Available online at www.sciencedirect.com
SCIENCE @ DIRECT®

PERGAMON

International Journal of Hydrogen Energy 29 (2004) 985–990

International Journal of HYDROGEN ENERGY

www.elsevier.com/locate/ijhydene

Mass production cost of PEM fuel cell by learning curve

Haruki Tsuchiya[a,*], Osamu Kobayashi[b]

[a] *Research Institute for Systems Technology, 2-1-6, Higashinihonbashi, Cuouku, Tokyo, Japan*
[b] *WE-NET Center, Institute of Applied Energy, 1-14-2, Nishishinbashi, Minatoku, Tokyo, Japan*

Received in revised form 15 October 2003; accepted 20 October 2003

Abstract

A learning curve model has been developed to analyze the mass production cost structure of proton exchange membrane fuel cells for automobiles. The fuel cell stack cost is aggregated by the cost of membranes, platinum, electrodes, bipolar plates, peripherals and assembly process. The mass production effects on these components are estimated. Nine scenarios with different progress ratios and future power densities are calculated by the learning curve for cumulative production of 50 000 and 5 million vehicles. The results showed that the fuel cell stack cost could be reduced to the same level as that of an internal combustion engine today, and that the key factors are power density improvement and mass production process of bipolar plates and electrodes for reducing total cost of fuel cell stack.

Keywords: PEM Fuel cell; Learning curve; Mass production

1. Introduction

Proton exchange membrane (PEM) fuel cell is expected to provide power to automobiles, homes, buildings, personal computers, wireless phones and outdoor electric tools [1]. They are expected to be commercialized by around 2010 and the following decades. The modular structure of the fuel cell implies that it is suitable for mass production and the cost could be greatly reduced if mass production would begin. The purpose of this paper is to discuss the cost structure of the fuel cell and the possibility of reducing cost by learning curve analysis.

2. Learning curve

Learning curve or experimental curve is a kind of macroscope model describing the human activity of accumulating knowledge or experience by cumulative production, and is usually adapted to an industrial production process. The typical learning curve is described as follows:

$$Y_i = AX_i^{-r} \tag{1}$$

where the variables are defined as follows:
X_i: cumulative number of products at ith production
Y_i: product cost at ith production
A: constant.

The number "r" in the exponent is not easy to understand, so a simpler expression is introduced as a progress ratio, $F = 2^{-r}$. F shows how the production cost could be reduced each time when cumulative production is doubled. When F is 90%, it means that the cost is reduced to 90% each time the cumulative production volume is doubled. If we have historical cost data, we can estimate progress ratio F by regression analysis. Experience data in a variety of industrial products show that F is 80–95% for mechanical assembly products and 70–85% for semiconductors and electronic devices. But 70% appears to be a minimum number known as the progress ratio.

The progress ratio of photovoltaic cost was 82% from 1979 to 1999 in Japan [2]. Model T of Ford had 85% progress ratio from 1909 to 1918. Laser diode of Sony had a

* Corresponding author. Tel.: +81-3-5687-1052; fax: +81-3-5687-1053.
E-mail address: tsuchiya@systemken.com (H. Tsuchiya).

0360-3199/$ 30.00 © 2003 International Association for Hydrogen Energy. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijhydene.2003.10.011

electronic circuit boards

progress ratio of 75% at the initial stage and 80% thereafter [3].

Usually the learning curve is an analytical tool to discuss the history of mass production. However, there are some attempts to forecast the future overall fuel cell cost in mass production by learning curve [3,4]. In this paper a learning curve has been applied to estimate the cost of each component of fuel cell stack and to discuss the cost structure in mass production.

3. Cost of fuel cell stack

A typical PEM fuel cell stack consists of a number of cells, which have proton exchange membranes, electrodes, bipolar plates and peripherals. Also, catalyst metal of platinum is included in electrodes or membranes but the cost of platinum is treated separately in this paper.

The cost of fuel cell stack (\$/kW) is described by assuming power density per cell area, the material cost per cell area, and the assembly cost as follows:

$$C = (C_m + C_e + C_b + C_{pt} + C_o)/P + C_a, \tag{2}$$

$$C_{pt} = C_{wpt} * Y_{pt}, \tag{3}$$

$$P = 10 * V_c * A_c, \tag{4}$$

where, C is the fuel cell stack cost per kW (\$/kW), C_m the membrane cost (\$/m^2), C_e the Electrode cost (\$/m^2), C_b the bipolar plates cost (\$/m^2), C_{pt} the cost of platinum catalyst loading (\$/m^2), C_{wpt} the weight of platinum catalyst loading (g/m^2), Y_{pt} the unit cost of platinum (\$/g), C_o the cost of peripheral materials (\$/m^2), P the power density per cell area (kW/m^2), C_a the assembly cost (\$/kW), V_c the cell voltage (V) and, A_c the cell current density (A/cm^2).

