An Assessment of the Current Level of Automation in the Manufacture of Fuel Cell Systems for Combined Heat and Power Applications

Michael Ulsh
National Renewable Energy Laboratory

Douglas Wheeler
DJW Technology

Peter Protopappas
Sentech

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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NATIONAL RENEWABLE ENERGY LABORATORY

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National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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Executive Summary

The U.S. Department of Energy (DOE) is interested in supporting manufacturing research and development (R&D) for fuel cell systems in the 1–1,000 kilowatt (kW) power range relevant to stationary and distributed combined heat and power (CHP) applications, with the intent to reduce manufacturing costs and increase production throughput. To assist in future decision-making, DOE requested that the National Renewable Energy Laboratory (NREL) provide a baseline understanding of the current levels of adoption of automation in manufacturing processes and flow, as well as of continuous processes. NREL identified and visited or interviewed key manufacturers, universities, and laboratories relevant to the study using a standard questionnaire. The questionnaire covered the following topics:

- Current level of vertical integration
- Importance of quality control developments for automation
- Current level of automation and source of automation design
- Critical balance of plant (BOP) issues
- Potential for continuous cell manufacturing
- Key manufacturing steps or processes that would benefit from DOE support for manufacturing R&D
- Potential for cell or stack design changes to support automation
- The relationship between production volume and decisions on automation.

Companies with known advanced levels of adoption of continuous processes or automation are referenced in appropriate sections of the report as comparison cases. In addition to the manufacturers, two automation companies were also interviewed to understand the critical factors for automation from the design and implementation perspective. Both of these companies have experience working with fuel cell manufacturers.

Table ES-1 summarizes key information about current and projected production capabilities at these companies for the fuel cell systems of interest.

Detailed information about the manufacturing status and directions of the key manufacturers are presented in two sections—one summarizing the status of automation for cell and stack manufacture, and the other for BOP and system manufacture. As noted above, the manufacturers were asked what specific development areas would be the most effective in reducing manufacturing cost and/or improving throughput and quality. Tables ES-2 and ES-3 summarize these results for cells and stacks (ES-2) and BOP and systems (ES-3).

Table ES-1. Fuel Cell Manufacturers and Capacities as of July 2010

Manufacturer	Current Unit Size	Current Build Rate	Current Capacity	Annual Max Capacity with Current Facility	Capacity with Automation
FuelCell Energy	350 kW	25 MW	70 MW	140 MW	280 MW
UTC Power	400 kW	20-30 units (8-12 MW)	50 units (20 MW)	100 units (40 MW)	
Acumentrics	1-2 kW		100 units (100-200 kW)	150 units (150-300 kW)	400 units (400-800 kW)
Versa Power	1-20 kW	10s of units (~200-400 kW)	500 kW		
Rolls-Royce	25 kW				
ClearEdge Power	5 kW	~50 units (250 kW)	1-2 units/day	2,200 units (11 MW)	36,000 units (180 MW)
Altergy	5 kW	1 MW/qtr (4 MW)	2200 units (11 MW)		10,000 units (50 MW)

Table ES-2. Summary of Suggested Development Areas for Cells and Stacks

Company	Suggested Areas of Support for Cell and Stack Manufacture
FuelCell Energy	- Increase casting thickness capability for electrolyte matrix - Increase throughput and control of sintering furnaces - Decrease break-in time of the stack - Automation of cell assembly, enabled by improved cell frame welding techniques - Automation of stack assembly
UTC Power	- Eliminating the machining of separator plates by developing molding or other processes - Development of new matrix coating method - Automation of stack assembly
Acumentrics	- Barcoding of tubes for quality data tracking - Improved process for application of silver current collector to tube - Development of continuous firing furnaces that allow the tube to remain vertical - Continuous plasma spraying of tube interconnects - Develop continuous dry molding of tubes
ClearEdge Power	- Automation of stack repeating part assembly - Development of quality control methods at the MEA level - Automation of subassembly quality control and testing
Versa Power Systems	- Development of methods to identify defects in cell components - Automation of stack assembly - Improved methods for printing of active layers and application of seals
Rolls-Royce	- Automation of stack repeat unit assembly - Automation of the process to collect process control data
Roberts Sinto, PMD and RPI	- Automation of stack assembly, including stack redesign for improved benefits from automation - Developing in-line inspection and quality control; quality 'mapping' - Further innovation to reduce the cycle time (or transition from batch to continuous) of individual process steps - Automate entire process from receipt of parts to gain the greatest benefit from automation

Table ES-3. Summary of Suggested Development Areas for BOP and Systems

Company	Suggested Areas of Support for BOP and System Manufacture
FuelCell Energy	- Decrease cost and improve performance of fuel gas cleanup - Improve processes for metal stamping
UTC Power	- Decrease the cost of reformer - Improve design of power conditioning system and heat exchangers - Decrease time for system test and conditioning
Acumentrics	- Development of stamping of manifold plates
ClearEdge Power	- Decrease the cost of reformers - Decrease the cost of welding and sheet metal operations
Versa Power Systems	- Develop increased experience in supply chain for working with high temperature metals
Rolls-Royce	

In addition to these specific development areas, some overarching key insights were realized as a result of the study. Summarized below, these insights provide a higher level understanding of the implications of implementing automation to decrease manufacturing costs.

