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# Emerging Manufacturing Technologies for Fuel Cells and Electrolyzers

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**Abstract**

Fuel cells have emerged as viable solutions in areas such as stationary and backup power systems, material handling equipment (MHE), and fuel cell electric vehicles (FCEV). Persistent challenges for fuel cells and electrolyzers include high initial cost and the availability of hydrogen infrastructure to support FCEV and MHE fleets. Cost of fuel cells are still high compared to other power generation systems such as diesel and natural gas generators. This, however, can be linked to two facts: first is low production volumes generally and second is emerging manufacturing technologies currently in R&D that need to be scaled up to factory production volumes. This study investigates current manufacturing processes used in production of fuel cells (e.g., spray coating and manual assembly) and emerging manufacturing technologies (e.g., roll-to-roll catalyst coating) to investigate key cost drivers and potential cost reductions in manufacturing of fuel cells and electrolyzers. In particular, we focus on how cost reductions for advance manufacturing technologies may be more significant at scale than existing technologies.



*Keywords:* Cost; Electrolyzer; Fuel Cells; Manufacturing

## 1. Introduction

Fuel cells have recently emerged as a technology of choice for backup power and material handling equipment for several reasons, including the ability to produce power while operating in closed locations (e.g., factories and storage facilities) with zero emissions and fast startup time for backup applications. Fuel cell electric vehicles (FCEVs), on the other hand, have also entered the market in the last few years as a viable option among zero-emissions vehicles (ZEV), particularly in states such as California (USA), and countries such as Germany and Japan. FCEVs will represent part of the future sustainable transportation sector. Original equipment manufacturers such as Toyota, Honda,

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and Hyundai have released commercial cars in parallel with efforts focusing on the development of hydrogen refueling infrastructure to support new FCEV fleets. Persistent challenges for FCEVs include high initial vehicle cost because of the high cost of the fuel cell-powered drivetrain and the availability of hydrogen stations to support FCEV fleets. Stationary fuel cells are another example where fuel cell technology can provide a sustainable solution for power generation. Emissions from fuel cells are much lower than counterpart diesel generators [1-2].

The goals of this paper are to study the impact of advanced manufacturing processes on the cost of fuel cells and electrolyzers and to examine which components in the fuel cell can be made using such techniques. In this paper, we first briefly discuss the types of fuel cells and key components in the polymer electrolyte membrane (PEM) fuel cells and PEM electrolyzers, as major technologies for fuel cell electric vehicles and water electrolysis, respectively. Then we will discuss major manufacturing processes used in production key components in the fuel cell and electrolyzer stacks, and the economics and technology impacts of the emerging manufacturing technologies on the cost of fuel cells and electrolyzers. Examples of emerging manufacturing technologies with some cost analysis will be discussed in Section 2. In Section 3, we discuss learning curves for several clean energy systems, namely solar photovoltaic (PV) cells, li-ion batteries, and the trends of cost over the past few years, and we then will compare learning rates for these technologies with hypothetical learning curves for PEM and solid oxide fuel cells.

**Nomenclature**

| | |
|---|---|
| AFC | alkaline fuel cells |
| BPP | bipolar plate |
| CCM | catalyst coated membrane |
| DMFC | direct methanol fuel cells |
| FC | fuel cell |
| FCEV | fuel cell electric vehicles |
| GDL | gas diffusion layer |
| LIB | li-ion battery |
| MCFC | molten carbonate fuel cells |
| MEA | membrane electrode assembly |
| MW | megawatts |
| NSTF | nanostructure thin film |
| PAFC | phosphoric acid fuel cells |
| PEM | polymer electrolyte membrane |
| PTL | porous transport layer |
| PV | photovoltaic |
| SOFC | solid oxide fuel cell |

## Types and structure of fuel cells and electrolyzers

The major types of fuel cells are:

- Polymer electrolyte membrane (PEM) fuel cells: low-temperature PEM operate at temperatures around 80°C and high temperature PEM operate at temperature around 120°C
- Direct methanol fuel cells (DMFC)
- Alkaline fuel cells (AFC)
- Phosphoric acid fuel cells (PAFC)
- Molten carbonate fuel cells (MCFC)
- Solid oxide fuel cells (SOFC).

