosphoric acid fuel cell systems produced by such companies as International Fuel Cells is approximately $3,000 per kW. As DTI notes, however, the manufacturing costs of PEM fuel cell systems for vehicle applications could be expected to be lower than for stationary phosphoric acid systems, even at the present time, because the demands on them are less rigorous. PEM systems would only need to have operating lives 10 to 20 times lower than those of stationary systems, and they also would operate near peak power much less of the time (Thomas et al. (1998a)).

Rogner (1998) contended with the uncertainty in the present cost of PEM fuel cell systems by considering a very wide range of values for this parameter, from $10,000 per kW to $2,500 per kW. This range is probably unnecessarily wide, but given the present uncertainty in this parameter, some range of values should be included. Based on the estimates discussed above, we choose a central case estimate of $2,000 per kW, with a low value of $1,500 per kW, a high value of $2,500 per kW, and intermediate values of $1,800 per kW and $2,200 per kW.

Next, MPF slope values must be selected. As discussed above and shown in figure 4, the historical range of variation in this parameter is typically between 70 % and 90 %, with a few exceptional high and low cases. In one analysis, Thomas et al. (1998b) used a MPF to connect their high-volume PEM fuel cell system cost estimate with their present cost estimate of $1,500 per kW, and calculated the resulting slope at 81.9 %. This is one possible approach, but the calculated slope would be different with a different estimate for the present PEM system cost, which as discussed above is uncertain. We prefer to consider a range of slope values, and to use the data on historical MPF slopes to guide our choice of estimates. We use the commonly assumed value of 80 % for the central case estimate, with 70 %, 75 %, 85 %, and 90 % for other cases. Table 1 shows the combinations of present manufacturing cost and MPF slope values used in the five cases assessed.

Table 1: Cases Considered in PEM Fuel Cell System Cost Forecast

Case	Present $/kW System Cost	MPF Slope Value
Case 1	$1,500 per kW (net)	0.70
Case 2	$1,800 per kW (net)	0.75
Case 3	$2,000 per kW (net)	0.80
Case 4	$2,200 per kW (net)	0.85
Case 5	$2,500 per kW (net)	0.90

As discussed above, one potential concern with experience curve and MPF analyses is that if carried out far enough, they may at some point forecast costs that are unreasonably low. One way to prevent this is to impose some lower limit on the cost forecast, but arriving at a reasonable lower limit is not generally straightforward. Furthermore, doing so may introduce undue conservatism to the analysis and rob it of one of its strengths, namely the ability to capture the long-term and often dramatic cost reductions that are sometimes observed for products that are highly successful and do survive to reach high levels of accumulated production. Despite this concern, however, we believe that the possibility of forecasting unrealistically low manufacturing costs with experience curve and MPF analyses should be considered. Particularly for technologies that may have very long product life cycles, and/or for cases in which steep curves are assumed, bounding an MPF analysis with a cost target or very high volume manufacturing cost estimate could prevent an overly optimistic forecast.

Another way to bound a cost forecast would be to use estimates for materials costs in high volume production, if they can be obtained, plus an increment for processing costs that is based on an analysis of the processing costs for a similar mature product. This approach is reasonable because when products reach high-volume, automated production, materials costs often dominate the total manufacturing cost. However, estimating "ultimate" materials costs can be difficult, particularly if the product uses any relatively novel components or materials that themselves have the potential for cost reduction, or if there are opportunities to eventually substitute for less expensive materials in some subcomponents.

Another approach would be to use an established cost goal as a lower bound, under the assumption that companies will be satisfied if costs reach this level and will not strive to reduce them further. For example, in the case of PEM fuel cell systems, the Partnership for a New Generation of Vehicles (PNGV) has established year 2004 cost targets of \$40/kW for fuel cell systems (stack and auxiliaries) and \$10/kW for fuel processors (Teagan et al. (1998)). Also, Kalhammer et al. (1998) have identified cost targets for automotive fuel cell system components of \$20/kW for PEM fuel cell stacks, \$20/kW for fuel processors, and \$20/kW for "balance of plant" auxiliary components. These cost targets could be used to bound MPF forecasts.

