U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competitiveness Analysis

Prepared for:
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**GLWN is a non-profit international wind and renewable energy advisory group and supply chain network whose mission is to increase the domestic content of North America's wind turbines, hydrogen fuel cell stacks 7 vessels, and to localize new business opportunities in the industry. Launched in 2007, GLWN is an initiative of WIRE-Net, the Westside Industrial Retention and Expansion Network, 4855 W. 130th St., Cleveland, OH 44135*

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ABBREVIATIONS

Atm	Atmosphere
AFCC	Automotive Fuel Cell Corporation
AFCS	Automotive Fuel Cell System
APEE	Anreizprogramm Energieeffizienz
BOP	Balance of Plant
BMWi	German Federal Ministry for Economic Affairs and Energy
CBA	Cost Breakdown Analysis
CCM	Catalyst Coated Membrane
CEO	Chief Executive Officer
CF	Carbon Fiber
CEM	Compressor/Expander/Motor
CNG	Compressed Natural Gas
CNGV	Compressed Natural Gas Vehicle
DCF	Discounted Cash Flow
DFMA	Design for Manufacture and Assembly
DOE	U.S. Department of Energy
EERE	Energy, Efficiency, and Renewable Energy
ePTFE	Expanded Polytetrafluoroethylene
FCH 2JU	Fuel Cell and Hydrogen Joint Undertaking
FCTO	Fuel Cell Technologies Office (of the U.S. DOE)
GDL	Gas Diffusion Layer
H_2	Hydrogen
HBOP	Hydrogen Balance of Plant
HDPE	High Density Polyethylene
HRS	Hydrogen Refueling Station
JIT	Just-In-Time
kW	Kilowatt
LRIP	Low Rate Initial Production
METI	(Japanese) Ministry of Economy, Trade and Industry
MNC	Multinational Corporation
MPL	Microporous Layer
MRL	Manufacturing Readiness Level
MSP	Minimum Sustainable Price
OEDC	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PFSA	Perfluorosulfonic acid
PGM	Platinum Group Metal
Pt	Platinum
PVD	Physical Vapor Deposition
QC	Quality Control
R&D	Research and Development

RPS	Renewable Portfolio Standard
SAAR	Seasonally Adjusted Annual Rate
SEC	Security and Exchange Commission
SG&A	Sales, General, and Administrative
SS	Stainless steel
TRL	Technology Readiness Level
UNDP	United Nations Development Programme
VSM	Value Stream Map

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1 Executive Summary

1.1 Introduction and implications

Enabling the hydrogen and fuel cell industry to position itself to take maximum advantage of the anticipated future growth in automotive fuel cells is likely to require actions to support both supply and demand. The U.S. has some significant strengths in specific areas of the supply chain (e.g., membranes and membrane electrode assemblies, and compressed gas storage) but is weak in others. If indigenous demand is not supported then some U.S. companies are likely to supply overseas markets, but will not benefit from a local market and comparatively low economic benefit will result. Conversely, if local demand exists, but there are no local suppliers, then many components may be supplied by organizations either located or headquartered overseas. Supporting both will bring the likelihood of greatest value capture and economic security for the nation.

In order for a competitive industry to emerge from its currently early-market state, several major achievements are required:

- Fuel cell vehicles that compete on cost and performance with extant vehicles;
- Sufficient hydrogen refueling infrastructure to meet customers' needs;
- A robust and profitable supply chain, from materials sourcing and component manufacture through to servicing and recycling.

The focus of this study is on fuel cell vehicles in the light duty sector. Hydrogen infrastructure is not addressed in this report. The competitiveness of fuel cell vehicles is only addressed inasmuch as it can be influenced by the supply chain and the supply chain focus for this effort was focused on a few key components. Even with these constraints, many limitations have been identified, and the potential supporting actions required are complex. These actions fall under three main headings:

- Actions to support demand
- Actions to support manufacturing scale-up
- Actions to support component development

Actions to support demand:

  - A wide range of tools are available, and different countries and regions use different ones depending on local circumstances. Such tools include subsidies – to manufacturers or customers; mandates – for certain types of vehicles or technical performance characteristics; fiscal incentives – which might improve business competitiveness; benefits – such as use of high occupancy lanes or free parking; and many others. If the size of the incentive is suitable then demand can be created, and the incentives can be altered or removed once the demand is stable and self-sustaining. However, this first set of actions regarding policies and incentives is not the primary focus of this report.

Actions to support manufacturing scale-up:

- Actions to facilitate industry efforts to increase manufacturing capacity such as: encouraging large scale projects, regional fuel cell hubs, and encouraging local development. Supporting manufacturing scale-up by freezing the design and optimizing the manufacturing process for all key components; development of a near continuous high-speed process for membrane electrode assembly (MEA) and bipolar plate fabrication; demonstration of a high-speed, high-accuracy, geometry-neutral fuel cell stacking system; demonstration of a low-cost, high-speed, geometry-neutral bipolar plate (BPP) welding system; development of a consortium where investment cost for scale up of manufacturing processes are shared between suppliers and OEMs; formation of product teams, e.g., OEM with BPP and MEA manufacturers for one specific fuel cell system design with a multidiscipline product team utilizing Value Analysis and Design of Experiments tools to optimize designs and reduce cost; investment needed by industry and government to develop manufacturing capabilities for 100,000 fuel cell systems per year.

Actions to support component development:

- Supporting component development through primary conventional research and development such as: development of new, low-cost fibers as alternatives to existing carbon fiber; development of alternative BPP forming techniques that solve the metal thinning limitations of conventional stamping; development of catalysts with superior polarization performance and/or lower cost; laser welding optimization and design of experiments on weld length; trade-off of wet winding versus dry pre-preg and winding speed; enhancing carbon fiber rope strength and winding pattern.

These actions are the result of a comprehensive analysis carried out for the U.S. DOE FCTO. The analysis was commissioned with the purpose of understanding and supporting competitiveness in the context of a nascent automotive fuel cell industry. At the same time, it was important to understand how the fuel cell industry is developing as a whole. As a result, data on fuel cell system and component shipments were gathered, based on available information. These data show that in 2015, 350 MW of fuel cell systems were shipped, considerably more than the 170 MW in 2014, and preliminary data for 2016 suggest that this number has further increased to nearly 500 MW including 280 MW of transport. Unit shipments in transport have risen from 2,900 in 2014, to 5,200 in 2015, and 6,400 in 2016. This trajectory is positive for the industry, though minuscule in global automotive terms.

The first fuel cell vehicles were developed in the 1960s, but only now are OEMs starting to produce cars for lease and purchase by private customers. While much of the focus of development over the past fifty years has been on science and technology, recent efforts have also included manufacturing capability and supply chain development. The automotive companies who were first to market – Hyundai, followed by Toyota and Honda – are also those with the most developed supply chains. Others, including Daimler and to some extent GM, have strong existing or latent relationships with suppliers.

The automotive fuel cell supply chain is however in its infancy. The vehicle technology, though fit for early roll-out of a few thousands of vehicles yearly, is not yet mature enough for conventional automotive single-model mass production of 500,000 and more units per annum. Mass-production techniques and equipment also require further development or scale-up. Only a handful of suppliers exist who could potentially supply each component at the quality and numbers required for a competitive automotive product offering.

The United States does not currently have any automotive manufacturers producing fuel cell cars, and no U.S. automaker has made a firm announcement of when they may commence (although GM has announced plans anticipated approximately in the 2020 time frame and has partnered with Honda on manufacturing fuel cell stacks). Some component suppliers are already active however, supplying manufacturers outside of the U.S. Other manufacturers have capabilities that could be utilized in future supply chains.

In order to better understand possible strategies to support U.S. manufacturers, the U.S. DOE FCTO commissioned this study to examine the existing global supply chain, with its strengths, weaknesses and actors. The team included experts in supply chains, cost, and manufacturing analysis, fuel cell science and technology, and the global fuel cell industry. The study considered many facets of the issue, examining costs and cost structures; existing and required manufacturing capabilities; shipments, trade flows, support, and motivation internationally; supply chain structures and manufacturing layouts. Detailed modeling was supported by data from literature and from 35 telephone and face-to-face interviews, and by site visits and walk-throughs. Developers in the U.S., Japan, China, and Europe were visited for the purpose of information gathering and comparison without attribution.

The detailed focus of the study was on five components of the Automotive Fuel Cell System (AFCS). The catalyst ink and application, membrane, gas diffusion layer (GDL), bipolar plates, and hydrogen storage vessel represent the majority of the cost in a delivered fuel cell system. At both 1k and 100k vehicles per year, these five components represent more than 60% of the cost of both the fuel cell system and on-board H_2 storage system as shown in Figure 1-1. Other important components such as the compressor/expander/motor were investigated in much less depth, while other components unique to electric vehicles such as power conditioning, battery, and electric motor were not considered. The **items** included in “Other” cost shown in Figure 1.1, but not studied: **H_2 storage balance of system** (regulator, valve, tubing, fittings, system controller, and fill port); **fuel cell stack components** (gaskets, end plates, current collectors, compression bands, stack insulation housing, stack assembly, stack conditioning); **fuel cell balance of plant** (CEM & motor controller, H_2 sensors, coolant & air handling components, fuel system components, humidifier, system controller).

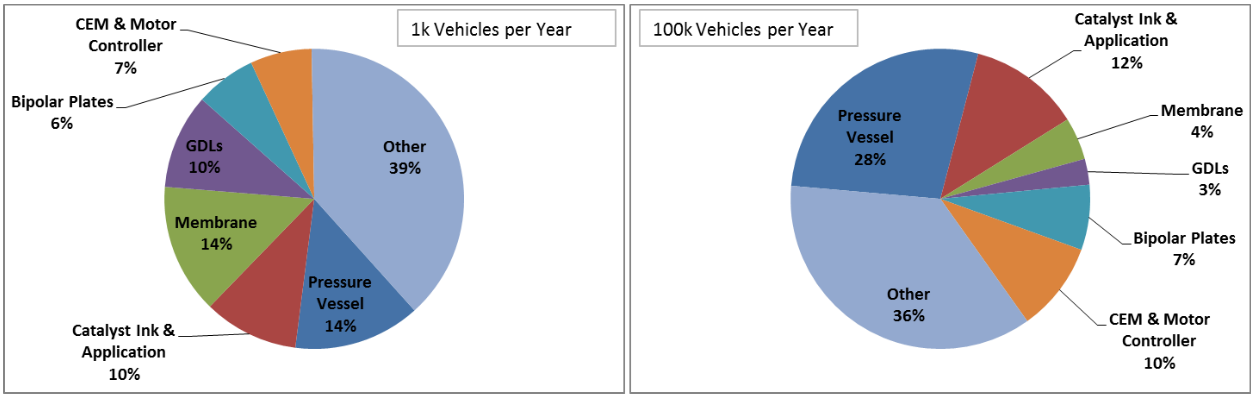

Figure 1-1: Fuel cell system (80 kW_{net}) and 700 bar H_2 (5.6 kg) storage system cost breakdowns at 1k and 100k per year productions rates.

The study clearly shows that the current status of the automotive fuel cell supply chain is far from what will be required in a mature market. Supplier choice is very limited, costs are high, material supplies are not guaranteed, and manufacturing capability is generally inadequate. Support and investment are required globally in order to enable the supply chain to match the status of the existing internal combustion engine equivalent. Some of this will be driven by increased demand, as large companies will invest in developing their own capabilities and in capital equipment. Some would benefit from government intervention, either in direct support for R&D to improve component performance, or in applied research on such things as quality assurance techniques, or in support in purchasing production equipment and scaling up. Support for the demand side is required in parallel to the supply side in order to increase the amount of benefit captured locally.

Globally, although at least 28 suppliers of the different components above were identified, only 18 are considered capable of delivering to automotive manufacturers' requirements. Of those, only 6 are U.S. companies. All OEMs currently source their components from a range of countries, with performance and price more relevant criteria than location. Only Japanese manufacturers obtain almost all components from Japanese suppliers, though European OEMs would also, in principle, be able to focus only on Europe. Inevitably the picture is complicated by the multinational nature of most relevant companies.

Analysis of how supply chains have evolved in the past gives some indication of what may happen in the future, though replacing an existing mature supply chain in a global industry is different from building an entirely new industry. The analysis here, supported by interviews, suggests that initial small-scale supply will be pragmatic, in the sense that OEMs will simply choose the best component for them at the best price. Pre-existing supplier relationships will have some influence, but may not dominate. Production will largely be in batches at existing plants, as the technology continues to evolve and it will be important to monitor it closely. As volumes increase, bespoke production lines will be built, and ultimately these are likely to be located at the OEM's assembly plant so that production can be matched to other lines. Plants local to production may nevertheless be owned and operated by overseas companies, so an MEA plant at a Toyota factory in Japan may come from a company such as, for example, W.L. Gore.

Detailed *Design for Manufacture and Assembly* analysis of component cost, *Value Stream Mapping* of manufacturing techniques and lines, and *Discounted Cash Flow* modeling show small differences in delivered component cost by region, driven by differences in labor, electricity and other prices. However these are within uncertainty margins of each other, and aspects such as local taxation regimes and export duties are likely to play a much bigger role. Both OEMs and suppliers interviewed said that quality and reliability were absolute requirements, and while cost was important, less expensive items which did not meet the first criteria would never be competitive.

Interviewees were in agreement that current technology was fit for its purpose of enabling small production runs of a few thousand FCEVs, but that both technology and manufacturing improvements were required in order to deliver hundreds of thousands. In all cases technology improvement was required, but in some, manufacturing scale-up was understood (e.g., in catalyst), while in most cases, it was considered that manufacturing technology development itself was required. A frequently mentioned issue was that of quality assurance for large-scale high-throughput manufacture. Since the 'representative' automotive fuel cell stack modelled for this study contains around 370 cells, all of which need to be more or less identical with no defects, manufacturing tolerances and quality assessment techniques must be incredibly stringent and accurate. Some processes, such as the manufacture of gas diffusion layers, are currently inherently stochastic and so achieving near-perfection is an extreme challenge. The table below summarizes the modeling and interview data and shows clearly the lack of readiness, both by component and region, for high volume manufacture (100k per year).

Industry Scorecard

	Technology Readiness																				
	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	MOD	MOD	MOD	MOD	LOW	H-M	H-M	H-M	H-M	H-M	H-M	H-M	H-M

	Manufacturing Readiness																				
	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	LOW	M-L	MOD	MOD	LOW	LOW	MOD	M-L	LOW	M-L	M-L	M-L	M-L

Figure 1-2: Industry Component Scorecard

Readiness Legend:

HIGH	Currently sufficient to produce to stated demand
HIGH TO MODERATE	Capability and capacity exist, although no current production demonstrated at stated demand
MODERATE	Requires some advancements or capital investment to produce to stated demand
MODERATE TO LOW	Requires some advancements capital investment, and no current production demonstrated at stated demand
LOW	Requires major advancements or major capital investments to produced to stated demand

The table also sets in context the U.S. position *vis-à-vis* other major world regions. It can be seen that the U.S. ranks slightly lower than Europe and Japan, though above China, in most categories for both small- and large-scale manufacture. Korea is not shown separately but also has strengths, though concentrated around a single OEM, Hyundai-Kia and its suppliers.

Japan and Korea have focused hard on developing their industries, seeing them both as opportunities to continue to export vehicles and to achieve security-of-supply and emissions goals at home. Europe has also supported industry, for the same reasons, with countries such as Germany adding considerable local support to EU-wide measures. China has until recently focused on other areas, such as pure battery vehicles, but is now firmly focused on rolling out fuel cell vehicles and refueling infrastructure, and building a fully indigenous supply chain. History suggests that they will succeed, though it will take several years and at present they are working closely with overseas companies in partnerships and joint ventures as part of their learning process.

Figure 1-3 shows a different summary; that of U.S. competitiveness in manufacturing and innovation in the components studied here in detail. As can be seen, the U.S. potential is broadly moderate to high, though with weaknesses in bipolar plate manufacturing and ionomers in the near term.

	BPP		Membrane		Catalyst		GDL		Vessel	
	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
Manuf. Potential	Forming Low	Forming High	Ionomer Low	Ionomer Mod	Low	Mod-Low	Mod	Mod	Fiber High-Mod	Fiber High-Mod
	Coating Mod-Low	Coating High	Support Mod	Support Mod					Fabricate High	Fabricate High
	Joining Low	Joining High	R2R High-Mod	R2R High-Mod						
Innov. Potential	Forming Low	Forming High	Ionomer High-Mod	Ionomer High-Mod	Mod	Mod	Mod	Mod	Fiber High-Mod	Fiber High-Mod
	Coating Mod	Coating High	Support High	Support High					Fabricate High	Fabricate High
	Joining High	Joining High	R2R High-Mod	R2R High-Mod						

Figure 1-3: Summary of U.S. Competitiveness in Manufacturing and Innovation

Despite the implications of the tables above, the U.S. still has potential to be well positioned. It has great depth in the science and technology of fuel cells, a high quality existing automotive industry and supply chain capability, and California in particular has been a global driver of the fuel cell industry for 2-3 decades. It seems clear that U.S. companies could be competitive in delivering many of the components assessed. But while this may happen without support, if large corporations decide they see a future in supplying overseas OEMs, the benefit to the U.S. will be limited. Smaller companies with good technology will find it hard to develop a competitive position. Ultimately few U.S. companies will participate in the supply chain, and until demand for vehicles starts to pick up in the U.S., manufacturing will be overseas. Supporting local demand is likely to mean that local production plants are built, though some of these will be built by overseas corporations with more competitive technologies. Supporting both local demand and some aspects of supply – for example assisting firms in building high-quality, low-defect lines even while demand is not yet quite large enough to justify them fully – could maximize U.S. participation and benefit.

Two examples illustrate some of the opportunity available. Canada, though it has neither indigenous automotive manufacturers nor high local demand for fuel cells, nevertheless hosts the fuel cell manufacturing plant for the Daimler-Ford-Nissan partnership. This is due to the development of very high local skills and know-how through previous government (and other) support. And China, though currently lagging other regions of the world, strongly believes that it can compete. In other words, the supply chain is still far from locked down, and new entrants can still play a role. This will not be true for long, but the industry is only just beginning, and judicious investment now could reap benefits for many years to come.

1.2 Methodology

In order to build a detailed view of the current state of the supply chain, the project was approached from several angles, subsequently combined to build a more sophisticated overall picture:

- A brief historical perspective was developed on how automotive supply chains have evolved in general, and what implications this may have specifically for the automotive fuel cell supply chain;
- Cost analysis was conducted to identify the components contributing most to the final automotive FC system, to focus the evaluation on the highest value aspects;
- A structured interview process was developed to gather data on the actual status of development of different components, and the views of key stakeholders on what would influence future supply chain structure;
- Interviews and plant visits were conducted to the most important regions to allow visualization and in-depth discussion on relevant development needs;
- Detailed data on the fuel cell industry were gathered, including annual shipment numbers and different regional approaches to supporting industry development, to allow comparisons to be drawn;
- Value stream mapping was applied, to identify the flows within the relevant manufacturing processes

- Learning from each of these parts of the overall investigation was brought together, and implications for the U.S. were drawn out. These implications were used to develop different possible approaches to increase both U.S. participation in the emerging supply chain, and the value derived from it.

1.2.1 Technical Approach

Each of the components of the study described above was designed to allow an overall supply chain picture to be developed. They are described below in more detail.

Supply Chain Evolution

Historical context was used to guide the potential future evolution of the automotive fuel cell supply chain. Previous supply chain evolutions were considered and set alongside the state of the fuel cell chain. Data collection took several forms:

1. Primary Data Collection: interviews with OEMs and companies active in the automotive supply chain were carried out using a Questionnaire developed by the project team, discussed below.
2. Secondary Data Collection: a literature study of the development of the existing automotive supply chain was conducted;
3. A literature review of the U.S. sales of fuel cell vehicles and data collection from manufacturers was used to hypothesize production rates of fuel cell vehicles.

These data established the basis for the anticipated development and evolution of the automotive fuel cell system supply chain. Understanding that the light duty fuel cell vehicle was in a very early development stage of the Product-Life-Cycle, the evolution of the fuel cell automotive supply chain was assumed to evolve in manner consistent with the 100-year evolution of the internal combustion engine automotive supply chain. The pace was considered to be much accelerated since the evolutionary result could be anticipated to be consistent with the very sophisticated existing automotive supply chain within a much shorter period.

A **Questionnaire** was developed to understand the global hydrogen and fuel cell manufacturing supply chain landscape and elicit insight from OEMs and manufacturers about how supply chains will be structured as the fuel cell market reaches maturity. It was used in the identification of technical and manufacturing barriers and key drivers of competitiveness in the US, Asia, and Europe. The questionnaire was structured to share the current DOE thinking on both the process and cost models at 4 volume levels chosen to approximately represent different stages of industry evolution (1,000 – 10,000 – 100,000 – 500,000 vehicles per year). Seven OEMs and twenty-eight suppliers were asked whether the numbers were aligned with their own thinking, or how big the differences were.

Supplier Identification: The list of suppliers interviewed was generated by the project team from noted HFC industry suppliers, participants in prior DOE studies, and suppliers recommended by active OEMs. The active top 2 or 3 global suppliers in each of the 3 regions were identified for the 5 major components (bipolar plates, membrane, gas diffusion layer, catalyst ink, and pressure vessels). Table 1-1 shows the suppliers visited or interviewed in depth by the team.

Table 1-1: Automotive-capable suppliers globally

COMPONENT	U.S.	Asia	Europe
Bipolar Plates	2	2	2
Membrane	1	2	1
Gas Diffusion Layer	1*	1	2
Catalyst Ink	1*	1	2
Pressure Vessels	1	1	1

*Data gathered in interview process

Standardized component specifications and detailed drawings were developed with knowledge from Strategic Analysis, GLWN, and industry knowledge. Suppliers were invited to submit cost quotations based on these drawings to enable an apples-to-apples comparison between global manufacturers active in the industry, but with non-proprietary designs.

Plant Visits: GLWN, E4tech, and SA visited and collected **manufacturing cost and process data** from 20 suppliers in the U.S., Europe, and Asia for bipolar plates, membrane, gas diffusion layer, catalyst ink, and high pressure hydrogen storage vessels. Analysis tools: DFMA, CBA and VSM (described below) were used to understand the cost and manufacturing process.

Design for Manufacture and Assembly (DFMA) is a process-based, ground up, engineering model used to estimate the manufacturing cost of a component. Assumptions used in the DFMA® model are based on conventional North American automotive operations and are used to estimate the cost of producing a component for a new manufacturing line installed in an existing facility [1]. The analysis reported here differs from the approach in Reference [1] in that facilities costs were included, since developed land cost is expected to be one potentially significant regional cost difference. By convention, Strategic Analysis excludes business expenses (sometimes called Sales, General & Administrative (SG&A) expenses) when modeling cost using DFMA®, since the purpose of DFMA® is to estimate the impact of technology choices on system cost. Outputs from the DFMA® models provide estimates of capital equipment costs, tooling, materials, electricity and natural gas usage, and labor requirements broken down by each process step. Moreover, these parameters are appropriately sized to correspond to each target production volume.

Cost Breakdown Analysis (CBA) is a means of understanding the quoted cost in cost accounting categories. A cost breakdown analysis form was developed for each of the five key components. It included a complete bill of materials with net weights, general process steps for labor and burden (overhead), categories of SGA (sales, general & administrative) costs, engineering, and profit. Most suppliers were understandably protective and would only share general information. Based upon the general cost information, a derived cost was developed through the DFMA.

Value Stream Mapping (VSM) is used to characterize both information and material flow from the point of getting a customer order at the manufacturing plant, through the orders forwarded by the manufacturing plant to the material suppliers, the material being received at the manufacturing plant and processed through the system, to the final product ready to be shipped to the customer. VS Maps were generated for each manufacturer from data gathered during the plant visit and from prior knowledge. This enabled the identification of areas of waste (value added and non-value added) and improvement opportunities for domestic suppliers taking into consideration the situation of global suppliers.

It must be considered in this study, as in any commercial quotation activity, that some suppliers will be aggressive with quoted prices while others will be conservative. Where multiple cost input was received, it was found that the cost data were generally consistent, giving some confidence in the aggregated numbers presented here.

1.3 Major Project Themes and Findings

The status of manufacturing and the emerging supply chain can be considered from different perspectives. While it is clear that the majority of the industry is ready – and many companies are in fact manufacturing – at the several thousand per annum level, very few areas of the supply chain are ready for full mass production.

Regional market development trends and any potential impact on manufacturing scale up
Asia is leading in the automotive fuel cell space by some margin, though some components or materials are supplied from Europe and the U.S. National support in Asia is strong and covers both fuel cell system deployments and market development.

Japan
National support for a wide range of fuel cell markets has enabled suppliers to develop manufacturing knowledge and capability. OEMs have invested heavily alongside this –Toyota, Honda, and even Nissan in the automotive space, and companies like Panasonic and Toshiba in stationary fuel cells. Serial production of auto fuel cell systems is being demonstrated by Toyota (Mirai) and to some extent Honda (Clarity; a nascent supply chain exists to support them.) Supply chains for stationary systems are also further developed than elsewhere. Major Japanese component suppliers are making incremental steps in line with automotive company development timelines. They are reluctant to invest in major manufacturing capability until the market reaches ~10k-100k vehicles per year (depending on the component).

China
Support in the form of subsidies at the national and provincial level is focused on applications relevant to China's national goals of reducing GHG emissions and air pollution, but also where China could develop high value manufacturing and an indigenous supply chain. Primary markets include buses. Subsidies help to make FC buses cost competitive with ICE buses, and are combined with mandates to reduce the number of ICE buses. HFC component suppliers are developing design and manufacturing experience with components on FC buses as well as fulfilling design requests for car OEMs. While Chinese fuel cell suppliers have relatively immature technical and manufacturing capabilities, it is plausible to assume that a growing domestic market will stimulate Chinese manufacturing capability and position them to supply a future global market. However, Chinese stack, membrane, and bipolar plate manufacturers are currently near capacity. Meanwhile Chinese suppliers are attending the U.S. DOE HFC Annual Merit Review and asking for technology support from U.S. National Labs.

While many of the international automotive OEMs are developing their own stacks, Chinese OEMs (SAIC, Great Wall, and others) and a large number of regional bus manufacturers) are unique in that they outsource stack development and manufacturing. In a future supply chain, stacks could be manufactured in China and shipped to regionally located vehicle assembly plants.

Europe
Suppliers enjoy less national support for market development than their Asian counterparts (though Germany has some strong support programs), but substantial efforts are being made to address technological and cost barriers. In most cases developers have access both to national funding and to broader European programs. Strong German tier 1 suppliers in particular are building on current products and processes, such as engine gaskets, to develop fuel cell products. German fueling infrastructure developments are the most advanced in Europe.

United States

The U.S. market has support both from federal and state programs. California is strongly behind both automotive and stationary fuel cells, and rollout of fueling infrastructure is supporting a nascent fuel cell market in the state. Some other regions have fuel cell bus demonstrations and small fueling demonstrations. While the supply chain is of interest, there is little or no 'demand pull' from U.S.-based manufacturing, and so there is limited investment apart from some of the larger corporations.

1.4 Global Competitiveness Analysis of Five Key Components

The five components chosen for detailed evaluation represent the major cost contributors to the stack and to the onboard H_2 storage system. For some components, the manufacturing adds a significant proportion of the total cost, while for others the materials are inherently expensive or the scrap rates are very high. Achieving future manufacturing cost targets will require both technological innovation and manufacturing improvement. To assess the status and requirements of these components a 'mature' manufacturing system is assumed, producing hundreds of thousands of stacks per year. The focus below is on cost and performance, but a wider indicator of competitiveness is the very few companies currently able to offer a component to the market.

Bipolar Plates

Bipolar plates contribute 23% of the stack cost at a production rate of 100,000 vehicles per year (7% of the combined fuel cell system and hydrogen storage system cost) and are the second largest cost contributor. 50% of this cost is burden, with equipment and tooling 65% of the burden cost. Stamping, handling and assembly of the thin bipolar plates is a significant challenge, and welding is a process bottleneck. The latter can be addressed in part through engineering solutions via multiple welding beams and progressive welding stations.

Catalyst

Catalyst is the largest cost contributor, at 40% of the stack at 100,000 vehicles per year (12% of the combined fuel cell system and hydrogen storage system cost), of which 91% is material. Precious metal (predominantly Pt) catalysts will dominate for the foreseeable future, given the stringent requirements for durability and performance. Much focus is on Pt reduction, to 7-9 g Pt per system. High barriers exist to entry into the catalyst business, including the requirement to handle and guarantee the security of large quantities of precious metal, and only 3-4 global catalyst companies are viewed as suitable reliable suppliers for OEM long term relationships. Developing and scaling up catalyst formulations requires long development cycles, high overhead, much IP and considerable know-how.

Membrane

Membrane is the third largest cost contributor in a fuel cell stack at 15% at 100k vehicles per year (4% of the combined fuel cell system and hydrogen storage system cost), and 74% of this is the material. Not all membrane suppliers are at the same technology level, therefore the price remains high until you have multiple comparable competitors. Future designs are generally envisioned as thin (7-10 micron) ePTFE-supported membranes to achieve a balance between strength and performance.

Gas Diffusion Layer

Although the Gas Diffusion Layer is the fourth largest cost contributor in a fuel cell stack at only 9% at 100,000 vehicles per year (3% of the combined fuel cell system and hydrogen storage system cost), it is a complex piece of engineering. In this case the burden is at 47% of the total cost, and of that 50% comes from equipment payments. The fragility of the supply chain is highlighted again, as only around 3 suppliers worldwide are currently capable of supplying GDL to automotive requirements. Complex processing knowledge is held as trade secrets, so barriers to market entry are high.

H_2 Pressure Vessel

The 700 bar H_2 storage vessel contributes 68% of the total storage system cost (or 28% of the combined storage system and fuel cell system cost). The material cost contributes 73% of the total, and the majority of that is carbon fiber. Five to six suppliers exist globally with lower tensile strength carbon fiber products, but few companies can supply the high strength fiber required for pressure vessels. Winding is a further major cost contributor, partly because scaling up requires multiple machines, even with process utilization efficiency 90%+ at many manufacturers.

1.5 Total Fuel Cell cost by Region

The key risks to U.S. competitiveness are from foreign sourced fuel cell stacks and hydrogen storage vessels. A simplified analysis of the fuel cell stack suggests that indigenous regional factors such as low cost labor, electricity, land cost, and local inflation are not expected to dominate. Instead, this simplified analysis, which relied on marginal corporate tax rates rather than effective tax rates, suggested that these factors will determine regional competitiveness at low volume production (10k vehicles per year), but will have negligible impact at high volume (100k vehicles per year).

1.6 Supply Chain Evolution

Historically the automotive internal combustion engine supply chain evolved from a vertical supply chain with a majority, if not all, of the component development and assembly conducted by the automotive OEM. As the automotive design became more complex and the number of components increased dramatically, the OEMs transferred manufacturing responsibility for specific components to suppliers with the development of Tier 1 suppliers. As a result, the supply chain evolved from the original vertical configuration to a more horizontal configuration. The ever-increasing transition to a horizontally configured supply chain resulted in the transfer of additional manufacturing and design responsibility to the suppliers. The analysis of the fuel cell supply chain evolution builds on this historical context and foresees the transition from a highly vertical fuel cell supply chain in the current, early development stage of the fuel cell vehicle Product-Life-Cycle to a horizontal fuel cell supply chain at the future maturity stage of the fuel cell vehicle Product-Life-Cycle.

1.7 General Observations, Conclusions, and Options to Improve U.S. Fuel Cell Competitiveness

The automotive fuel cell supply chain is very early in its evolution. In a mature end-game, each OEM would prefer open markets to help drive down prices, with multiple capable suppliers for each component. In principle, each OEM will require at least 2 interchangeable suppliers. In the early stages of market development, reliability of components and of supply is more important than price, and suppliers will typically quote higher prices than cost modeling suggests. This reflects the lack of competition, but also the risk taken by a supplier who may not have a mature process or a fully utilized line. In a typical mature automotive situation, the OEM (or OEM partnership) will have a very close relationship with at least two suppliers, so competition is very high and prices are essentially transparent.

