Fuel Cell Cost Study by Learning Curve

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Abstract:
This paper presents a study of the PEM fuel cell cost for vehicle application in massive production by learning curve. The typical fuel cell stack consists of membranes, platinum, electrodes, bipolar plates and peripherals. In order to examine the progress ratios for each element, the readiness for automatic production in massive volume and the bottom line cost of each element are analyzed. After checking the present cost and the present volume of cumulative production of fuel cell, the learning curve was applied to cumulative production of 50 thousands and 5 millions. The results showed that the fuel cell stack cost could be reduced to the same level as that of internal combustion engine today and that power density improvement and cost reduction of bipolar plates and electrode are effective for reducing total cost of fuel cell stack.

1. Introduction

PEM (Proton Exchange Membrane) fuel cell is expected to provide power to automobiles, homes, buildings, PCs, handy phones and electronic mobile tools. (1) Increasing number of people think it will be realized in the latter 2000s and next decades. The structure of fuel cell implies that it is suitable for massive production and the cost could be greatly reduced if massive production would begin. The purpose of this paper is to discuss the cost structure of fuel cell and the possibility of reducing cost by learning curve analysis.

2. Learning Curve

Learning curve or experimental curve is a kind of macro scope model of human activity of accumulating knowledge or experiences, and is usually adapted to industrial production process.
The typical learning curve is described as follows,

$$Yi=A*Xi^{-r} \quad (1)$$

Where the variables are defined as follows,

Xi: cumulative number of products at i th production

Yi: product cost at i th production

A: constant

The number “r” on the shoulder is not easy to understood, so simpler expression is introduced as progress ratio, $F=2^{-r}$. F shows how production cost could be reduced at each time when cumulative production is doubled. If we have historical cost data, we can estimate progress ratio F by regression analysis. Experience data in variety of industrial products show that F is 80-95% for mechanical assembly products and 70-85% for semiconductors and electronic devices. But 70% looks minimum number known as progress ratio.

The progress ratio of photovoltaic cost is 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 progress ratio of 75% at initial stage and 80% thereafter. (3)

Usually the learning curve is an analytical tool to discuss the history of massive production. However there are some attempts to forecast the overall fuel cell cost in massive production by learning curve. (3)(4) We applied learning curve to estimate cost of each element of fuel cell stack and to discuss the cost structure in massive production.

3. Cost of Fuel Cell Stack

The typical PEM fuel cell stack consists of numbers 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.

$$C=(Cm+Ce+Cb+Cpt+Co)/P+Ca \quad (2)$$

$$Cpt=Cwpt * Ypt \quad (3)$$

$$P=10*Vc*Ac \quad (4)$$

Where,

C: Fuel cell stack cost per kW ($/kW)

Cm: Membrane cost ($/m2)

Ce: Electrode cost ($/m2)

Cb: Bipolar plates cost ($/m2)

Cpt: Cost of platinum catalyst loading ($/m2)

Cwpt: Weight of platinum catalyst loading (g/m2)

Ypt: Unit cost of platinum ($/g)

Co: Cost of peripheral materials ($/m2)

P: Power density per cell area (kW/m2)

Ca: Assembly cost ($/ kW)

Vc: Cell voltage (V)

Ac: Cell current density (A/cm2)

This description is based on summing up all cell area and has no explicit expression of number of cells. Cost of materials such as electrodes, bipolar plates and peripherals are independent of power density. But the performance of membrane and weight of platinum have sometimes a strong relationship with power density. So, if such performance change occurred together with cost change then the overall progress ratio should be examined whether it is within the experimentally known range. The assembly cost is estimated by a certain model of automatic production system. We assumed 50kW fuel cell production systems for average sized automobile.

The typical performance of single fuel cell has 0.6-0.7 Volts and 0.3-0.4 A/cm2 cell current density, which is nearly 2 kW/m2 of power density. For example, if an automobile has 50 kW rated output, then the cell area must be 25 m2, that is 278 layers of cell with 30cmx30cm cell area. The power density is expected to increase to the level of 5 kW/m2 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 long run and the initial cumulative production scale. To begin with, the cost structure is as follows.