- Manufacturing cost is largely material-driven. This means that reducing labor and/or increasing throughput are not necessarily strong drivers for adopting automation.
- Given the current state of the industry, the drivers for increased implementation of automation are repeatability, quality, safety, and better use of factory space.
- The key opportunities for automation at this point are in repeat part fabrication and operations, such as for cell and stack assembly, and for automation or further development of individual process steps.
- Metal working was universally identified as high cost and an issue relative to strong competencies in the supply chain.
- Automation is most useful in a fully vertically integrated operation.
- Manufacturers agreed that lack of supply chain leverage resulting from low market volumes increases manufacturing cost.

Based on the knowledge gained from this study, NREL recommends manufacturing R&D support for stationary/CHP fuel cell systems with the following objectives:

- Automation of repeat part processes such as cell and stack assembly
- Decreased cycle time of continuous processes or transition from batch to continuous processes
- Improved supply chain capabilities and reduced costs for metal forming operations and use of high-temperature metals
- In-line inspection and quality control techniques for continuous and automated processes.

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1 Introduction

1.1 Charter

The U.S. Department of Energy (DOE) is interested in supporting manufacturing research and development (R&D) for fuel cell systems in the 1–1,000 kilowatt (kW) power range relevant to stationary and distributed combined heat and power (CHP) applications, with the intent to reduce manufacturing costs and increase production throughput. To assist in future decision-making, DOE has requested that the National Renewable Energy Laboratory (NREL) provide a baseline of understanding of the current levels of adoption of automation in manufacturing processes and flow, as well as of continuous processes, where applicable. The scope for this study includes the supply chain from cell production to system assembly and testing, and includes major balance of plant (BOP) components. In addition to literature and public media sources, NREL communicated directly with fuel cell and component manufacturers supporting this market to gather relevant information, including site visits to key manufacturers. To support the data gathering process and guide the discussion toward important topics, NREL developed and used a questionnaire (see Appendix A).

1.2 Process

Key manufacturers, universities, and laboratories were identified early in the project and are shown in the tables below. Table 1 identifies the fuel cell manufacturers that were visited or interviewed for this study. The table also summarizes key information about current and projected production capabilities at these companies for the fuel cell systems of interest. A contact list for each of the companies interviewed is provided in Appendix B.

Table 1. Fuel Cell Manufacturers and Capacities (as of July 2010)

Manufacturer	Current Unit Size	Current Build Rate	Current Capacity	Max Capacity With Current Facility	Capacity with Automation
FuelCell Energy	350 kW	25 megawatts (MW)	70 MW	140 MW	280 MW
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ClearEdge Power	5 kW	~50 units (250 kW)	1–2 units/day	2,200 units (11 MW)	36,000 units (180 MW)
Altergy	5 kW	1 MW/qtr (4 MW)	2,200 units (11 MW)	N/A	10,000 units (50 MW)

Note that Bloom Energy, Toshiba, Samsung, and Fuji Electric were also contacted, but indicated that they were either no longer active in the stationary/CHP market or not interested in participating, or they provided advertising literature only.

Table 2 identifies comparator companies that have a high degree of adoption of automation and/or continuous processes. These companies will be discussed in terms of best practices for this work.

Table 2. Comparator Companies

Manufacturer	Operation
Ballard Power Systems	Proton exchange membrane (PEM) cell and stack
Altergy	PEM stack and system
BASF	Polybenzimidazole (PBI) membrane electrode assemblies (MEAs)
3M	PEM MEAs

Table 3 identifies university and laboratory programs that were contacted as part of this study. Companies with experience designing and implementing automation in fuel cell manufacturing operations were also identified. These companies provided valuable insight into the processes used to understand how, and with what priority, automated systems should be applied in this industry.

Table 3. Other Organizations Contacted

Company or Laboratory	Point of Contact	Activity
Roberts Sinto	Bob Conrad and Scott Bethke	Automation systems
Progressive Machine & Design	Garry Sperrick	Automation systems
Rensselaer Polytechnic Institute – Center for Automation Technologies and Systems	Ray Puffer and Steve Rock	R&D, design and test of automated processes and systems
University of Connecticut – Center for Clean Energy Engineering	Trent Molter	R&D
Ohio State University – SOFC Manufacturing and Reliability Laboratory	Winston Ho	R&D, membrane casting
Southwest Research Institute	Mike Miller and Joe Redfield	R&D, vacuum process development
Pacific Northwest National Lab	Subhash Singhal	R&D

2 Discussion

2.1 Synopsis

Detailed information about the manufacturing practices and status of each company interviewed was gathered in this study and is presented in this section of the report. Similarities in the level of adoption of continuous and automated processes were seen at the cell and stack level for these manufacturers. Likewise, similarities were seen at the balance of plant (BOP), subassembly, and system levels. Therefore, the information is presented in two subsections, one for the status of automation at the cell and stack level and one for the status of automation at the BOP and system level. Within each subsection, detailed information about each participating company is provided. After the company details in the cell and stack subsection, there is a discussion of comparator companies whose best practices may inform future activities or advances for the companies in this study. At the end of each of these subsections, a table is provided that lists the main suggestions from the manufacturers regarding areas of development in terms of automation or process improvement. In addition, standard manufacturing practices are discussed in the descriptions. These practices are detailed in the Manufacturing Methodologies subsection. Finally, the discussion ends with key insights.