Future supply chains will be much more driven by cost, with reliability and performance assumed to be fully proven. In this case, the development of the industry will be strongly focused on reducing cost while maintaining performance, and all promising avenues will be considered. Future supply chains are also likely to be similar to those that currently exist in the automotive industry. These are complex and heavily interdependent, and typically consist of many tiers (1, 2, 3 etc.) to reduce the number of direct relationships the OEM has to handle. Suppliers are treated differently depending on how much they bring to the relationship – a company making screws will not have the OEM access of one making complex engine management systems.

For the components considered here, neither labor cost nor shipping cost are dominant considerations. Performance, final price, and in-house know-how are stronger contributors. That said, the very high number of repeat parts (300-400 identical cells in every stack) has several implications. The handling of large numbers of discrete parts is cumbersome and will be delayed as long as possible (components will be kept and shipped in roll form as long as possible). The likelihood is therefore that parts will be discretized at the same site as stack assembly, which will probably also be next to (or very close to) the automotive assembly site. This leads to the likelihood of the high volume fuel cell supply chain mimicking the current ICE automotive supply chain: North American FC production for the North American FC market, Asia production for the Asian market, European production for the European market.

Historically, manufacturers found it to be profitable to outsource so the suppliers could deal with the complexity of specialized components and achieve economies of scale. Suppliers had technological expertise, lower labor costs, and often more efficient work rules and labor practices. This is likely to be true also for fuel cells, as few OEMs aspire to be experts in electrochemistry or roll-good production. Other considerations include the preference for collaboration in development, or within alliances (GM/Honda, Toyota/BMW, Daimler/Ford/Renault-Nissan). This spreads cost and risk and pools demand for components and systems, reducing cost to each company, as the demand pooling brings both buying power for the OEM and higher utilization for the supplier's machinery. It suggests that ultimately groups of OEMs and groups of suppliers will exist, much as today.

The United States possesses strengths that could aid it to become a global player in the future automotive fuel cell market. However, no single nation is clearly dominant regarding prospects for the long-term fuel cell market, and in relative terms the U.S.'s strengths and weaknesses are generally slight in comparison to other nations. Consequently, the question is not if the U.S. will (in the long-term) be a significant global competitor (it clearly will be), but rather success or failure will be measured primarily by the rapidity and extent of U.S. participation in the global fuel cell marketplace.

The following U.S. strengths are generally applicable to all five of the key AFCS components.

- **Presence of a high-technology domestic automotive industry**
  - The fuel cell supply chain is expected to build-out in the same manner as the internal combustion engine vehicle (ICEV) supply chain has developed. Consequently, the existence of a domestic precursor auto manufacturing capability is a significant advantage.
- **R&D/Innovation**
  - The U.S. is a leader in (general) innovation: The long history of U.S. innovation, and expectation of continued innovation, will have a beneficial impact to all aspects of the fuel cell supply chain.
  - Superb innovation ecosystem: The U.S. has an excellent innovation ecosystem of collaborative work between large industry, start-ups, National Labs, and universities.
  - Robust research funding at national laboratories and universities which is exploited by the private sector.
- **Infrastructure**
  - While the U.S. physical infrastructure is aging, the U.S. road, rail, and coastal port infrastructure remains one of the best in the world for moving freight.
- **Educated Workforce**
  - Access to an educated workforce is increasingly a critical factor for manufacturing jobs. In general, the U.S. ranks high in this category although regional availability of sufficient employees may be a factor.
- **Reliable and low-cost electricity supply**
  - The U.S. has a comparative advantage in the reliable supply of low-cost electricity. (However, electricity cost is, in general, a low fraction of total fuel cell system cost.)

The U.S. also has some disadvantages compared to other nations.

- **Growth in the Asian automotive and bus fuel cell market will come before growth in the U.S./rest-of-world. Demand will most likely be met by Asian suppliers, who then will use their manufacturing economies of scale to outcompete U.S. suppliers.**
- **Lack of Coordinated Incentives/Facilitation:** Other countries use incentives or mandates to create domestic demand. The U.S. has made no national long-term commitment to fuel cell technology.
- **High-cost labor:** Average U.S. labor costs are significantly higher than in Korea, China, and Mexico. (Labor rates are moderately higher in Germany and U.S. rates are comparable to those in Japan.)
- **High corporate tax rate:** The U.S. currently has one of the highest marginal federal corporate tax rates in the world (35%), potentially posing a burden to manufacturers and making the cost of manufacturing in the U.S. less competitive. (However, we note that the U.S. effective corporate tax

(27.1%) is in-line with the average effective rate (27.7%) from the other 30 OECD[1] countries, potentially diminishing the competitive disadvantage of the U.S. high marginal rate.[2])

- **Increasing R&D investments outside of the U.S.:** There is a trend of U.S.-based manufacturing companies increasing their R&D efforts in Asia to take advantage of favorable R&D incentives and also to be closer to their markets.

Based on the analysis described above, a set of options to increase U.S. competitiveness in the global fuel cell marketplace have been identified. The options are not mutually exclusive, nor are they completely independent of each other. (Further details of the options are discussed in 7.4.)

We note that in the long term (i.e., in a mature AFCS economy governed by a Tier One-Half supply chain), AFCS manufacturing is expected to be located in the U.S. as is currently the case for the analogous production of ICEs and ICEVs. Thus, there will be North American production (for at least some components) and assembly for the North America FCEV marketplace. While this may be the inevitable outcome in the far-term, industry/DOE action to improve U.S. manufacturing capability in the near-term may hasten the process and may deepen the extent to which design of the vehicles occurs in the U.S., and whether U.S. companies own the eventual design/production facilities.

Options include:

- **Actions to Support Demand:** Increasing domestic fuel cell demand is viewed as a critical enabler of domestic fuel cell system production. Some options to accomplish this are:
  - **Increase Demand by Lowering Cost to Consumer:** this may be accomplished through numerous efforts such as direct subsidies, tax credits, etc.
  - **Increase Demand by Guaranteed Purchase Plan:** The government could guarantee to purchase a certain number of vehicles every year so as to stimulate the supply chain.

- **Actions to Support Manufacturing Scale-up:** This addresses the "supply side" by encouraging manufacturers to build domestic production capacity at-scale. Development of volume production is identified as key enabler of low-cost, and low-cost is a key enabler of demand. Some options to accomplish this are:
  - **Go big:** Economies of scale is a potent strategy to reduce cost and dominate market share. Strategies and policy should be encouraged that "Think Big" in contrast to strategies that assume steady, incremental capacity growth starting from a very low baseline. We further conclude that "Going Big" is more important than being first to market.
  - **Encourage Fuel Cell Hubs:** Encouragement of a vibrant community of domestic fuel cell related businesses, co-located and interactive, may have a supply chain impact greater than the sum of its parts.

[1] Organization for Economic Co-operation and Development

- **Encourage local development:** U.S. OEMs and manufacturers need to re-start local development as they have fallen behind Japan and Europe in BPP, membrane, GDL, and catalyst (and are on par in H_2 vessels). Federal, state, or regional efforts, working with manufacturers to address any issues and increase engagement would maintain or improve the U.S. capacity to capitalize on market growth.

- **Actions to Support Component Development**
  - **Invest in R&D:** The U.S. has a robust and exemplary history of innovation, thus encouraging FC-related U.S. R&D will increase the chances of U.S.-based production in the early years.
  - **Component Specific Manufacturing Development Projects:** Manufacturing-related actions to enhance U.S. competitiveness can be taken for specific fuel cell system components. These manufacturing opportunities are divided into two categories: a high priority category representing nearer-term applied research, and a lower priority category representing longer-term basic research.
  - **High Priority Manufacturing Opportunities (generally applied research)**

    MEA
    - Opportunity #1: Development of a (near-)continuous, high-speed process for MEA fabrication
    - Opportunity #2: Development of low-cost methods for gasket application

    Vessels
    - Opportunity #3: Development of high production rate pressure vessel fabrication lines
    - Opportunity #4: Development of new, low-cost fibers as alternatives to carbon fiber

    Bipolar Plates
    - Opportunity #5: Development of (near-)continuous, high-speed process for BPP fabrication
    - Opportunity #6: Program to characterize and assess the problem of thinning of metal in BPP
    - Opportunity #7: Development of alternate forming techniques that solve the metal thinning limitations of conventional stamping.

    Industry standardization of some balance of plant components
    - Opportunity #7: Standardization of the Compressor/Expander/Motor.

    Manufacturing R&D/Demonstrations
    - Opportunity #8: Demonstration of high-speed, high accuracy, geometry-neutral fuel cell stacking system
    - Opportunity #9: Demonstration of low-cost, high-speed, high-accuracy, geometry-neutral BPP welding systems

- **Lower priority manufacturing opportunities: (generally basic research)**

  Catalyst
  - Opportunity #10: Optimize the structure of ultra-thin catalyst layers (e.g., nanostructured thin film (NSTF) with water-management/flooding problems solved)

  Membrane
  - Opportunity #11: Understanding and performance of PFSA membranes is fairly advanced
  - Opportunity #12: Improvements for increased durability
  - Opportunity #13: Improvement for lower cost

2 Background and Introduction

This study was commissioned by the DOE FCTO to investigate in greater detail the current supply chain structure, ways in which the supply chain may evolve, the most important and relevant components in terms of fuel cell system value, fuel cell industry growth and trends, and key influencing factors on future supply chain choices. The purpose of this data gathering was to conduct analysis on the ways in which the supply chain could be supported, with a particular emphasis on positioning U.S. entities, be it companies or research organizations, to take best advantage.

Fuel cells use a fuel to generate electricity directly, and some heat. They can be highly efficient and emit very low or zero pollutants. Used in transport applications, with hydrogen as a fuel, they can offer locally clean mobility, improving air quality and reducing negative health impacts. Hydrogen can be produced from locally abundant resources, giving the opportunity to improve energy security, and can also reduce greenhouse gas emissions.

The global automotive industry is in a period of rapid change. Technology improvements and stringent emissions legislation are leading manufacturers to develop and introduce electrical vehicles much faster than had previously been expected. These electric vehicles operate purely from on-board batteries, from hybridization with internal combustion engines, or with fuel cells.

An automotive fuel cell industry is beginning to emerge following several decades of research, development and demonstration. As cars are introduced into different regions of the world, the manufacturing and supply chain is starting to coalesce around the leading automotive OEMs, for example Hyundai and Toyota. The vehicles – and their components – are produced in small quantities and few if any aspects of the supply chain are optimized.

Government and other plans in Japan, California, parts of Europe, Korea and China call for increasing vehicle roll-out, summing to close to one hundred thousand globally by 2020. Delivery of this number of vehicles will require improvements in technology and manufacturing processes, and greater robustness in the supply chain. U.S. companies currently produce some components for some actors. These may not be produced actually in the U.S. however. Other countries and regions, including Japan and Europe, have greater participation and are positioning themselves for the anticipated growth in the industry.

As the industry develops, labor and equipment will be located in regions providing the right framework conditions. The regions ultimately benefitting from this new industry will be those that have local demand (jobs in sales, servicing, building fueling stations, etc.) and competitive supply (manufacturing jobs and exports). Measures of competitiveness include both cost and high technology capability.

2.1 Technical Approach

In order to build a detailed view of the current state of the supply chain, the project was approached from several angles, subsequently combined to build a sophisticated overall picture:

- A brief historical perspective was developed on how automotive supply chains have evolved in general, and what implications this may have specifically for the automotive fuel cell supply chain;
- Cost analysis was conducted to identify the components contributing most to the final automotive FC system, to focus the evaluation on the highest value aspects;
- A structured interview process was developed to gather data on the actual status of development of different components, and the views of key stakeholders on what would influence future supply chain structure;
- Interviews and plant visits were conducted in the most important regions to allow visualization and in-depth discussion on relevant development needs;
- Detailed data on the fuel cell industry were gathered, including annual shipment numbers and different regional approaches to supporting industry development, to allow comparisons to be drawn;
- Value stream mapping was applied, to identify the flows within the relevant manufacturing processes

Learning from each of these parts of the overall investigation was brought together, and implications for the U.S. were drawn out. These implications were used to develop different possible approaches to increase both U.S. participation in the emerging supply chain, and the value derived from it.

2.2 Fuel Cell Stack and Components Overview

The basic components of a polymer electrolyte membrane (PEM) fuel cell, from the outside in, are the bipolar plates, gas diffusion layers, electrodes (anode and cathode), and polymer electrolyte membrane. This is shown schematically in Figure **2-1**. Fuel cell power density is on the order of 1 W/m^2, and automotive fuel cells have active areas ~250 cm^2, so several cells (~380) are joined together in a stack to generate sufficient power (~80 kW).

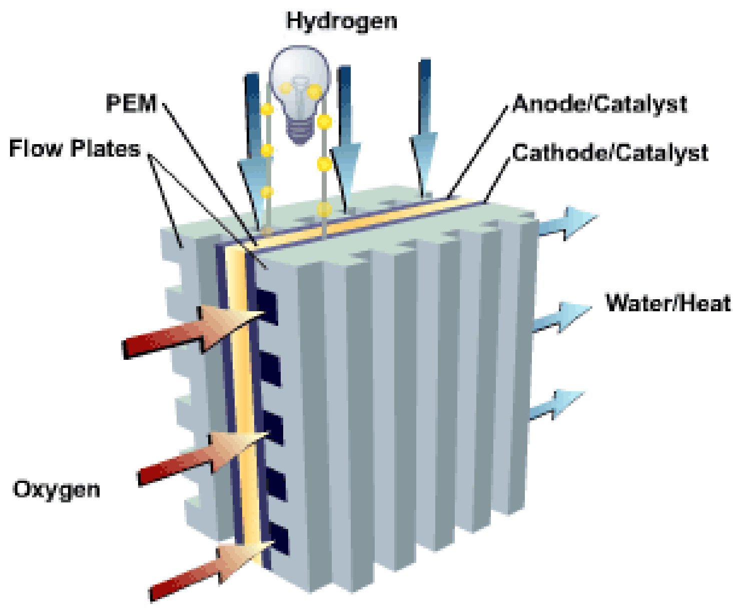

Figure 2-1**: Diagram of a polymer electrolyte membrane (PEM) fuel cell (Source: DOE).**

2.2.1 Bipolar plates

Bipolar plates for light duty automotive applications must be lightweight, durable under potential cycling, and low cost. While non-metallic bipolar plates are considered by some (e.g., carbon composite), metal appears to be the material of choice for automakers. Stainless steel (316L and 304) are used for their relatively low cost and ease of forming, while titanium has been used for its corrosion durability. An anti-corrosion coating is typically applied to 1) prevent passivation layer formation which leads to increased contact resistance and 2) prevent leaching of metal ions (e.g., Fe^{3+}) which can accelerate degradation of the catalyst and membrane layers. Several coating materials have been investigated, including thin and nano-dispersed gold [3], nitride surface modification [4], conducting lacquer films [5], amorphous carbon [6] [7], and conductive oxides [8]. Finally, the bipolar plate of one anode is joined with the bipolar plate of the adjacent cathode to connect cells electrically and to form cooling channels to thermally manage the fuel cell. The two dominant joining approaches are laser welding and adhesive joining.

Progressive die stamping, laser welding, and a proprietary conductive oxide coating developed by TreadStone were assumed in our model. The manufacturing process flow diagram is presented in Figure

2-2. Stamping is the rate controlling step in bipolar plate manufacture, and is assumed to have a 3.5 second cycle time. A single stamping press, therefore, can supply bipolar plates for approximately 12,000 stacks (with 370 cells per stack) per year.

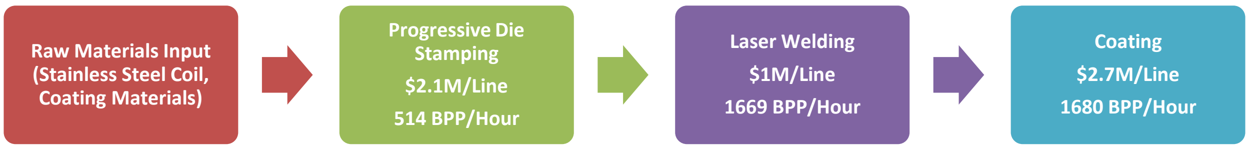

Figure 2-2: Bipolar plate process flow. Production rates refer to welded bipolar plate assemblies with flow fields on the anode and cathode sides and coolant channels between.

2.2.2 Gas Diffusion Layer

The gas diffusion layer for light duty automotive application serves three roles: providing a medium to supply reactants to the electrode, removing product water from the cathode by capillary action, and electrically connecting the electrode to the bipolar plate. Conventional gas diffusion layers are composed of a carbon fiber paper substrate treated with polytetrafluorethylene to control wetting and the paper porosity, and a carbon powder coating to provide electrical connection to the electrode and a high number of triple phase boundaries between at the catalyst interface. A conventional gas diffusion layer was modeled for this analysis as summarized in the manufacturing process flow diagram shown in Figure 2-3. The gas diffusion layer manufacturing process and inputs are based on previous manufacturing studies [9] and updated for low and intermediate volume production [1]. The two heat treatment steps (oxidation and sintering) and papermaking have the largest impact on cost, while the three coating steps are somewhat smaller in magnitude.

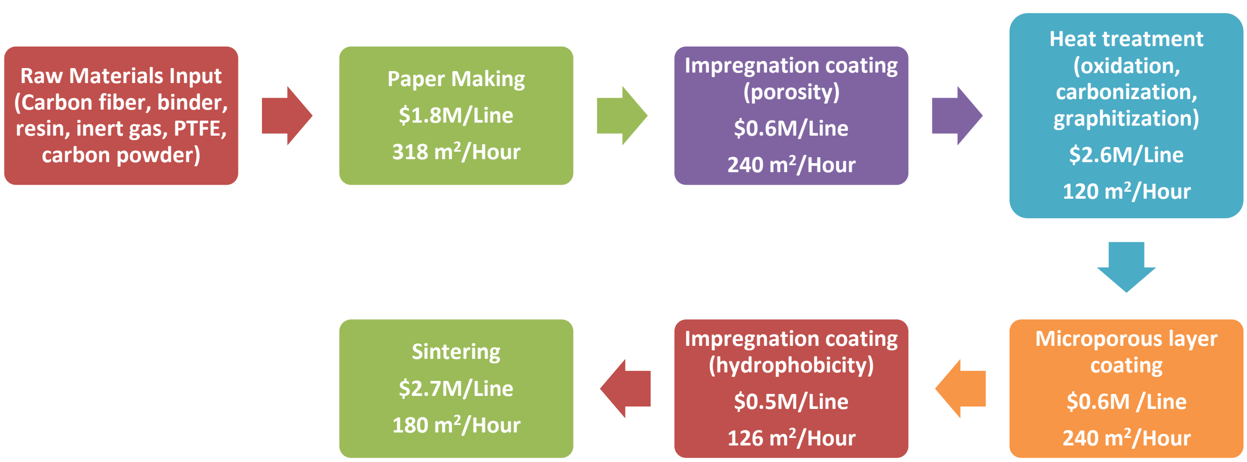

Figure 2-3: Gas diffusion layer manufacturing process.

2.2.3 Catalyst

Catalyst for light duty automotive applications is based on platinum or platinum alloy powder dispersion. Alternative morphologies such as extended thin films (e.g., 3M's nano-structured thin film) have yet to fulfill their promise of very low platinum content for automotive applications. While the anode is typically a conventional platinum on carbon support (Pt/C) with low Pt loadings around 0.05 $mgPt/cm^2$ due to favorable kinetics of hydrogen oxidation and low to negligible catalyst corrosion, the cathode has been the subject of significant research effort due to the much slower oxygen reduction reaction, presence of free radicals generated from byproducts and contaminants, oxygen transport resistance at high power densities. Typical state-of-the-art cathode Pt loading is ~0.12 $mgPt/cm^2$; however, it is worth noting that vehicles on the road today are expected to have much higher Pt loadings (~0.3 mg/cm^2) based on discussions with OEMs during the interview process. A state-of-the-art de-alloyed PtNi cathode catalyst jointly developed by General Motors and Johnson Matthey, under a U.S. Department of Energy award was modeled. The manufacturing process flow diagram is presented in Figure 2-4.

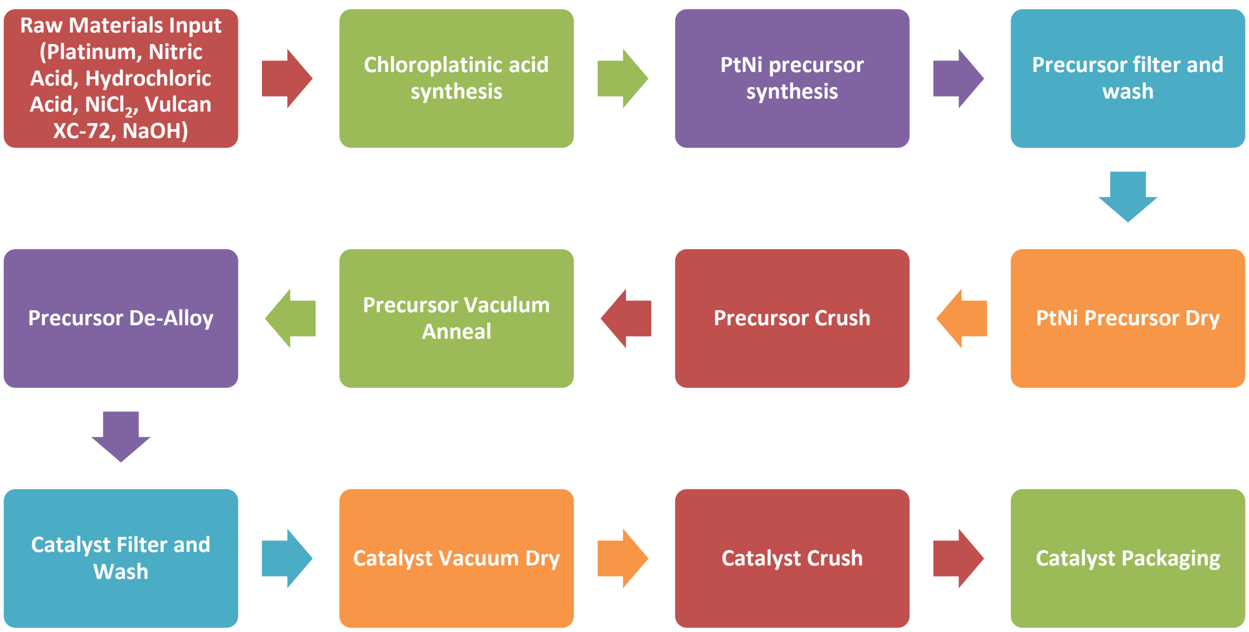

Figure 2-4: De-alloyed PtNi cathode catalyst manufacturing process flow.

2.2.4 Polymer Electrolyte Membrane

The membrane for light duty automotive application allows protons to move from the anode to the cathode while acting as an insulator to electrical current. Conventional membranes are made from a perfluorosulfonic acid (PFSA) ionomer and an inert material that provides mechanical support. Alternative ionomers have been investigated, including hydrocarbons and alternative fluoropolymer formulations; however, PFSA is the only ionomer currently commercially available. The dominant support material is expanded polytetrafluoroethylene (ePTFE). Other support materials investigated that are near commercialization include perforated inert hydrocarbon membranes and electro-spun nanofiber mats. An ePTFE-supported PFSA membrane was modeled for this analysis. The manufacturing process flow diagram is presented Figure 2-5. Note: The five steps in the process flow occur within a single roll-to-roll operation with inline heating steps after each ionomer deposition.

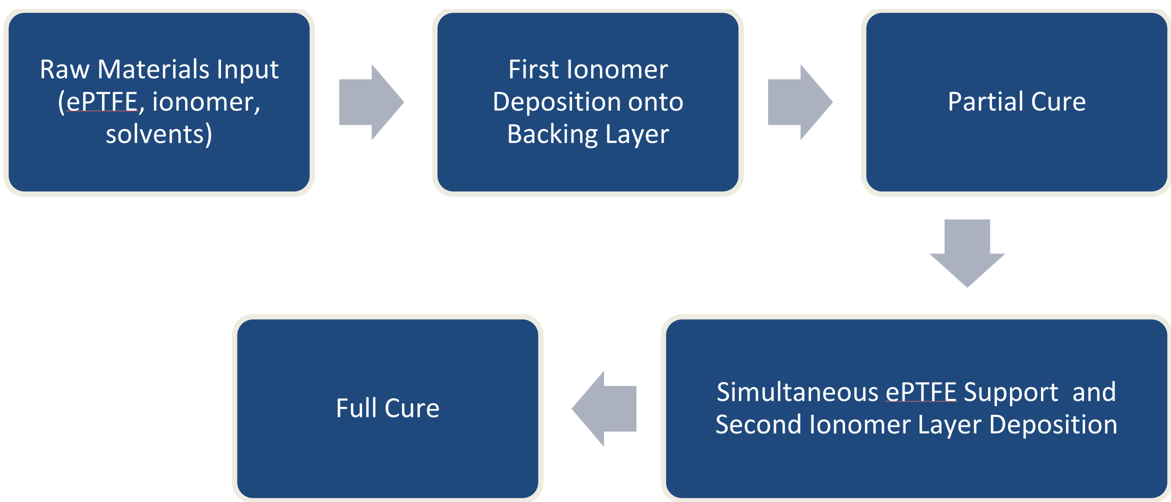

Figure 2-5: Manufacturing process flow for ePTFE-supported PFSA membrane

2.2.5 700 bar Type IV H_2 Pressure Vessel

While a number of on-board storage strategies are being actively explored, 350 and 700 bar compressed hydrogen is used in the current generation of vehicles with a preference for 700 bar. Type IV pressure vessels are made of a polymer (e.g., HDPE - high-density polyethylene or Nylon) permeation barrier with a carbon fiber composite overwrap. Although different pressures are used in operation, hydrogen pressure vessels are manufactured in the same way as CNG pressure vessels. A manufacturing process flow is presented in Figure 2-6.

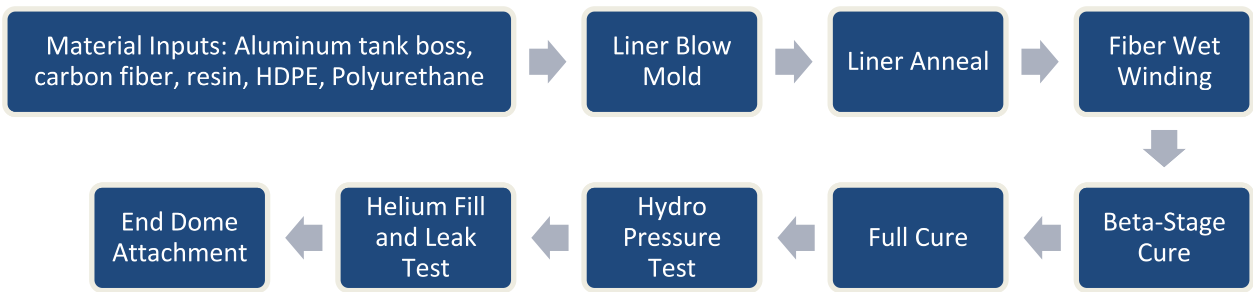

Figure 2-6: H_2 pressure vessel manufacturing process flow.

2.3 Fuel Cell and On-Board Storage Cost for Fuel Cell Electric Vehicles

Figure 2-7 shows the cost breakdown for the hydrogen storage system (pressure vessel and storage balance of plant) and fuel cell system (fuel cell stack and balance of plant). Based on feedback from OEMs and suppliers, the five highest cost key components are shown in Figure 2-7 at multiple production volumes. The key system components consist of the key elements of the stack (bipolar plates, gas diffusion layers, cathode catalyst, and polymer electrolyte membrane) and the 700 bar Type IV pressure vessel (includes the polymer liner, carbon fiber composite overwrap, and tank boss).

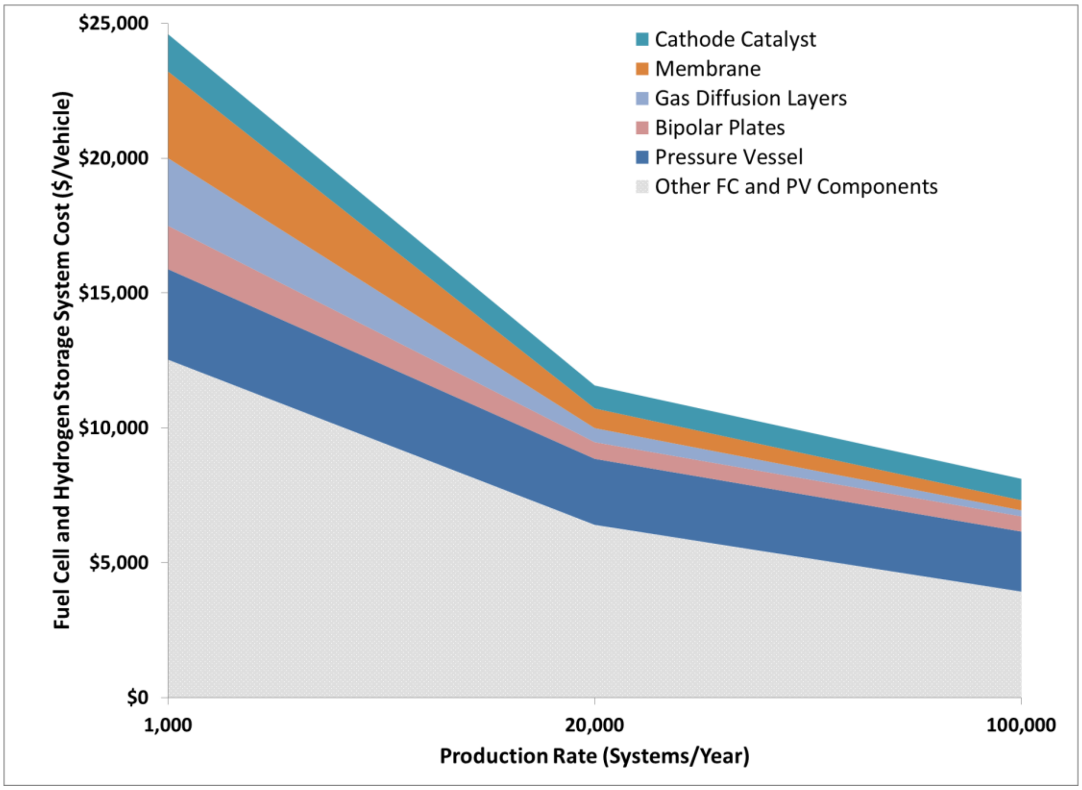

Figure 2-7: Key components cost breakdown at multiple production volumes.

The fuel cell supply chain for automotive applications is in the early stages of development and is controlled by the progress in the development of rugged, economically sound fuel cell system. The AFCS has not achieved a sufficiently high level of technology readiness for investment in large scale manufacturing. Projections for the development of commercial AFCS manufacturing costs have been developed based on FCTO funding. These projections are based on future production rates of 100,000 to 500,000 vehicles per year while the present production levels are less; at 1,000 vehicles per year.[2] The modelled cost projections of James are given in Figure 2-8. Present costs at production rates of less than 10,000 vehicles per year are approximately $300/kW for the fuel cell system and $200/kW for the fuel cell stack.

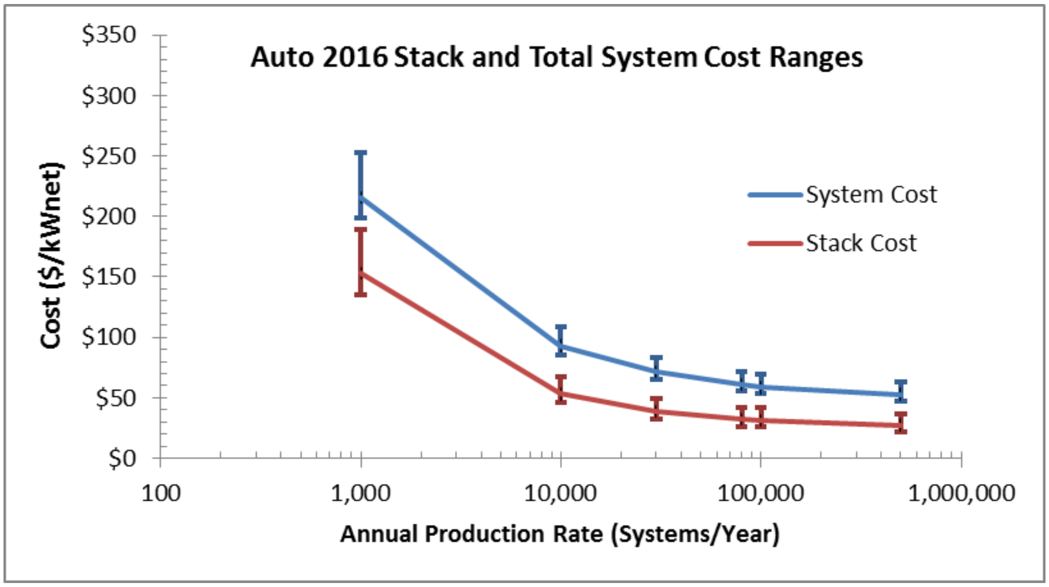

Figure 2-8: Projected Automotive Fuel Cell System and Fuel Cell Stack Costs, after James

At high- commercial rates of production of AFCSs, the projected cost approaches the DOE System 2020 cost target of $40/kW.[3] The 2016 AFCS cost projections by James et al. based on existing manufacturing and materials cost was $53/kW.