The proton exchange membrane is vigorously being developed. While the Nafion (Du pont) has 100 microns thickness and $500/m2 today, the experts says it will be $50/m2 on the production scale 150 thousands of fuel cell cars annually. ADL report says membrane cost could be $59/m2 for 50kWe output with 30m2 cell area.(5) The thinner and tougher membranes are being developed, the thickness will be 20-50 microns in the near future. The weight of membrane is quite small, and the cost share will be not large because weight determines material cost finally in massive production.

The necessary weight of platinum attracts keen notices. The platinum cost depends on market fluctuations but it is assumed as $15.4/g average today. Today platinum loading in MEA (electrodes and membrane assembly) is 2-4g/m2, which is $32-64/m2. The best experimental data at Los Alamos laboratory are nearly 1/10, which are used as future numbers in this study conservatively.

Typical electrode is a porous carbon paper or a carbon cloth with vacancy rate 80% so that hydrogen and air/oxygen can permeate. MEA has 0.8 mm thickness and about 340g/m2 weight. ADL report says electrodes cost could be $177/m2. The production process of MEA today is rather complex, but this study assumed that it would be massively produced automatically in factory.

Bipolar plates work as electric conducting materials and impermeable walls. Also they haves pattern of flow fields like serpentine that are manufactured by NC machining of graphite sheet, this process is time-consuming and very expensive today. 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 elements in PEM fuel cell. The reason is that they have nearly 80% dominant share of total stack weight as shown in Fig.1. They will determine the stack cost finally if massive production would begin and the stack cost would approach to the raw material cost.

Peripherals include end plates, plastic frame and thrust bolts, which have weight 0.5kg/m2 and ordinary material is enough for them. They have not so much room for improvement. The assembly is now by hand work. We assumed an automatic production line with annual production capacity of 18 thousands vehicle equivalent stack (50kW). The production line is based on sheet processing machines and handling robotics. The analysis shows it is a very time-consuming process to stack up many cells.

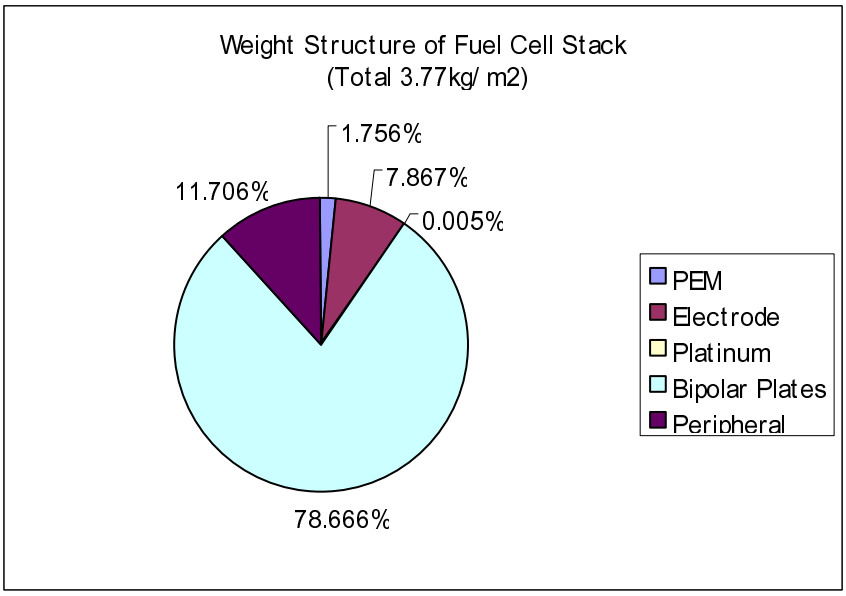

Fig.1 Weight Structure of Fuel Cell Stack

Learning curve calculation sometimes goes to too small cost numbers by its exponential characteristics, and the bottom line cost is introduced to limit the cost at the bottom. The bottom line cost is related with raw material cost, which is expressed in per kg such as 50 cents for steel, $1-$2 for plastics, and $3 for cupper and aluminum in automobile industry. However the ordinary average cost of elements widely known in automobile industry is about $8/kg for steel, metals, plastics and glass if it is massively produced. (Exchange rate of Japanese Yen is assumed as 130 yen per $1) We decided to set the bottom line cost for this number, because it is based on experience and

knowledge in automobile industry. The summary of present, future and bottom line cost is shown in Tab.1