2.2 Manufacturing Methodologies

Currently, manufacturing operations in the fuel cell industry are set up to support a low-volume market in the demonstration phase. As the market expands, manufacturers and their suppliers must adopt processes and methodologies that fit their business models, and provide the ability to increase production volume while improving quality. A basis of terms for this progression is provided in Appendix A. The term “pick and place” refers to manual material flow and assembly of parts. Note that others use this term to refer to a certain type of automation. In addition, a process flow that combines robotic or machine-controlled motion with manual activity is referred to as semi-automated in this report. An example would be an operator loading a part into a rig, followed by a robot performing some operation on that part. An automated flow would then be fully operated by robots or machine motion. Similarly, continuous process refers to a roll-to-roll or belt-fed operation of a continuous sheet material. Examples would be tape casting of an electrolyte or anode support, or coating of an electrode active layer onto a gas diffusion layer (GDL). A process that operates in a continuous fashion, but operates on individual parts rather than a continuous sheet of material, is referred to as semi-continuous. An example would be continuous coating of an electrolyte matrix onto individual backings that have already been cut to the planform and size of the cell.

Beyond these process and flow descriptors, manufacturers often adopt continuous improvement methodologies to provide a consistent framework for their operations. Two often-used examples are lean and Six Sigma, both of which are typically seen as suites of tools sewn together with a standard method of use. Two examples of lean tools that were observed are ‘5s’, which is a methodology for work station organization, and kanban, which is a process flow and tracking methodology where all required parts or materials for a particular assembly step are provided to the work station along with associated documentation that describes when and how many of each assembly are required. Both methodologies provide structured systems to understand where waste and poor quality exist and utilize measurements to quantify these issues. This information is then used to address the issues in a defined and ongoing manner. There are similarities and differences between the two, and implementation of either is more often undertaken in a "pick and choose" fashion rather than adoption of the entire system. But for the purposes of this report, both can be useful methods to organize process flow, reduce waste, and improve quality.

2.3 State of Automation for Cells and Stacks

The industry's incorporation of automation and continuous manufacturing methods in the manufacture of fuel cell stacks, stack components, and cell components addresses the need to control the physical, chemical, and material properties of the cell components and to assure repeatable quality in the performance and durability of the fuel cell stacks. However, automation and continuous manufacturing methods have only been applied to those critical cell component manufacturing processes that demand the repeatability and precision afforded by robotic and continuous processes. The majority of manufacturers have production facilities that are underutilized because of the limited demand for fuel cells. All of the manufacturers report that they are in the initial phase of market growth and predict that an order of magnitude increase in deliveries of fuel cell systems will occur in the next 2–3 years. Still, most of the fuel cell manufacturers indicated that an additional investment in high rate cell stack manufacturing processes will only be considered in response to an increase in demand.

2.3.1 FuelCell Energy

FuelCell Energy's production facility in Torrington, Connecticut, operates a continuous tape casting method for the manufacture of matrix electrolyte support and anodes. Throughput of the matrix tape casting process is limited by the need to control the porosity and pore size distribution of the support. Research and development is needed on the continuous manufacture of a full thickness matrix tape, as this one process development would double the throughput of the casting process.

Manufacturing of the nickel electrode is performed in a semi-continuous manner. Automation has been incorporated in the loading of the nickel powder into the drop coater, while coating of the nickel powder is performed onto individual backings. The sintering of the nickel electrode in a reducing gas furnace is a throughput limitation. A sintering furnace with a greater capability for continuous, large-scale processing of full-size electrodes is a proposed development effort. The size of the electrodes, about 2 feet by 4 feet, impacts the design of a continuous sintering furnace.

The initial assembly of the cell components into a single plate is a manual lay-up operation that can be readily automated, the primary advantage of which would be greater precision and repeatability during production. The application of metal strips that form the picture frame cell holder, i.e., bipolar plate, is a combination of manual assembly and robotic assembly. FuelCell Energy has automated the welding of the bipolar plate metal frame to bind the individual cells, using robots to move and weld the frame, and optical inspection methods to complete the cell assembly. The current bipolar plate design drives much of the labor and level of automation. Therefore, the development of a bipolar plate that can facilitate automated assembly is important.

Assembly of the internal reformer is time consuming and results in a throughput limitation in the overall manufacturing process. Automation of this process may require a new design of the internal reformer.

Stack assembly is a manual process that could be automated. FuelCell Energy's business model is to produce cells that are readily shipped to stack assembly locations. The stack assembly stations may be close to the end users.

There is extensive welding of stainless steel reactant flow piping used to deliver reactants, recycle carbon dioxide to the cathode, and remove gas products. Automation of the welding of the flow manifolds and flow delivery piping is one approach to reduce costs.

First-time conditioning of the 350 kW molten carbonate fuel cell system takes 7–14 days. FuelCell Energy recommends research and development in the optimization of electrode design and system break-in practices as part of a manufacturing R&D effort.

FuelCell Energy discussed in some detail a future capability analysis that was performed to establish a production rate of 280 megawatts (MW)/yr. At this rate, the company would need to produce 1 cell per minute, or 1,200 cells per day, or 275,000 cells per year. As of July 2010, FuelCell Energy was producing about 100 cells per day. The company provided some very instructive examples of the manufacturing enterprise that would need to be put into place to support 280 MW per year of production. For example, just for material handling within the factory, greater than 1 MM lbs of material per year would have to be moved around. At this rate, the entire layout and infrastructure of the facility would need to be re-designed to "feed the beast". Relative to current production facilities and volumes, FuelCell Energy has plans to increase production to about 140 MW per year at its current facility. For higher volumes, the company states that a new facility should be designed to facilitate higher levels of automation. This would include changing from wood to returnable pallets, automated loading and unloading, material handling modifications, and process cycle time improvements.

2.3.2 UTC Power

UTC Power outsources the manufacture of the major repeat cell components, catalyzed electrodes (gas diffusion electrodes [GDE]), and bipolar plates. Other stack components, such as reactant and product manifolds, are also outsourced, as well as major subsystems, such as the fuel processor and power control system (e.g., inverter). UTC Power manufactures the individual cells, assembles the cells into stacks, and assembles the subsystem components into the 400 kW PureCell power system. Present production capacities are 50 units per year with the capability to reach 100 units per year.