This description is based on summing up all cell areas and has no explicit expression of the number of cells. The cost of materials such as electrodes, bipolar plates and peripherals is assumed to be independent of power density. But the performance of the membrane and the weight of platinum sometimes have a strong relationship with power density. So, if such performance change occurs together with cost change then the overall progress ratio should be examined as to whether it is within the experienced range or not. A certain model of automatic production system is used to estimate the assembly cost. We assumed 50 kW fuel cell production systems for an average-sized automobile.

The typical performance of a single fuel cell has 0.6–0.7 V and 0.3–0.6 A/cm^2 cell current density, which is 2 kW/m^2 or more of power density. But the stack performance is somewhat less than that of a single cell. If an automobile has 50 kW rated output, then the cell area for 2 kW/m^2 power density is 25 m^2, that is, 278 layers of cell with 30 cm × 30 cm cell area. The power density is expected to increase to the level of 5 kW/m^2 or more.

4. Prospects for cost reduction

To apply a learning curve to fuel cell stack cost, it is necessary to know the cost structure, bottom line cost of materials in the long run, and the initial cumulative production scale. To begin with, the cost structure is as follows:

The proton exchange membrane is being vigorously developed. While the Nafion (Du pont) has 100 μm thickness and \$500/m^2 today, according to the experts, it will be \$50/m^2 on the production scale 150 thousands of fuel cell vehicles annually [5]. ADL report shows that membrane cost could be \$59/m^2 for 50 kW output with 30 m^2 cell area [6]. The thickness of the membrane is 20–50 μm today, as the thinner and tougher membranes are being developed. The weight of the membrane is quite small, and the cost share will not be large because weight determines the material cost finally in mass production.

The necessary weight of platinum attracts a lot of attention. The platinum cost depends on market fluctuations but it is assumed in this study as \$15.4/g average today. Today, platinum loading in MEA (electrodes and membrane assembly) is 2–4 g/m^2, which is \$32–64/m^2. A Japanese catalyst maker reported that a value of 0.5 g/m^2 could be possible [5], which is used as the future number in this study.

A typical electrode is a porous carbon paper or a carbon cloth with a vacancy rate of 80% so that hydrogen and air/oxygen can easily permeate. MEA has around 0.8 mm thickness and about 340 g/m^2 weight. ADL report shows that the electrode cost could be \$177/m^2 [6]. The production process of MEA today is rather complex, but this study assumed that it would be massively produced automatically by the calendar roll process in a factory.

Bipolar plates work as electric conducting materials and impermeable walls. Some of them have a pattern of flow fields like serpentine and are manufactured by NC machining of a graphite sheet; this process is time-consuming and very expensive today, but will be substituted by inexpensive injection molding systems in the near future. There are tremendous efforts to reduce the cost of bipolar plates, trying carbon composites, injection molding of graphite filled polymer and metals such as stainless steel or titanium. Bipolar plates are very important as they have a nearly 80% dominant share of the total stack weight as shown in Fig. 1. They will determine the stack cost finally if mass production would begin and the stack cost would be closer to the raw material cost.

Peripherals include end plates, plastic frame and thrust bolts, which weight 0.5 kg/m^2 and ordinary material is enough for them. They do not have so much room for improvement. The assembly is now by hand work. We assumed an automatic production line with an annual production capacity of 18 000 vehicles with 50 kW equivalent stack. The production line is based on sheet processing machines and handling robotics. Our analysis shows that it is a very time-consuming process to stack up many cells.

Table 1
Present, future and bottom line cost of each element

Element	Present	Future	Bottom line
Proton exchange membrane	Nafion 100 μm $500/m^2 (Du Pont)	Thickness 20–50 μm $50/m^2 at mass production	60cents/m2 for thickness 50 μm
Platinum	2–4 g/m^2 $32–$64/m^2	0.5 g/m^2 $7.7/m^2	Platinum cost is assumed constant as $15.4/g
Electrode	Total thickness is 0.8 mm for single cell. $1423/m^2	Roll sheet production. $96/m^2	$2.58/m^2
Bipolar plates	Total thickness for single cell is 4 mm. $1650/m^2	Improved molding $35/m^2	$13.6/m^2 for 4 mm thickness
Peripheral parts	End Plates, Thrust bolts, Plastic Frame. 0.5 kg/m^2, $15.4/m^2	Ordinary materials 0.5 kg/m^2	$3.46/m^2
Assembly	Hand assembly $385/50 kW	Automatic Assembly. Roll supply of membrane and electrodes. Stacking by Robotics	Assuming a production line $94/50 kW, $1.88/kW