With agreement from the FCTO of the DOE, seven major cost components of the AFCS were chosen by the project team. Five of these were considered in the detailed analysis. The seven together represent 64% of the AFCS cost and the 5 studied components represent 54% of the combined fuel cell system and hydrogen storage system cost. The major cost components are given in Table 2-1 where they are segregated by the subsystem of the AFCS: fuel cell stack, hydrogen storage system, and fuel cell balance of plant. Specific cost factors are described in the following sections.

[2] James,B., "2016 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2016

[3] A. Wilson, J. Marcinkoski, and D. Papageorgopoulos "DOE Fuel Cell Technologies Office Record, Record # 160020, September, 2016, https://www.hydrogen.energy.gov/pdfs/16020_fuel_cell_system_cost_2016.pdf

2.4 Major Cost Components

Major cost components segregated by subsystems of the AFCS	
Subsystem	**Cost Component**
FUEL CELL STACK (system)	
MEA	
	Catalyst
	Membrane
	Gas Diffusion Layer
	Bipolar Plates
Hydrogen Storage Vessel	
	Carbon Fiber (CF) composite
	Hydrogen Balance of Plant (HBOP)
Fuel Cell Balance of Plant (BOP)	
	Compressor/Expander/Motor (CEM)

Table 2-1: Major cost components segregated by Subsystems of the AFCS

The following are brief descriptions of the major cost components in Table 2-1. The bold face items are the 5 components selected for detailed evaluation in the study.

2.4.1 Fuel Cell Stack

The *catalyst* cost component has the platinum group metal (PGM)) catalyst dispersed on particulate carbon support. Typically, the catalyst is prepared by a company specializing in fabrication of PGM catalyst because of the high cost of raw materials and complexity of the catalyst preparation and recovery of scrap. The catalyst cost component includes the development of the catalyst ink for coating onto the membrane to fabricate a catalyst coated membrane.

The current *membrane* of choice is Nafion™; a perfluorinated sulfonic acid (PFSA) membrane, although there is on-going research and development of alternative membrane materials. Nafion™ has functionalities of proton and water transfer across the membrane while minimizing the transport of reactants across the membrane. The Nafion™ fuel cell membrane is not a mainstream product for industrial membrane manufacturers. Production volumes of fuel cell membrane are small in comparison to the industrial chemical industry where membranes with similar, but not identical, ion transport properties for use in Chlor-Alkali plants are in large demand. The membrane manufacturers have developed high volume, roll-to-roll fabrication procedures for their industrial products. The production rate of these roll-to-roll processes far exceeds the demand for fuel cell membrane. In addition, the fuel cell membrane is thinner than industrial (Chlor-Alkali) membranes and, while both

Chlor-Alkali and fuel cell membranes are reinforced, the fuel cell membrane's reinforcement is very different than the reinforcement of the commercial Chlor-Alkali membrane.[4, 5] The membrane manufacturers are expected to operate pilot scale facilities for the production of fuel cell quality membrane with the fuel cell membrane delivered to the OEM as cut sheets or as a roll product. Roll-to-roll processing is capable of production rates consistent with the needs of 100,000 to 500,000 AFCSs/year.

Many *catalyst* fabrication companies have a close association with the precious metal mining industry and these precious metal fabricators produce most, if not all, of the fuel cell catalyst. These companies have established protocols that minimize precious metal scrap, in some cases the precious metal fabricators have developed proprietary processes for producing fuel cell-quality catalysts. The OEM specifies the catalyst composition, structure, and quality to the catalyst fabricator. Many of the catalyst producers have established working relationships with light vehicle manufacturers based on catalytic converters currently used with internal combustion engines.

The *gas diffusion layer* is a carbon fiber paper, carbon felt, or a carbon cloth. The GDL has a Microporous Layer (MPL) deposited on one side of the carbon paper/cloth. The MPL enhances the removal of product water from cathode of the fuel cell while facilitating the transport of oxygen-carrying reactant to the cathode. The production process is roll-to-roll processing with the thin MPL a mixture of carbon/Teflon™. Manufacture of the GDL by roll-to-roll processing is consistent with the production rates for 100,000 to 500,000 AFCSs/year.

The combination of GDLs, catalyst, and membrane make up the membrane electrode assembly, which is the major component in the fuel cell for producing power.

The *bipolar plate* in the analysis by James et al.[6] is stainless steel with a titanium oxide coating containing gold islands that was developed by TreadStone Technologies Inc. The purpose of the gold islands is to maintain electronic conductivity between the stainless steel bipolar plate and the MEA, while the titanium oxide provides corrosion protection for the stainless steel bipolar plate. An alternative to coating gold-containing titanium oxide is a carbon coating deposited by carbon vapor deposition, typically, onto titanium substrates rather than stainless steel plates. The carbon coating provides electronic conductivity between the titanium bipolar plate and the MEA. The in situ formation of titanium oxide on the titanium bipolar plate provides corrosion protection.

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[4] Kolde, J., Bahar, B., Wilson, M., Zawodzinski, T., and Gottesfeld, S., "Advance Composite Polymer Electrolyte Fuel Cell Membranes", published in *Proceedings of the First International Symposium on Proton Conducting Membrane Fuel Cells I,* Electrochemical Proceedings, /Vol. 95-23, p. 193-201, 1995

[5] US8795923 B2, "Reinforced electrolyte membrane for fuel cell, fuel cell membrane electrode assembly, and solid polymer electrolyte fuel cell comprising the fuel cell membrane electrode assembly", Assignee Toyotal Jidosha Kabushiki Kaisha, W.L. Gore & Associates Co. Ltd.

[6] Ibid, ref 14

The *bipolar plate* has flow fields that distribute the reactants to the MEA. The center of the bipolar plate is a cooling chamber through which coolant flows to maintain temperature control of the fuel cell stack. Manufacturing methods for preparing bipolar plates includes: stamping, embossing, and hydroforming. The analysis by James[7] used high-rate stamping. Two plates are prepared by any the above manufacturing methods and bonded together to form a bipolar plate using either welding[8] technology or using an adhesive. The manufacture of bipolar plates by stamping is considered to be time consuming and costly. The welding processing speeds need to be improved.

2.4.2 Hydrogen Storage System

The two major cost components of the hydrogen storage system are the *carbon fiber composite* and the *Hydrogen Balance of Plant (HBOP)*. The outer tank of the hydrogen storage system is made from a high strength carbon fiber composite able to withstand 2.25 safety factor over the 700 bar nominal hydrogen pressure. Such fiber, for example Toray's T700S, is in high demand for military[9] and aircraft applications. The high demand keeps the cost of the carbon fiber composite for the hydrogen storage system high. The winding of the carbon fiber composite to form the hydrogen storage tank is time consuming and may limit production rates. The *HBOP* includes the valves, pressure regulators, and an integrated in-tank valve with temperature transducers, filters, flow valves, and solenoid valve.[10] Many of the components in the HBOP are designed for very high pressure storage (700 bar) operation adding to the cost for these components.

2.4.3 Balance of Plant

The *fuel cell balance of plant (BOP)* contains the compressor/expander/motor (CEM) as a major cost component. The CEM delivers pressurized air to the fuel cell stack (typically 2-2.5 atm, though some OEMs use lower pressures and hence different types of air handling machinery). Requirements of the CEM include high efficiency of the compressor/expander and high efficiency of the electric motor and motor controller both of which contribute to the overall cost of the BOP.

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[7] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

[8] Ream, S., "Fiber Laser Welding for Fuel Cells and Batteries", Fraunhofer 5th International Workshop on Fiber Lasers

[9] Committee on Benchmarking the Technology and Application of Lightweighting, National Materials and Manufacturing Board, Division on Engineering and Physical Sciences, National Research Council, "Application of Lightweighting Technology to Military Vehicles, Vessels, and Aircraft", National Academies Press, Apr 10, 2012-Technology & Engineering", p. 66. https://books.google.com/books?id=3ZGURCWUWSoC&pg=PA66&dq=t700s+carbon+fiber+in+aircraft&hl=en&sa=X&ved=0ahUKEwjSlJi3hO7KAhXM7yYKHb-vAvwQ6AEILzAA#v=onepage&q=t700s%20carbon%20fiber%20in%20aircraft&f=false

[10] James, B., Moton, J., and Colella, W., "Hydrogen Storage Cost Analysis", Strategic Analysis, Inc. presented at U.S. Department of Energy's (DOE's) 2013 Annual Merit Review and Peer Evaluation Meeting (AMR) for the Hydrogen and Fuel Cell Technologies (FCT) Program, Arlington, Virginia, May 14th, 2013.

The Strategic Analysis cost breakdown of these major components, for production rates of 1,000 to 100,000 AFCSs per year found in Figure 2-9. The data in Figure 2-9 show a decrease in the cost for fuel cell stack components per system from approximately $7,680 at 1,000 systems per year to approximately $1,750 at 100,000 systems per year.

The decrease in the HBOP cost was approximately $5,520 at 1,000 systems per year to approximately $2,100 at 100,000 systems per year, a drop of $3,400 per system. The carbon fiber composite cost remains relatively constant for the production span of 1,000 units/year to 100,000 units/year.

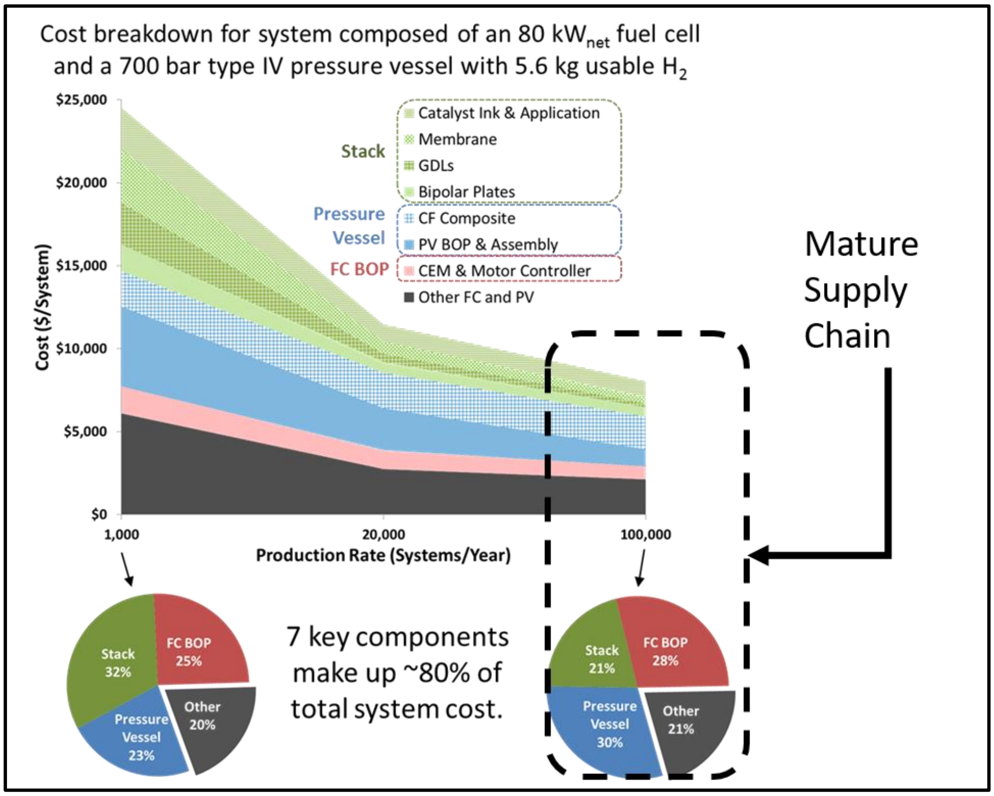

Figure 2-9: Cost analysis of major components of AFCS evaluated in this study.

The mature supply chain region of the Figure 2-9 cost analysis is identified by the dotted rectangle with the percentages of the cost identified by the Pie Chart inside of the rectangle. The mature supply chain region is consistent with moving toward the 2020 DOE $40/unit target at production rates of 500,000 units/year.[11]

[11] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

3 Global Fuel Cell Trade-Flows

3.1 Total shipments by application

The shipment data collected is aggregated to three main application types: Portable, Stationary, and Transport. Portable fuel cells are those designed to be moved, including auxiliary power units (APU); Stationary power fuel cells are units designed to provide power to a fixed location; Transport fuel cells provide either primary propulsion or range-extending capability for vehicles. Total shipments of fuel cell units by number and power in 2015 have topped those of 2014, but perhaps more interestingly, the composition of the total has begun to change. While portable shipments in 2015 are lower than in 2014 and stationary fuel cell units higher, transport numbers have almost doubled by 2015. This change is revealed in even starker terms when expressed by MW: as always portable units barely register; the power capacity of stationary units is higher than in 2014; but transport, with more than 1,000 fuel cell cars hitting the road in 2015, has more than tripled.

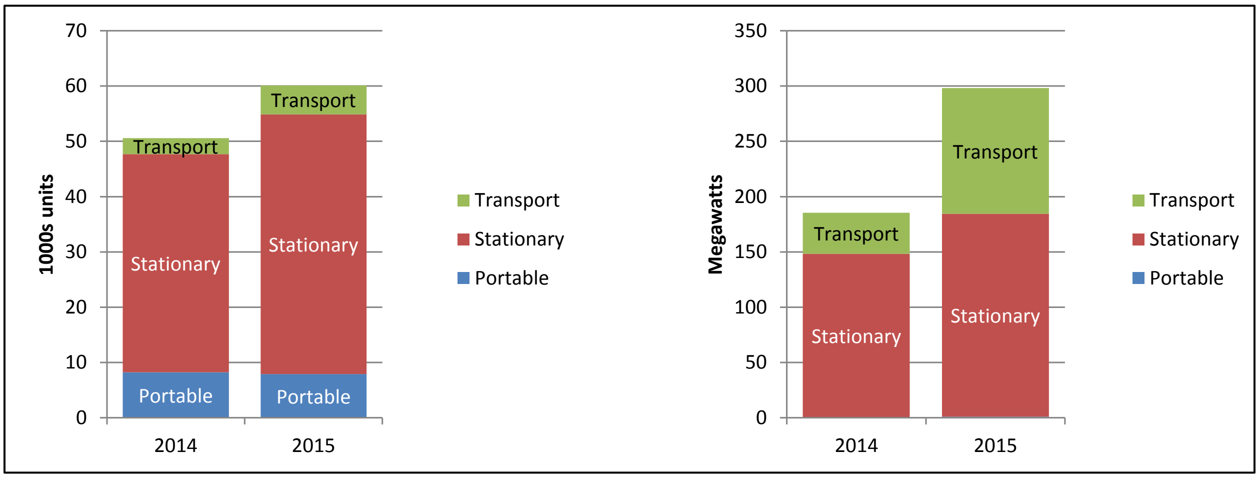

Figure 3-1: Fuel cell shipments by application, 2014-2015

Table 3-1: Fuel cell shipments by application, 2014-2015

Shipments by application (1000s units)	2014	2015	Megawatts by application	2014	2015
Portable	8.2	7.9	Portable	0.4	0.9
Stationary	39.5	47.0	Stationary	147.8	183.6
Transport	2.9	5.2	Transport	37.2	113.6
Total	**50.6**	**60.2**	**Total**	**185.4**	**298.1**

3.1.1 Transport applications

Fuel cells for transport are dominated by Toyota and Hyundai, while at the same time fuel cell range extenders for light goods vehicles, exemplified by the products of Symbio FCell of France, have further added to the unit numbers and MW figures in 2014 and 2015.

Mass transit applications of fuel cells are also increasing, as witnessed by Ballard's (Canada) shipments of modules to China where dedicated support schemes are now reported to be in place. Even though they do not figure in the 2015 total, announcements of fuel cells for trains in Germany, and trams in China will strengthen mass transit applications in the coming years.

Materials handling applications have dominated the transport sector for a number of years. U.S. based Plug Power, using Ballard modules clearly is leading here with nearly 4,000 new units deployed in 2015. Other players are also apparent in this sector with vehicles being demonstrated at airports and other locations, and Hyster-Yale's Nuvera purchase suggests some interesting competition ahead.

The diversity of applications in the transport sector includes fuel cells for unmanned aerial vehicles (drones) and other unmanned military vehicles, which although sometimes high profile, are estimated low in terms of numbers and power.

3.1.2 Stationary applications

Stationary fuel cell shipments fall mainly into the three well-worn categories evident in past years: back-up or off-grid power for telecoms equipment, fuel cells for micro-CHP, and larger CHP or power-only systems of hundreds of kW to MW electrical output.

Shipments of small systems - around the 1 to 5 kW size - for back-up and off-grid applications continue to be the main deployments into the more exotic markets around the world, including India, South East Asia, China, the Middle East and Africa, but also in Europe and North America. Established fuel cell players in North America and Europe, as well as from Asia, are targeting these markets. However, this segment only accounts for a small amount of total MW.

Micro-CHP fuel cell shipments dominate unit numbers in the stationary sector. The Ene-Farm program in Japan provides the market for Panasonic, Toshiba and Aisin, and together these three continue to grow their output in 2015, reaching around 40 thousand units on an annual basis. Elsewhere, numbers of micro-CHP units are much smaller, and most of those are in Europe where the Ene.Field program benefits the likes of BDR Thermea, Vaillant, SolidPower, Bosch, and Elcore. Collectively Europe's shipments in this field are higher than in 2014, despite CFCL's 2015 demise - though shipments of their BlueGen units are reported to be resuming following SOLIDpower's acquisition of certain CFCL assets. A residential fuel cell support scheme launched in Germany during 2016 has the means to lift European deployment (and production) in this segment in the future.

Large scale stationary fuel cells of the 100 kW to MW scale, dominate the sector in terms of capacity shipped. FuelCell Energy, shipping MCFCs with its Korean partner POSCO Energy; Bloom Energy with its SOFC units, and Doosan's PAFC units; collectively shipped more in 2015 than ever before. The primary destination of these fuel cells is Korea, and to a lesser extent the U.S., still Bloom Energy's core market.

3.1.3 Portable applications

Shipments of portable units run into the thousands, but their total power output is small. Chargers of 5 W unsurprisingly contribute little to the MW total. Suppliers include Horizon, which has been working on the Brunton Hydrogen Reactor in the U.S., and MyFC, which has launched their JAQ recharger at the end of 2015 after phasing out the PowerTrekk line earlier that year. More significant are the 50 to 100 W auxiliary power units used for leisure purposes, and those for off-grid applications such as construction sites, for sensors in transport, and oil and gas infrastructures - seen as a growth area. Lastly there are military applications, including those with power outputs of 50 W to several hundreds of Watts.

3.2 Shipments by application and key countries

The total shipments in the transport sector where nearly 3,000 units in 2014 and a bit above 5,000 units in 2015. The major contributors are fuel cell lift trucks, contributing more than 90% to the sum in 2014 and still more than 70% to the sum in 2015. The majority of these fuel cell lift trucks are manufactured in the U.S.

Fuel cell light duty vehicles contributed nearly 5% to the 2014 figures, while in 2015 their share climbed to more than 20%. With exception of fuel cell range extender vehicles mainly manufactured in France, the majority of fuel cell cars came from Japan and Korea. The remaining unit shipments are shared by fuel cell buses and other transport fuel cells.

The corresponding MW figures of shipments in the transport sector cannot be specified as this would reveal company information that was received in confidence.

In the stationary sector, the total number of fuel cell systems shipped was nearly 40,000 units in 2014, compared to 47,000 units in 2015. Roughly 90% of these units came from Japan, whereas the remaining 10% were shared a number of other countries. The total megawatts shipped in the stationary sector were nearly 150 MW in 2014 compared to nearly 185 MW in 2015. The share of Japanese production in these megawatt numbers is between 15 and 20%, while the share of the U.S. was between 70% and 80%. Germany, Korea and other countries did not contribute substantial megawatts to the totals in stationary fuel cells, but it is worth noting that we count the system integration by POSCO Energy in Korea of fuel cell modules sourced from FuelCell Energy in the U.S. as U.S.-based manufacturing. In March 2017 it was announced that going forward, POSCO Energy will focus on servicing existing installations in Korea, while FuelCell Energy will address the Korean and Asian market directly. This announcement may indicate that POSCO Energy has discontinued plans to manufacture fuel cell systems in Korea for the Asian market, and instead will only produce replacement modules for existing installations.

In portable fuel cells, between 2,000 and 2,500 units were manufactured in Germany in 2014 and 2015, which also contributed the largest part to the megawatt figure in this segment. Other countries with portable fuel cell production in 2014 and 2015 were Sweden, United Kingdom, the U.S., and China.

3.3 Stationary shipments by system size

Of the stationary units shipped in 2014 and 2015, more than 98% were in the small size category (<10 kW), which reflects the dominance of Japanese Ene-Farm residential fuel cells in this segment. In terms of megawatts shipped, roughly 20% are attributable to this small size category, whereas almost 80% come from large stationary units (≥100 kW). The medium size category (10 – 99 kW) contributes less than 1% to the unit and megawatts sums in stationary shipments.

3.4 Fuel cell systems manufactured in the U.S.

The U.S. manufactured more than 3,000 fuel cell systems in 2014 comparing to more than 5,000 systems in 2015. The megawatt figure was more than 125 MW in 2014 and more than 155 MW in 2015. In both years, more than 90% of the units shipped were for the domestic market. As the number of units exported is comparably small, reporting details on where they have been shipped to would indirectly reveal some of the companies' confidential shipment data. More than 50% of the MW manufactured in 2014 in the U.S. were for the domestic market, vs. more than 70% in 2015. In terms of megawatts exported, the major share in both years went to Korea.

3.5 Global Trends 2014 and 2015

3.5.1 Fuel cell shipment summary 2014 and 2015

The main highlights in the 2014 and 2015 figures are the strong increase in megawatts shipped from Asian manufacturers, mainly due to the launch of Toyota's Mirai fuel cell car and growing numbers of Hyundai's Tucson fuel cell car. Although 2016 shipment data have not been finalized yet, it can already be said that this trend has continued, and fuel cell cars have become the major driver for industry growth in the fuel cell sector. China is just starting to deploy numbers of FCEVs such as buses and commercial delivery vehicles and this could rapidly accelerate over the next few years, as indicated by a large number of stacks and subsystems shipped to China in 2016, and more orders announced for integration into various types of road vehicles.

3.5.2 Reported data and methodology

E4tech gathered fuel cell system shipment data for 2014 and 2015, and will subsequently also deliver data to DOE for 2016 and 2017.

Reported shipment data

Data are presented for each year in terms of annual system shipments and the sum total of those systems in megawatts, both divided by application, region and fuel cell type (chemistry). These numbers do not include stack replacements for previously installed fuel cell systems. Shipments are reported by numbers of units (systems) and by total megawatts shipped annually (calendar year). Shipment numbers are rounded to the nearest 100 units and megawatt data to the nearest 0.1 MW. The power ratings refer to the electrical output, and in general we use the nominal not peak power of the system, with the exception of transport. Because continuous power depends heavily on system design and how it is used, we report peak power for these units. The reported figures refer to shipments by the final manufacturer, usually the system integrator (e.g., for fuel cell cars, OEMs such as Toyota and Hyundai).

Toys and educational kits, as well as any units below 3W power rating are not included in the presented data.

Data sources and methodology

The numbers as presented in this report have been collected and aggregated by E4tech through direct contact, either verbally or in writing, with close to 100 companies globally. Some of these companies are not yet shipping other than small quantities for tests, but of those that are shipping only very few declined to provide primary data. In addition to primary data, publicly available sources such as company statements and statutory reports, press releases, and demonstration and roll-out programs, have also been used to cross-correlate the numbers. Original company data collected by E4tech was aggregated prior to sharing it with the project consortium and DOE.

3.5.3 Total shipments by region

The regional split in the data presented here refers to the countries of where the fuel cells are made. This is different from E4tech's Fuel Cell Industry Review publication, in which shipments are presented by region of adoption.

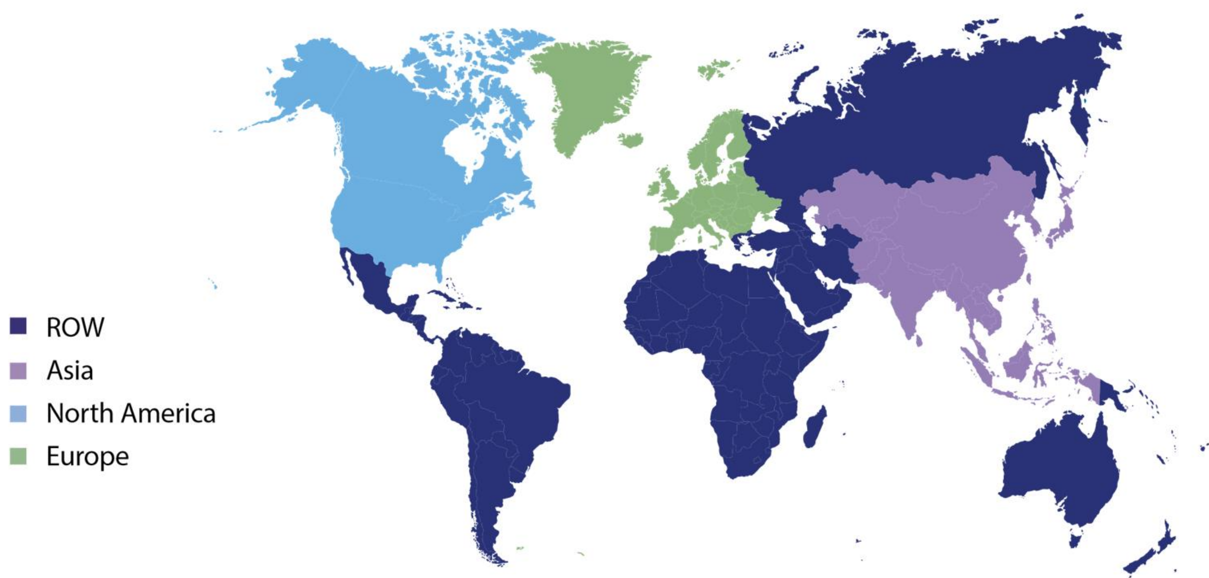

Figure 3-2: World regions used for reporting fuel cell shipments

Asian fuel cell makers continue to dominate the unit shipment numbers in 2015. As in 2014, this reflects the large numbers of micro-CHP units shipped in Japan under the Ene-Farm. However, if measured in megawatts, which relates better to the economic value of fuel cell manufacturing (scales more or less by area of cells), North America continued to play the main role globally in 2015. This is essentially due to

FuelCell Energy, Bloom Energy, and Doosan Fuel Cell America. It is worth noting that fuel cell modules shipped by FuelCell Energy to POSCO Energy in Korea are counted as U.S. production, although the final system integration takes place in Korea. While Doosan Fuel Cell America contributed significantly to U.S. fuel cell output and has announced several tens of MW orders during 2015, some news in 2016 indicated that Doosan is planning to move part of the manufacturing to Korea, though details have not been released.

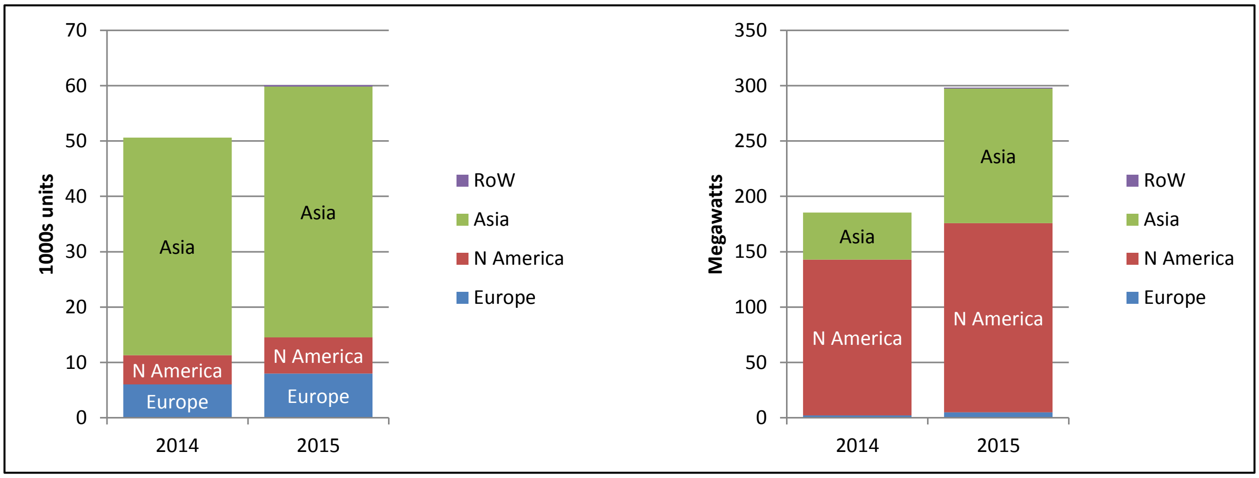

Figure 3-3: Fuel cell shipments by world region, 2014-2015

Table 3-2: Fuel cell shipments by world region, 2014-2015

Shipments by region of manufacture (1000s units)	2014	2015	Megawatts by region	2014	2015
Europe	6.0	8.0	Europe	2.1	4.8
N America	5.3	6.5	N America	140.8	171.0
Asia	39.3	45.4	Asia	42.5	121.6
RoW	0.0	0.2	RoW	0.0	0.7
Total	**50.6**	**60.2**	**Total**	**185.4**	**298.1**

Besides a growing market of large stationary systems that has been served almost exclusively by U.S. based manufacturing, the growth from 185 MW in 2014 to nearly 300 MW in 2015 comes mainly from fuel cell cars manufactured in Japan and Korea (Toyota's Mirai and Hyundai's Tucson/ix35). This trend continued in 2016, and although numbers for 2016 are not yet finalized, it is already clear, that Asia now also dominates the megawatt shipments. More generally, the launch of commercial fuel cell cars is the major driver of industry growth in recent years.

Comparably few fuel cell systems were manufactured in Europe, despite a large number of local companies. Policy support for fuel cells remains strong in several European countries. Growing production numbers are to be expected from residential fuel cell manufacturers that profit from a European demonstration program and a German market support program. In the transport sector Symbio FCell has grown production rapidly in recent years. Automotive OEMs from Europe all have some fuel cell activity, but only Daimler is to introduce a commercial fuel cell car in the near future (expected at the end of 2017). Several activities in Europe exist for fuel cell powered forklifts, but unit numbers of fuel cells sourced from Europe remained low in 2014 and 2015.

4 Supply Chain Evolution

4.1 Introduction and context

In order to set the correct context, included in this project is the anticipated evolution of the fuel cell automotive supply chain with the advent of commercialization of the Automotive Fuel Cell System (AFCS) as the engine to power the fuel cell light vehicle. The term AFCS is chosen specifically to represent the technologies and components most relevant to this analysis. The present status of the fuel cell powered vehicle is in the early stages with research and development of the fuel cell power plant. The AFCS has not achieved a sufficiently high level of technology readiness to necessitate investment in large scale manufacturing, though this is anticipated in the coming few years.