UTC Power's cell assembly is automated and conducted through a combination of continuous processing and robotic movement of the cell system through the assembly stages. In the continuous process, each GDE—anode or cathode—is given an edge seal coating to form a silicon-carbide-based picture frame around the catalyst layer. A silicon carbide matrix coating is then applied to each GDE while moving on a continuous belt. The belt holding the silicon carbide-matrix-coated GDE passes through a heat treatment oven to fix the silicon carbide matrix. Phosphoric acid is applied to the GDE-matrix component and absorbed into the porous matrix-electrode. Sequential anode and cathode GDEs are lifted from the belt by robots and sandwiched together to form an MEA. The MEA is applied to a porous anode bipolar plate containing phosphoric acid. Then, a non-porous cathode bipolar plate/separator plate is applied on top of the anode bipolar plate/MEA subassembly to form a complete cell. All of these actions are performed on the continuous moving belt using robots to add components to the emerging cell. After that, eight of the completed cells are robotically stacked to form a substack. Multiple substacks are then manually stacked to form a full-size stack.

An important function of the continuous belt/robotic manufacture of the phosphoric acid cells is to maintain repeatability and quality control in the cell. An equally important feature is the reduction in scrap, which is accomplished by minimizing hand touches of the fragile cell components until they are fully assembled into a substack.

UTC Power indicated the following areas that could benefit from further development: elimination of the machining of separator plates (by molding or other means), reduction of cycle time for system testing and conditioning, and the creation of new matrix coating methods. UTC Power does not see the need to redesign cells or the stack for automation. Rather, the company sees a need to focus on improving supply chain leverage.

UTC Power assembles the three major subsystems, the fuel processor, the cell stack assembly, and the power conditioning unit, using lean manufacturing methods and 5S methodology. The company is managing the investment on the next stages of system-level automation until there is a demonstrated and sustainable market pull. Automation and process improvement of individual manufacturing steps is UTC Power's suggested focus. Furthermore, the company stated that volume is not going to reduce its costs dramatically, and that technical advancements and simplification are still needed to reduce costs. UTC Power verified the comment from FuelCell Energy that cost is largely driven by materials as opposed to labor or processes. The company also indicated that a sales volume of thousands of units per year would be required to consider a highly automated manufacturing facility.

2.3.3 Acumentrics

Acumentrics suggested that DOE support for high-temperature system manufacturing R&D can be analogous to recent support of proton exchange membrane (PEM) systems. While CHP is the eventual goal, support for the development (technical and manufacturing) of nearer term, or more economically feasible applications needs to be considered to enable advancements that will not only benefit current markets, but enable progress toward target markets. Acumentrics discussed a recent joint development effort with Ariston Thermal Group, a condensing boiler company in Italy, to offer a 1kW(e)/20kW(thermal) on-wall residential CHP system for the European market. Acumentrics states that it can produce about 100 systems per year now, and would keep the same manufacturing system up to about 1,000–2,000 systems per year, above which would require a change in manufacturing approach.

The company is essentially fully vertically integrated for cell and stack production, and, like FuelCell Energy, starts with ceramic raw materials. Acumentrics then fabricates tube cells and assembles stacks. The company discussed the importance of future decisions regarding when and to what extent it should begin to establish a supply chain. Regarding quality control, Acumentrics indicated that it wanted to develop a way to barcode each tube so that quality control (QC) data can be tracked. In addition, the company sees a need to develop quality control methods for the plasma spray process.

Currently, Acumentrics uses a high level of individual process automation in cell fabrication, such as, tube-end forming, dip coating, active layer coating, spraying, and QC on diameter/runout of fired tubes. To increase throughput and quality, the company recently changed its tube forming process from extrusion to hydraulic molding. At present, tube molding and firing are batch processes. The cell fabrication flow is manual, as is application of the current collector wire, and stack assembly. Acumentrics stated that their current process automation was internally designed. They stated that adoption of increased levels of automation will not cause a design change to the stack.

According to Acumentrics, the following areas could benefit from further development: improved methods for applying current collectors to tubes, continuous firing furnaces that enable the tube to stay vertical, better temperature control of a batch furnace to reduce cycle time, a continuous process for the plasma spray of tube interconnects, stamping of manifold plates for some applications where , moving to dry tube molding which could be implemented in a continuous or semi-continuous fashion, and general loading and unloading of tubes for each step in the cell fabrication process.

2.3.4 ClearEdge Power

ClearEdge Power manufactures a 5 kW polybenzimidazole (PBI)-based fuel cell system for residential and commercial micro-CHP applications. The company's initial market was in California, for high-end early adopter residences and small businesses. ClearEdge Power has a binding contract with a Korean company for a minimum of 800 units and considers Asia, Australia, and South America to be major market areas. The company provides an average of 750 gallons of hot water per day at 130°F–150°F from its ClearEdge5 system, which is used for boiler preheat, domestic hot water, or heating pools. ClearEdge Power indicated that the electrical efficiency of the system was about 37% averaged over the 2–3 year stack life. Furthermore, consumers receive a 5-year product warranty, which includes change out of the stack after 2.5 years.

Currently, ClearEdge Power has about 100 systems installed, with current production capacity at approximately 2 units per day. The company expects to achieve 5 units per day by the fourth quarter of 2011. ClearEdge Power recently performed an automation study for its current manufacturing process and determined that its maximum capacity is about 2,200 units per year. With full implementation of automation and running three shifts, the company could achieve 36,000 units per year in the same facility for an investment of approximately $12–$15 million.