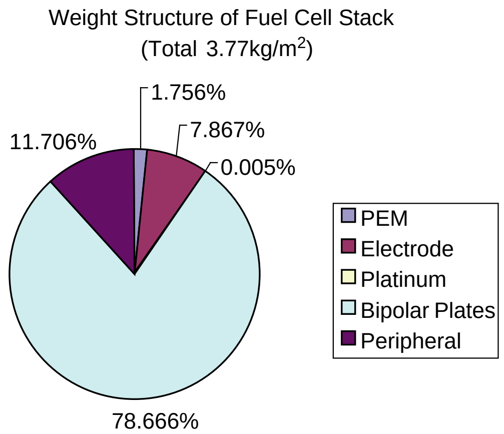

Fig. 1. Weight structure of fuel cell stack.

Learning curve calculation sometimes yields too small values for cost because of its exponential characteristics, and the bottom line cost is introduced to limit the cost at minimum. The bottom line cost is related to raw material cost, which is expressed per kg such as 50 cents for steel, $1–$2 for plastics, and $3 for copper and aluminum in the automobile industry. However, the ordinary average cost of elements widely known in the automobile industry is about $8/kg for steel, metals, plastics and glass if it is massively produced. (The exchange rate of Japanese Yen is assumed as 130 yen for $1). Based on the experience and knowledge in the automobile industry we decided to set this average cost of element as the bottom line cost. The summary of the present, future and bottom line cost is shown in Table 1.

The initial number of cumulative production and the cost are necessary to calculate learning curve effects. There are several data which suggest that the fuel cell stack cost in 2000 was around $2000/kW. (3) We assumed by summing up the cost data that 40 fuel cell vehicles each of 50 kW have been manufactured in Japan till 2000 and their factory cost was $1833/kW.

5. Learning effects

The automobile industry hopes to have fuel cell stack at $40/kW, which is nearly the same as the internal combustion engine. This possibility is examined by the learning curve approach. The Advisory Panel on Fuel Cell for the Agency of Natural Resources and Energy in Japan predicted officially that the number of fuel cell vehicles is 50 000 in 2010 and 5 million in 2020. Using these numbers we constructed nine scenarios with combinations of power density improvement (three scenarios) and cost reduction speed (three scenarios) as shown in Table 2.

Power density improvement is assumed as from 2 kW/m^2 at the initial stage to 5 kW/m^2 for the H (high-power density) scenario, 4 kW/m^2 for M (medium-power density) scenario and 3 kW/m^2 for L (low-power density) scenario at 5 million cumulative vehicles. The power density improvement process is calculated by an equivalent learning curve with progress ratio $F = 94.5\%$ for scenario H, $F = 96\%$ for scenario M, and $F = 97.5\%$ for scenario L. Cost reduction speeds of membrane, electrodes and bipolar plates are assumed as $F = 78\%$ for rapid scenario (A), $F = 82\%$ for moderate scenario (B), and $F = 88\%$ for slow scenario (C). The highest learning effect case is HA scenario, and the integrated progress ratio is $94.5\% \times 78\% = 73.7\%$, which is in the range of experimentally known progress ratios.

Platinum loading begins with 0.4 mg/cm^2 and decreases to 0.05 mg/cm^2 for scenario A (equivalent $F = 89\%$), to 0.1 mg/cm^2 for scenario B (equivalent $F = 92\%$) and to 0.2 mg/cm^2 for scenario C (equivalent $F = 96\%$). Platinum cost is assumed to be constant throughout the simulation.

Table 2
Fuel cell stack cost ($/kW) and the share of platinum cost by learning curve

Scenario	Progress ratio/ Pt loading	High power density (H) 2 to 5 kW/m2, $F = 94.5\%$		Medium power density (M), 2 to 4 kW/m2, $F = 96\%$		Low power density (L) 2 to 3 kW/m2, $F = 97.5\%$	
		Fuel Cell stack stack cost ($/kW)	Share of Platinum cost (%)	Fuel Cell stack cost ($/kW)	Share of Platinum cost (%)	Fuel Cell stack cost ($/kW)	Share of Platinum cost (%)
Rapid	$F = 78\%$	88	5.9	103	5.9	121	5.9
(A)	Pt :0.4 to 0.05 mg/cm^2	15	10.8	19	11.1	25	11.4
Moderate	$F = 82\%$	143	5.1	167	4.9	196	5.1
(B)	Pt :0.4 to 0.1 mg/cm^2	30	9.7	38	9.8	49	9.9
Slow	$F = 88\%$	285	3.9	334	4.0	392	4.0
(C)	Pt :0.4 to 0.2 mg/cm^2	88	6.7	114	6.8	145	6.8

(Upper numbers for 2010, 50,000 cumulative vehicles and lower numbers for 2020, 5 millions cumulative vehicles).