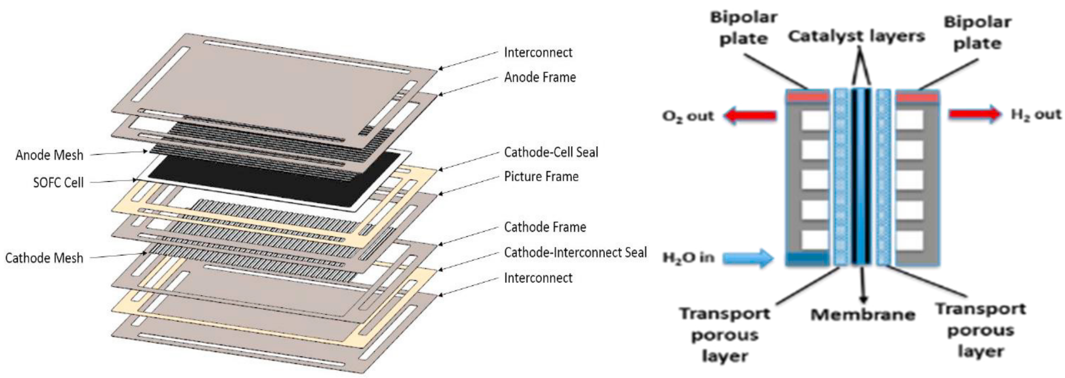
Three major types of electrolyzers are produced commercially today:

- Polymer electrolyte membrane (PEM) electrolyzers working at temperatures between 80°C and 120°C

- Alkaline electrolyzers
- Solid oxide electrolyzers[†].

Low-temperature PEM fuel cells are widely used in fuel cell electric vehicles (FCEV), material handling equipment, and backup power systems. Solid oxide fuel cells are the main technologies used in stationary power generation systems, and they usually have larger capacities (MW scale). Other fuel cell technologies find their applications mainly in stationary applications and backup power. For water electrolysis, alkaline electrolysis is a mature technology. PEM electrolysis technology has positioned itself as a competitive technology, but PEM systems are still designed at lower capacities (<1 MW), and they have higher cost than alkaline electrolyzers [1].

PEM fuel cells and electrolyzers share similar components at the stack level. Fuel cell stacks consist of repeating cells hydraulically connected in series and electrically connected in parallel (Figure 1). Thick metal plates (called end plates) from both ends are added to structurally hold these cells inside the stack. At the core of each of these modules is a polymer membrane with cathode and anode catalyst layers being coated on the surfaces of the membrane. The gas diffusion layer is a diffusion enhancing layer that enhances the reaction between hydrogen and oxygen at the surface of the membrane (enhances water diffusion and water splitting reaction on the surface of the membrane in the electrolysis cells). Bipolar plates, as the name indicates, have a cathodic side and an anodic side. These plates are used to separate repeating cells in the stack and have channels that facilitate the transport of water/hydrogen/oxygen inside the stack [1–3].




**(a) PEM fuel cell** **(b) PEM electrolyzer**

Figure 1. Cell repeat unit showing key components in the PEM electrolyzer (source of image (a) is reference [2])