Tab.1 Present, future and bottom line cost of each element

Element	Present	Future	Bottom line
Proton exchange membrane	Nafion 100micron $500/m2(Du Pont)	Thickness 20-50 micron $50/m2 at massive production	60 cents /m2 for thickness 50 micron
Platinum	2-4g/m2 $32-$64/m2	0.2-0.4g/m2 (Best experimental data today) $3.2-$6.4/m2	Expected less than 0.2-0.4g/m2, $3/m2
Electrode	Total thickness is 0.8 mm for single cell. $1423/m2	Roll sheet production. $96/m2	$2.58 /m2
Bipolar plates	Total thickness for single cell is 4mm. $1650/m2	Improved molding $35/m2.	$13.6/m2 for 4 mm thickness
Peripheral parts	End Plates, Thrust bolts, Plastic Frame. 0.5kg/m2, $15.4/m2	Ordinary materials 0.5 kg/m2	$3.46 /m2
Assembly	Hand assembly $385/50kW	Automatic Assembly. Roll supply of membrane and electrodes. Stacking by Robotics	Assuming a production line $94/50kW $1.88/kW

The initial number of cumulative production and the cost are necessary to calculate learning curve effects. There are several data that the fuel cell stack cost in 2000 was around $2,000/kW. (3) We assumed that 40 fuel cell vehicles(50kW) have been manufactured in Japan till 2000 and the factory cost of them 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 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 thousands in 2010 and 5 millions in 2020. Using these numbers we assumed 9 scenarios with combinations of power density improvement (3 scenarios) and cost reduction speed (3 scenarios) as shown in Tab.2.

Power density improvement is assumed as from 2 kW/m2 at initial stage to 5 kW/m2 for H (High power density) scenario, 4 kW/m2 for M(Medium power density) scenario and 3 kW/m2 for L(Low power density) scenario at 5 million cumulative vehicles. The power density improvement process is calculated by 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).

Tab.2 Fuel Cell Stack Cost ($/kW) and the share of platinum cost by Learning Curve

Scenario		High Power Density (H) 2 to 5kW/m2 F=94.5%		Medium Power Density (M), 2 to 4kW/m2, F=96%		Low Power Density (L) 2 to 3kW/m2 F=97.5%	
	Progress Ratio /Pt loading	Fuel Cell 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 (A)	F=78% Pt :0.4 to 0.05mg/cm2	88 15	5.9 10.8	103 19	5.9 11.1	121 25	5.9 11.4
Moderate (B)	F=82% Pt :0.4 to 0.1mg/cm2	143 30	5.1 9.7	167 38	4.9 9.8	196 49	5.1 9.9
Slow (C)	F=88% Pt :0.4 to 0.2mg/cm2	285 88	3.9 6.7	334 114	4.0 6.8	392 145	4.0 6.8