The automobile manufacturers (Original Equipment Manufacturers – OEMs) report their combined AFCS production capability is well below 10,000 units per year in 2016. AFCS sales in the 2015 – 2016 auto sales season (ending September, 2016) marginally exceeded 1,000 units. *AutoBlog* reported in 2015[12] Hyundai's sales projections of 1,000 Tucson fuel cell vehicles worldwide did not reach the target and there had been only 273 sales of Tucson fuel cell vehicles by May, 2015. Toyota is producing fuel cell automobiles with the development and early commercialization of their Mirai. Toyota announced in 2015 "…eight California dealers deliver 200 Mirai's before the end of the year, followed by another 2800 cars over the next two years."[13, 14] U. S. sales data for the Mirai identified 72 vehicles sold in 2015 and 641 Mirais sold over the period January 1, 2016 to September, 2016.[15] Demand for the Mirai in Japan is greater than in the U.S. and over 1,500 were ordered within one month of the December, 2014 launch. Toyota announced they would increase annual production to 2,000 vehicles.[16] In March, 2016, Honda began sales of their Clarity fuel cell vehicle in Japan "…with lease sales to government bodies…"[17, 18] The Clarity will be available for the American and European market at a later date. In the AUTOWEEK article, they report the Clarity is "essentially a hand-built specialty car at this point."[19]

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[12] Bruce, C., "Hyundai Tucson Fuel Cell sales not hitting target [UPDATE]" http://www.autoblog.com/2015/06/17/hyundai-tucson-fuel-cell-sales-missing-target/

[13] Sherman, D., "2016 Toyota Mirai Fuel-Cell Sedan", http://www.caranddriver.com/toyota/mirai; August, 2015

[14] http://www.caranddriver.com/news/2016-toyota-mirai-fuel-cell-sedan-photos-and-info-news

[15] http://left-lane.com/us-car-sales-data/toyota/toyota-mirai/

[16] "Toyota to quadruple production of the Mirai fuel-cell vehicles by 2017", The Japan Times, January 23, 2015, http://www.japantimes.co.jp/news/2015/01/23/business/corporate-business/toyota-to-quadruple-production-of-mirai-fuel-cell-vehicles-by-2017/#.WHxElRsrJhE

[17] AutoWeek, "2016 Honda Clarity hydrogen fuel cell sedan: First Impression", November, 2015 http://autoweek.com/article/green-cars/2016-honda-clarity-hydrogen-fuel-cell-sedan-first-impressions

[18] http://world.honda.com/news/2016/4160310eng.html

[19] AutoWeek, "2016 Honda Clarity hydrogen fuel cell sedan: First Impression", November, 2015 http://autoweek.com/article/green-cars/2016-honda-clarity-hydrogen-fuel-cell-sedan-first-impressions

Daimler announced a new fuel cell vehicle generation based on the Mercedes-Benz GLC is being launched in 2017.[20] The GLC F-CELL will have a compact fuel cell system that fits into a conventional engine compartment. The GLC F-CELL is a hybrid system with lithium ion battery and plug-in technology. The fuel cell stack was developed by Automotive Fuel Cell Corporation (AFCC) at the Vancouver, Canada facility in a joint venture with Ford and Daimler AG. The fuel cell and battery system will give the GLC F-CELL a range of around 500 km.

The Seasonally Adjusted Annual Rate (SAAR) of light vehicle sales in the U.S. for September, 2016 was 17.76 million, which can be broken down into 7.24 million automobiles and 10.51 light trucks.[21] Global car sales (includes light trucks for North America) for 2015 reached 72.61 million units and the projected 2016 sales are 75.76 million units.[22]

The AFCS vehicle sales are minuscule compared to U.S. and global auto sales volumes and, clearly, the AFCS supply chain is in its infancy. This is similar to the automobile supply chain in the 1920s to 1930s, which was characterized by vertical integration where production facilities for automotive components were owned and operated by the OEM and most located near the automotive assembly plant.

4.2 Product-Life-Cycle: Comparison to Toyota Hybrid Sales

The commercialization of the AFCS, like the Toyota Hybrid, is expected to follow a conventional product-life-cycle with an introduction stage, a growth stage, and maturity stage as shown in Figure 4-2.

There are limits to the comparison of hybrid vehicles to the fuel cell vehicle, specifically:

- FCEVs, unlike hybrids, require infrastructure to be built which will be done by a separate supply chain industry; i.e., the infrastructure for hydrogen fueling.
- Supply chain strategies may continue to evolve, so this analysis assumes that there may be further optimization.

Commercialization of AFCSs is in the introduction stage with less than 5,000 sold in 2016; similar to the Toyota Hybrid[23] introduction in 1997 as shown in Figure 4-1. Worldwide sales of the Prius did not approach 100,000 until 2004. Comparing with the DOE 2020 goal of \$40.00/kW_{net} at 500,000 AFCSs

[20] Daimler Global Media Site, "Under the microscope: Mercedes-Benz GLC F-CELL: The fuel cell gets a plug, http://media.daimler.com/marsMediaSite/en/instance/ko/Under-the-microscope-Mercedes-Benz-GLC-F-CELL-The-fuel-cell-.xhtml?oid=11111320

[21] Motor Intelligence, "SAAR Data", Excel file "%5Cdb%5CSR_SAAR73, September, 2016 http://www.motorintelligence.com/m_frameset.html

[22] "Global Economics/Global Auto Report", Scotiabank, September 29. 2016, http://www.gbm.scotiabank.com/English/bns_econ/bns_auto.pdf

[23] "Worldwide Sales of Toyota Hybrids top 6 Million Units", February 9, 2016, http://corporatenews.pressroom.toyota.com/releases/worlwide+toyota+sales+top+6+million.htm

manufactured per year identified by James et al.[24] in the DOE AMR reports, full worldwide commercialization (500,000 Toyota Hybrid vehicles per year) was not reached until 2009, though would likely have been in 2008 had the financial crisis not hit. These results are shown in Figure 4-1. Anticipating a similar incubation period, manufacture of 500,000 AFCS per year would not be reached until 2029, though the Toyota Hybrid was commercialized by a sole manufacturer while several manufacturers are already looking to scale up AFCS.

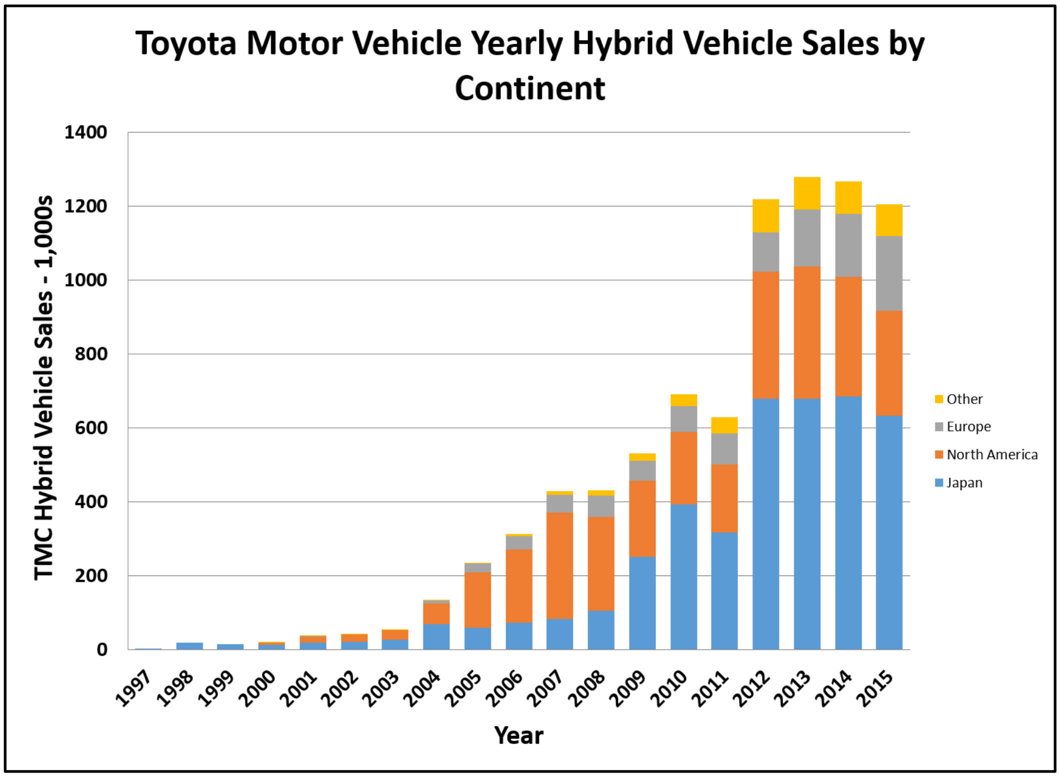

Figure 4-1: Worldwide annual sales of Toyota Hybrid with AFCS sales insert

[24] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

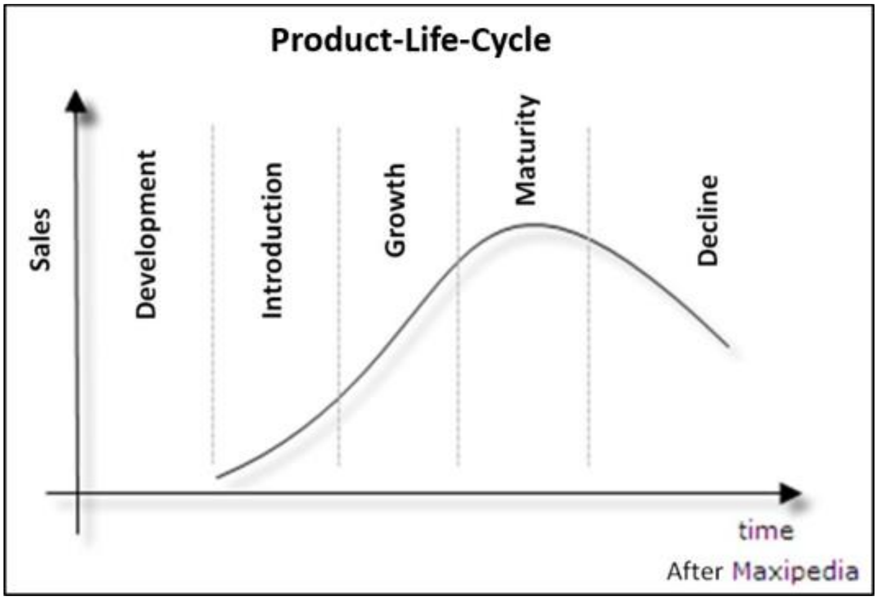

Figure 4-2: Product-Life-Cycle Identifying five stages. (Source: Maxipedia)

Comparison of Figure 4-2 to the data in Figure 4-1 indicates the AFCS product-life-cycle is in the Introduction stage. Using the timing from Figure 4-2, the AFCS production cycle would enter the growth stage in approximately 2023 and transition to the maturity stage around 2029. The data in Figure 4-1 includes sales of Toyota Hybrid vehicles during the 2008 worldwide recession.

Technical readiness and manufacturing processes and facilities will vary depending on the product-life-cycle stage. OEMs and suppliers will adjust their manufacturing readiness to meet the demand; however, in the early stages of development of a supply chain, price and manufacturing capacity may not be primary concerns for the product-life-cycle.

4.2.1 Metrics for the Product-Life-Cycle and Supply Chain Evolution

The three metrics 1) Technical Readiness, 2) Manufacturing Readiness, and 3) Manufacturing Volume establish the metrics for evolution of the automotive supply chain.

Technical Readiness Requirements

For assessment of the Supply Chain Evolution, Technology Readiness Levels[25] (TRLs) are key metrics and correlate with product-life-cycle stages, as summarized below. (A full explanation of Technology Readiness Levels is "Hydrogen Program Technology Readiness Levels.[26])

[25] Wheeler, D. and Ulsh, M., "Manufacturing Readiness Assessment for Fuel Cell Stacks and Systems for the Back-up Power and Material Handling Equipment Emerging Markets", National Renewable Energy Laboratory Technical Report NREL/TP-560-45406 Revised February 2010, DOE Contract No. DE-AC36-08-GO28308

[26] Payne, T., "Hydrogen Program Technology Readiness Levels", received May, 2008

1. TRL 7 corresponds to the Development product-life-cycle stage
   a. System prototype demonstrated in an operational environment.
   b. Integrated test system with collateral and ancillary systems completed.
   c. Technology verified at semi-commercial/commercial scale.
2. TRL 8 corresponds to the Introduction product-life-cycle stage
   a. System completed and incorporated in commercial design and proven through testing in an operational environment.
   b. Fully integrated operational hardware and software systems developed.
   c. Technology proven by early adopters to work in final form under real-world conditions.
3. TRL 9/10 corresponds to the Growth and Maturity product-life-cycle stages
   a. System is successfully demonstrated in field.
   b. Fully integrated operational hardware/software systems are developed.
   c. Actual application of the technology is in final form and demonstrated in the field.
   d. Sustained engineering support is in place.

Manufacturing Readiness Requirements

The key metrics of Manufacturing Readiness Levels[27] (MRLs) for evolution of the supply chain have a dependence on the TRLs; specifically, a Manufacturing Readiness Level cannot be greater than the Technology Readiness Level.

1. MRL 7 corresponds to the Development product-life-cycle: < 1,000 units/year.
   a. Prototype built with soft tooling by OEM.
   b. Low Rate Initial Production (LRIP).
   c. Manufacturing process initially demonstrated by OEM.
2. MRL 8 corresponds to the Introduction product life cycle: 1,000 to 20,000 units/year
   a. Manufacturing processes demonstrate yield and producibility for pilot line manufacture.
   b. All design requirements satisfied.
   c. Cost estimates < 125% cost goals.
   d. Initial supply chain under development.
3. MRL 9 corresponds to the Growth product-life-cycle stage: 20,000 to 100,000 units/year
   a. Manufacturing processes proven.
   b. Manufacturing operating at initial sigma level with stable production.
   c. Supply chain developed to meet initial production demands.
   d. Cost estimates < 110% of cost goals.
4. MRL 10 corresponds to the Mature product-life-cycle stage: 100,000 to 500,000 units/year
   a. Full Rate Production demonstrated and lean production practices in place.
   b. Quality at six sigma or defined quality target.

[27] Wheeler, D. and Ulsh, M., "Manufacturing Readiness Assessment for Fuel Cell Stacks and Systems for the Back-up Power and Material Handling Equipment Emerging Markets", National Renewable Energy Laboratory Technical Report NREL/TP-560-45406 Revised February 2010, DOE Contract No. DE-AC36-08-GO28308

c. Just-In-Time processes define supply chain.
d. Manufacturing meets cost goals.

Manufacturing Volume Requirements (parts count)
The manufacturing volume for major components identified in Table 2-1 depends on the stages in Product-life-cycle identified in Table 4-1. Production requirements in each of the product-life-cycle stages are different. The following are proposed yearly production rates established by this project team for each of the product-life-cycle stages:

- Development: <1,000 AFCSs
- Introduction: 1,000 to 20,000 AFCSs
- Growth: 20,001 to 100,000 AFCSs
- Maturity: 100,001 to 500,000 AFCSs
- Decline: < 100,000 AFCSs

These production rates are chosen based on the DOE 2020 goal of "widespread commercialization and cross-targets". A "knee" in the cost versus annual production curve in Figure 4-2 occurs at approximately 20,000 AFCSs per year. Following the analysis of James,[28] the automotive fuel cell stack has net power of 80 kW with 372 individual fuel cells (i.e., repeat unit of MEA and bipolar plate assembly) in each stack, and each fuel cell having an active area of 299 cm^2. The production volumes for each fuel cell stack Cost Components in Table 2-1 are given in Table 4-1 for the first four stages in the product-life-cycle.

Table 4-1: Maximum AFCS Cost Component Annual Volume Production for Product-Life-Cycles; values assume no waste

Maximum AFCS Cost Component Annual Volume Production (assuming no waste) for Product-Life-Cycles (given in millions for parts and millions of square meters)				
	Product-Life-Cycles			
	Development	**Introduction**	**Growth**	**Maturity**
AFCS Production	**(1,000)**	**(20,000)**	**(100,000)**	**(500,000)**
Component				
Membrane				
Millions of parts	0.37	7.44	37.20	186.00
Millions of m^2	0.01	0.22	1.11	5.56
Gas Diffusion Layer				
Millions of parts	0.74	14.88	74.40	372.00

[28] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

Maximum AFCS Cost Component Annual Volume Production (assuming no waste) for Product-Life-Cycles (given in millions for parts and millions of square meters)				
	Product-Life-Cycles			
	Development	**Introduction**	**Growth**	**Maturity**
Millions of m^2	0.02	0.44	2.22	11.12
Bipolar Plates				
Millions of parts	0.74	14.88	74.40	372.00
Millions of m^2 (active area)	0.02	0.44	2.22	11.12

The production volumes given in Table 4-1 illustrate that even during the Development Stage of the product-life-cycle production rates in excess of 740,000 parts (20,000 square meters) for each will be required for the GDLs and bipolar plates. OEMs will identify suppliers with production capabilities meeting the volume demand at the Development and Introduction stages. At the Growth and Maturity stages, we anticipate dedicated supplier production facilities will be required to meet manufacturing demands for the AFCS.

4.3 Data Collection

For this report interviews with seven of the primary OEMs for automotive fuel cell systems were conducted to determine their perspective on the development and evolution of the automotive fuel cell supply chain.

Additionally, interviews were conducted with component suppliers, 28 in all. Supplier interview results are reported where the number of interviews per cost component were three or greater. Specific responses are not reported for those cost components with supplier interviews less than three because the interviews were conducted with the agreement of no attribution to a specific supplier. Summary results do include all of the inputs of all of the suppliers where there is no possibility of attribution.

Data collection took several forms. Interviews with OEMs and companies active in the automotive supply chain were carried out. Prior to the initiation of the interviews (Primary Data Collection), a literature study of the automotive supply chain was conducted; i.e., Secondary Data Collection. Primary Data Collection and Secondary Data Collection for the purposes of this analysis are defined in below.

Following the definitions, the results of the Primary Data Collection effort are given followed by results of the Secondary Data Collection effort. This Secondary Data identifies the status of the automotive fuel cell sales and the evolution of the automotive supply chain.

Primary Data Definition

Primary data include data from questionnaires and interviews with OEMs and automotive component suppliers. Primary data from supply chain participants provide the most detailed information and insights regarding the existing supply chain as the evolution of the automotive supply chain for the AFCSs market expands from the development stage to a mature, commercial automotive transportation product.

The interview data were collected from seven OEMs. Interview data are objective, but typically have a count of one with rich content, i.e., are not statistically significant because the sample size is not large but none-the-less convey meaningful information. Interview data and questionnaires require large sample sizes in order to have statistical significance, but the fuel cell industry has not evolved to a point where large samples are possible. The data were important because they afford insight regarding the present status of the AFCS development and the emerging AFCS supply chain. The interviewed OEMs and suppliers forecast the long-term manufacturing and supply chain targets for the AFCS.

Secondary Data Definition

Secondary data were collected throughout the study. In the initial phases, secondary data were used to increase the team's understanding of fuel cells for automotive applications, to focus interview guides, to explore supply chain models, to develop metrics and measures, and to develop the evolution map. The secondary data provided background data for the collection of primary data. Later in the project, the scope of the secondary data collection was expanded to capture more detailed information on the structure of the present supply chain. Examples of the secondary information sources reviewed include:

- Articles and data from FC 2000 and FC Today reports.
- Reviews of the fuel cell industry e.g., The Fuel Cell Industry Review[29].
- Information from automobile companies and suppliers web sites and press releases.
- Trade association: the Original Equipment Suppliers Association, the Motor & Equipment Manufacturers Association.
- Security and Exchange Commission (SEC) filings through EDGAR (SEC data portal).
- Department of Commerce Reports, International Trade Administration Reports and Reviews.
- Reviews and discussion of existing automotive and aerospace supply chains including trade publications such as the Automotive Supply Chain.
- Internet searches of publications and public information on relevant subject matter, e.g., the McKinsey report, and the Future of the North American Automobile Supplier Industry: Evolution of Component Costs, Penetration, and Value Creation Potential Through 2020.

[29] www.FuelCellIndustryReview.com

Insight from the data collection

One key objective of the interview questionnaire was to elicit insight from OEMs and suppliers with reference to how supply chains will be structured as the fuel cell market reaches maturity. At maturity, the supply chain questionnaire assumes: 1) there are not any major technical or cost barriers, 2) several OEMs are producing fuel cell vehicles, and 3) the supply chain has multiple competing suppliers. The results of the interviews show that automotive fuel cell manufacturing and the automotive fuel cell supply chain will need significant improvement in Technical Readiness and Manufacturing Readiness.

The following excerpts from the interview results addresses only those questions directly related to the evolution of the automotive fuel cell supply chain. As indicated previously, the results are reported in summary form without attribution to any of the specific automotive OEMs interviewed.

Supply Chain Maturity

The OEMs and suppliers were asked to identify the manufacturing volume where a mature supply chain would be absolutely necessary. The options were split into the following general production categories

a) 1,000 vehicles—low rate initial production.
b) 100,000 to 500,000—volume production.
c) 10% of vehicle sales—10% of U.S. sales is 2 million units/year.

The options were chosen to reflect the stages of market maturity discussed earlier.

OEMs' response to *"At what vehicle production rate do you expect the supply chain to be mature?"*

The responses were varied with three of the OEMs reporting a mature volume of 20,000 to 50,000 AFCSs per year while the other four OEMs anticipated a mature supply chain at annual production rates of 100,000 AFCSs or greater. Those OEMs identifying supply chain maturity at the lower volume production emphasized that AFCS design and architecture changes (compared to the present design) would be needed; however, they did not provide design change specifics. The OEMs anticipating production volumes of 100,000 or greater to reach a mature supply chain anticipated that today's technology would reach Technical Readiness and Manufacturing Readiness levels consistent with a robust, cost-effective AFCS; however, even these OEMs expressed some reservations regarding today's technology and of particular concern was the manufacture of bipolar plates.

Suppliers' response to *"At what vehicle production rate do you expect the supply chain to be mature?"*

The suppliers agreed that production of the cost components at <1,000 vehicles per year was feasible with some suppliers confident that production of cost components at 100,000 units/year would be feasible while others stated that additional investment in production facilities would be necessary to achieve 100,000 vehicles per year.

4.4 Primary Data Collection

Supply chain strawman diagrams are presented for the three subsystems (Fuel Cell Stack, Hydrogen Storage System, and Fuel Cell Balance-of-Plant which includes the compressor/expander/motor and their respective cost components identified in Table 2-1. The strawman supply chain diagrams are based on the team's perceptions at the start of the project and reflect the assumptions of a mature market. Additional underlying assumptions that led to the asserted supply chain diagram are presented below. Strawman diagrams were designed to elicit comments, agreement, or disagreement from the interviewees. It is important to note that the OEM interviews conducted were with OEMs with existing detailed supply chain understanding and participation.

<u>Bipolar Plates Supply Chain for a mature FCEV Market – Production</u>

The bipolar plate is produced from two plate stampings that are either welded or adhesively bonded together into a finished bipolar plate assembly with three flow fields: anode reactant (hydrogen) flow field, cathode reactant (air – oxygen) flow field, and coolant (typically water-glycol) flow field for temperature control of the fuel cell.

Bipolar Plate Assumptions:

- Stamped (stainless steel) metal plates from coil.
    - Factory siting decision driven primarily by proximity to market/OEM.
- Likely produced in existing manufacturing hub near auto OEM.
    - Volume stamping operation from roll coil.
    - High tech coating process.

  Coating
    - Coating technology licensed to stamping house.
    - Coating can be added before or after stamping.
    - Factory siting decision driven primarily by co-location or proximity to stamping facility.

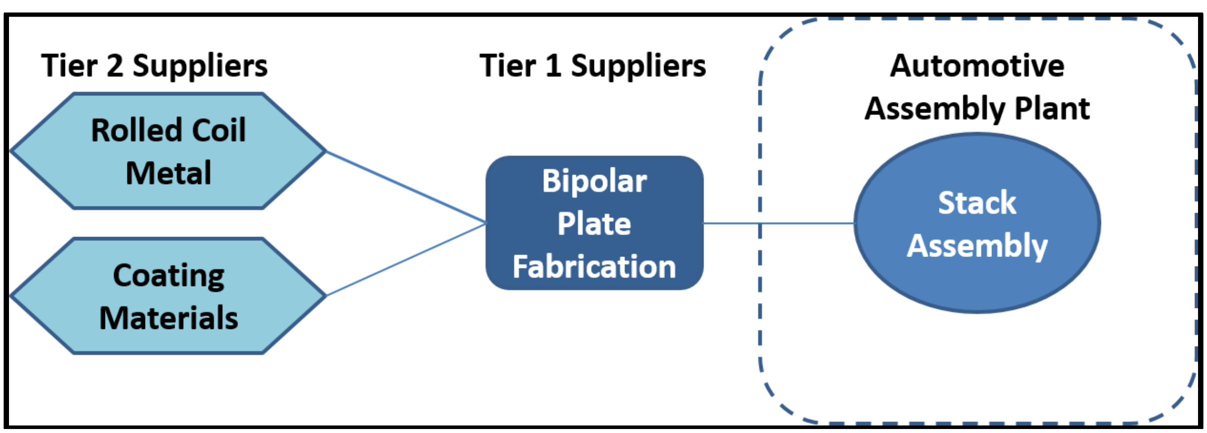

Figure 4-3: Proposed Bipolar Plate Supply Chain for Mature Manufacturing of AFCS.

In Figure 4-3, the two Tier 2 suppliers deliver materials to the Tier 1 bipolar plate fabricator. The multiple flow field bipolar plates are fabricated from two separate bipolar plates that have been coated to enhance corrosion resistance and electrical conductivity. There was no consensus among the OEMs that the plates would be coated prior to forming a flow field from the metal coil or after forming the flow field from the metal coil. The two plates are bonded together either by an adhesive or by welding. The choice of bonding technique is a differentiator between OEMs.

OEM views on bipolar plates:

A majority of the OEMs believed the fabrication of bipolar plates will be outsourced with a supply chain organization similar, if not identical, to that shown in Figure 4-3. The OEMs are agreed that co-location of the bipolar plate manufacturer was important and most agreed that a Tier 1 supplier would fabricate the bipolar plates, i.e. horizontal integration. It is noted that OEM fabrication of bipolar plates was espoused by a minority of the OEMs i.e. vertical integration. The concept of a Tier 1 supplier that would build and deliver a unit cell with integrated bipolar plate, membrane electrode assembly, and seals was presented. All of the OEMs agreed that they were at Technical Readiness and Manufacturing Readiness Levels for the production of <1,000 AFCSs per year. There was a mix of responses for TRLs and MRLs for production of 100,000 AFCSs per year with four OEMs stating current TRLs and MRLs were acceptable for production of 100,000 AFCS units per year. The other three OEMs stated additional development of manufacturing processes and a more robust system would be necessary to meet the TRL and MRL requirements for production of 100,000 AFCSs per year.

Supplier views on bipolar plates:

The suppliers agreed that the BPP fabrication would be outsourced (to them) and agreed with the supply chain configuration in Figure 4-3. The BPP suppliers agreed that the TRL and MRL for <1,000 AFCS units per year were in place now. There was some disagreement for production rates greater than 1,000 and up to 100,000 AFCS units per year. One supplier was confident they could produce BPPs for up to 100,000 AFCS units per year. Other suppliers were confident current BPP production facilities could supply BPPs for up to 10,000 AFCS units per year, and these suppliers suggested improvements in design and manufacturing processes were necessary to reach BPP production rates for 100,000 AFCS units per year.

<u>Membrane Electrode Assembly Supply Chain for a Mature FCEV Market – Production</u>

As shown in Table 2-1 the MEA has three major components: the ion-conducting membrane, the fuel cell catalyst that promotes the electrochemical reactions (hydrogen oxidation and oxygen reduction), and the gas diffusion layer that controls the distribution of reactants and water to and from the catalyst layer and membrane.

MEA Assumptions:

Membrane

- Factory siting decision driven primarily by:
  - Environmental/Safety concerns.
  - Access to low-cost materials.

- Ionomer likely produced in a single country (e.g., China) as pellets to be dispersed and cast by the membrane supplier at a dedicated facility producing roll good membranes.
- Ionomer supplier will likely prefer to sell higher value roll-good membrane.
- OEM will likely prefer to buy membrane in roll-good form to reduce NRE costs associated with casting.

GDL

- No clear drivers for factory siting.
- Specialty product manufactured using paper-making techniques.
- Likely supplied by a specialty carbon fiber paper company as a roll good with custom surface treatment(s).

Catalyst

- Factory siting decision driven primarily by need for experienced and educated workforce.
- Specialty product produced by catalyst companies with significant stake in precious metal mining.
- Likely sold as an ink or powder directly from the developer.
- Assumed catalyst is purchased and not leased.

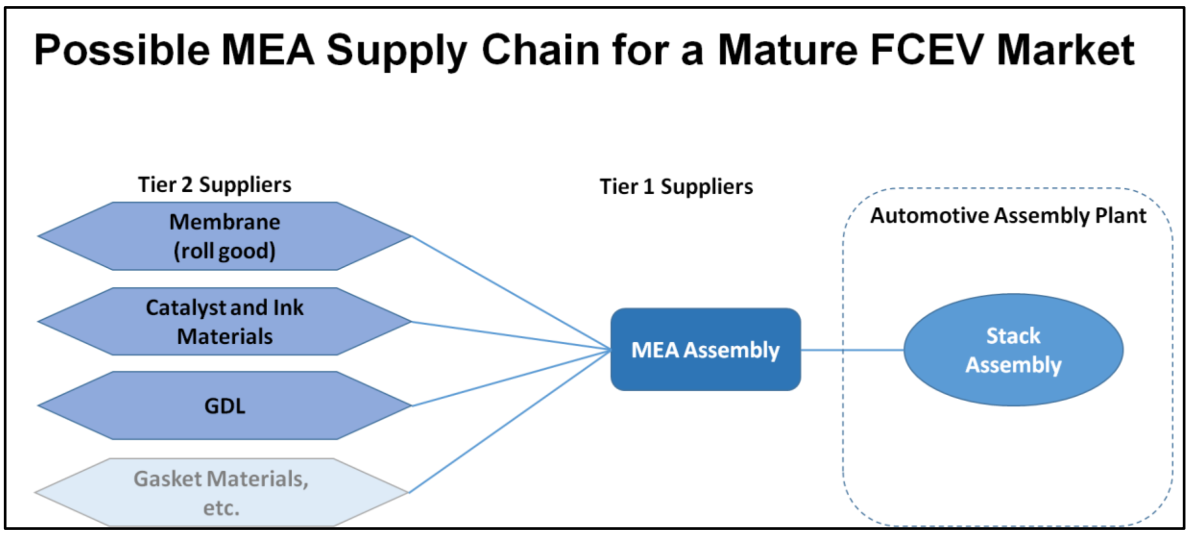

Figure 4-4: Proposed MEA Supply Chain for Mature Manufacturing of AFCS.

In Figure 4-4 the three Tier 2 suppliers deliver materials to the Tier 1 for MEA assembly. There is a fourth Tier 2 supplier that fabricates gasket materials for sealing the MEA components and insuring that the reactants (oxygen and hydrogen) do not mix and are restricted to only fuel cell operation. The membrane is delivered as a roll good. Application of the catalyst to the membrane, i.e., anode catalyst to one side of the membrane and cathode catalyst to the opposite side of the membrane to fabricate a catalyst coated membrane (CCM), to yield a CCM roll good. The GDL is also delivered as a roll good and is applied to the CCM using role processing techniques. The Tier 1 MEA assembler has two options for MEA assembly: 1) two separate roll processing steps – CCM roll production with separate rolling process for the addition of the GDL, and 2) a single roll process fabrication with sequential addition of the GDL after the catalyst layer is applied to the membrane.

The membrane, catalyst, and GDL interview data are consolidated to assure that attribution of the responses cannot be established.

OEM views on Membrane Electrode Assemblies:

The OEM majority consensus is the membrane would be purchased as a roll good and the MEA will be made by a Tier 1 supplier with assembly of the fuel cell stack by the OEM. However, two OEMs had different views. One thought that MEA production would be conducted at the automotive assembly plant since it was closely associated with a specific fuel cell stack design. Another OEM proposed the Tier 1 supplier be replaced by division of the OEM to prepare the MEA.

At very high volumes, greater than 100,000 AFCSs per year, the concept of a Tier 1 supplier that would assemble the MEA, bipolar plates, and seals and gaskets to deliver a fully assembled fuel cell module would be considered by the OEMs. The OEMs would use the fuel cell modules to assemble fuel cell stacks of different size and power ratings depending on the vehicle size and application.

Most of the OEMs agreed that ionomer may have a single country for production where regulation of the fluorine-based chemistry to produce the ionomer is not restrictive. Membrane manufacture at the ionomer production facility was considered a high probability with the membrane delivered as a roll good, as previously stated. More than one OEM identified the quality of the membrane to be the driving factor suggesting the low-cost ionomer/membrane producer may not be the manufacturer of choice and a premium could be accepted for the highest quality membrane.