## 2. Manufacturing of fuel cells and electrolyzers

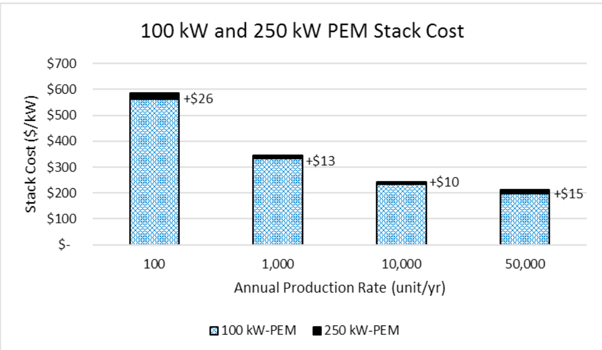
A critical challenge facing the widespread deployment of fuel cells and electrolyzers is their cost. Low cost projections addressed in the techno-economic models do not align with what manufacturers see in their facilities because demand and manufacturing capacities today do not justify high volume productions. High production volumes are expected to play a major role in reducing the manufacturing cost of fuel cells and electrolyzers. Cost reduction from economies of scale encompasses two facets that could lead to such reductions: first is the spread of fixed cost over larger number of units produced, and second is the learning rate (or learning by doing) [4]. Learning rate, which will be discussed in section 3, is an important factor that was seen to have a key role in the cost reduction in several clean energy technologies, including solar PV cells, wind turbines, li-ion batteries, and LED lights. Additional challenges in the manufacturing of the fuel cell and electrolyzer stack components include the low maturity level of manufacturing and the associated low production volumes of individuals components as well as the flexibility of the current production lines to handle new materials and new manufacturing processes. At the same time, reducing the

[†] This technology is still inearly commericlization stage.

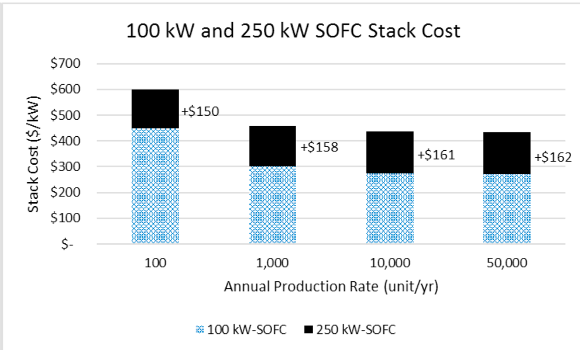
cost of manufacturing of fuel cells components and systems is expected to lead to increased market pull for hydrogen and fuel cell technologies.

In the last two decades, R&D efforts have been targeting several areas to bring the cost of fuel cells down to make fuel cells more competitive than other power generation systems. While most R&D today is focuses on discovery and improvement of materials used in the fuel cell stack, less effort is spent on developing new manufacturing processes that can reduce the cost and improve the quality of fuel cell components. This is likely because material cost is still the dominant cost contributor in the fuel cell stacks, but manufacturing is also important and definitely contributes to the cost of fuel cells and electrolyzers.

In the literature, we find several techno-economic analyses for fuel cells and electrolyzers [2,3,5]. Most of these studies focus on the impact of manufacturing and changes in the cell design on the overall stack and system design. A few of them have discussed impact of balance of plant design and possible technology improvements on the overall system cost. Figure 2 summarizes some of the results of these cost analyses for PEM and SOFC fuel cells. For both PEM and SOFC, we see that cost is expected to decrease with higher production rates. While these charts show a decreasing trend with annual production rate, all these studies assume some improvement in the manufacturing yield (i.e., lower scrap rates with higher production rates). Accordingly, current manufacturing processes are not expected to deliver these cost levels, and all these studies assume some form of advanced manufacturing technologies (e.g., roll-to-roll manufacturing, stamping of plates, and online quality checking) at larger production volumes to justify their cost reduction estimates.




(a)




(b)

Figure 2. Stack cost at different production rates: a) PEM fuel cell, and b) Solid oxide fuel cell (source of data: references [2,3,5,6] and NREL analysis 2018)

### *2.1. Examples of Emerging Manufacturing Technologies*

Current manufacturing processes are slow, expensive, and labor intensive (i.e., have low automation levels). This fact should not be isolated from the fact that higher levels of automation are usually associated with larger demand and require larger investments. Neither one has been met in the fuel cells industry today. Table 1 summarizes the main manufacturing processes used in production of fuel cell and electrolyzer components.