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

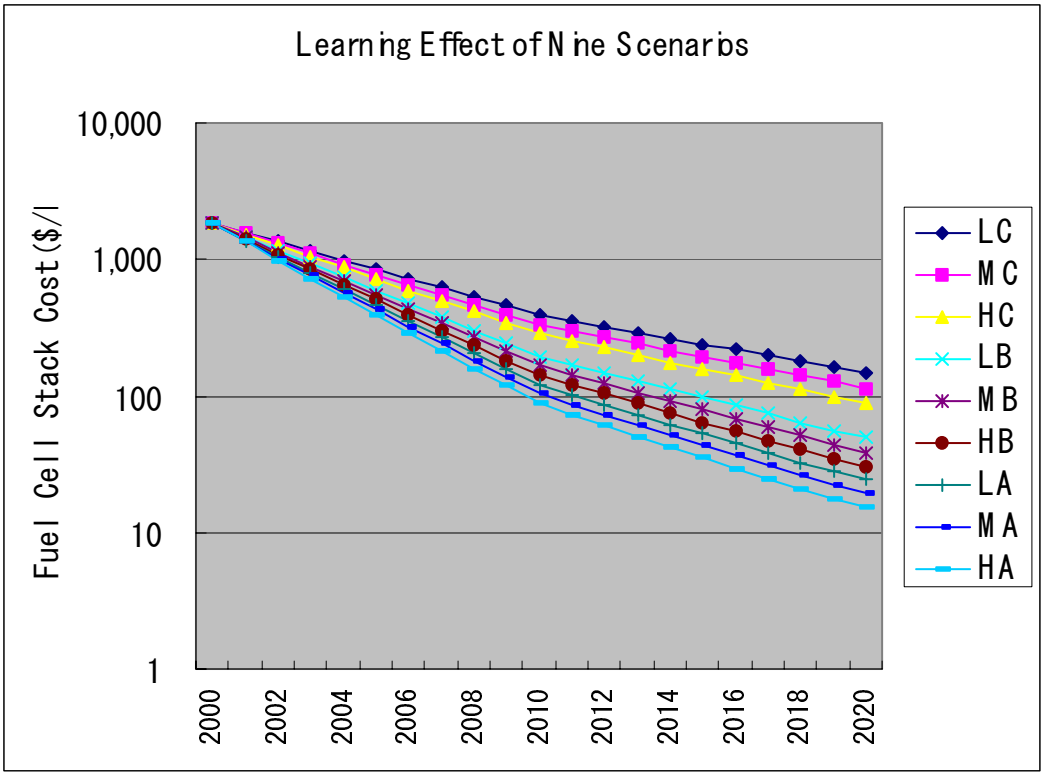

Fig.2 Learning Effects of Nine Scenarios

Platinum loading begins with 0.4 mg/cm2 and decreases to 0.05mg/cm2 for scenario A(equivalent F=89%), to 0.1mg/cm2 for scenario B (equivalent F=92%) and to 0.2 mg/cm2 for scenario C (equivalent F=96%). The highest learning effect case is HA

scenario, and the integrated progress ratio is 94.5% x 78%=73.7%, which is in the range of experientially known progress ratios.

Progress ratio of peripheral cost is assumed 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. 9 scenarios are generated by combining power density improvement and cost reduction speed such as HA,HB,HC,MA,MB,MC,LA,LB and LC.

Fig.2 shows the learning process of 9 scenarios. Tab.2 shows the results in 2010 and 2020.The learning curve calculation shows that the fuel cell stack cost in 2020 would be $15/kW to $145//kW depending on scenarios. The cost reduction went to the bottom line cost incase of bipolar plates of HA,MA and LA scenarios in the year 2020 only. The platinum cost share is 1.7% at initial stage but it increases gradually to the level of 7-11 % for 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 introduction of constant growth ratio 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 learning curve. But it only shows what would happen if massive penetration of official prediction become realistic. The results show that fuel cell stack cost could be comparable with internal combustion engine if it is massively manufactured.

Table 3 Scenario MB: Moderate with Medium Power Density

		Case: Moderate with Medium Power Density (MB)								
		Cost ($/m2)				Platinum				
Year	Number of FC Vehicles	Proton Exchange Membran	Electrode	Bipolar Plates	Peripherials	Pt Weight (g/m2)	Pt cost ($/m2)	Power density (kW/m2)	Assembly Cost ($/50kw)	Total ($/kW)
	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	1,255,943	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.3 shows the cost structure in 2000 at initial stage for all scenarios. Fig.4 shows the cost structure at 5 millions cumulative vehicles in 2020 for Scenario MB. Bipolar plates and electrodes dominate the cost share at initial stage, but will become less dominated by gradual increase of cost share of platinum, peripherals and assembly as shown in Fig 4. This is because massive production would decrease total fuel cell stack cost ($/kW) and at the same time increase gradually 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 future cost reduction by massive production. It is estimated that cost reduction to the level of internal combustion engine is possible, if massive production is applied. The analysis of cost structure shows that bipolar plates and electrodes have large share of stack cost and would be very significant cost factor even when the massive production would happen in large scale. The power density improvement is essential to reduce 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 to 5 millions vehicles.