Alternately, the detailed, very high-volume cost estimates developed by DTI provide a possible lower bound. Of course, costs could ultimately be lower than even these optimistic estimates. However, the estimation methodology used by DTI was specifically designed to identify the lowest cost PEM stack design configuration, and the choice of a production volume of 300,000 units per year suggests that it would be difficult to construe a lower cost case. We choose to bound our forecast with DTI's high-volume PEM fuel cell system cost estimate, believing that the risk of estimating an unrealistically low cost with an unbounded forecast is greater than the risk of conservatism that this choice will introduce. This lower bound is given by Equation 2, and it varies somewhat with the size of the stack (Thomas et al. (1998a)).

$$C_{HV} = 1{,}073 + P_N \times \left(18.70 + \frac{5.34 + 27 \times L_P}{P_D} \right) \qquad (2)$$

where

C_{HV} : high volume cost of PEM fuel cell system (in \$)
P_N : net fuel cell peak power output, in kW
L_P : total cell platinum catalyst loading in mg/cm^2
P_D : cell peak power density, in W/cm^2

Using values of 0.25 mg/cm^2 for the total platinum catalyst loading (anode plus cathode) and 0.646 W/cm^2 for the cell peak power density gives the simpler Equation 3:

$$C_{HV} = 1{,}073 + 21.97 \times P_N \qquad (3)$$

where

C_{HV} : high volume cost of PEM fuel cell system (in $)

P_N : net fuel cell peak power output, in kW

For stack sizes in the 60 - 80 kW range, the DTI estimate produces values of about $35 per kW to $40 per kW. These estimates agree well with the PNGV and Kalhammer et al. (1998) cost targets of $40 per kW, so using any of these figures as lower bounds would produce similar results.

10.4 Results

The results of the MPF analysis for the future costs of automotive PEM fuel cell systems, using the assumptions described above, are shown in figure 5. The five sets of assumptions used to generate the curves shown produce significantly different results. The central case, using a present value of $2,000 per kW and an 80 % MPF slope, predicts that the high volume DTI estimate of about $37 per kW for a 70 kW system will not be achieved until a cumulative production volume of about one million MW is achieved. The more conservative cases suggest that this cost level will not be achieved even after 10 million MW of accumulated production. The cases using the 75 % and 70 % curves predict that the high volume cost estimate will be reached with cumulative production levels of about 100,000 MW and 10,000 MW, respectively.

Figure 5 also shows an "unbounded" 70 % curve. This curve forecasts costs below the high volume estimate of about $37 per kW at a cumulative production volume of 10,000 MW. This example shows the potential for forecasting unrealistically low costs using MPF or experience curve techniques, particularly for optimistic cases in which relatively steep curve slopes are assumed. It is interesting to note that while 70 % curve slopes are at the low end of the observed range shown in figure 3, the Daimler-Benz fuel cell cost forecast (Willand (1996)) closely matches a 70 % MPF when plotted in terms of cumulative production volume on a log-log scale (Lipman and Sperling (1997)). Such steep curves may be observed relatively rarely, but they certainly are possible (presumably for products whose manufacture is particularly amenable to automated production). It is also worth noting that the cumulative production level of 10,000 MW, beyond which the 70 % curve drops below the high-volume forecast, would be achieved in just a few years by a manufacturer that produced

20,000 70 kW systems in the first year and ramped up production at an incremental rate of 20,000 systems per year. Even the 100,000 MW cumulative production level, beyond which an unbounded 75 % curve would forecast system costs below the high volume estimate, would be reached in less than twelve years by a manufacturer whose production had at that point ramped up to about 220,000 units per year.