Roll-to roll coating has been investigated extensively in the last few years as a viable replacement of current catalyst deposition processes such as spray coating. Spray deposition processes start by cutting membrane into certain dimensions. Cathode layer is deposited and dried first; then, the same membrane is flipped over and returned to the spraying station to deposit the anode layer (or vice versa). This kind of deposition is suitable for low production volumes and tends to have longer cycle times. Advanced coating technologies such as roll-to-roll not only represents higher throughput option but are also expected to reduce the cost of the catalyst coated membrane (CCM) by providing a process to produce thicker uniform catalyst layers. Another advantage of the continuous roll-to-roll production line is that it can be equipped with a continuous quality inspection system (e.g., an infrared or optical system), which would save time and cost required for offline quality check. A comparative cost analysis of spray and roll-to-roll depositions is shown in Figure 3. Roll-to-roll starts to be more economic at around 20,000 kW-equivalent or 1,500m$^2$

of CCM area. Roll-to-roll coating is expected to be the technology of choice in the long term when the manufacturing volumes achieve economies of scale [5].

Table 1. Current and emerging manufacturing technologies used in production of fuel cell stack components

| **Process** | **Typical Manufacturing Process** | **Emerging Manufacturing Technologies** | **Advantages of Emerging Manufacturing Technologies** | **Limitations of Emerging Manufacturing Technologies** |
|---|---|---|---|---|
| Catalyst deposition | Spray coating and screen printing | Tape casting,<br>Selective slot die coating with decal transfer<br>Nanostructure thin film (NSTF) | Better quality products,<br>high throughputs, lower cost (at economies of scale) | Cost at low production rates<br>Capital cost for machinery |
| Gas diffusion layer (GDL) | Carbon paper/cloth<br>And porous titanium layers† | Compression molding for talinum layer, additive manufacturing | Controlled properties (e.g., porosity and thickness) | Cost, slow process |
| Bipolar plates | Compression molding for composite plates and spray coating of stamped metal plates | Hydroforming for metal plates<br>Additive manufacturing (composite and metal plates)<br>Machining (composite and metal plates) | Higher-quality products, high throughputs, lower cost (at economies of scale) | Cost at low production rates<br>Capital cost for machinery |
| MEA forming | Blade cutting of plastic sheets | Injection molding<br>Screen printing<br>Laser cutting of plastic sheets | Higher-quality products,<br>high throughputs, lower cost (at economies of scale) | Cost at low production rates<br>Capital cost for machinery |
| Gasket/seal forming | Injection molding | Screen printing | Lower cost (at economies of scale) | n/a |
| End plates | Sand casting & machining<br>Die casting | Stamping and welding | Higher-quality products, high throughputs, lower cost (at economies of scale) | Capital cost for machinery |

† A gas diffusion layer made from carbon cloth is used in PEM fuel cells, and a porous transport layer (made from titanium) is usually used in PEM electrolyzers.

Some of the advanced manufacturing (e.g., additive manufacturing and some plate coating technologies such as physical and chemical vaper depositions) may be more expensive than current methods. However, at present and with current volumes, we expect advanced manufacturing would result in more rapid and more sizable cost reductions with increased volume in most cases. Accordingly, we should work to develop these advanced methods in anticipation of increased volume and realization of greater cost reductions.

Another example where we can see the impact of the level of automation on the cost of fuel cells is the stack assembly process. Most of the stack assembly lines today rely less on automation and more on manual operations where workers stack, align, and connect the components in the fuel cell stack. However, fuel cell manufacturers can replicate the success of battery assembly lines in their factories by investing in automation of assembly lines. Fuel cell manufacturers should relate any increase in automation levels to the expected benefits (cost, time and quality), so any investment in the automation of the assembly line could be justified by the production volumes and payback period.