All of the contributing OEMs recognized the importance of a catalyst company who has well-established quality control procedures, minimizes scrap, and has the ability to recover and recycle precious metal catalysts. Location of the catalyst manufacturer adjacent to the MEA or stack assembly facility was not considered a critical factor. The concept of a separate CCM fabrication by a catalyst company would be considered based on the drivers, i.e., performance and cost. MEA manufacture by the catalyst manufacturer with delivery of a roll good MEA would be considered by at least one of the OEMs assembling a stack.

Manufacture of the GDL by a Tier 2 supplier was considered by all the OEMs. Several of the OEMs called for technical improvement of the GDL with one OEM seeking to eliminate the GDL.

The concept of supplier parks located adjacent or as part of the fuel cell vehicle assembly facility was discussed with at least one OEM and would be considered based on production volume, component cost, and delivered quality

Finally, several of the OEMs emphasized that TRLs and MRLs for <1,000 AFCSs per year were at acceptable levels. At production rates of 20,000 to 100,000/year, the TRL was acceptable to some manufacturers, but the MRL was not ready and additional manufacturing process development was necessary. For one OEM, it was not clear there was an economic justification at this time to develop manufacturing processes for fabricating 20,000 to 100,000 AFCS units per year, and only when the business model justifies making 20,000 to 100,000 AFCS units per year should the manufacturing process development be completed. One OEM did not believe quality (i.e., durability and performance) had been sufficiently demonstrated to justify going beyond 1,000 AFCS units per year and, in addition, the hydrogen infrastructure did not exist to support 20,000 to 100,000 fuel cell vehicles. This OEM believed that after fuel cell quality and hydrogen infrastructure were demonstrated only one demonstration cycle would be needed to build customer demand.

Suppliers views on Membrane Electrode Assemblies:

The majority of the suppliers agreed with the proposed MEA supply chain identified in Figure 4-4 and accepted the proposal that the MEA Assembly facility could be co-located near the automotive assembly plant. Although, again, there was not a consensus regarding co-location. The membrane and GDL for the MEA would be delivered as a roll good. Catalyst manufacture would be with companies with a high experience level in quality control and typically with an organization associated with the mining industry. Recycling of catalyst was identified as an important cost control factor.

The suppliers reported that the TRL and MRL were acceptable for production of MEAs at < 1,000 AFCS units per year. The TRL for 100,000 AFCS units per year would require some additional development for three of the suppliers, although one supplier stated the TRL was already ready for 100,000 AFCS units per year. All of the suppliers believed that additional manufacturing development and substantial investment would be required to achieve the MRL for 100,000 AFCS units per year.

The suppliers agreed that a mature market would be at 100,000 AFCS units per year.

Hydrogen Storage System

The hydrogen storage system has two major components: 1) the hydrogen storage vessel fabricated from carbon fiber (CF) composite and 2) the hydrogen balance of plant (HBOP) with high pressure regulators and valves (700 bar). These components are identified in Table 2-1.

Hydrogen Storage System Assumptions:

- 700 bar Type 4 vessels.
- Factory siting decision driven primarily by:
    - Proximity to OEM/Market.
- Specialty product supplied to OEM.
- Carbon Fiber.
    - Factory siting decision driven primarily by:
        - First to Market with economies of scale and dominant market position.
        - Energy cost.
        - Access to raw materials.
    - Specialty material with significant Intellectual Property (IP).
    - No obvious countries dominating market.
- Liner material:
    - Commodity material with no special considerations.

Hydrogen Balance of Plant:

- Mature supply chain components purchased from existing compressed natural gas vehicle (CNGV) suppliers.
- Factory siting decisions driven by:
    - Labor cost.
    - Proximity to market.

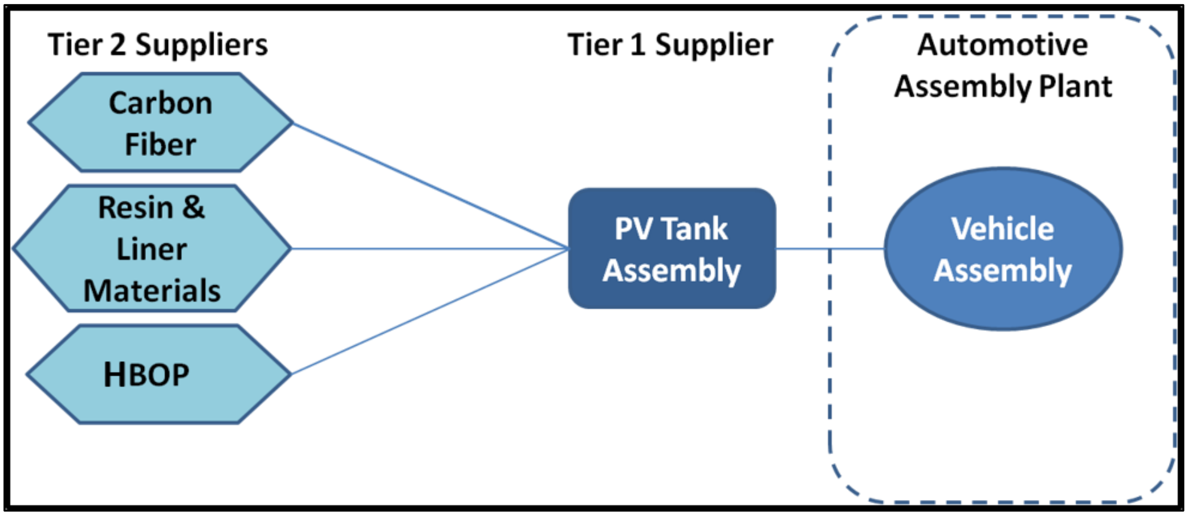

Figure 4-5: Proposed Supply Chain for Hydrogen Storage System

In Figure 4-5 , the Tier 2 companies supply materials to the Tier 1 pressure vessel (PV) Tank assembler that delivers the finished PV Tank to the automotive company doing vehicle assembly. The carbon fiber is the highest cost component and is combined with a resin to form a carbon fiber composite that is wound around the pre-formed liner vessel and cured by the PV Tank assembler. The PV Tank assembler integrates the carbon fiber wound pressure tank with the pressure regulator, high pressure valves, and the hydrogen storage controller to complete the hydrogen storage module that is delivered to the OEM's automotive assembly plant for insertion into the vehicle.

OEM views on Hydrogen Storage:

The OEMs agreed with the assumptions and the supply chain configuration in Figure 4-5. The OEMs stated there is a need for a low-cost carbon fiber feed stock but did not anticipate a reduction in carbon fiber cost in the near future. Carbon fiber cost is driven by the aircraft industry that has the highest demand and when the automotive application becomes dominant, the carbon fiber cost will become more competitive. Overall, the cost of carbon fiber and time required to fabricate the hydrogen pressure vessel are currently excessive. One OEM stated the liner cost was expensive because the properties of the liner made it a specialized component. It was also suggested by some of the OEMs that location of the PV Tank assembly be near or adjacent to the OEM assembly plant because the hydrogen storage system was bulky and shipping cost from an offsite PV tank assembler could be high, although this view was not held by all of the OEMs. One OEM recommended a strategic partnership between the OEM and the PV Tank assembler/carbon fiber suppliers could bring costs down.

The OEMs agreed that the technical readiness and manufacturing readiness was sufficient for the production of <1,000 storage systems per year. The OEMs did not believe the PV Tank assemblers manufacturing readiness was capable of fabricating 100,000 storage system per year. The capability of the HBOP suppliers to deliver components was not sufficient for 100,000 vehicles per year. One OEM suggested it would be helpful if OEMs collaborate to build the supply base.

Fuel Cell Balance of Plant

As discussed in Section 2.4.3, the compressor/expander/motor (CEM) and associated motor controller were identified as high value balance of plant components. The proposed supply chain structure for the CEM and motor controller are shown in Table 2-1 (the CEM is identified as "Other Components" in Figure 4-6).

CEM Assumptions:

- Stack Operates at 2.5 atm.
- Expander is used to reduce parasitic load.
- Factory siting decision driven primarily by:
    - Proximity to market/OEM.
    - Standard requirements (high volume production, reliability, track record as supplier).
- Likely produced in existing manufacturing hub near auto OEM:
    - Parallels to internal combustion engine air handling components (super/turbo-charger)
- The motor controller is purchased from trusted vendor to OEM Spec

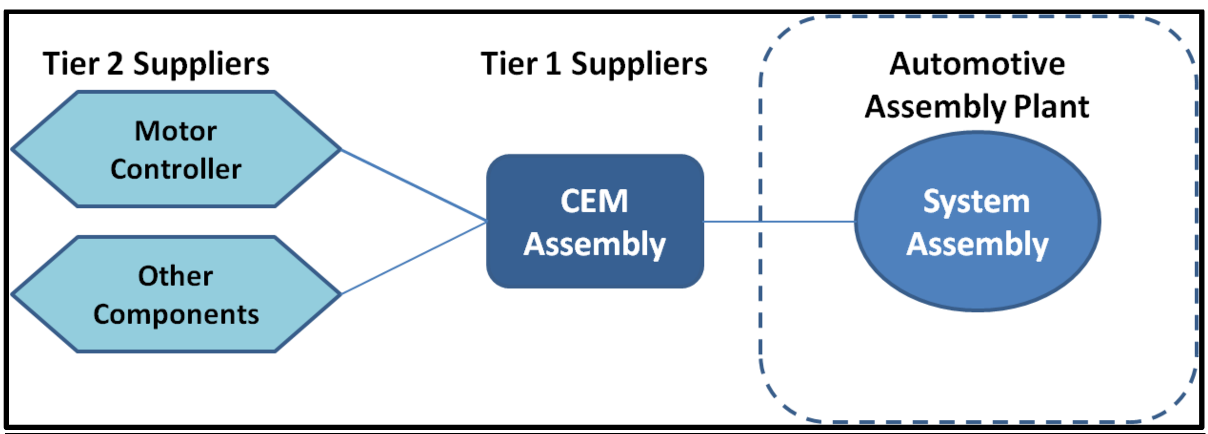

Figure 4-6: Proposed Supply Chain for CEM Production

In Figure 4-6, the Tier 2 suppliers deliver the motor controller and compressor/expander/motor (Other Components) to the Tier 1 CEM assembler. The pressure specification for the CEM is based on a fuel cell stack operating at 2.5 atmospheres. The Tier 1 CEM assembler integrates the motor controller and the compressor/expander/motor into the CEM module that is delivered to the automotive assembly plant. At the automotive assembly plant, the CEM module is inserted into the vehicle as part of the AFCS.

OEM views on Balance of Plant/CEM:

The OEMs agreed with the structure of the CEM supply chain for a mature market as shown in Figure 4-6. However, there was considerable disagreement regarding the operating pressure of the fuel cell stack and, hence, the requirements for the compressor/expander. Three categories were identified for the operating pressure of the fuel cell stack and compressor/expander

1. Lower pressure operation using a compressor/expander with operating pressure of 2.0 atmospheres; i.e., still greater than 1.0 atmospheres. The supply chain in Figure 4-6 remains valid, but operation at lower pressure could reduce cost of the compressor/expander.

2. Very low pressure operation of the fuel cell stack i.e., less than 1 atmosphere where the compressor/expander would be replaced by an air blower. The use of an air blower could reduce the overall cost of the CEM module, but would be dependent on a significant change in the fuel cell stack architecture.

3. Higher pressure operation than 2.5 atmospheres with the potential for reaching high speed turbo technology. High pressure operation would result in a change in Figure 4-6 with the compressor/expander replaced by the fabrication of a high-speed turbine facility.

Outsourcing the CEM was supported by the OEMs. One OEM suggested the Fuel Cell Balance of Plant was an opportunity to develop the supply chain with common or core components to be used by multiple OEMs.

The technical readiness and manufacturing readiness was not identified by all of the OEMs. Those that did identify the status of TRLs and MRLs believed suppliers were ready for delivery of the CEMs at production rates of <1,000 units per year. Production of CEMs at 100,000 units per year had mixed manufacturing readiness responses from the OEMs with some believing 100,000 units per year was possible, but qualifying the manufacturing readiness with the requirement that cost must be reduced.

None of the OEMs indicated that location of the CEM assembly facility was critical. There was a consensus that countries with a well-developed manufacturing infrastructure, such as North America, Japan, Germany, and Korea, would be the likely fabricators of the CEM.

4.5 Secondary Data Collection

The automobile supply chain evolved from a vertical structure in the early beginnings of automobile production with a majority of the components locally produced by the OEMs to a horizontal structure with the development of tiered structure of suppliers during the 20th century. In the horizontal supply chain, minimally three tiers of suppliers were established: Tier 1 suppliers that developed finished systems and assemblies that they deliver directly to the OEMs; Tier 2 suppliers produce products sold directly to the Tier 1 suppliers; and Tier 3 suppliers supply components and possibly raw materials to the

Tier 2 suppliers.[30] Up until the 1970s with the horizontal supply chain, OEMs maintained responsibility for engineering and product design work, investment cost in production facilities, inventory costs, and all vehicle assembly. The OEM would contract with multiple Tier 1 suppliers chosen by a bidding process to develop "build to print" components.

At the end of the 20th century and into the 21st century, Just-In-Time (JIT) assembly processes with short supply lines and small batch delivery of components to the OEM were instituted. The JIT assembly process required expanded, collaborative interaction between the OEMs and suppliers. A new tier structure developed with the formation of the "Tier One-Half" supplier also identified as a Strategic Partner. The Tier One-Half supplier became an integrator building complete modules with responsibility for product design, module assembly, investment in production facilities, and management of their supply chain. Tier One-Half suppliers located their production facilities on or adjacent to the OEM facilities to assure rapid delivery of the integrated modules consistent with JIT principles. The integrated OEM/supplier cooperative production facility benefited greatly from advances in high data exchange technology where the OEM issues an electronic order identifying final configuration of vehicle to be produced every 88 seconds. The Tier One-Half supplier has two hours to respond and deliver to the OEM.[31]

In this context, analysis of the evolution of the AFCS supply chain is made easier because the end point of the evolution is well understood; i.e., Tier One-Half - the integrated OEM/supplier cooperative production facility. The one-hundred-year development of the present automotive supply chain has established the base and target for the AFCS supply chain. The key issue for the AFCS is in the development and mass production of a low-cost, robust fuel cell system.

Four elements of the evolution of the AFCS supply chain are discussed below based on Secondary Data Collection: Development Stage, Introduction Stage, Growth Stage, and Maturity Stage.

As of 2016, AFCS production levels are less than 1,000 vehicles per year for any one company and AFCSs are in the Development Stage of the product-life-cycle based on 2015 – 2016 sales data. The design of

[30] Miller, R., "The American Automotive Industry Supply Chain – In the Throes of a Rattling Revolution", International Trade Administration, April, 2005, http://www.trade.gov/td/auto/domestic/SupplyChain.pdf

[31] Vonderembse, M., and Dobrzykowski, D., "Understanding the Automotive Supply Chain: The Case for Chrysler's Toledo Supplier Park and its Integrated Partners KTPO, Magna, and OMMC", The University of Toledo, (no date given), http://www.wistrans.org/cfire/documents/AutoSupplyChainCase10_30_09%20FINAL.pdf

the AFCS is in flux with changes or new models announced by several companies indicative of a TRL-7.[32, 33]

1. **Development Stage**: The AFCS supply chain is in the early stages of development and vertical integration is dominant as shown in Figure 4-7.

   The Development Stage Metrics for AFCS production and the automotive fuel cell supply chain are:

   1. TRL 7:
      - System prototype demonstrated in an operational environment
      - Integrated test system with collateral and ancillary systems completed
   2. MRL 7
      - Low Rate Initial Production
      - Manufacturing processes initial demonstration by OEM
   3. Manufacturing Volume Requirements
      - < 1,000 AFCS per year

   In-house OEM assembly of the fuel cell stack module and integration of the hydrogen storage system and fuel cell BOP is the primary mode of AFCS fabrication in the Development Stage. The OEM has responsibility for design, materials specification, investment in manufacturing and assembly equipment. In most cases, the OEM reimburses suppliers for their investment in specialized manufacturing equipment and the OEM owns the manufacturing equipment and the processes developed by the supplier. The suppliers are identified as Tier 2 suppliers in Figure 4-7.

   Performance and durability are the important factors to be proved in the Development Stage with AFCS production rates of 1,000 or less. The customer base is often Early Adopters with a strong interest in new technology. The early adopters give OEMs and supply chain manufacturers consumer based information on performance and durability; identify malfunctions and limitations of components; and assistance in developing a commercially viable product.

   Membrane and catalyst are components fabricated by industry specialists, identified as Tier 2 suppliers in Figure 4-7. Each fuel stack will require 372 membrane sheets with an active area of approximately 299 cm^2/cell[34] and, at peak production of 1,000 AFCS unit/year, 10,000 square meters

[32] Voelcker, J., "Smaller, cheaper Toyota Mirai fuel-cell car coming in 2019, company says", Green Car Reports, May 9, 2016, http://www.greencarreports.com/news/1103847_smaller-cheaper-toyota-mirai-fuel-cell-car-coming-in-2019-company-says

[33] Daimler Global Media Site, "Under the microscope: Mercedes-Benz GLC F-CELL: The fuel cell gets a plug, http://media.daimler.com/marsMediaSite/en/instance/ko/Under-the-microscope-Mercedes-Benz-GLC-F-CELL-The-fuel-cell-.xhtml?oid=11111320

[34] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

of membrane per year. The membrane can be delivered to the OEM as cut sheets or as a (uncut) roll product.

The fuel cell catalyst is delivered to the CCM fabricator either as a dry powder dispersed as an ink ready for processing onto the membrane to form a catalyzed-coated-membrane (CCM). Slot die coating is used to deposit the catalyst onto the membrane. James[35] reports 17 grams of Pt is used for the fuel cell system using Pt/Mn/Co catalyst developed by 3M Inc. In their 2014 AMR presentation, James et al,[36] report 16.9 grams of Pt for PtNi catalyst from Johnson Matthey for an 80 kW_{net} fuel cell; this is not considered a high usage of catalyst.

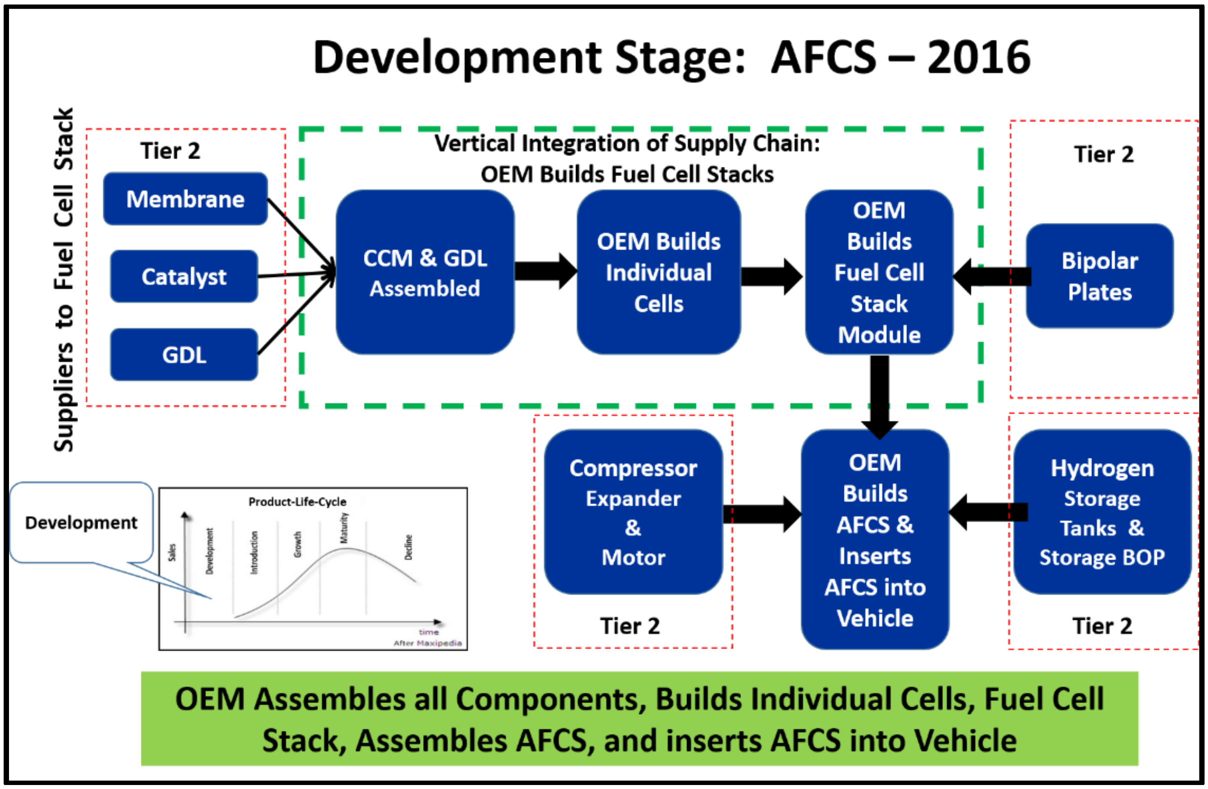

Figure 4-7: Development Stage with Vertical Integration of Automotive Supply Chain Fabrication of AFCS

The Gas Diffusion Layer fabricator, identified as a Tier 2 supplier in Figure 4-7, specializes in the preparation of carbon papers or carbon cloths. The GDL can be delivered to the OEM as either a roll

[35] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

[36] James, B., Moton, J., and Colella, W., "Fuel Cell transportation Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy's 2014 Annual Merit Review and Peer Evaluation Meeting (AMR) for the Hydrogen and Fuel Cell Technologies (FCT) Program, Project ID #FC018, Washington, DC, June 19, 2014

or a cut sheet. In the very early stages of development, individual sheets of GDLs have been manually fabricated in the laboratory.

Stainless steel bipolar plates are fabricated to the OEM's specification by an industrial metal fabricator, identified as a Tier 2 supplier in Figure 4-7. Using the 372 cells per 80 kW_{net} automotive stack referenced above, each fuel stack will require 744 plate formings (stampings or hydroforming) per 80 kW_{net} stack. The plates are coated by the metal fabricator to the specification of the OEM to prevent corrosion. Bonding of two plates to form a bipolar plate using welding or adhesive is the responsibility of the metal fabricator with delivery of 372 bipolar plates per AFCS to the OEM. At full Development Stage production, 20,000 square feet of bipolar plates are required.

The compressor/expander/motor is manufactured by a supplier specializing in the fabrication of compressor/expander/motor systems as indicated in Figure 4-7 as a Tier 2 supplier. The CEM is fabricated to the OEM specifications and is delivered to the OEM as a complete and integrated CEM system. The OEM integrates the CEM with the fuel cell stack module.

The Hydrogen Storage module is fabricated to the OEM specification by a Tier 2 supplier that specializes in winding carbon fiber composite materials to form a hydrogen storage tank. The hydrogen storage system is delivered with an integrated 70 MPa compatible HBOP as a complete module. The OEM integrates the hydrogen storage module with the fuel cell stack module as shown in Figure 4-8.

2. **Introduction Stage**: At production rates below 20,000 but greater than 1,000 units per year, the costs are decreasing in Figure 2-8. Price, delivery, manufacturing capability, and reliability are becoming the primary drivers in the growth stage. However, due to limited manufacturing capability reflecting limited investment by the OEMs and suppliers, manufacturing costs are only starting to approach levels consistent with the cost target (the 2020 DOE Target is $40/unit). To achieve the increased production volumes of the Introduction Stage, the extent of horizontal integration is increased, as shown in Figure 4-8.

   The Introduction Stage Metrics for the AFCS production and automotive supply chain are:

   1. TRL 8
      - AFCS development completed with changes in the design and components determined by performance and cost data advanced in the Development Stage.
      - Technology proven by early adopters to have fully integrated and operational hardware and software under real world conditions.
   2. MRL 8
      - Manufacturing processes demonstrate yield and productivity for pilot line manufacture.
      - All design requirements satisfied by pilot line production.
      - Cost estimates < 125% of cost goals.
      - Initial supply chain under development.
   3. Manufacturing Volume Requirements

- Beginning of Introduction Stage production at 1,000 AFCS units per year or greater.
- Conclusion of Introduction Stage production reaches 20,000 AFCS units per year.

The fabrication of membrane, catalyst, GDL, and bipolar plates remains with the Tier 2 suppliers. However, a new Tier emerges – the Tier 1 supplier – that takes responsibility assembling the fuel cell stack as shown in Figure 4-8. Communication between the Tier 2 membrane, catalyst, GDL, and bipolar plate suppliers and the OEM is decreased with the Tier 1 supplier becoming the interface with these Tier 2 suppliers. The OEM retains design and development responsibilities with manufacturing of selected components out-sourced to the Tier 1 supplier that has responsibility to communicate production and design requirements to the Tier 2 membrane, catalyst, GDL, and bipolar plate suppliers. The OEM retains responsibility to build the fuel cell stack cells, delivered by the Tier 1 supplier, into fuel cell stacks. The OEM retains responsibility to interface the fuel cell stack with the Tier 2 CEM and Tier 2 hydrogen storage suppliers following the procedures identified in the Development Stage.

The OEM retains responsibility to assemble the AFCS while horizontal integration of the supply chain increases.

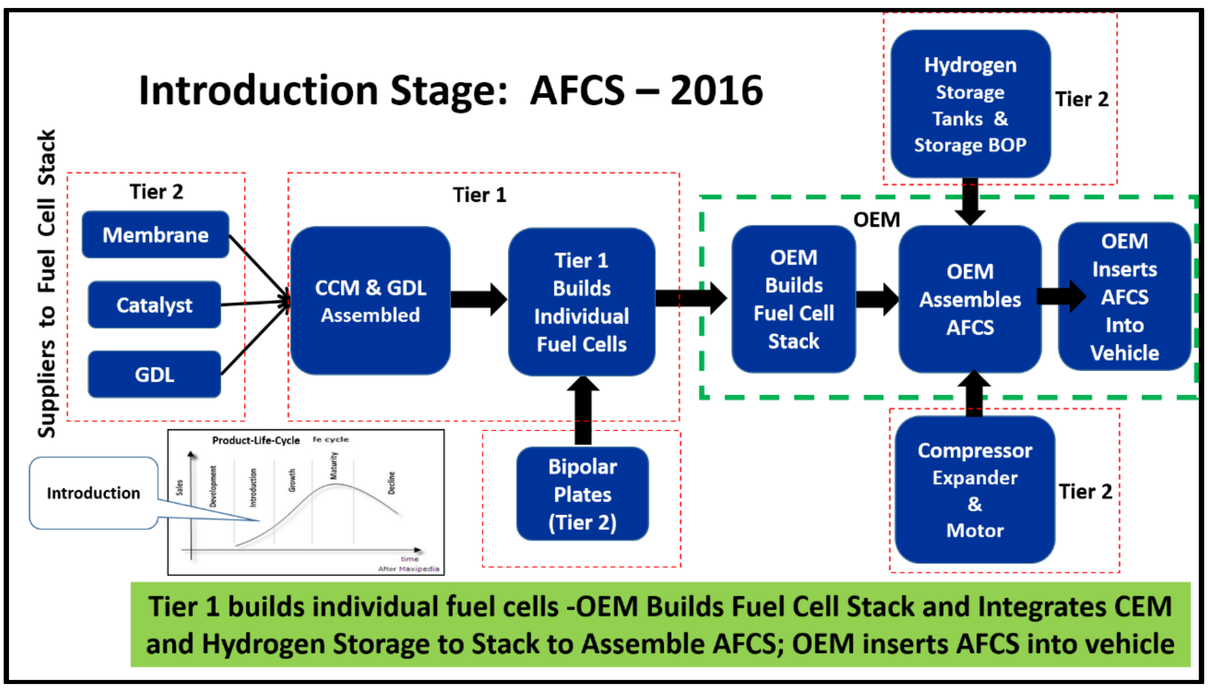

Figure 4-8: Introduction Stage with increased Horizontal Integration of Automotive Supply Chain Fabrication for AFCS

3. **Growth Stage:** At production rates of 20,000 AFCSs per year to 100,000 AFCSs per year, the cost versus production curve in Figure 2-8 begins to level suggesting design, material, and manufacturing processes are becoming fixed. Price, delivery, manufacturing capability, and reliability are the primary drivers in the Growth Stage. To achieve price targets at high rates of manufacturing, OEMs

distribute the manufacturing capabilities to Tier 1 suppliers further increasing the horizontal structure of the AFCS supply chain. Even with this evolution to a more horizontal structure, the OEM still retains AFCS design and development responsibilities. Manufacturing equipment investments by the supply chain manufacturers are reimbursed through the guaranteed purchase of components.

Technology Readiness Level has reached its maximum value at TRL 9. Growth Stage Metrics are:

1. TRL 9
    - System is successfully demonstrated in the field.
    - Fully integrated operations hardware/software systems are developed.
    - Actual application of the technology is in final form and demonstrated in the field.
    - Sustained engineering support is in place.
2. MRL 9
    - Manufacturing processes are proven.
    - Manufacturing operating at company defined sigma level with stable production.
    - Supply chain developed to meet initial production demands.
    - Cost estimates < 110% of cost goals.
3. Manufacturing Volume Requirements
    - Beginning of Growth Stage production is 20,000 AFCS units per year or greater.
    - Conclusion of Growth Stage production reaches 100,000 units per year (or higher).

The fabrication of membrane, catalyst, and GDL remains with the Tier 2 suppliers since both of these components are made by roll-to-roll processing and transportation to the Tier 1 supplier is easily and inexpensively accomplished. Fabrication rates for the bipolar plates by either stamping or hydroforming are reaching a level where production capabilities are limited to a few companies. New stamping facilities located at or adjacent to the Tier 1 facility may be needed to minimize the transport time of these bulky materials and this investment in production facilities may be the responsibility of the bipolar plate manufacturer. The Tier 1 supplier takes on additional responsibility for assembling the fuel cell stack as shown in Figure 4-9. The Tier 1 supplier may also assume investment responsibility for the design and installation of additional manufacturing capabilities. The OEM retains responsibility to assemble the AFCS while horizontal integration of the supply chain increases.

At the conclusion of the Growth Stage, AFCS reaches 100,000 units per year, a production capability consistent with full commercialization of a fuel cell vehicle. A transition to MRL 10 is attained at production rates of 100,000 units/year. Greater integration of the automotive supply chain for the AFCS at production rates five-fold greater is anticipated in the transition to the Maturity Stage. The automotive supply chain for the AFCS given in Figure 4-9 may not have peaked at 100,000 units per year and the Growth Stage automotive supply chain for AFCS may be extended to production rates of 200,000 to 300,000 AFCS units per year.

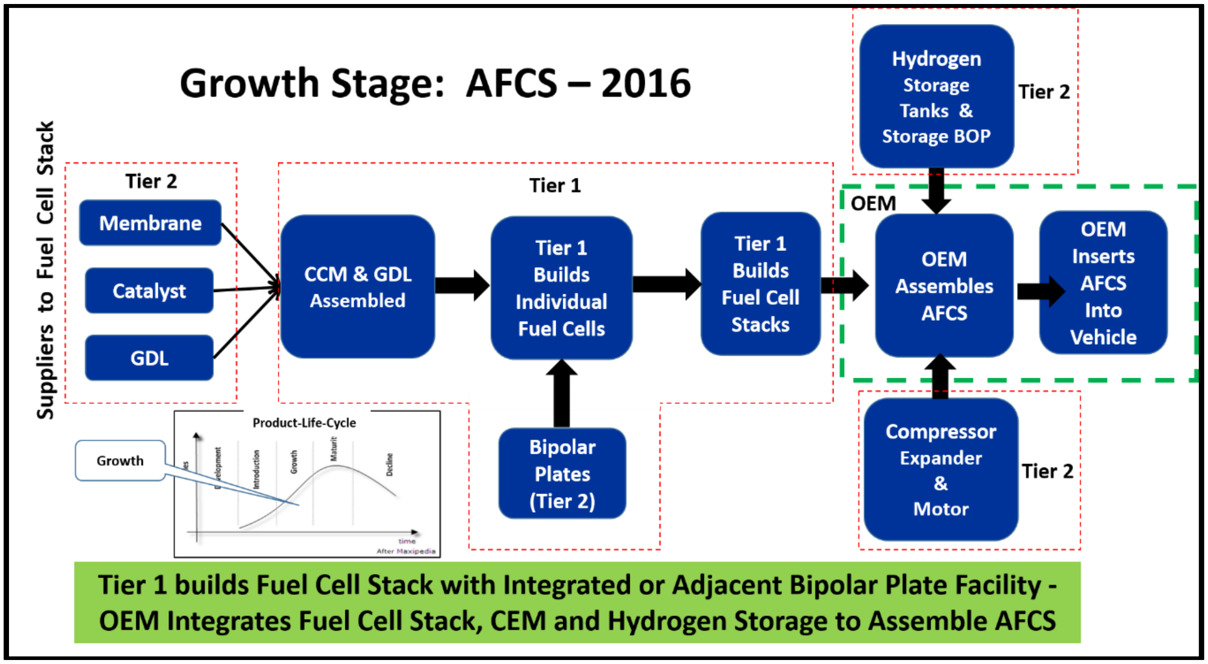

Figure 4-9: Growth Stage with increased Horizontal Integration of Automotive Supply Chain Fabrication for AFCS

4. **Maturity Stage:** In the final stages (maturity and decline), full manufacturing capability is achieved with AFCS manufacturing efficiencies improved to reach the 2020 DOE $40/kW target at production rates of 500,000 units/year.[37] At the Maturity Stage, the AFCS assembly facility is anticipated to be fully integrated with the addition of a new AFCS automotive supply chain Tier; the Tier One-Half is shown in Figure 4-10.