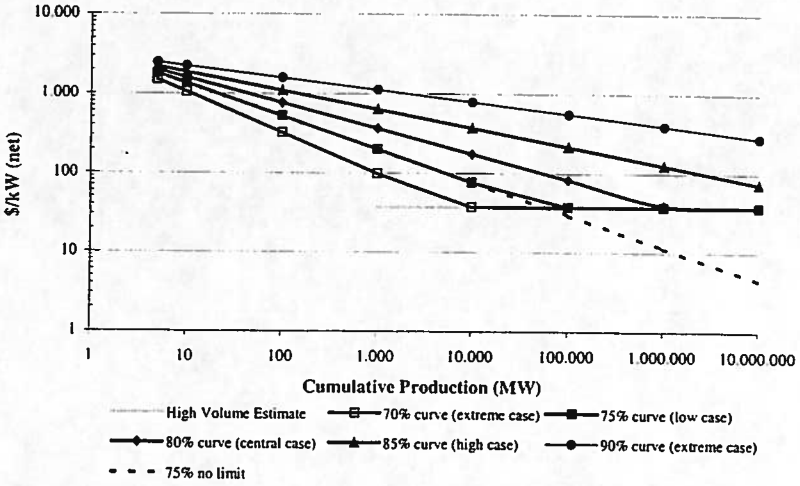

Figure 5: PEM Fuel Cell Cost Forecasts (for 70 kW net power system)

Based on the histogram of MPF slopes observed historically, we suggest using as a central case estimate the Case 3 MPF forecast that employs an 80 % curve slope. Cases 2 and 4 represent likely upper and lower bounds, while cases 1 and 5 represent low likelihood, extreme cases. Table 2 presents numerical results for cases 2, 3, and 4, using the DTI projection of $37.30 per kW for 70 kW (net) systems as a lower bound.

These suggested MPF slopes are further indicated by analyzing the curve slope necessary to connect the present PEM fuel cell system cost with the DTI high volume estimate of about $37 per kW at 300,000 units of annual production. Depending on the production ramp-up schedule assumed, a production level of 300,000 units per year would correspond with a cumulative production level of from about 150,000 MW (rapid ramp-up) to about 1,000,000 MW (slow ramp-up). These cumulative production levels imply MPF slopes ranging from about 76 % to 80 %, respectively. Also, recent data show that commercially produced 200 kW phosphoric acid fuel cell systems (the "PC25" system manufactured by International Fuel Cells) have been declining in cost along a 75 % MPF slope (Whitaker (1998)).

Table 2: Results for PEM Fuel Cell Cost Forecast Cases 2, 3, and 4 (for 70 kW net system)

Cumulative Production Level (MW)	Case 2: 75% MPF slope ($/net kW)	Case 3: 80% MPF slope ($/net kW)	Case 4: 85% MPF slope ($/net kW)
5	$1,800.00	$2,000.00	$2,200.00
10	$1,350.04	$1,600.33	$1,870.35
100	$519.17	$762.57	$1,090.08
1,000	$199.65	$363.37	$635.32
10,000	$76.78	$173.15	$370.28
100,000	$37.30	$82.51	$215.80
1,000,000	$37.30	$39.32	$125.78
10,000,000	$37.30	$37.30	$73.30

10.5 Conclusions

We presented here a forecast for automotive PEM fuel cell system costs based on a simple MPF analysis. The results for the most likely cases suggest that fuel cell system costs will drop relatively rapidly with mass production, such that manufacturing costs of $100 per kW are likely to be achieved when about 90 thousand MW of cumulative production are achieved by a single manufacturer, with lower and upper bounds of about nine thousand MW and one million MW of cumulative production. The DTI high volume cost estimate of about $37 per kW is likely to be achieved when manufacturer cumulative production reaches one million MW, with lower and upper bounds of about 90 thousand MW and more than ten million MW.

In order to guard against the potential problem of forecasting unrealistically low manufacturing costs at high levels of accumulated production, we suggest putting a lower bound on MPF and experience curve cost forecasts. This can be done as in the example here, using detailed, high volume estimates of the production costs for least-cost product designs, or based on analyses of high-volume materials costs (as in Lipman and Sperling (1997)). Established cost targets also could represent lower bounds to manufacturing cost forecasts, such as the fuel cell system cost goals established by the PNGV or the $150/kWh EV battery cost target established by the U.S. Advanced Battery Consortium.