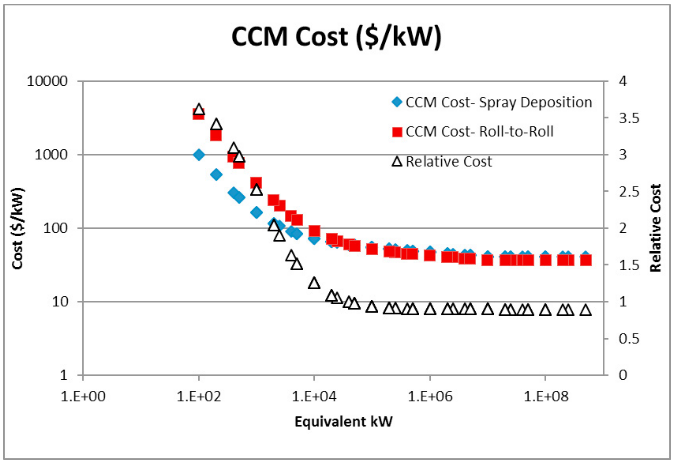



Figure 3. Cost of catalyst coated membrane cost using spray painting process and roll-to-roll deposition

Figure 4 shows the proposed selection criterion of assembly line as proposed by Lawrence Berkeley National Laboratory's cost study [5]. For a 5-kW fuel cell system which has ~5,060 MEA's (membrane electrode assembly), shifting from semi-automatic to automatic assembly line occurs at a volume that exceeds 11,000 fuel cell systems per year or 600,000–750,000 MEA's [5]. Cost curves for several PEM fuel cell sizes are shown in Figure 4. The important points to highlight here are: 1) the increased capital cost of assembly production lines (as a direct result of increasing levels of automation) is expected to be paid off by a larger number of assembled cells per year, 2) an increased level of automation becomes necessary to lower production cost and to get higher-quality products at the same time, 3) assembly time could be reduced significantly with semiautomatic and fully automatic assembly lines, which this saves time, cost, and space for the manufacturers to produce larger volumes.

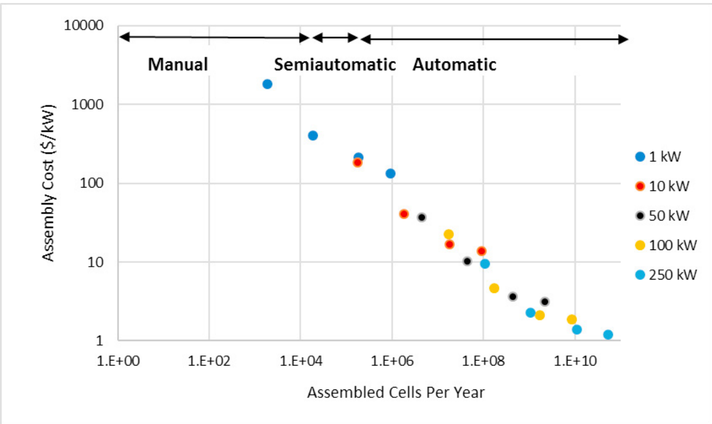



Figure 4. Cost of fuel cell stack assembly process assuming 0 robot for manual, 2 robots for semiautomatic, and 7 robots for fully automated assembly lines, respectively. Cost of robot is $50,000. (source of data [5] and NREL analysis 2018)

### 3. Learning curve for fuel cells

Cost can be lowered in three ways over time [11–13]:

1. R&D: This process is likely to result in significant cost reductions over time. Improvements in technology efficiency and lifetime in association with other improvements in manufacturing practices will definitely play key role in reducing the cost of clean energy technologies. For example, improvements in the PV cell efficiency and li-ion specific energy in the last decade have impacted the prices of both technologies.

2. Learning by Doing: This is a combination of improvements in manufacturing processes, increases in manufacturing yield, reductions in cycle time, and cumulative experience of workers in the production shop.
3. Economies of Scale: This is a direct result of spreading fixed costs over a larger volume of products, so fixed cost per unit of production will be lower at larger production volumes.