   Price, delivery, manufacturing capability, and reliability are the primary drivers in the Maturity Stage. To achieve the price at production rates exceeding 100,000 units per year, OEMs distribute the complete manufacturing responsibility to Tier One-Half suppliers to fully optimize the horizontal structure of the AFCS supply chain. It is anticipated that the OEM would relinquish design and manufacturing responsibility but even with this evolution to a more horizontal structure in the supply chain, the OEM would retain ownership of the design. Investments by the supply chain manufacturers in manufacturing equipment are reimbursed through the guaranteed purchase of components.

[37] James, B., "2015 DOE Hydrogen and Fuel Cells Program Review - Fuel Cell Vehicle and Bus Cost Analysis", Strategic Analysis, Inc., U.S. Department of Energy, Fuel Cell Technologies Annual Merit Review, Project ID# FC018, June, 2015

The Maturity Stage Metrics have reached their maximum values and are:

1. TRL 10
   - System is successfully demonstrated in the field.
   - Fully integrated operations hardware/software systems are developed.
   - Actual application of the technology is in final form and demonstrated in the field.
   - Sustained engineering support is in place.
2. MRL 10
   - Full rate production demonstrated and lean production practices in place.
   - Quality at six sigma or defined quality target.
   - Just-In-Time processes define supply chain
   - Manufacturing meets cost goals.
3. Manufacturing Volume Requirements
   - Beginning of Maturity Stage production at 100,000 AFCS units per year or greater.
   - Conclusion of Maturity Stage production reaches 500,000 AFCS units per year.

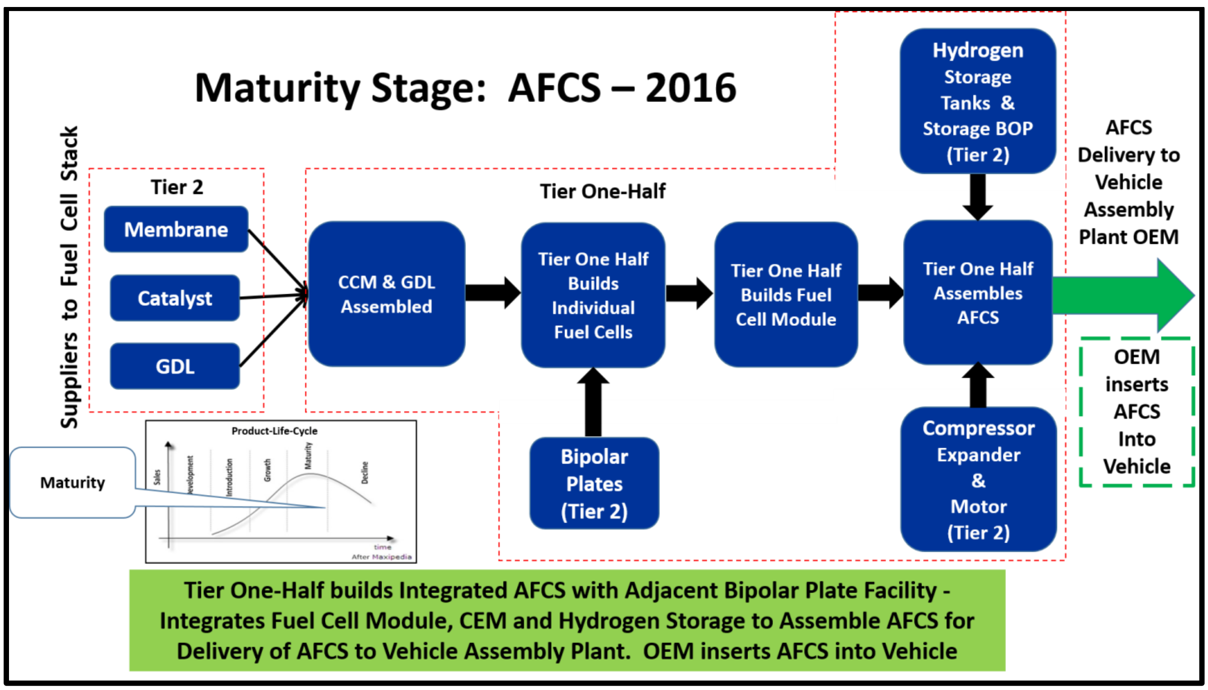

Figure 4-10: Maturity Stage with Fully Integrated Assembly of the AFCS by a Tier One-Half Supplier

The Maturity Stage represents full implementation of the JIT assembly methodology. AFCS production rates would match those of current mass produced conventional vehicle power plants: thirty-five vehicles per hour, two 8 hour shifts/day, 220 work-days/year, 120,000+ vehicles per year, using data from the Vonderembse and Dobrzykowski.[38]

The fabrication of membrane, catalyst, and GDL remains with the Tier 2 suppliers since both of these components are made by roll-to-roll processing and transportation to the Tier One-Half supplier is not an issue. Fabrication rates for the bipolar plates by either stamping or hydroforming are at a level where production capabilities are limited to a few companies. New stamping facilities located at or adjacent to the Tier One-Half facility may be needed to minimize the transport time of these bulky materials and this investment in production facilities may be the responsibility of the bipolar plate manufacturer. The Tier One-Half supplier takes on the responsibility for building both the fuel cell stack and complete AFCS, as shown in Figure 4-10, and may also assume investment responsibility for the design and installation of additional manufacturing capabilities.

[38] Vonderembse, M., and Dobrzykowski, D., "Understanding the Automotive Supply Chain: The Case for Chrysler's Toledo Supplier Park and its Integrated Partners KTPO, Magna, and OMMC", The University of Toledo, (no date given), http://www.wistrans.org/cfire/documents/AutoSupplyChainCase10_30_09%20FINAL.pdf

4.6 Mapping of the Evolution of the Automotive Supply Chain:

The evolution of the automotive supply chain for the fabrication of the AFCS will make the transition from vertical integration at the vehicle manufacturer to a horizontal integration working with suppliers as the volume of AFCSs manufactured increases from <1,000 to greater than 20,000/year. At full commercial volumes of 500,000/year, we anticipate the development of a Tier One-Half supplier; however, the establishment of a Tier One-Half supplier will be dependent upon each of the OEMs. Some OEMs may not be willing to relinquish design control and manufacturing responsibilities and maintain AFCS assembly responsibility. The transition in responsibilities of the production of the AFCS by the OEM is mapped in Figure 4-11.

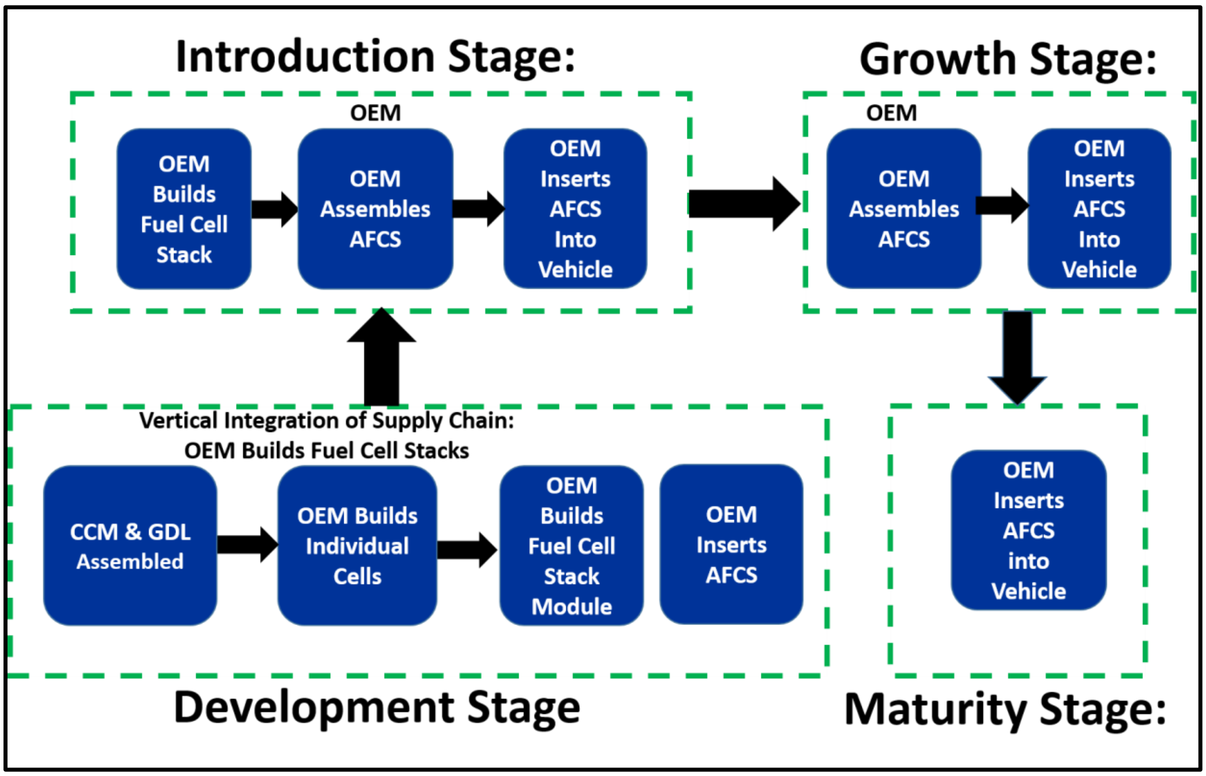

Figure 4-11: Map of the anticipated OEM transition in responsibility for the production of the AFCS with different life cycles.

In the Product-Life-Cycle concept presented below for the evolution of the supply chain, the OEM relinquishes design and manufacturing responsibility to the Tier 1 supplier with the eventual development of the Tier One-Half supplier as mapped in Figure 4-12.

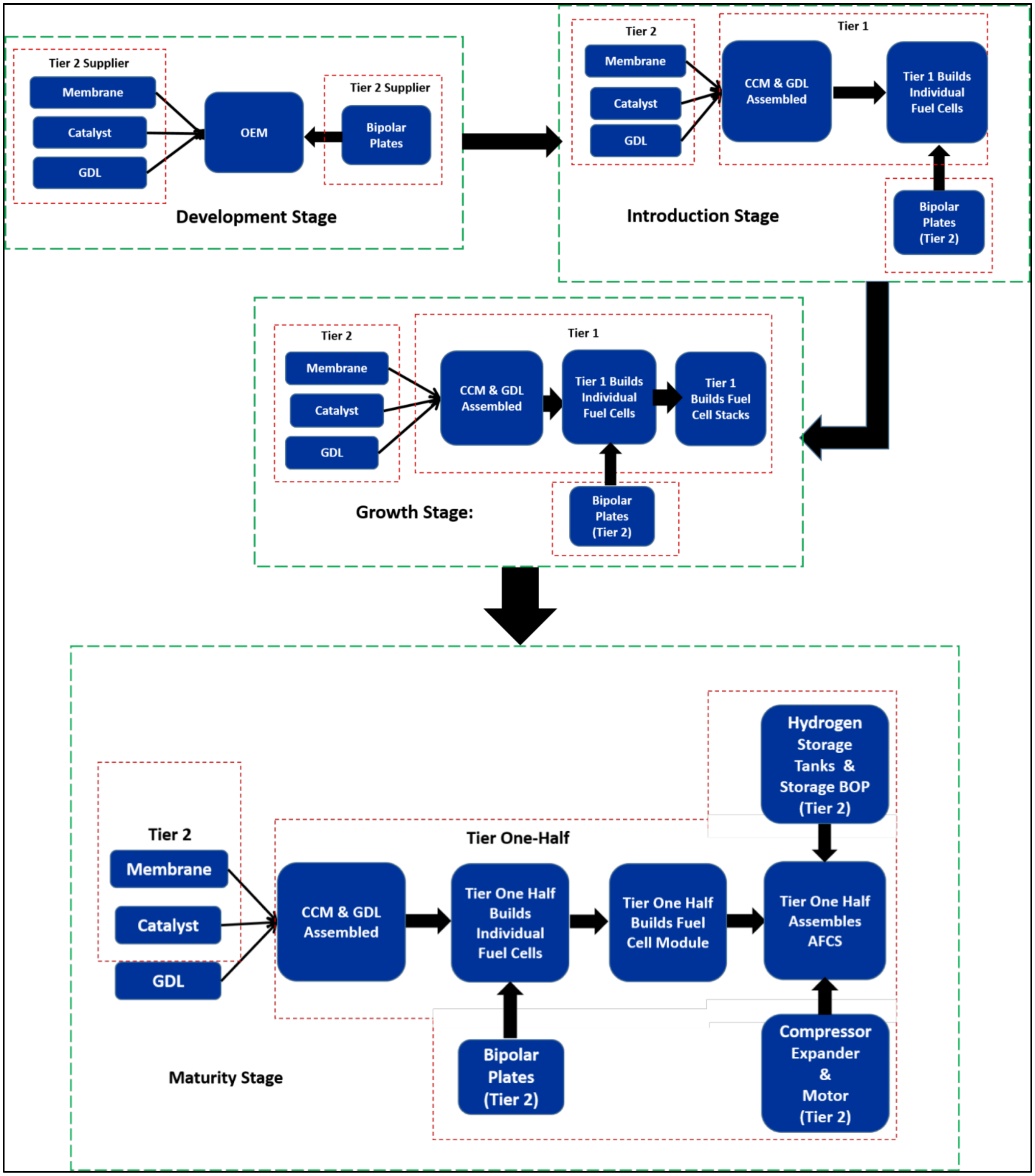

Figure 4-12: Map of the Transition of Tier 1 supplier to Tier One-Half for the Production of AFCS.

5 Global Component Cost Comparison

In a mature market, cost and performance are expected to drive competition. However, the fuel cell automotive industry is nascent and is characterized by a supply chain that is more focused on improving cost and performance through technical innovation rather than on siting manufacturing with the lowest costs. Studies were carried out to understand how regional cost differences might figure in to where fuel cell component suppliers will ultimately build new manufacturing facilities.

Several approaches were taken to probe regional cost differences as will be described below. The analysis focused on production rates for a hypothetical company producing components sufficient to supply an OEM producing 10k and 100k fuel cell vehicles per year. The fuel cell stack is assumed to be 80 kW_{net}, and 5.6 kg of available H_2 is assumed to be stored on-board in 700 bar type IV pressure vessels. These production rates (10k and 100k vehicles per year) were selected because they represent the point at which manufacturing equipment begins to be highly utilized at the low end and the minimum number of annual fuel cell vehicle sales that OEMs felt would represent a mature fuel cell vehicle market.

There are a number of limitations of this analysis that should be noted. There are limited numbers of manufacturers producing fuel cell components, thus manufacturers are reluctant to share many details for fear of exposing competitive details. This is especially true of manufacturer's current commercial products, which are produced in low volume. At high volume, there are no manufacturers producing fuel cell components (with the exception of type IV pressure vessels, which are produced at high volume for the CNG market). The manufacturing assumptions made in the models, therefore, represent our best assumptions based on what is available in the open literature, engineering extrapolation of analogous processes, and are supported by discussions with manufacturers and OEMs.

The regional cost analysis below was conducted for the five highest cost components (membranes, catalyst, gas diffusion layer, bipolar plates, and type IV pressure vessels).

5.1 Analysis Methodology

Multiple approaches were used in this project to understand regional manufacturing cost factors. Briefly, Design for Manufacture and Assembly (DFMA®) was used to estimate the size and number of capital equipment and material costs required for a greenfield manufacturing plant. In addition, DFMA® provides insight into what if any processing steps or materials are dominant cost categories. To assess regional cost variations, two approaches were taken. Cost breakdown analysis (CBA) was used to adjust the DFMA® results and account for operating expenses based on feedback received from suppliers interviewed, representing our attempt to quantify regional differences from the common DFMA® baseline. Since the number of suppliers we were able to interview and, indeed, the number of suppliers who are producing at the scale and volume studies is limited, we also report discounted cash flow cost results as a way to understand the regional costs found in the CBA. Finally, a value stream map was generated to track the labor content in each component. Figure 5-1 graphically illustrates the connections between the different cost analysis approaches, and further details of the three methodologies are provided below.

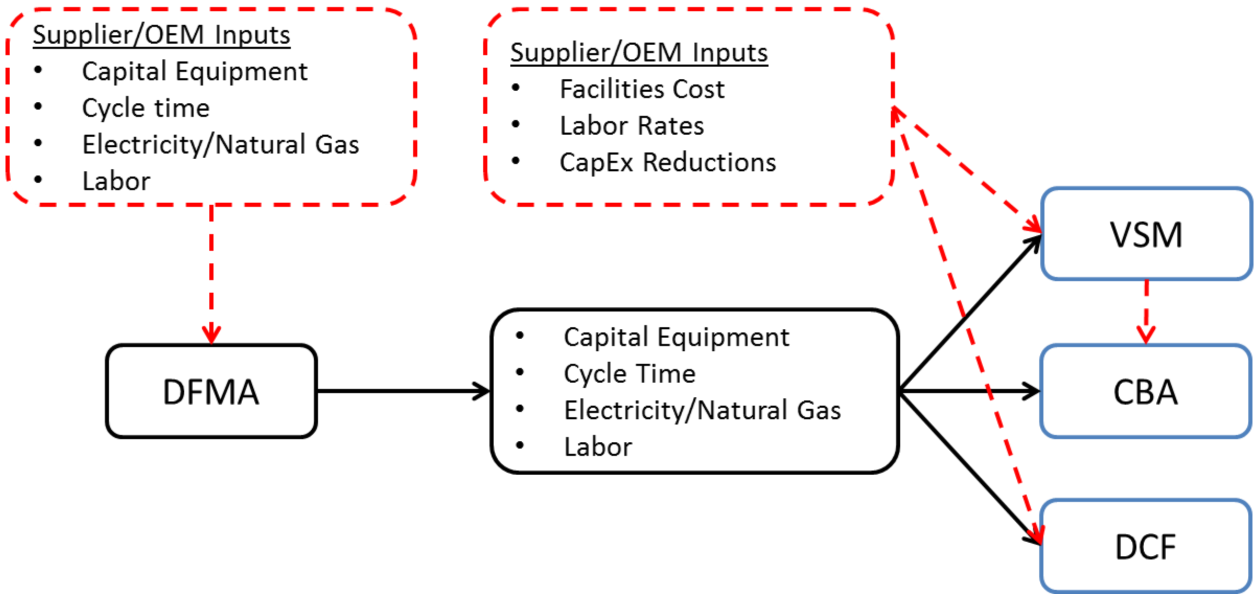

Figure 5-1: A schematic representation of the inter-relatedness of the different cost analysis approaches.

Fuel cell system and H_2 storage system components selection, manufacturing assumptions and performance are described in detail elsewhere [1], [10] and are consistent with an 80 kW_{net} light-duty (automotive) system. A summary of the system operating conditions is presented in Table 9-2 and the H_2 storage system assumptions are presented in Table 9-3.

5.2 Cost Model Assumptions

5.2.1 DFMA

Design for manufacture and assembly (DFMA®) is a process-based, ground up, engineering model used to estimate the manufacturing cost of a component. Assumptions used in the DFMA® model are based on conventional North American automotive operations and are used to estimate the cost of producing a component for a new manufacturing line installed in an existing facility [1]. The analysis reported here differs from the approach in Reference [1] in that facilities costs were estimated since developed land cost is expected to be one potentially significant regional cost difference. By convention, Strategic Analysis excludes business expenses (sometimes called Sales, General & Administrative (SG&A) expenses) when modeling cost using DFMA® since the purpose of DFMA® is to estimate the impact of technology choices on system cost. Outputs from the DFMA® models provide estimates of capital equipment costs, tooling, materials, electricity and natural gas usage, and labor requirements broken down by each process step. Moreover, these are accurately sized to achieve a target production volume.

5.2.2 DCF

Discounted Cash Flow (DCF) is a business valuation model used to identify a minimum sustainable price (MSP), which meets an expected rate of return for regionally varying levels of investment risk. A hybrid approach was taken for capital and operational expenses. DCF is used with publicly available inputs (e.g., Bureau of Labor Statistics) to provide insight into the other models based on referenceable regional cost factors. DCF also provides a one-to-one comparison with competitiveness analysis reports from other EERE technology offices. The DCF and CBA models are very similar yet come about their estimates in slightly different fashions: thus insight and validation can be achieved by a comparing the two results.

As shown in Figure 5-1, the DFMA® results feed into the DCF analysis. While the DCF explicitly uses many of the DFMA® values (for capital equipment cost, electricity usage, cycle times, labor usage), several cost categories only appear in the DCF analysis:

- Sales, General & Administrative (SG&A)
- Facility costs
- R&D costs
- Profit/Return on Investment

Sources of the country specific data values are discussed below.

Wage data, broken down by labor category in the United States, are reported in the Bureau of Labor Statistics and were used for unskilled, skilled, and supervisors.[39] These wages were scaled by the international labor comparison rates[40] to estimate labor costs by category for non-U.S. labor. Utilities costs were taken from the international energy price comparison statistics.[41] Average historical average inflation from the International Monetary Fund reported for the period between 2000 and 2016 was used.[42]

The cost of capital is both industry and region specific. Past competitiveness analyses of lithium-ion batteries [11] and solar photovoltaics [12] investigate the impact of the cost of capital using data from publicly traded companies to develop a weighted average cost of capital within a capital assets pricing model. The fuel cell industry is in an earlier stage of development, thus publicly available data are scarce and the rates of return that investors demand are expected to be different. Consequently, a common industry-wide rate of return of 10% (real, after tax) was assumed. The discounted cash flow model therefore provides insight into regional costs of doing business that can be quantified using well-established data (e.g., inflation, labor, and utilities).

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[39] https://www.bls.gov/OES/current/oes519198.htm#ind https://www.bls.gov/oes/current/oes519141.htm www.bls.gov/oes/current/oes511011.htm
[40] https://www.bls.gov/ilc/country.htm
[41] https://www.gov.uk/government/collections/international-energy-price-comparisons
[42] https://www.imf.org/external/pubs/ft/weo/2016/01/weodata/index.aspx

5.2.3 CBA

Cost Breakdown Analysis (CBA) model is used to estimate the projected component sales price based on a set of regionally varying assumptions for capital equipment, labor, and utility rate inputs. Inputs to the CBA are obtained from the DFMA® model, the VSM, and supplier/OEM input from RFQs and interviews. A cost breakdown analysis form was developed for each of the five key components. It included a complete bill of materials with net weights, general process steps for labor and burden, categories of SGA, engineering, and profit. Most suppliers were protective of the detailed information and would only share general information. Based upon the general cost information, a derived cost was developed through the DFMA. The CBA utilized the material cost from the DFMA® unless advised otherwise by supplier; labor was used from the VSM, burden utilized the DFMA® equipment payments, maintenance, facilities, tooling and electricity; and standard SGA, Engineering, and profit mark-ups were used. Data were consolidated into a spread sheet and aggregated for this final report out.

It must be considered in this study, as in any commercial quotation activity, that some suppliers will be aggressive with quoted prices while others will be conservative. In the regions where we had multiple cost input, it was found that the cost data in a given region were consistent, which supports the use of the aggregated numbers reported in this project.

Global suppliers were identified in the U.S., Europe, Japan, and China through prior DOE project work, awareness by our project team, and recommendations from some OEMs in the interview process. Targeted suppliers were asked to participate. The goal was at least one supplier per region. In the case of bipolar plates, we were able to interview and/or visit the number of manufacturers shown below. Table 5-1 shows that manufacturers interviewed and or visited are currently making components for automotive or bus PEM fuel cell vehicles today or in the recent past. *Indicates that data were gathered during the interviews.

Table 5-1: Number of suppliers for each of the five components studied.

COMPONENT	U.S.	Asia	Europe
Bipolar Plates	2	2	2
Cathode Catalyst	*1	1	2
Gas Diffusion Layer	*1	1	2
Membrane	**1**	**2**	**1**
H_2 Pressure Vessel	1	1	1

VSMs are a display format that concisely illustrates each manufacturing unit operation, cycle time, material input, and labor cost. The VSMs are informed by the DFMA® and refined by feedback provided during interviews and plant visits with suppliers and OEMs. This is a project team tool for process refinement and cost reduction. Figure 5-2 below shows a representative value stream map.

VSM is an important tool that characterizes both information and material flow from the point of getting a customer order at the manufacturing plant, through the orders forwarded by the manufacturing plant to the material suppliers, the material being received at the manufacturing plant and processed through the system, to the final product ready to be shipped to the customer.

VSMs were generated for each manufacturer from data gathered during the plant visit and prior knowledge. This tool enables the identification of areas of waste (value added and non-value added) and improvement opportunities for domestic suppliers with a look across all global suppliers. Six Sigma and Lean can be applied to improve the process. Complete value stream maps for the components studied can be found in Appendix 4 Component Value Stream Maps.

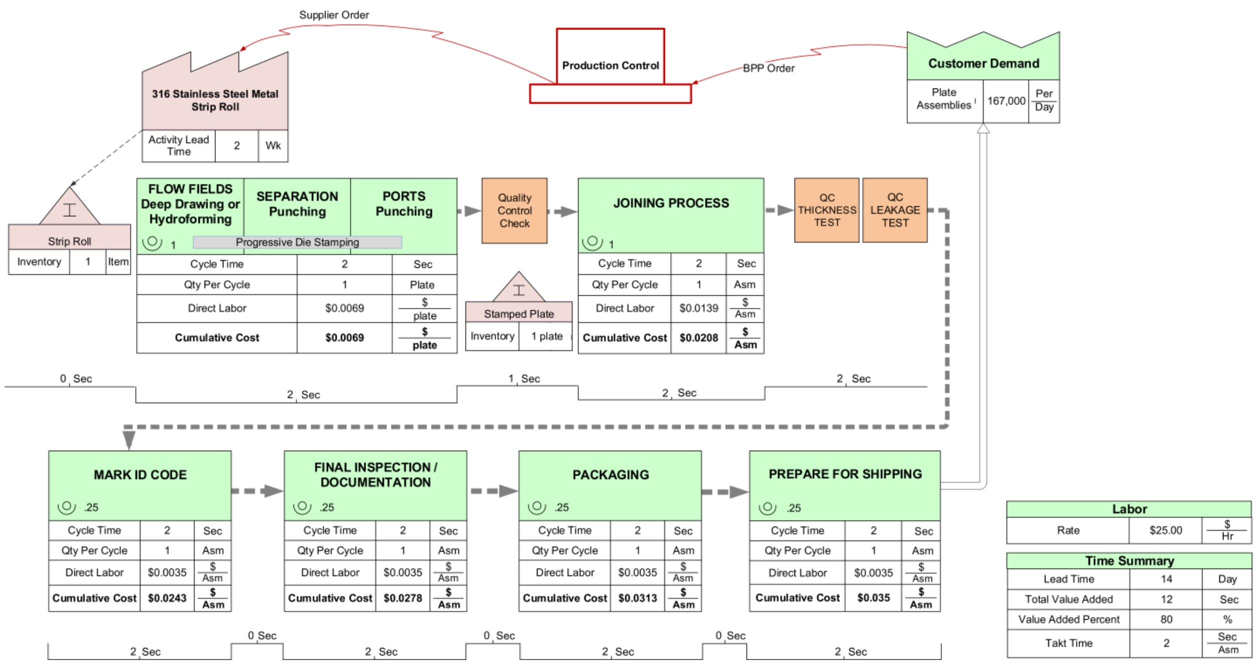

Figure 5-2: Representative value stream map of bipolar plate process

Standardized component specifications and detailed drawings were developed with knowledge from Strategic Analysis, GLWN, and industry. Suppliers were invited to submit cost quotations based on these drawings to enable an apples-to-apples comparison between global manufacturers' active in the industry, but with non-proprietary designs. Component specifications can be found in Appendix 5: Component Specifications for Supplier Quotes.

Team members from GLWN, E4tech, and Strategic Analysis visited and collected manufacturing cost and process data from 20 suppliers in U.S., Europe, and Asia for bipolar plates, membrane, gas diffusion layer, catalyst ink, and high pressure hydrogen storage vessel. The tools of DFMA, CBA, and VSM were used to understand the cost and manufacturing process.

5.3 Bipolar Plate

Initial capital investment (Table 5-2) to build a greenfield bipolar plate facility in the United States capable of producing approximately 3.7M and 37M welded bipolar plate assemblies per year (to supply 10k and 100k vehicles per year) is estimated to be $16.4M and $116.1M, respectively.

Table 5-2: Estimated bipolar plate manufacturing facility capital cost and direct process line labor requirements

	10k/year	100k/year
Facilities Cost (U.S.$)	5.1M	35.7M
Capital Equipment (Installed, U.S.$)	11.3M	80.4M
Workforce (skilled, unskilled, and supervisors)	3	17

A cost breakdown from the DFMA® model by the processing steps defined and by operating cost is shown in Figure 5-3. Bipolar plate cost is dominated by the forming operation, progressive die stamping in this case, at both volumes investigated. Materials and capital equipment cost dominate the operating expenses.

A DFMA® cost breakdown analysis for bipolar plates produced in the United States at 100,000 vehicles/yr (3.7M BPP assemblies per year) is presented in Figure 5-3. Multiple lines will be required. For the PEM automotive fuel cell, we have found that the stainless steel plate is preferred. One design was developed with a common bill of material (BOM) to obtain a global cost comparison. GLWN collaborated with SA and industry manufacturers in developing a generic, non-proprietary bipolar plate design to enable quoted cost comparisons between global manufacturers (see Appendix 5.1: Bipolar Plates). Figure 5-4 shows the aggregated regional cost breakdown of a 26 gram, welded stainless steel bipolar plate by major cost categories of material, labor, burden, SGA, engineering, and profit. Material accounted for 39% of the total cost, with direct labor at 2%, burden at 49%, SGA at 2%, Engineering at 2%, and profit at 5%. Burden is the highest at 49% with equipment payments, tooling, maintenance, electricity and facilities cost included. Suppliers in all countries noted that the DFMA® total costs are close to target. It is noteworthy that there is relatively little cost difference between regions in quoted cost.

The material specified was 316 Stainless Steel and is a global commodity with global pricing. The direct labor cost was developed with the VSM and shows the variation in labor rate and process manpower observed by region. Burden cost from DFMA® is primarily driven by the new stamping-assembly-welding-assembly process equipment payments. The equipment is globally available. Standard rates were applied to SGA at 3%, Engineering at 3%, and Profit 5% unless noted different. ***Overall we do not see significant variation by region.***

Bipolar plates are the second largest cost contributor in a fuel cell stack at 23% for 100k vehicles/year volume. The burden cost is at 50% of the total cost with equipment and tooling 65% of the burden cost. The process of stamping- handling-assembly of the thin bipolar plates is a significant challenge. Welding is the bottleneck of the steel plates. Engineering solutions can achieve faster cycle times (<2 s) via multiple welding beams and progressive welding stations. R&D (Research and Development) areas for improvement would be laser welding process, roll-to-roll continuous production, custom design of materials, sealing material and process, coating material and process, and power density flow field.