ClearEdge Power sources MEAs and manually assembles stacks. The company specifies the properties of the catalyst layer and GDL for its sourced MEAs and specifies the properties of the bipolar plates. Automation of stack assembly (stack repeating parts) was identified as a manufacturing operation that could benefit from DOE support. The company also indicated that quality control at the MEA level is an ongoing need and agreed with DOE support of MEA-level QC development. ClearEdge Power does not expect that major stack redesign to be required to support the implementation of automation.

The company relies on its suppliers for MEA and subassembly/component quality assurance. For stack and subassemblies, QA testing is performed. Break-in and testing of the final system is for an 8-hour period and then a 48-hour period, most of which is not for break-in, but to try to identify hardware or stack performance issues before the system is in the field. ClearEdge Power stated that automation of subassembly quality control and testing was an area of interest.

The company indicated that the decision to implement automation would depend on the economics of each subassembly, but stated that it would only consider the implementation of automation for its manufacturing process when the market demand justified the investment.

2.3.5 Versa Power Systems

Versa Power Systems has developed two fully integrated 3–10 kW solid oxide fuel cell (SOFC) systems in its Solid State Energy Conversion Alliance (SECA) programs with FuelCell Energy and Cummins Power Generation. The company has aligned its current manufacturing capabilities and methods with the current demonstration (as opposed to commercialization) stage of the market for these systems. As a result, Versa Power Systems indicated that there is a significant amount of overdesign—in instrumentation and redundancy—currently built into its systems, specifically, “So that the stack can show its potential.” As the market shifts to commercialization, the company indicated that design simplification will be undertaken which will reduce costs.

Versa Power Systems manufactures its own cells from the ceramic powders, using continuous tape casting and co-firing (sintering) for anode support layers, and semi-continuous screen printing processes for cell active layers. Cells are assembled into stacks by hand. Versa indicated that there is not a mature supply chain for high-temperature cells, and that cell production is the company’s core intellectual property. Versa Power Systems stated that maintaining cell production within the company enables maximum control over design and quality.

The company is strongly committed to quality control to best address the demonstration stage of the market and stated that the time to build a stack is a huge investment. For example, if the stack fails after 1,000 hours, a huge amount of time and funds are wasted. Versa Power Systems also indicated that defects must be caught as soon as possible, and that new in-line QC and inspection methods, including process feedback, must be developed to support higher volume production processes. The company gathers large amounts of quality data, and understands its control limits for production. Versa Power Systems stated that transition to continuous or automated processes is justified just as much for improvement in quality as for increase in capacity. The company stated that it currently performs visual and dimensional inspections, and that methods are needed to identify these defects in continuous processes.

At this time, Versa Power Systems is engaged with automation manufacturers to explore automation of stack assembly. The stack build would be performed by subassembly to assist in quality control. Printing of active layers and application of seals are other processes that are of interest to transition to continuous or automated processes. The company cautioned, however, that, at this point in the market, more automation means less flexibility to respond to design changes, and that a balance must be kept in the short term.

Versa Power Systems stated that it has always had a focus on high-volume manufacturing, and thus its base stack design should not require significant design modifications to implement automation. However, as expressed above, the company indicated that, as a result of the demonstration phase of the market, its current system is purposefully overdesigned. Thus, a simplification of design will occur as the market becomes more mature.

2.3.6 Rolls-Royce

Rolls-Royce operates a pilot manufacturing line in Canton, Ohio, for its SOFC system. The company stated that its target is a 1 MW system, comprised of four 250 kW modules, each of which having 8–10 stack blocks (about 25 kW each). To date, Rolls-Royce has demonstrated systems containing multiple stack blocks, but not yet at the level of a full 250 kW module. The company indicated that it is in the development stage of addressing the market for its systems.

Rolls-Royce sources the flat tube supports for its cells, then applies the active layers to these tubes in-house. Ceramic raw materials for the electrolyte and active layers are also sourced. Semi-continuous screen printing processes are used to coat the multiple active layers on the flat tube support. Sintering is currently a batch process and is the bottleneck on the pilot manufacturing line. However, a predecessor operation in the United Kingdom uses a continuous tunnel furnace. Most of the stack assembly steps are performed by hand, although Rolls-Royce has partially automated some steps, such as robot-assisted glue dispensing for sealing. The company relies mainly on internal resources for design but uses outside suppliers for implementing automation. Rolls-Royce does not envision a need to change the design of the stack to assist with the implementation of automation.

The company considers automation of stack repeat unit assembly to be a major near-term opportunity as it allows the process to be developed and demonstrated in the pilot facility. Rolls-Royce also sees the need to automate the collection and management of process control data as higher levels of process automation are adopted.

2.3.7 Automation and Continuous Processes for Cell and Stacks: Comparator Companies

Manufacture of MEAs for fuel cell applications has advanced to the use of continuous and semi-automated processes. 3M reports that roll-to-roll processes have been designed and implemented for continuous production of MEA components and MEAs, including a hot roll laminating step to replace the slow hot press bonding process. The continuous process brings together membrane, electrodes—either in the form of catalyst-coated membranes or gas diffusion electrodes (GDE)—the gas diffusion layers (GDL), and seals to form a full MEA. BASF reports that roll goods of membrane, GDE, and membrane seal are semi-continuously assembled into an MEA. Additionally, RPI reports strong progress in the development of ultrasonic processes for both welding of MEA components and gaskets and pressing of the MEA. This work is concentrated on PBI-based MEAs, but is also expected to be applicable to PEM MEAs.