All these potential cost reduction ways can be grouped together and plotted in a learning curve (Figure 6). This log-log curve has cumulative production along the x-axis and the observed price along the y-axis. A learning rate can be derived by fitting the data in a power trend line in the log-log chart (cumulative production vs. price) using the following equation:

$$Y=AX^b \quad (1)$$

where: Y = time or cost per cycle or unit, A = time or cost for first cycle or unit, X = number of cycles or units
b = log(m)/log(2), LR = slope of learning curve

Learning curves are used in clean energy manufacturing as a tool to forecast the price of these technologies as a function of cumulative production. Photovoltaic solar cells and li-ion batteries are two good examples of the effect of learning rate on price. Both technologies have seen high learning rates (m), with m=24.3% for PV solar cells and m=21.6% for li-ion batteries (see Figure 5). Nykvist and Nilsson [13] collected data from 80 different cost estimates for li-ion batteries. They estimated the cost reduction following a cumulative doubling of production to be between 6 and 9%. These learning rates are reflected in the decreasing price trends of PV modules and li-ion batteries in the last decade. For fuel cells, Tsuchiya and Kobayashi [14] discussed the effect of learning curve on the cost of PEM fuel cells and found that significant cost reductions can be achieved with increasing number of the produced fuel cells. Similarly, we applied an artificial price of PEM fuel cells and SOFCs using a median markup value (50%, see [4] for such estimate) to estimate the price of these technologies, we estimated learning rates of 5.7% for PEM and 3.9% for SOFC. These low learning rates indicate that these technologies are still at a lower R&D level and that many more improvements in materials, production, and efficiency are needed to observe a learning rate similar to what we have seen for PV and li-ion batteries. With greater economies of scale, we think there is the possibility for increased learning rates and ultimately lower the costs/prices for PEM and SOFC technologies.

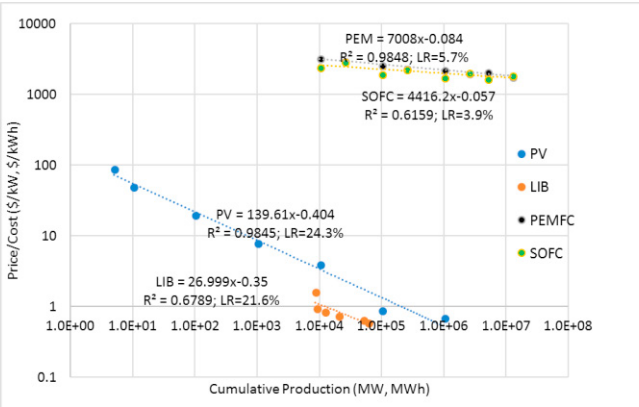



Figure 5. Historical prices for PV solar modules and li-ion battery packs and estimated cost of PEM and SOFC with estimated learning rates (m) (PV: PV-solar modules; LIB: li-ion batteries; PEM: PEM fuel cells; SOFC: solid oxide fuel cells) (source of data: BNEF 2014; E4Tech 2017; NREL analysis 2018)

## 4. Conclusion

We believe that in addition to the innovations in materials and system designs in the fuel cells and electrolyzers, emerging manufacturing technologies could also play key role in lowering the cost of clean energy technologies in the near term. To be considered as competitive power generation alternatives to diesel and natural gas generators, the cost of the polymer electrolyte membrane and solid oxide fuel cells need to come down. Increased production volumes and economies of scale will be critical to achieving cost reductions; however, the manner in which greater volumes are produced will also significantly impact the rate and extent of future cost reduction. Among many emerging manufacturing technologies, roll-to-roll coating, additive manufacturing for production of some components in the fuel cell and electrolyzer stacks, and automation of the stack assembly line provide potential solutions for higher production volumes and lower-cost parts. As these manufacturing technologies are not yet proven at commercial scales, more R&D work is needed to ensure that these emerging technologies can do their intended jobs smoothly at larger production volumes.

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