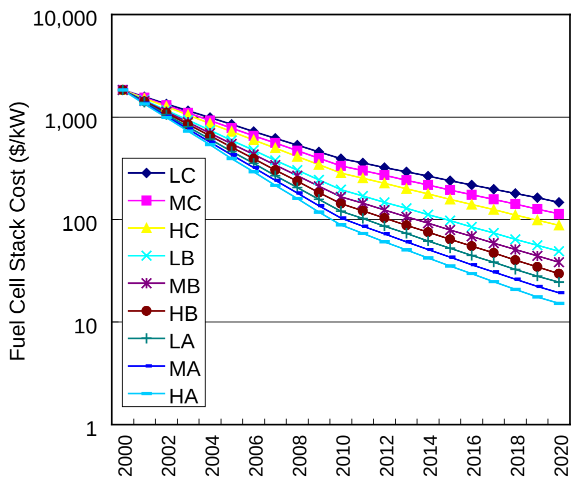

Fig. 2. Learning effects of nine scenarios.

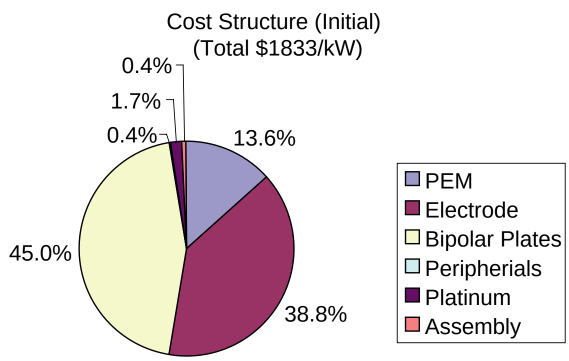

Fig. 3. Fuel cell stack cost structure at the beginning.

The progress ratio of peripheral cost is assumed to be 95%, and that of assembly cost 92% for all scenarios. The cost reduction limit is given by bottom line cost per weight as shown above. Nine scenarios are generated by combining power density improvement and cost reduction speed such as HA, HB, HC, MA, MB, MC, LA, LB and LC.

Table 2 shows the scenario framework and calculation results in 2010 and 2020. Fig. 2 shows the learning process of nine scenarios. The learning curve calculations show that the fuel cell stack cost in 2020 would be $15/kW to $145/kW depending on the scenarios. The cost reduction went to the bottom line cost only in the case of bipolar plates of HA, MA and LA scenarios in the year 2020. The platinum cost share is 1.7% at the beginning but it increases gradually to the level of 7–11% for a variety of scenarios.

Table 3 shows details of the scenario MB for moderate reduction speed with medium-power density improvement. Time scale is shown with cumulative numbers of fuel cell vehicles, which are calculated by the introduction of a constant growth ratio of 104% from 2000 to 2010, and 58% from 2010 to 2020. These growth ratios are calculated by vehicle numbers in 2000, 2010 and 2020. Basically the time scale has no relationship with the learning curve. But it shows what would happen when mass production of official prediction becomes realistic.

The results show that fuel cell stack cost could be comparable with the internal combustion engine today if it is massively manufactured.

Fig. 3 shows the cost structure in 2000 at the beginning. Fig. 4 shows the cost structure at 5 million cumulative vehicles in 2020 for Scenario MB. Bipolar plates and electrodes dominate the cost share at the beginning, but they become less dominated by a gradual increase of other cost shares of platinum, peripherals and assembly as shown in Fig. 4. This is because mass production will decrease the total fuel cell