Another manufacturer has established electrode manufacturing using a semi-continuous process with a discontinuous hot pressing step for the deposition of catalyst onto a gas diffusion layer to form a gas diffusion electrode. The hot pressing process was optimized to reduce the pressing time and maximize the throughput. This manufacturer reports that the hot pressing step ensures the quality of the electrodes and is essential for maintaining control of reactants and products in the GDEs.

Ballard has established three production lines each representing different levels of production maturity. The oldest production facility is the least mature and requires considerable hand labor for the production of the fuel cell stack. The second production line has partial automation with a pick-and-place assembly of the membrane electrode assemblies and then hand placement of the bipolar plates. The final production line, which is currently in development, is for continuous roll production of MEAs.

The above examples identify advances and best practices related to continuous and semi-continuous processes for MEA production. An example of automation best practices is Altergy's very sophisticated cell assembly facility. Starting with a pre-assembled MEA, the cell, including metal bipolar plates and seals, is assembled and welded, with the parts moving through the line on a belt, and robots performing individual assembly and joining steps. This line is capable of producing a complete cell every 30 seconds.

Table 4. Summary of Suggested Development Areas for Cells and Stacks

Company	Suggested Areas of Support for Cell and Stack Manufacture
FuelCell Energy	• Increase casting thickness capability for electrolyte matrix • Increase throughput and control of sintering furnaces • Decrease break-in time of the stack • Automate cell assembly, enabled by improved cell frame welding techniques • Automate stack assembly • Improve processes for metal stamping
UTC Power	• Eliminate the machining of separator plates by developing molding or other processes • Decrease time for system testing and conditioning • Develop new matrix coating method • Automate stack assembly
Acumentrics	• Barcode tubes for quality data tracking • Improve the process for application of current collector to tube • Develop continuous firing furnaces that allow the tube to remain vertical • Establish continuous plasma spraying of tube interconnects • Develop continuous dry molding of tubes
ClearEdge Power	• Automate stack repeating part assembly • Develop quality control methods at the MEA level • Automate subassembly quality control and testing
Versa Power Systems	• Develop methods to identify defects in cell components • Automate stack assembly • Improve methods for printing of active layers and seal application
Rolls-Royce	• Automate stack repeat unit assembly • Automate the method to collect process control data
Roberts Sinto, PMD, and RPI	• Automate stack assembly, including stack redesign for improved benefits from automation • Develop in-line inspection and quality control; quality 'mapping' • Further innovate to reduce the cycle time (or transition from batch to continuous) of individual process steps • Automate entire process from receipt of parts to gain the greatest benefit from automation

2.4 State of Automation in BOP and Final System Assembly

Overall, the level of automation for BOP assembly and final system assembly is relatively consistent across all of the companies interviewed. Each has established workstation assembly for BOP and final system components, and employs lean manufacturing principles in production facility layout and design. Major BOP components are typically purchased from outside suppliers. However, in some cases, the companies manufacture their own reformer, heat exchanger, and/or electronics components. All have identified the need for cost reduction of BOP components. Power electronics, reformers, inverters, stack end plates, and heat exchangers are all candidates for cost improvement and also improvement in design and assembly. Dual sourcing of specialty components is needed, but current production volumes are too low to justify the cost of qualifying or developing new suppliers. While obstacles exist in automating BOP and final system assembly, manufacturers are continually working to streamline this part of the manufacturing process.

2.4.1 FuelCell Energy

Final assembly of the fuel cell module at FuelCell Energy incorporates no automation and is highly labor-intensive. Due to the size and weight of the components, lifts or cranes are used as assembly aids in the final assembly process. Each 1.4 MW unit is assembled by hand with no more than one unit in process at a time. There are two stations in the final assembly process: the first station installs all BOP components and the stacks to the base of the unit housing; the second station integrates the top housing and final assembly (aided by an overhead crane). The stack module housing is constructed of thick, heavy steel and is insulated and designed to handle extreme internal and external events, although the module is not pressurized. The top housing is outsourced and insulation is installed at the supplier. Because of the large component size, several technicians are needed to install these large components. FuelCell Energy also indicated that improved processes and quality for metal stampings at its suppliers is an area of focus.

2.4.2 UTC Power

Similar to FuelCell Energy, UTC Power employs a very manual process in its BOP and final system assembly. Stacks are manually transported, with the aid of forklifts and cranes, to work stations where BOP components are integrated. Each station employs lean manufacturing and 5S principles, which ensures efficient piece flow throughout the assembly process. Many of the BOP components are delivered to the power plant assembly line as completed sub-assemblies. Recently, UTC Power has installed an assembly system utilizing a base frame, which can roll on rails though the final assembly, test, and conditioning system.

UTC Power stated that the reformer is the single most expensive BOP component in the system, and should be a candidate for manufacturing R&D support. Redesign and re-qualifying a new power conditioning system, as well as heat exchangers, were also identified as in need of further development.

2.4.3 Acumentrics

BOP and final assembly at Acumentrics are all done manually by technicians. There is a mix of in-house fabricated and sourced components: for example, heat exchangers, flow components, and electronics are fabricated in house. On the other hand, some wiring assemblies that were previously made in house are now outsourced. In each make/buy decision, cost has been the deciding factor. Lean manufacturing and 5S principles have not necessarily been implemented into the work station design or layout. Testing and conditioning at the final assembly level is conducted in a separate area where units are manually transported one unit at a time. Acumentrics plans to keep production of its hot box, or stack, in house.