Discounted cash flow analysis, and corresponding single point sensitivity analysis, is shown in Figure 5-5 at 10,000 vehicles per year and at 100,000 vehicles per year. The sensitivity results show that component costs are driven by capital equipment and materials costs. Material costs were assumed to be commodity prices that are constant across all regions; however, existing supplier relationships and bulk purchase could have a significant impact on the ability of U.S. companies to compete on the global fuel cell market. Access to low-cost capital and manufacturing equipment discounts could also tip U.S. competitiveness.

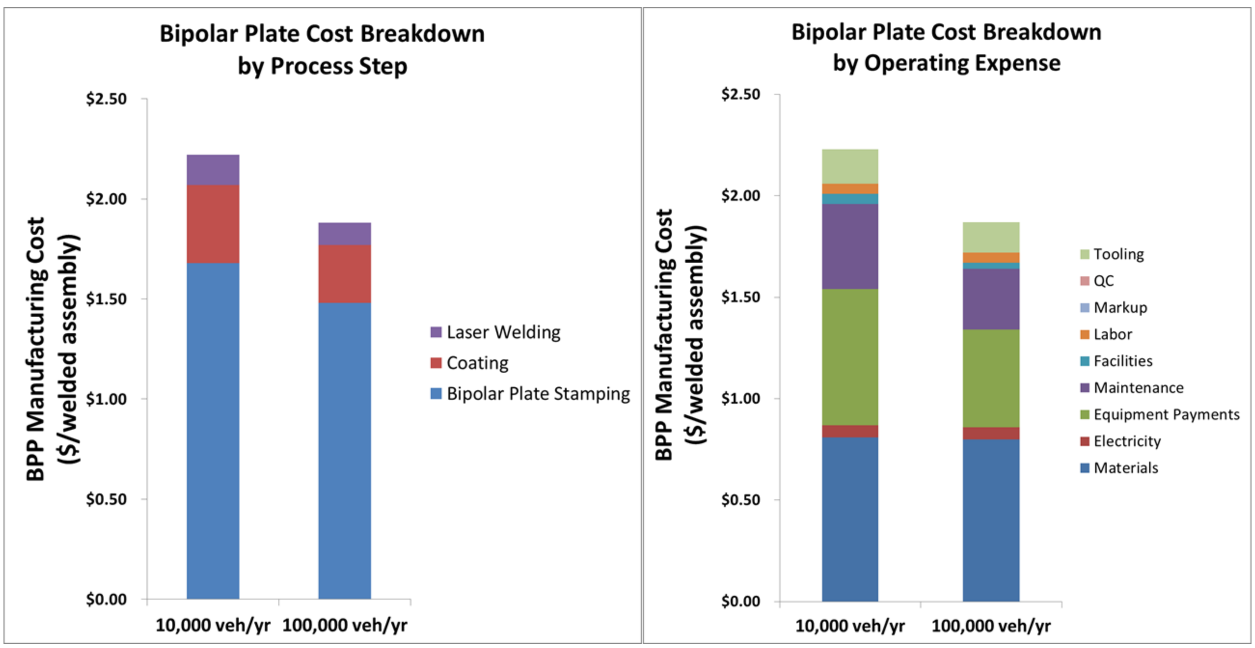

Figure 5-3: Bipolar plate cost breakdown by processing step (left) and operating expense (right).

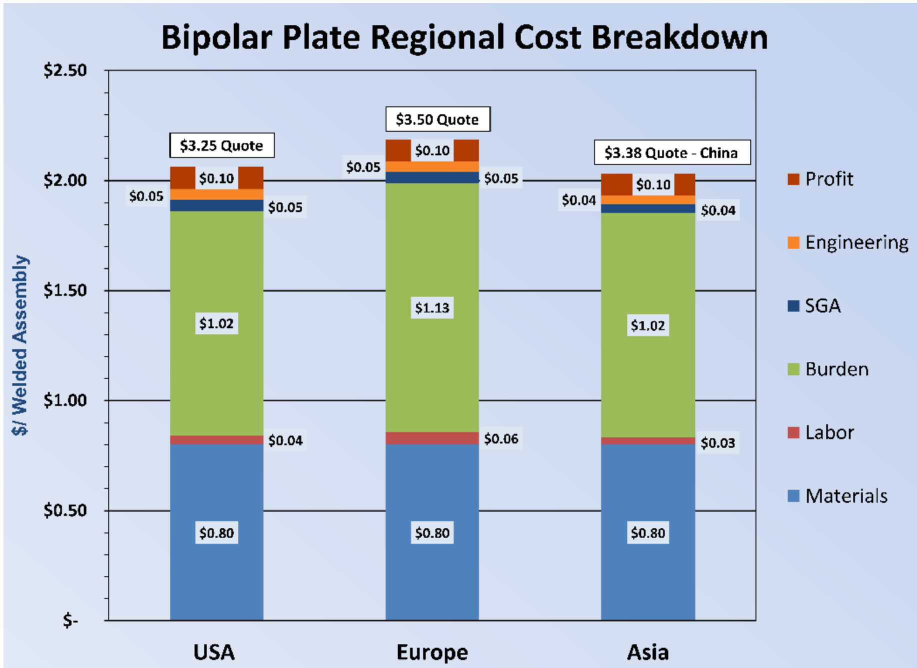

Figure 5-4: Regional cost breakdown for bipolar plate assembly at 100,000 veh/yr.

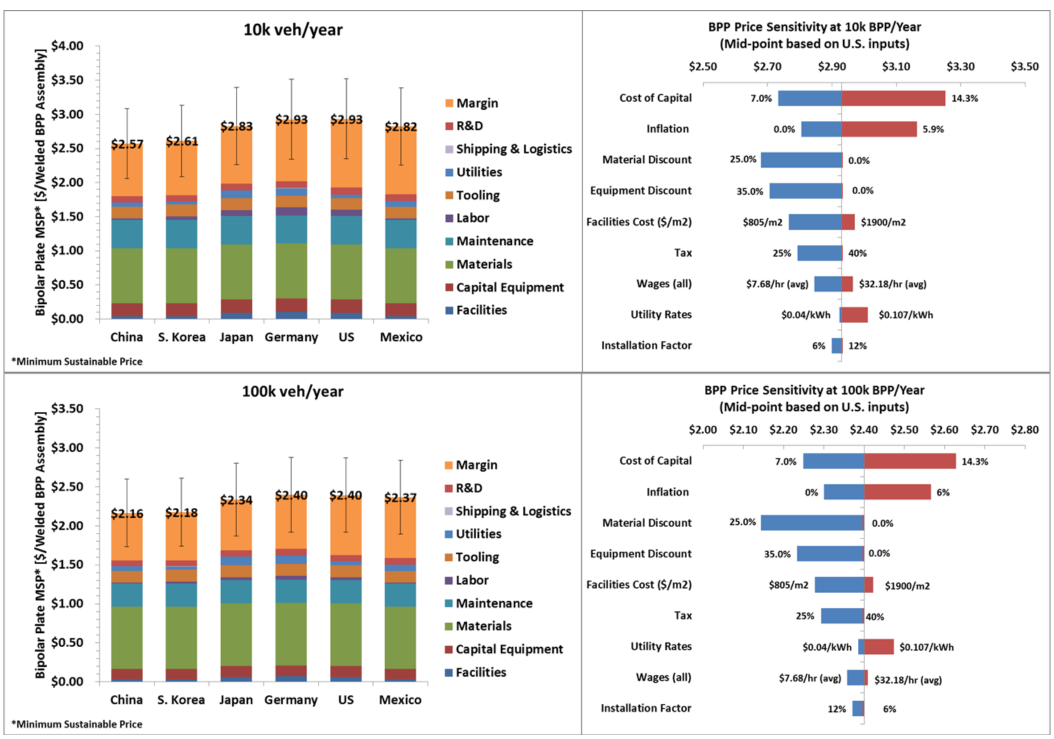

Figure 5-5: Summary bipolar plate discounted cash flow analysis.

Bipolar Plate Value Stream Mapping

The following Figure 5-6 is one of the bipolar plate value stream maps based upon plant visits and or data obtained in interviews with manufacturers or equipment suppliers. Table 5-3 shows bipolar plate key process steps and labor cost per part. Additional examples of VSMs are found in Appendix 4.1.

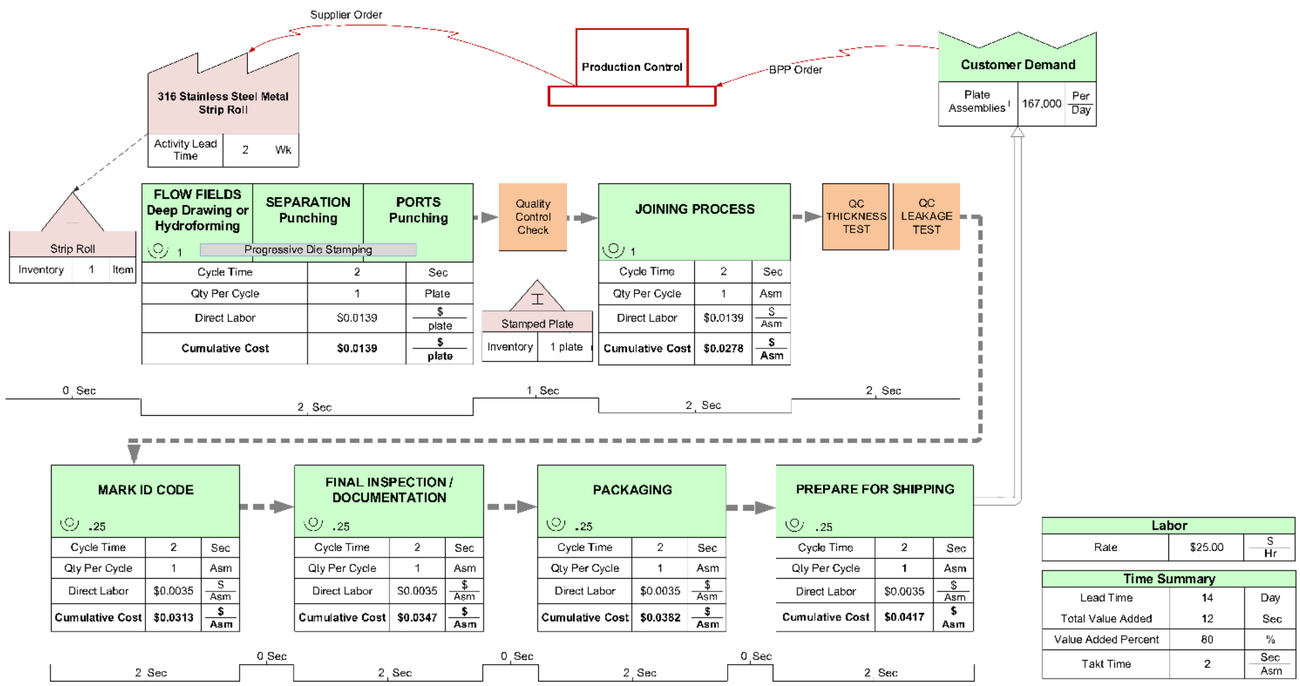

Figure 5-6: Bipolar Plate Manufacturing Value Stream Map

Process Specs	Hydroform, Separation, Ports	Joining	Marking	Final Inspect	Package	Prepare to Ship
No of Operators	1	1	0.25	0.25	0.25	0.25
Cycle Time (Sec)	2	2	2	2	2	2
Qty per Cycle	1	1	1	1	1	1
Direct Labor	$0.0139	$0.0139	$0.0035	$0.0035	$0.0035	$0.0035
Cumulative Labor	$0.0139	$0.0278	$0.0313	$0.0347	$0.0382	**$0.0417**

Rate per hour	$25.00
Rate per minute	$0.417
Rate per second (1)	$0.007

Table 5-3: Bipolar Plate labor cost per part by process

5.4 Cathode Catalyst

Initial capital investment (Table 5-4) to build a greenfield cathode catalyst facility in the United States to supply 10k and 100k vehicles per year, capable of producing approximately 530 kg/year and 5,200 kg/year of cathode catalyst per year, is estimated to be $12.3M and $16M, respectively.

Table 5-4: Estimated cathode catalyst manufacturing facility capital cost and direct process line labor.

	10k/year	100k/year
Facilities Cost (US$)	11.1M	13.6M
Capital Equipment (Installed, US$)	1.3M	2.4M
Workforce (skilled, unskilled, and supervisors)	3	24

A cost breakdown from the DFMA® model by the processing steps and by operating cost, is shown in Figure 5-7. Catalyst cost is dominated by material cost, specifically Pt, which appears in the PtNi precursor forming step. Equipment utilization and favorable equipment size scaling dominates the cost reduction from 10k to 100k vehicle per year volumes.

Figure 5-8 shows the aggregated cost breakdown by region (US, Europe, Asia) of 1 gram platinum ink at 100k vehicles per year by major cost categories of material, labor, burden, SGA, engineering, and profit. Material accounted for 91% of the total cost, with direct labor at 1%, burden at 3%, SGA at 1%, Engineering at 1%, profit at 2%.
Material is the highest at 91% due to price of platinum. For the material, platinum is a global commodity with global pricing. The direct labor cost was developed with the VSM and it shows the variation in labor rate and process manpower observed by region. Burden cost from DFMA® is primarily driven by quality checks, equipment payments, maintenance, facilities, and electricity. Standard rates were applied to SGA , Engineering and Profit.

Overall we do not see significant variation by region. Based on discussions with suppliers in Europe, labor is expected to be 1% of the total cost, while materials are expected to be 93% similar to the DFMA® results. Suppliers in Europe noted that the DFMA® total cost is within +/- 10%. Figure 5-9 shows the discounted cash flow analysis at 10k vehicles per year and 100k vehicles per year. Single point sensitivity analyses for each production rate are shown in the right panels.

Cathode catalyst conclusions:

- High cost of materials
- Not captured in our single point analyses, but engineering and physical security of the platinum will be significant drivers of cost and will probably also impact competitiveness.
- Shipping and logistics are taken as a single, per container, cost of $1500, which is sufficient from a weight and volume standpoint to ship catalyst at all volumes. This cost does not capture tariffs due to the high intrinsic cost of catalyst or the cost of securing the platinum during shipment.

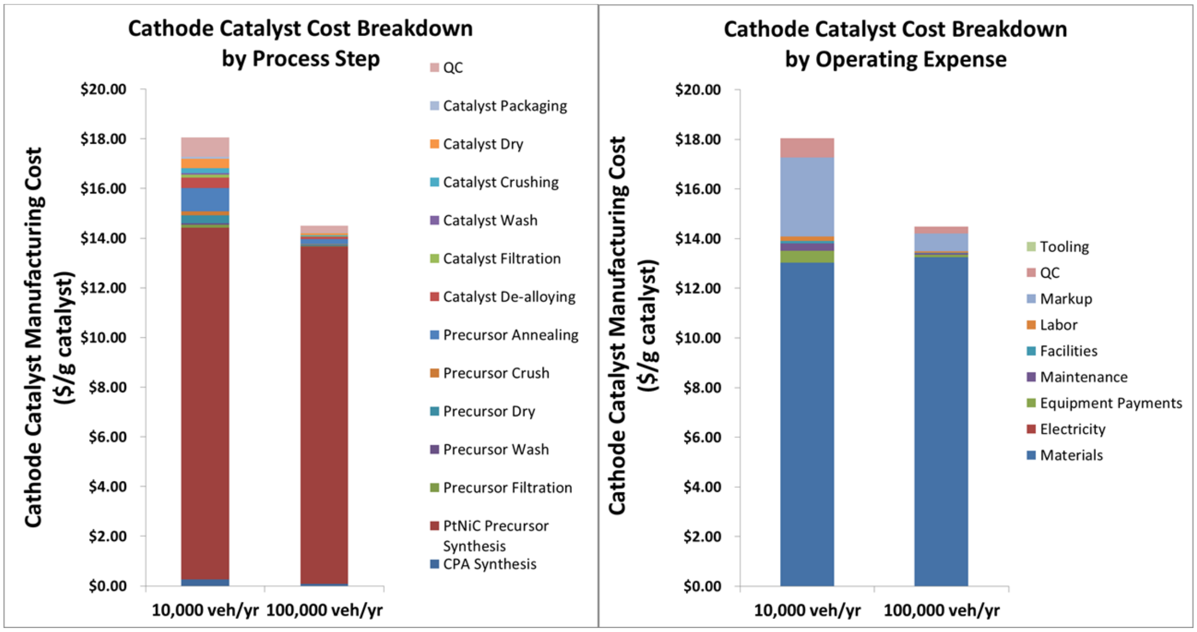

Figure 5-7: De-alloyed PtNi cathode catalyst cost breakdown by processing step (left) and operating expense (right).

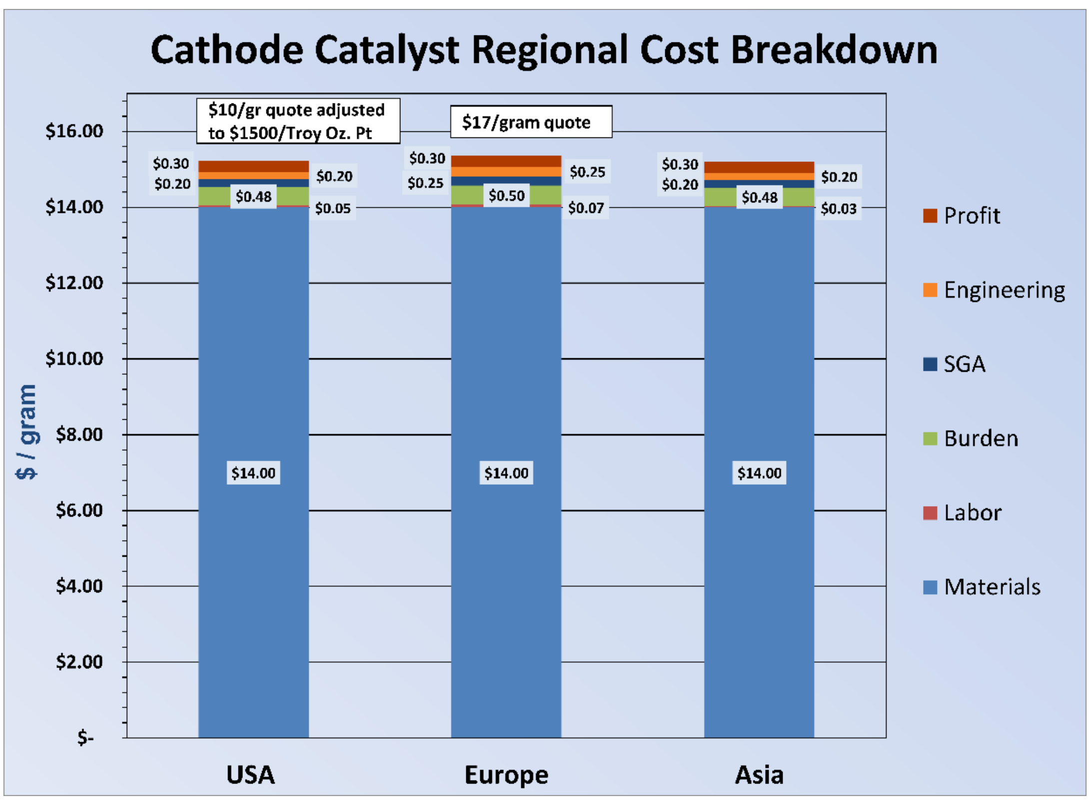

Figure 5-8: Regional cost breakdown for cathode catalyst at 100,000 veh/yr.

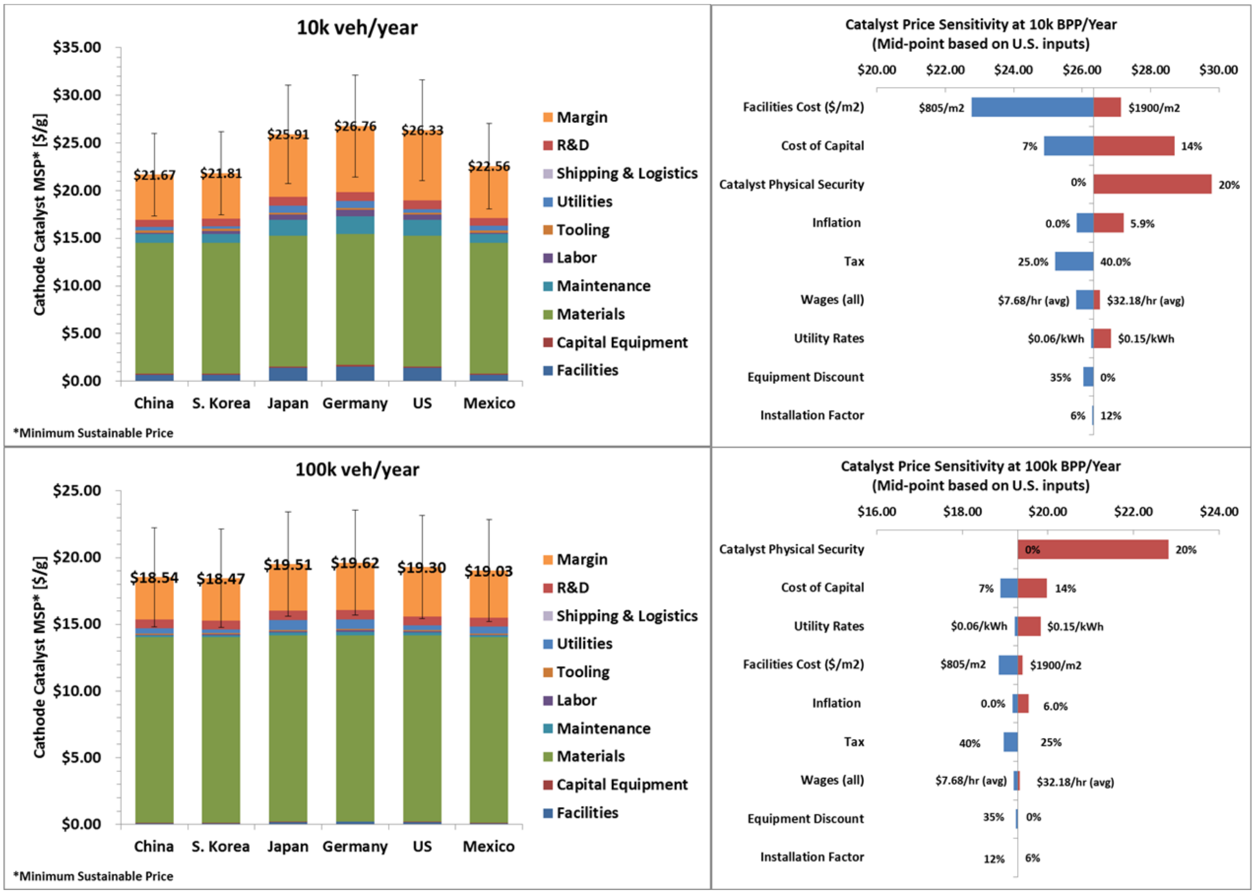

Figure 5-9: Summary cathode catalyst discounted cash flow analysis

Catalyst is the largest cost contributor in a fuel cell stack at 40%. The material cost is at 91% of the total cost. Precious metal (Pt) catalysts are expected for the foreseeable future. The focus is on durability, performance, and Pt reduction to 7-9 gram Pt per system. High barriers exist to entry into the catalyst business. Only three to four global catalyst suppliers viewed as suitable reliable suppliers for OEM long term relationships. Long development cycles, high overhead, much IP and trade secrets. Physical security of platinum through all stages is a concern. R&D (Research and Development) areas for improvement would be different ink formulation for cathode, different elements, and reduced Pt loading.

The catalyst cost component has the platinum group metal (PGM)) catalyst dispersed on particulate carbon support. Typically, the catalyst is prepared by a company specializing in fabrication of PGM catalyst because of the high cost of raw materials and complexity of the catalyst preparation and recovery of scrap. The catalyst cost component includes the development of the catalyst ink for coating onto the membrane to fabricate a catalyst coated membrane.

Catalyst fabrication companies have a close association with the precious metal mining industry and these precious metal fabricators produce most, if not all, of the fuel cell catalyst. These companies have established protocols that minimize precious metal scrap, in some cases the precious metal fabricators have developed proprietary processes for producing fuel cell quality catalysts. The OEM specifies the catalyst composition, structure, and quality to the catalyst fabricator. Many of the catalyst producers have established working relationships with light vehicle manufacturers based on catalytic converters currently used with internal combustion engines.

Cathode Catalyst Value Stream Mapping

The following Figure 5-10 is one of the cathode catalyst value stream maps based upon plant visits and or data obtained in interviews with manufacturers. Table 5-5 shows catalyst key process steps and labor cost. More examples of VSMs are found in Appendix 4.2.

Figure 5-10: Cathode Catalyst Manufacturing Value Stream Map

Table 5-5: Cathode Catalyst labor cost by process

Process Specs	CPA & Pt Donor Reactant	PtNi/C Precursor Reaction (2 lines)	Filter & Wash	PtNi/C Precursor Dry	PtNi/C Precur-sor Crush	Vacuum Anneal (2 lines)	De-Alloy	Filter & Wash	Vacuum Dry (2 lines)	Catalyst Crush	Pkg & Prep to Ship
No of Operators	0.33	0.48	0.25	0.42	0.10	0.22	0.10	0.30	0.23	0.10	1.00
Cycle Time (hrs)	36.4	5	11	4.5	5.4	46.1	25	11	36.5	1	1
Qty per cycle (kg)	43	73	36.7	36.7	2.1	36.7	36.7	36.7	36.7	2.1	200
Number of Lines	1	**2**	1	1	1	**2**	1	1	**2**	1	1
Direct Labor/ batch	$300.30	$120.00	$68.75	$47.25	$13.50	$507.10	$62.50	$82.50	$419.75	$2.50	$25.00
Direct Labor/kg	$6.98	$1.64	$1.87	$1.29	$6.43	$13.82	$1.70	$2.25	$11.44	$1.19	$0.13
Cumulative Labor/kg	$6.98	$8.63	$10.50	$11.79	$18.22	$32.03	$33.74	$35.99	$47.42	$48.61	$48.74
Rate per hour	$25.00										
Rate per minute	$0.417										

5.5 Gas Diffusion Layer

As modeled, capital equipment is a large cost factor with materials and labor making up a significant portion of the cost. Maintenance is estimated as a percentage of the capital equipment cost, so it is not surprising that maintenance is a large cost contribution.

Initial capital investment (Table 5-6) to build a greenfield GDL in the United States facility to supply 10k and 100k vehicles per year, capable of producing approximately 240k m^2/year and 2.4M m^2/year of gas diffusion layer per year, is estimated to be \$14.9M and \$42.4M, respectively.

Table 5-6: Estimated gas diffusion layer manufacturing facility capital cost and direct process line labor

	10k/year	100k/year
Facilities Cost (US$)	5.1M	12.8M
Capital Equipment (Installed, US$)	9.8M	29.6M
Workforce (skilled, unskilled, and supervisors)	9	24

A cost breakdown from the DFMA® model by the processing steps and by operating cost defined is shown in Figure 5-11: Gas diffusion layer cost breakdown by processing step (left) and operating expense (right). Three broad processing categories are seen for GDL manufacturing: paper making, coating, and heat treatment. The paper making and heat treatment steps contribute more to GDL cost than the coating step as shown in Figure 5-11. Discounted cash flow analysis is shown in Figure 5-13 at 10k vehicles per year and 100k vehicles per year along with single point sensitivity analysis figures.

A cost breakdown analysis for GDL produced in the United States, Europe, and Asia as presented in Figure 5-11, shows the aggregated regional cost breakdown of \$ per m^2 at 100k vehicles per year volume by major cost categories of material, labor, burden, SGA, engineering, and profit. Material accounted for 22% of the total cost, with direct labor at 11%, burden at 47%, SGA at 6%, Engineering at 6%, profit at 7%. Burden based on DFMA® is the highest cost element at 47% with equipment payments, maintenance, electricity and facilities cost included. The material is carbon fiber with global pricing. The direct labor cost was developed with the VSM and it shows the variation in labor rate and process manpower observed by region. Burden cost is primarily driven by the new process equipment payments. Standard rates were applied to SGA at 3%, Engineering at 3%, and Profit at 5% unless noted different. Overall, we do not see significant variation by region. Suppliers in Europe noted that the DFMA® total cost is 50% under-estimated.

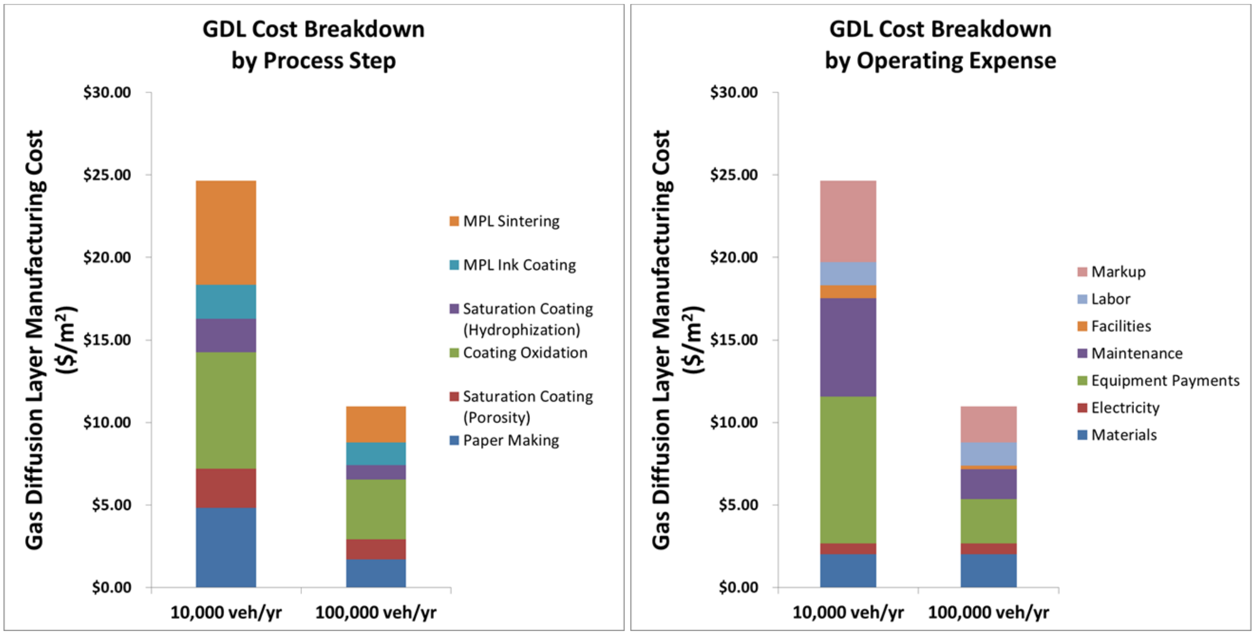

Figure 5-11: Gas diffusion layer cost breakdown by processing step (left) and operating expense (right).