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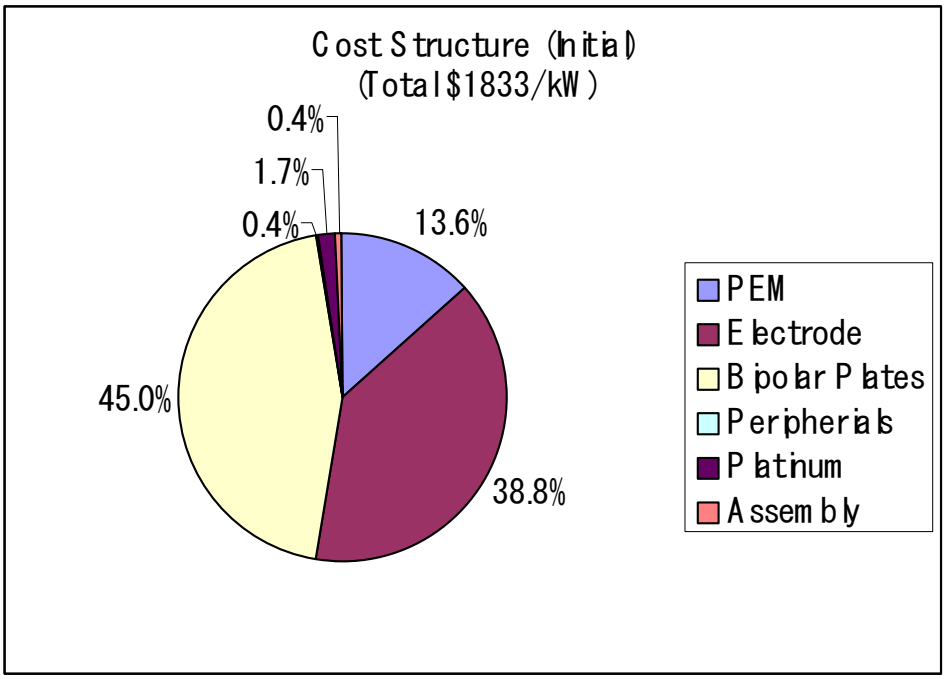

Fig.3 Fuel Cell Stack Cost Structure of MB Scenario in 2000

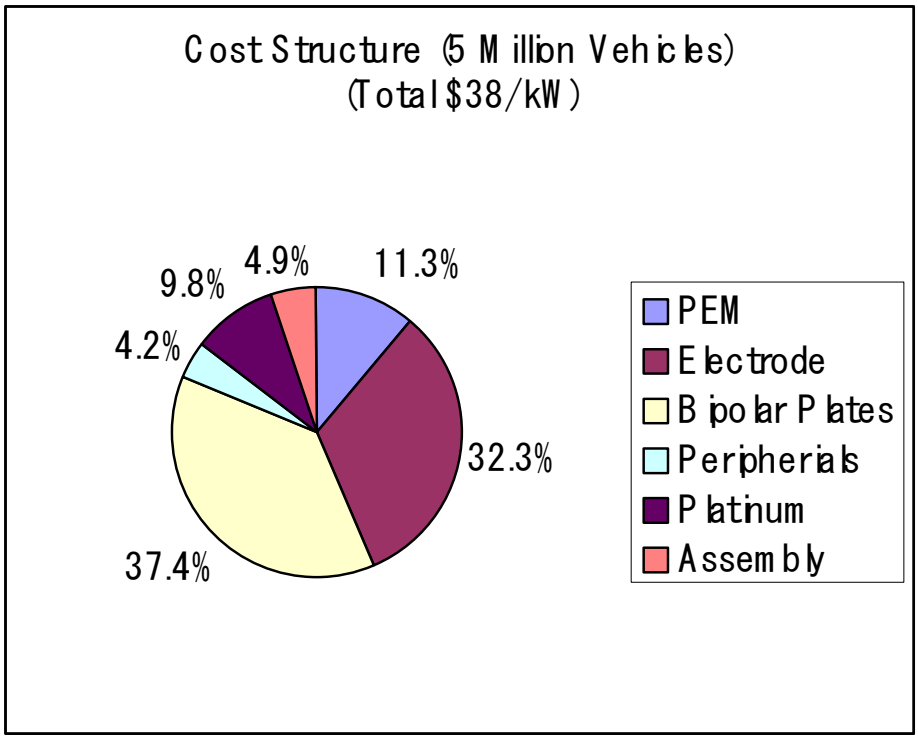

Fig.4 Fuel Cell Stack Cost Structure of MB Scenario at 5 Millions Cumulative Vehicles