2.4.4 ClearEdge Power

ClearEdge Power sources all of its BOP and final assembly components, including small BOP components, heat exchangers, inverters, and electronic assemblies. Some larger assemblies, such as the fuel processing system, are assembled in house. Reformer manufacturing, welding, and sheet metal operations were identified as high-cost activities. Some of these activities are performed by suppliers. All assembly is performed manually with high emphasis on lean methodologies, such as 5S and kanban, as well as piece process flow. No continuous or automated processes are currently being used, however, ClearEdge Power is exploring automation in every area of its manufacturing process. Currently, the company has the capability to perform final testing of 12 units simultaneously.

2.4.5 Versa Power Systems

Versa Power Systems assembles systems using manual flow. Metal work and machining are typically outsourced. In general, the company stated that BOP components are not significant needs. However, it did state that the supply chain needed to be further developed for BOP components requiring high-temperature metals such as nickel super-alloys.

Versa Power Systems has performed cost modeling, as a part of its participation in the SECA program, for a capacity of 50,000 systems per year. This modeling has provided the company with volume-based decision points for implementation of automation.

2.4.6 Rolls-Royce

System assembly at Rolls-Royce is currently manual, in accordance with the demonstration level of maturity of the market for its product. For BOP, Rolls-Royce relies on suppliers for some components, but also relies on manufacturing capabilities of its parent company for other components. The company considers BOP to be very specific to system design, and therefore not generic enough to warrant DOE support.

2.4.7 Conclusion

In all companies, BOP and final assembly are highly specialized and technicians are trained to meet the needs of the complete final assembly. Due to the nature of BOP assembly and final system assembly and testing, many companies identified that these operations could be either outsourced or moved to international locations closer to their target markets. This differs from cell and stack assembly, which were identified as core to their business and crucial in maintaining control over their intellectual property.

Table 5. Summary of Suggested Development Areas for BOP and Systems.

Company	Suggested Areas of Support for BOP and System Manufacture
FuelCell Energy	• Decrease cost and improve performance of fuel gas clean up • Improve processes for metal fabrication
UTC Power	• Decrease the cost of reformers • Improve design of power conditioning system and heat exchangers
Acumentrics	• Develop stamping of manifold plates
ClearEdge Power	• Decrease the cost of reformers • Decrease the cost of welding and sheet metal operations
Versa Power Systems	• Develop increased experience in supply chain for working with high-temperature metals
Rolls-Royce	N/A

3 Key Insights

Specific development areas for cell, stack, BOP, and system manufacturing have been discussed and summarized in section 2, above. However, in addition to these inputs from the participating companies, some overarching key insights were realized as a result of the study. Summarized below, these insights provide a higher level understanding of the implications of implementing automation to decrease manufacturing costs.

- Top level manufacturing cost is largely material-driven, and to a lesser extent, labor-driven. This means that reducing labor and/or increasing throughput are not necessarily strong drivers for adopting automation.
- Given the state of the industry at this time, the drivers for increased implementation of automation are repeatability, quality, safety, more efficient use of factory space, and labor cost reduction.
- The key opportunities for automation today are in the repeat part fabrication and repeat part operations, such as for cell and stack assembly, and for automation or further development of individual process steps.
- Metal working was universally identified as high cost and an issue relative to the need for stronger competencies in the supply chain. Specific processes that were mentioned were machining and stamping of plates and welding. Working with high-temperature steels for heat exchangers and other fuel-side components was also mentioned as an issue.
- Automation is most useful in a fully vertically integrated operation, driven by the maxim, “once you grab a part, don’t let go.” Typical automation of process flow can increase throughput by 10 times.
- Manufacturers agreed that lack of supply chain leverage resulting from low market volumes increases manufacturing cost.

4 Recommendations

Many differences were observed regarding the business plans and operational capabilities of the manufacturers that were interviewed. In addition, differences between fuel cell technologies lead to different material and process constraints. However, many common threads were heard, and strong opportunities exist for DOE to support increased production volume and reduced manufacturing cost. Based on this study, NREL's recommendations for areas of future support include the development of:

- Automation for repeat part processes such as cell and stack assembly
- Reduced cycle time of continuous processes (e.g., coating of electrolyte matrix or active layers) or transition from batch processes to continuous processes (e.g., sintering or tube molding)
- Improved supply chain capabilities and reduced costs for metal parts (e.g., welding, stamping, and machining) and use of high-temperature metals
- In-line inspection and quality control techniques for continuous and automated processes.

Appendix A

Manufacturer Questionnaire

Introduction

The U.S. Department of Energy (DOE) Fuel Cell Technologies Program requested the National Renewable Energy Laboratory (NREL) to conduct a review of manufacturing automation in the production (or potential production) of 1 kW to 1 MW stationary fuel cell systems. The approach for this review is to contact major fuel cell system manufacturers, fuel cell stack component manufacturers, and manufacturers of balance-of-plant (BOP) components to:

1. Discuss the status of automation for fuel cell system and component manufacturing
2. Obtain the recommendations of fuel cell manufacturers for accelerating and driving down the cost of fuel cell manufacturing through automation.

Manufacturing Approaches

Pick and place is the manufacturing process used by many fuel cell manufacturers. The process is manpower-intensive for the production of fuel cell components, fuel cell subsystems, and assembly of fuel cell systems. By "Pick and place", we mean that construction of the fuel cell component is done one operation at a time by using manpower to move fuel cell components and assemble these components into a fuel cell subsystem. The use of automation is minimal with an employee operating assembly equipment, for example, screen printers, presses, or stacking of cell components.