In conclusion, experience curve and MPF analyses have significant value for strategic planning and policy analysis, especially since detailed manufacturing cost data for emerging technologies are often unavailable or difficult to obtain. It is particularly difficult to assess manufacturing costs for a range of different production volumes, and experience curve and MPF analyses are especially useful for tracing likely "cost paths" for products as they move from pilot-scale to mass production. Company planners can use MPFs to explore possible cost futures for different technologies, and to set and assess production cost goals. Policy analysts can use MPFs and experience curves to help weigh the costs and benefits of emerging technologies, and to craft appropriate R&D strategies and effective policies for nurturing potentially attractive products. At UC Davis, we are developing both detailed and MPF cost models for a range of electric-drive technologies (from those used in pure battery-powered electric vehicles to systems for fuel cell hybrids). The output from these efforts will be detailed forecasts of future EV costs, and a dynamic cost model that can be refined as more information on actual EV production and diffusion becomes available.

References

Abernathy, W. J. and K. Wayne (1974). Limits of the Learning Curve. Harvard Business Review.52, 5, 109 - 119.

Argote, L. and D. Epple (1990). Learning Curves in Manufacturing. Science 247, February 23, 920 - 924.

Boston Consulting Group (1972). Perspectives on Experience. Boston.

Conley, P. (1970). Experience curves as a planning tool. IEEE Spectrum June 1970, 63 - 68.

Dino, R. N. (1985). Forecasting the Price Evolution of New Electronic Products. Journal of Forecasting 4, 1, 39 - 60.

Dutton, J. M. and A. Thomas (1984). Treating Progress Functions as a Managerial Opportunity. Academy of Management Review 9, 2, 235 - 247.

Ghemawat, P. (1985). Building strategy on the experience curve. Harvard Business Review March-April, 1985, 143 - 149

Kalhammer, F. R. et al. (1998). Status and Prospects of Fuel Cells as Automobile Engines: A Report of the Fuel Cell Technical Advisory Panel. California Air Resources Board, Sacramento, July 1998.

Lipman, T. E. and D. Sperling (1997). Forecasting Cost Path of Electric Vehicle Drive System: Monte Carlo Experience Curve Simulation. Transportation Research Record 1587, 19 - 26.

Lomax, F. D. et al. (1997). Detailed Manufacturing Cost Estimates for Polymer Electrolyte Membrane (PEM) Fuel Cells for Light Duty Vehicles. Directed Technologies, Inc., Arlington, October 1997.

Rogner, H.-H. (1998). Hydrogen Technologies and the Technology Learning Curve. International Journal of Hydrogen Energy 23, 9, 833 - 840.

Savoie, R. (1998). Personal Communication. Ballard Power Systems, 29 April 1998.

Teagan, W. P. et al. (1998). Cost reductions of fuel cells for transportation applications: fuel processing options. Journal of Power Sources 71, 80 - 85.

Thomas, C. E. et al. (1998a). Integrated Analysis of Hydrogen Passenger Vehicle Transportation Pathways. Directed Technologies, Inc., Arlington, March 1998

Thomas, C. E. et al. (1998b). Market Penetration Scenarios for Fuel Cell Vehicles. ternational Journal of Hydrogen Energy 23, 10, 949 - 966.

Whitaker, R. (1998). Investment in volume building: the 'virtuous cycle' in PAFC, Journal of Power Sources 71, 71 - 74.

Willand, J. (1996). State-of-the Art and Development Trends for Fuel Cell Vehicles. European Fuel Cell Group, Jalich, Germany.

Wood, S. (1998). Personal Communication, September 2.

Wright, T. P. (1936). Factors Affecting the Cost of Airplanes. Journal of Aeronautical Science 3, 122.

Yelle, L. E. (1983). Adding Life Cycles to Learning Curves. Long Range Planning 16, 82 - 87.