Table 3
Scenario MB: moderate with medium power density

Year	Number of FC vehicles	Case moderate with medium power density (MB)								
		Cost ($\$/m^2$)				Platinum				Total ($/kW)
		Proton exchange membrance	Electrode	Bipolar plates	Peripherals	Pt weight (g/m^2)	Pt cost ($\$m^2$)	Power density ($kW\ m^2$)	Assembly cost ($/50kW)	
	F	82	82	82	95	92		96	92	
	$-r$	−0.286	−0.286	−0.286	−0.074	−0.120		−0.059	−0.120	
2000	40	500	1,423	1,650	15	4.00	62	2.00	385	1,833
2001	82	408	1,160	1,345	15	3.67	56	2.09	353	1,438
2002	167	332	946	1,097	14	3.37	52	2.18	324	1,129
2003	340	271	771	894	13	3.09	48	2.27	297	886
2004	693	221	629	729	12	2.84	44	2.37	273	697
2005	1,414	180	513	595	12	2.60	40	2.47	250	548
2006	2,885	147	418	485	11	2.39	37	2.57	230	431
2007	5,887	120	341	395	11	2.19	34	2.68	211	340
2008	12,011	98	278	322	10	2.01	31	2.80	194	268
2009	24,506	80	227	263	10	1.85	28	2.92	178	212
2010	50,000	65	185	214	9	1.70	26	3.04	163	167
2011	79,245	57	162	188	9	1.60	25	3.13	154	144
2012	125,594	50	142	165	8	1.52	23	3.21	146	124
2013	199,054	44	124	144	8	1.44	22	3.30	138	107
2014	315,479	38	109	126	8	1.36	21	3.39	131	92
2015	500,000	34	96	111	8	1.29	20	3.49	124	79
2016	792,447	29	84	97	7	1.22	19	3.58	117	68
2017	1,225,943	26	73	85	7	1.15	18	3.68	111	59
2018	1,990,536	23	64	75	7	1.09	17	3.78	105	51
2019	3,154,787	20	56	65	7	1.03	16	3.89	99	44
2020	5,000,000	17	49	57	6	0.97	15	3.99	94	38

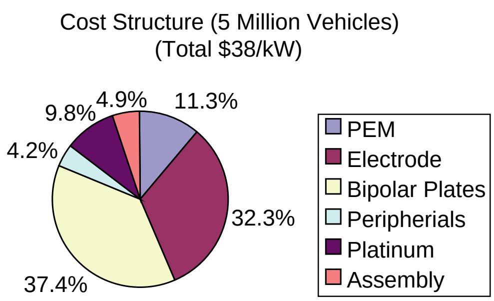

Fig. 4. Fuel cell stack cost structure of MB scenario at 5 million cumulative vehicles.

stack cost ($/kW) and at the same time gradually increase the share of the elements with relatively large F that would remain with less learning effects.

6. Conclusion

The cost structure of fuel cell stack is analyzed and the learning curve is used to estimate the future cost reduction by mass production. It is estimated that the cost reduction to the level of internal combustion engine is possible from the viewpoint of learning curve when mass production would occur. The analysis of cost structure shows that bipolar plates and electrodes have a large share of stack cost and would be very significant even at the mass production stage. The power density improvement is essential to reduce the overall stack cost, because it would decrease the resource use of other materials per unit power output. The share of platinum cost increases to nearly 7–11% for different scenarios when cumulative production would approach 5 million vehicles.

Acknowledgements

The authors would like to express their gratitude for the support by WE-NET project of NEDO (New Energy and Industrial Technology Development Organization) of Japan.

References

[1] Larminie J, Dicks A. Fuel cell systems explained. New York: Wiley; 2000.

[2] Tsuchiya H. Learning curve cost analysis for model building of renewable energy in Japan. In: Wene C-O, Voss A, Fried T, editors. Proceedings IEA Workshop on Experience Curve for Policy Making—the Case of Energy Technologies, 10–11 May 1999, Stuttgart, Germany. Germany: Forschungsbericht 67, Institute für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart; 1999. p. 67–76.

[3] Lipman T, Sperling D. Forecasting the cost of automotive PEM fuel cell systems—using bounded manufacturing progress functions. In: Wene C-O, Voss A, Fried T, editors. Proceedings IEA Workshop on Experience Curve for Policy Making—the Case of Energy Technologies, 10–11 May 1999, Stuttgart, Germany. Germany: Forschungsbericht 67, Institute für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart, 1999. p. 135–50.

[4] Roger H. Hydrogen technologies and the technology learning curve. Institute for Integrated Energy Systems, University of Victoria, Int J Hydrogen Energy 1998; 23(29):833–40.

[5] Nenryoudenchi Kaihatu Saizensen, Development Front of Fuel Cells. A special issue of Nikkei mechanical. Japan: Nikkei BP; June 2001.

[6] Arthur D. Little Report. Cost analysis of fuel cell system for transportation. Base line system cost estimate, March 2000.