Semi-continuous manufacturing of a fuel cell system incorporates continuous processing at different stages of the manufacturing process, but still has some operations that use pick and place. An example of semi-continuous manufacturing of cell components would be electrode manufacture where the worker prepares the catalyst for screen printing with subsequent deposition of the catalyst and bonding of the catalyst to a gas diffusion electrode by an automated continuous process. An example of fuel cell system semi-continuous manufacturing would include connecting (e.g. by welding) of a reformer to the shift converter during the assembly of the stationary fuel cell system.

Continuous/automated manufacturing of a fuel cell system incorporates processes such as roll-to-roll processing where fuel cell components are assembled continuously with minimal manpower contribution. For example, an operator loads roll stock materials (such as the membrane, gas diffusion material, and catalyst) into the roll processor which continuously assembles these components into membrane-electrode sheets, cuts the sheets to form MEAs, and applies seal materials to the MEA, which are immediately assembled into a cell stack, (for example, with robots), with bipolar plates alternating between the MEAs. In one continuous process, the precursor materials for the cell stack are processed and assembled into a final product.

Discussion

NREL recognizes that a combination of the manufacturing approaches may be used and would like to identify the different manufacturing approaches presently used, relative to automation and continuous processes, for different process steps. An example would be the process for electrode/catalyst/membrane (separator) assembly. Another example would be cell stack assembly and the connections to the reactant and exit manifolds of the cell stack.

NREL also recognizes that an important factor for the industry to invest in automation is the market demand for the fuel cell system. Only under certain market conditions (demand/pricing) will the industry make the investment in a highly automated production facility.

The DOE is interested in understanding the technical/manufacturing—as opposed to market—barriers to achieving highly automated production capabilities. What are the key technical or process barriers that inhibit adoption of highly automated production methods (or is the lack of implementation of these methods strictly market-based)? What specific process or automation technologies, if any, should the DOE focus on to assist in decreasing cost and increasing quality of these fuel cell systems?

Automation and manufacturing discussion points include:

1. What do you consider the benefits or limitations for the manufacture of fuel cell systems or components of vertical integration of the manufacturing process? Because vertical integration of the manufacturing process eliminates the "markup" associated with using a supplier network for components, it is argued that the savings from vertical integration offset the capital expenditure cost associated with establishing a vertically integrated production facility. Does a vertically integrated manufacturing process receive a greater benefit from automation than a manufacturing system built around a supplier network? Please describe your level of vertical integration for the components, subsystems, or systems you manufacture.
2. How are specifications and quality control addressed when working with a supplier—especially when working with MEA components? Is quality control established at the production line or is it achieved through selective sampling of the delivered components, and how does this impact the manufacturing process? How is manufacturing automation impacted by quality control requirements? Are quality control techniques and devices necessary to support the more continuous and/or automated manufacturing processes?
3. Describe the level of automation you presently employ for cell stack, cell components, and fuel cell system assembly. What will be the next automation improvements that will optimize the production rates? As you make improvements to your manufacturing process, do you use internal manufacturing expertise or do you contract with companies that specialize in developing manufacturing processes? If you use a contractor to assist in the development of your manufacturing processes, what level of fuel cell expertise do they bring into the manufacturing? Please identify, if possible, any contractors you have employed that specialize in fuel cell manufacturing.
4. Are major subcomponents such as reformers and power conditioning units obtained through a supplier network, and, if so, from whom? Are they delivered as completed subsystems that are readily "inserted" into the fuel cell system?
5. Is there an approach to continuous manufacture of cell components that will result in a continuous assembly process with stack components going directly to cell stack

assembly? If this is not part of your manufacturing system, what is the primary bottleneck in the continuous manufacture of cell components and their assembly into cell stacks?

6. Describe the levels of automation in the manufacturing processes, if improved in rate, scale, quality, or otherwise, which would most reduce manufacturing cost or increase production volume. What manufacturing process which is currently of the pick and place type would most reduce manufacturing cost or increase production volume if it was transitioned into a continuous process?
7. Please describe the opportunities to significantly reduce manufacturing cost by redesigning MEAs and cell stacks to facilitate automation in their manufacture.
8. At what level of production will cost savings associated with automation start to drive overall cost to the materials cost level? If one assumes a classical cost reduction learning curve, what would be the key production levels of stationary systems for the learning curve?

Appendix B

Contact List

Company/Laboratory	Location	Contacts
FuelCell Energy	Torrington, CT	Mohammad Farooque (Senior VP, DFC Technology), Neil Aiello (VP, MFG), Chris Bentley (Executive VP, Government Operations and Strategic Manufacturing Development), Pinakin Patel (Dir., Special Sys & Research), Carson Payne (Dir., Manufacturing Strategic Planning), and Tom Lucas (Engineering Manager)
UTC Power	South Windsor, CT	James Dayton (Manager, Operations), Steve Nelson (Manager, Cost/Producibility)
Acumentrics	Dedham, MA	Norman Bessette (CTO and Senior VP, Engineering), Jolyon Rawson (Engineering Manager)
Altergy	Folsom, CA	Mickey Oros (Senior VP, Business Development)
ClearEdge Power	Hillsboro, OR	Mike Upp (VP, Marketing), Bill Trivette (Senior VP, Operations), Zakiul Kabir (CTO and Senior VP, Engineering), Jonathan Iddings (Director Manufacturing, Engineering), Tom Prevish (Project Engineering Manager), Robert Billodeau (Manufacturing Engineer)
Versa Power Systems	Calgary, Alberta	Eric Tang (Manager, R&D), Casey Brown (Manufacturing)
Rolls-Royce Fuel Cells	Canton, OH	Dan Birmingham (Dir., Engineering)
Ballard Power Systems	Burnaby, British Columbia	Paul Cass (VP, Operations)