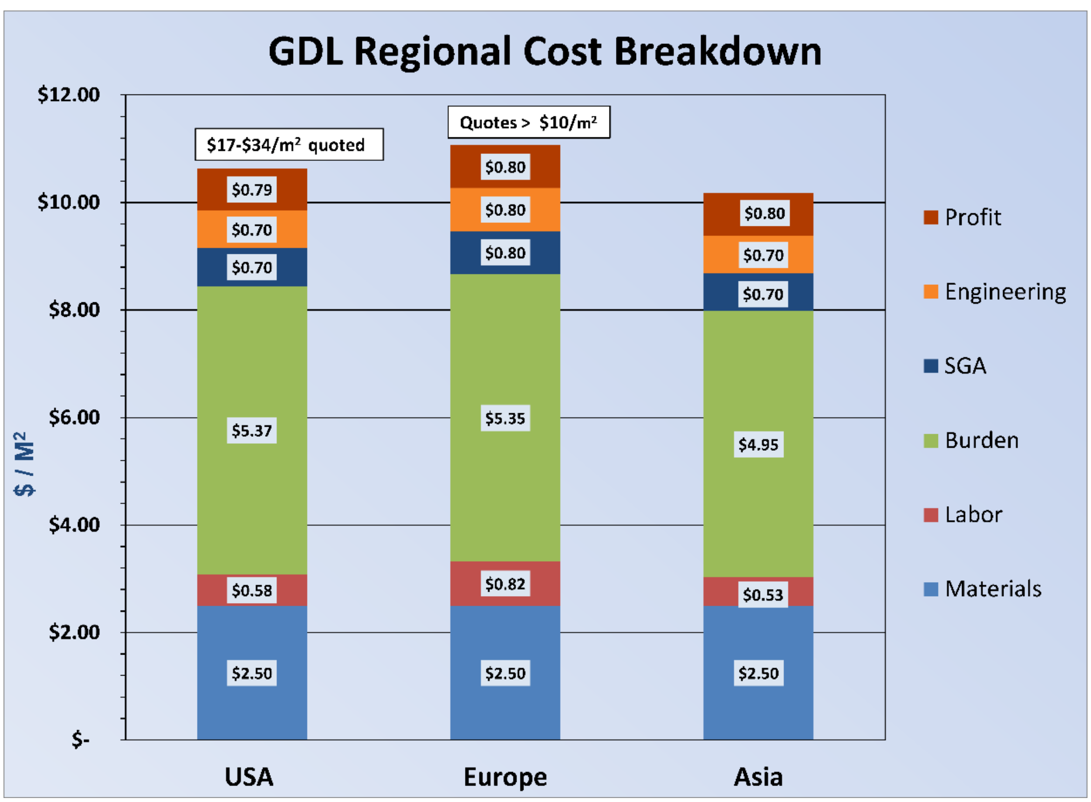

Figure 5-12: Regional cost breakdown for gas diffusion layer at 100,000 veh/yr

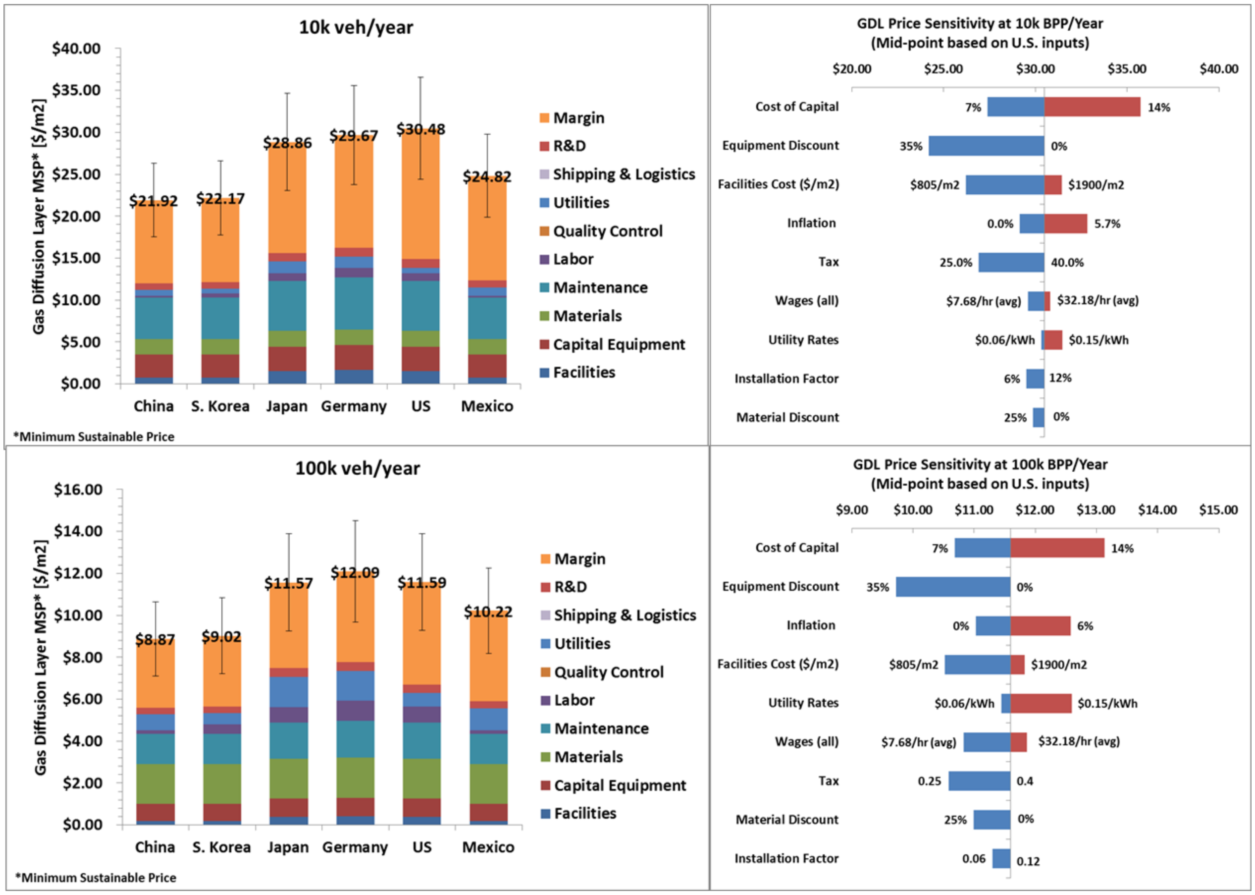

Figure 5-13: Summary gas diffusion layer discounted cash flow analysis

Gas Diffusion Layer is the fourth largest cost contributor in a fuel cell stack at 9%. Approximately 3 suppliers worldwide are currently capable of supplying GDL. Complex processing knowledge is held as trade secrets thereby creating a barrier to market entry. Characteristics needed for GDL are electrical conductivity, heat transfer and gas permeable. R&D (Research and Development) areas for improvement would be alternatives to carbon paper, reducing thickness.

The GDL is a carbon fiber paper or a carbon cloth. The GDL has a Microporous Layer (MPL) deposited on one side of the carbon paper/cloth. The MPL enhances the removal of product water from cathode of the fuel cell while facilitating the transport of oxygen carrying reactant to the cathode. The production process is roll-to-roll processing with the thin MPL a mixture of carbon/Teflon™. Manufacture of the GDL by roll-to-roll processing is consistent with the production rates for 100,000 to 500,000 AFCSs.

Gas Diffusion Layer Value Stream Mapping

The following Figure 5-14 the gas diffusion layer value stream map based upon plant visits and or data obtained in interviews with manufacturers. Table 5-5 shows gas diffusion layer key process steps and labor cost in U.S. dollars. . All are in-line continuous processes with process flow shown in the value stream diagrams.

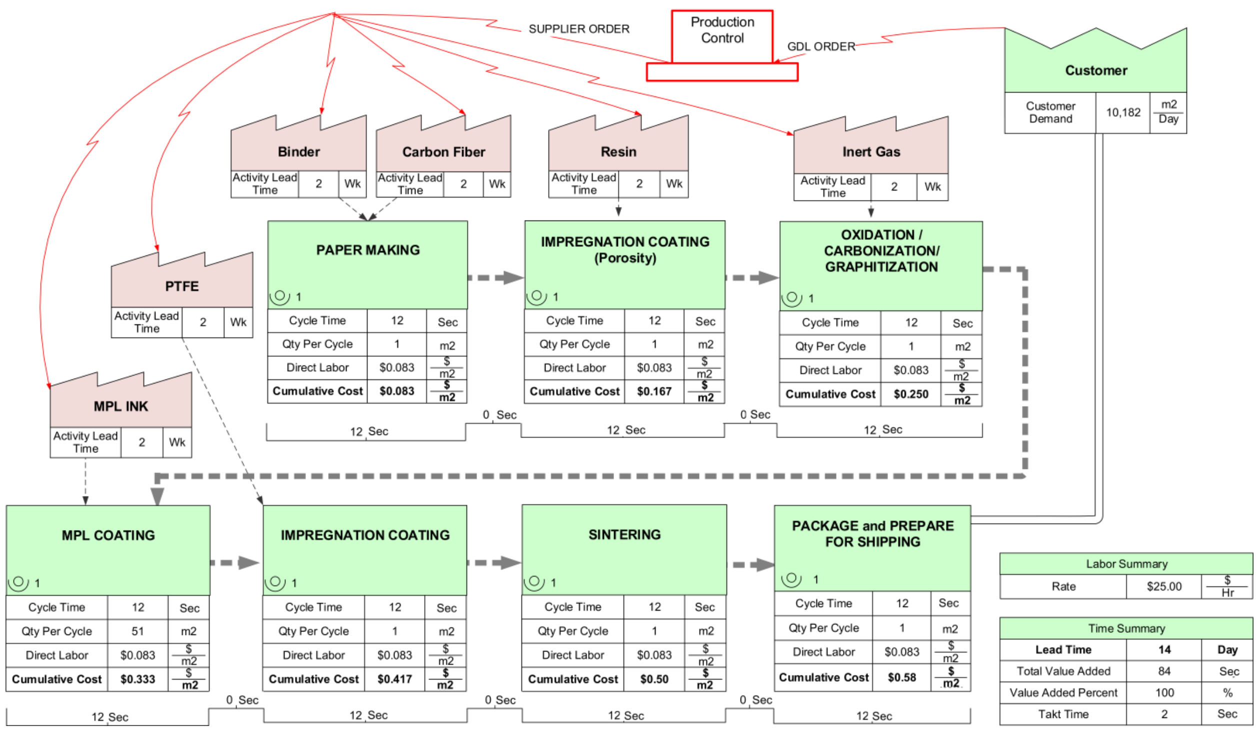

Figure 5-14: Gas Diffusion Manufacturing Value Stream Map

Table 5-7: GDL labor cost by process

Process Specs	Paper making (Binder Carbon Fiber)	Impreg-nation Coating	Carbon-ization	MPL Coating	Impreg-nation Ionomer	Sinter	Pkg & Pre-pare to Ship
No of Operators	1	1	1	1	1	1	1
Cycle Time (sec)	12	12	12	12	12	12	12
Qty per cycle (m2)	1	1	1	1	1	1	1
Direct Labor	$0.083	$0.083	$0.083	$0.083	$0.083	$0.083	$0.083
Cumulative Labor	$0.083	$0.167	$0.250	$0.333	$0.417	$0.500	**$0.583**
Rate per hour	**$25.00**						
Rate per minute	$0.417						
Rate per second (1)	$0.007						

5.6 Membrane

A cost breakdown from the DFMA® model by the processing steps and by operating cost defined is shown in Figure 5-15. Supported membranes manufacture is modeled as a single processing line, which coats ePTFE with ionomer in two passes with drying steps between coating passes. Materials cost of the ePTFE and PFSA ionomer dominate total membrane cost. Discounted cash flow analysis shown in Figure 5-17 at 10k vehicles per year and 100k vehicles per year along with single point sensitivity analysis figures continue to show the trend in other components that costs are driven by materials and capital equipment rather than intrinsic regional cost factors.

Initial capital investment (Table 5-8) to build a greenfield membrane facility in the United States to supply 10k and 100k vehicles per year, capable of producing approximately 240k m^2/year and 2.4M m^2/year of PTFE-supported membrane per year, is estimated to be \$5.1M and \$12M, respectively.

Table 5-8: Estimated membrane manufacturing facility capital cost and direct process line labor requirements

	10k/year	100k/year
Facilities Cost (US$)	2.1M	5.3M
Capital Equipment (Installed, US$)	3.0M	6.7M
Workforce (skilled, unskilled, and supervisors)	9	24

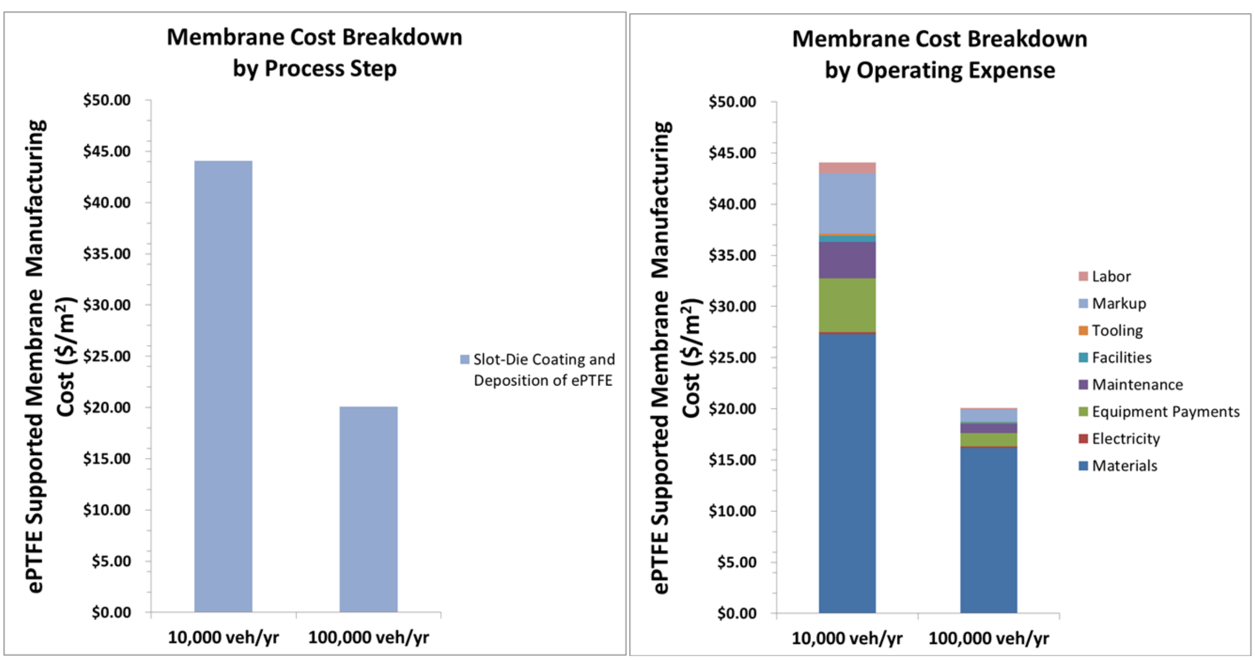

Figure 5-15: DFMA® cost breakdowns for membrane. The right panel shows the breakdown by operating expense.

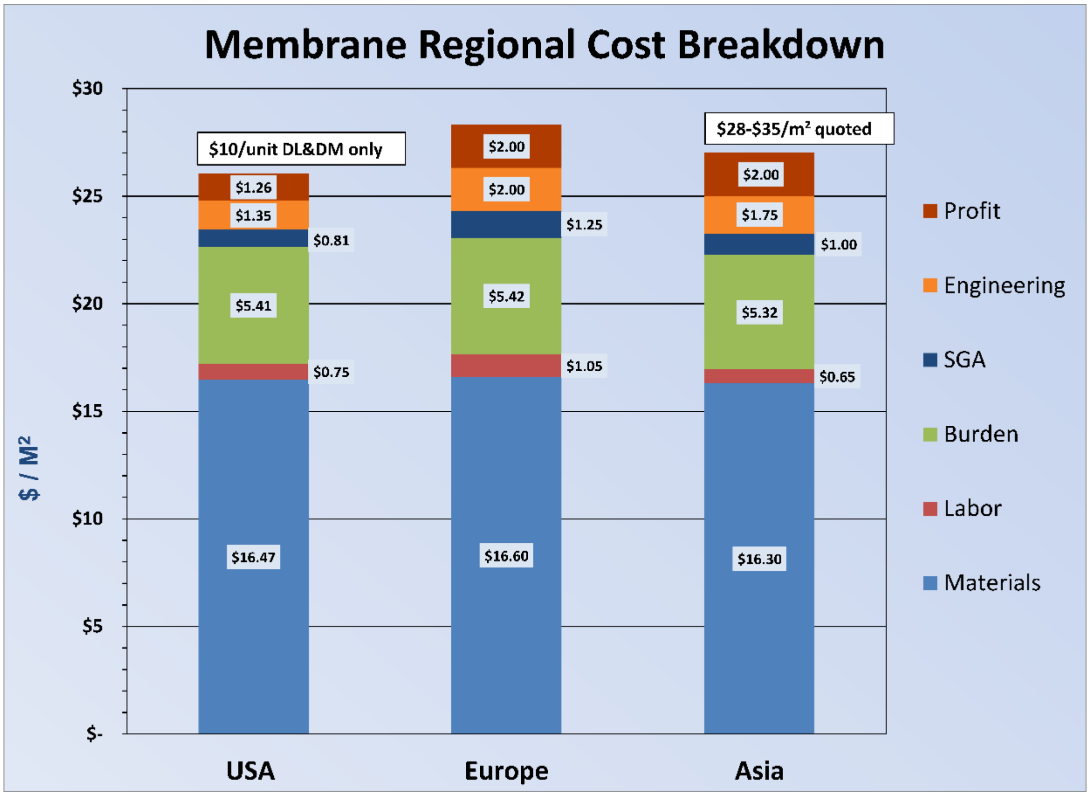

Figure 5-16: Regional cost breakdown analysis of membrane at 100,000 veh/yr

Figure 5-16 shows the aggregated regional cost breakdown of $/m² of membrane at 100k vehicles per year by major cost categories of material, labor, burden, SGA, engineering, and profit. Material accounted for 74% of the total cost, with direct labor at 3%, burden at 11%, SGA at 3%, Engineering at 3%, profit at 5%. Material is the highest cost element at 74% and burden is 2nd highest at 11% with equipment payments, maintenance, electricity and facilities cost included. Suppliers in Europe and Asia noted that the DFMA® total cost is 60% under estimated.

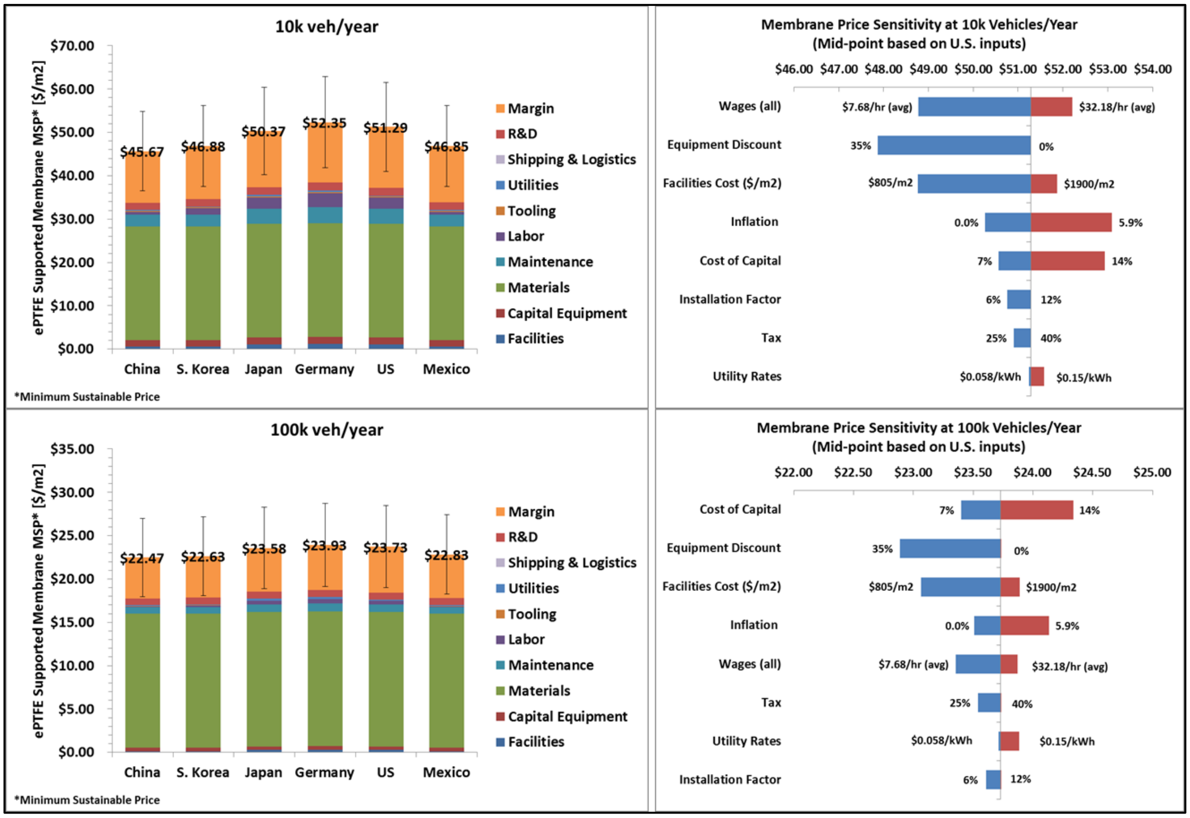

Figure 5-17: Summary membrane discounted cash flow analysis

Membrane is the third largest cost contributor in a fuel cell stack at 15%. The material cost is at 74% of the total cost. Not all membrane suppliers are at the same technology level therefore the price remains high until you have multiple comparable competitors. Future membrane generally envisioned as thin (7 to 10 micron) ePTFE-supported membranes to achieve balance point of strength and performance. R&D (Research and Development) areas for improvement would be reduce thickness of membrane, reduce platinum amount and catalyst cost, power density, durability, higher speed manufacturing, QC to correlate size and type of defect, fully flexible manufacturing facility with similar products in multiple markets.

The membrane is defined as Nafion™; a perfluorinated sulfonic acid (PFSA) membrane with the functionalities of proton and water transfer across the membrane while minimizing the transport of reactants across the membrane. The membrane for the fuel cell is not a mainstream product for industrial membrane manufacturers. Production volumes of fuel cell membrane are small in comparison to the industrial chemical industry where membranes with similar, but not identical, ion transport properties for use in Chlor-Alkali plants are in large demand. The membrane manufacturers have developed high-volume, roll-to-roll fabrication procedures for their industrial products. The production rate of these roll-to-roll processes far exceeds the demand for fuel cell membrane. In addition, the fuel cell membrane is thinner than industrial (Chlor-Alkali) membranes and, while both Chlor-Alkali and fuel cell membranes are reinforced, the fuel cell membranes reinforcement is very different than the reinforcement of the commercial Chor-Alkali membrane. The membrane manufacturers are expected to operate pilot scale facilities for the production of fuel cell quality membrane with the fuel cell membrane delivered to the OEM as cut sheets or as a roll product. Roll-to-roll processing is capable of production rates consistent with the needs of 100,000 to 500,000 AFCSs.

Membrane Value Stream Mapping

The following Figure 5-18 is the membrane value stream maps based upon plant visits, data obtained in interviews with manufacturers, and prior project work. Table 5-9 shows membrane key process steps and labor cost. Additional VSMs are found in Appendix 4.4. All are in-line continuous processes with process flow shown in the value stream diagrams.

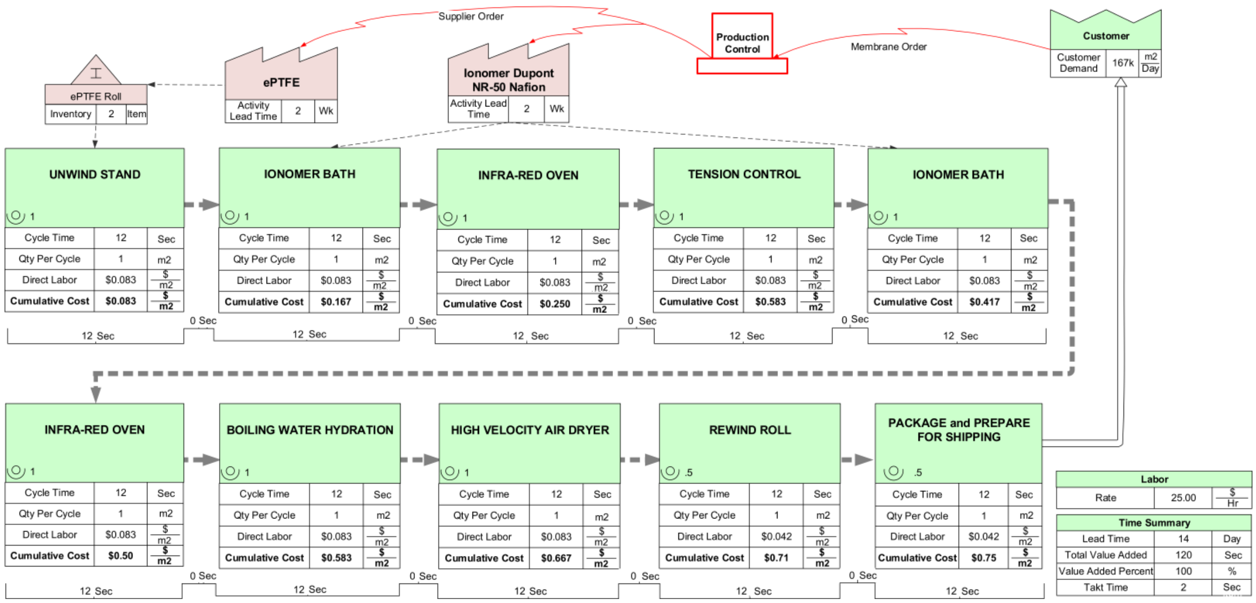

Figure 5-18: Membrane Manufacturing Value Stream Map

Table 5-9: Membrane labor cost by process

Process Spec	Unwind Stand	Ionomer Bath	Infra-Red Oven	Tension Control	Ionomeer Bath	Infared Oven	Boiling Water Hydration	High Velocity Air Dryer	Rewind Roll	Pkg & Prepare to Ship
No of Operators	1	1	1	1	1	1	1	1	0.50	0.50
Cycle Time (sec)	12	12	12	12	12	12	12	12	12	12
Qty per cycle (m2)	1	1	1	1	1	1	1	1	1	1
Direct Labor	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.04	$0.04
Cumulative Labor	$0.08	$0.17	$0.25	$0.33	$0.42	$0.50	$0.58	$0.67	$0.71	**$0.75**
Rate per hour	**$25.00**									
Rate per minute	$0.417									
Rate per second (1)	$0.007									

5.7 H_2 Pressure Vessel

The hydrogen pressure vessel includes the polymer permeation barrier, carbon fiber composite overwrap, and threaded aluminum tank bosses. As shown in the DFMA® analysis in Figure 5-19, materials cost dominate the cost of the pressure vessel. In particular, tank cost is driven by the carbon fiber, of which there is around 70 kg at approximately $30/kg per tank. Building a greenfield pressure vessel is more capital and labor intensive than other components considered in this analysis as shown in Table 5-10, which is reflected in the higher cost in countries with higher labor and land costs (Figure 5-20).

Table 5-10: Estimated Type IV pressure vessel manufacturing facility capital cost and direct process line labor requirements

	10k/year	100k/year
Facilities Cost (US$)	13.6M	74.0M
Capital Equipment (Installed, US$)	7.3M	32.8M
Workforce (skilled, unskilled, and supervisors)	18	78

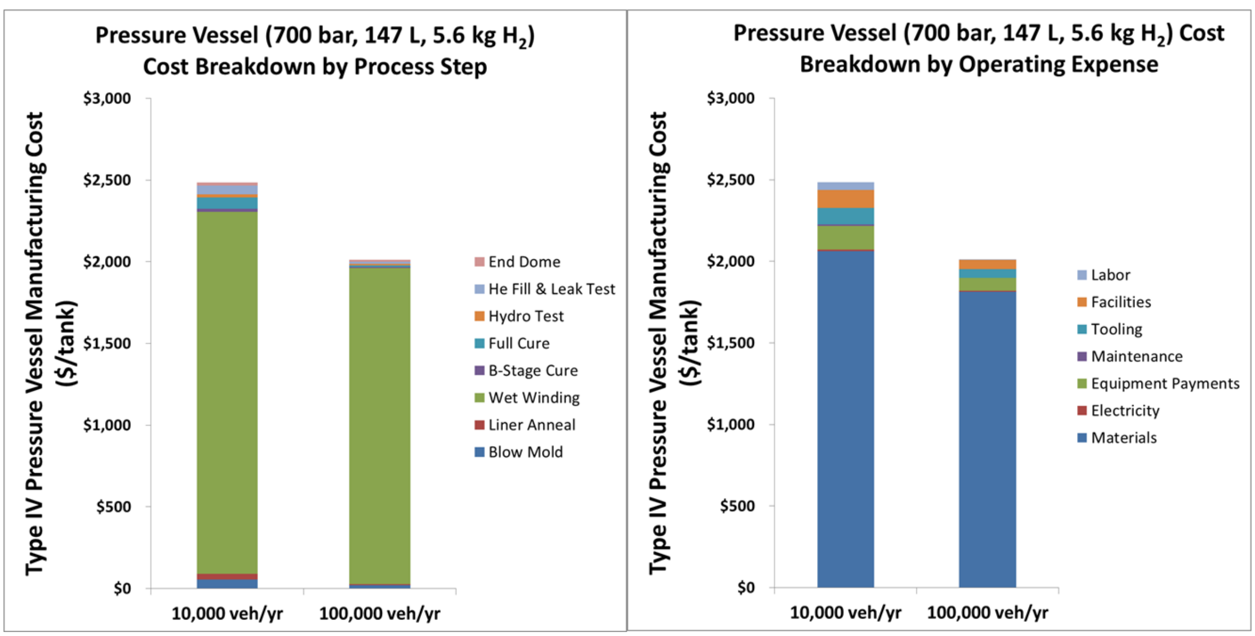

Figure 5-19: DFMA® cost breakdowns for pressure vessel. The right panel shows the breakdown by operating expense.

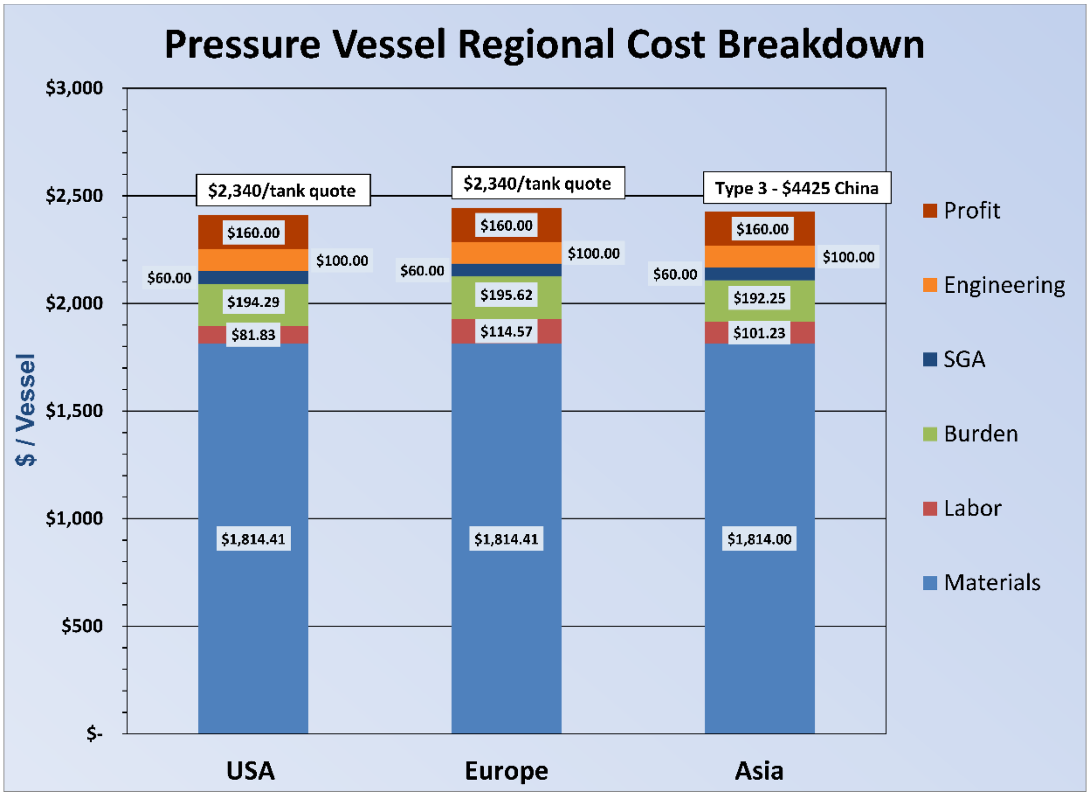

Figure 5-20: Regional cost breakdown analysis for hydrogen pressure vessel at 100,000 veh/yr.

Figure 5-20 shows the aggregated regional cost breakdown of $/vessel at 100k vehicles per year volume by major cost categories of material, labor, burden, SGA, engineering, and profit. Material accounted for 73% of the total cost, with direct labor at 6%, burden at 8%, SGA at 2%, Engineering at 4%, profit at 6%. Material is the highest cost element at 73% and burden is 2^{nd} highest at 8% with equipment payments, tooling, maintenance, electricity and facilities cost included. Suppliers in Europe and U.S., noted that the DFMA® total costs are 5% over estimated.

For the material carbon fiber, resin, HDPE are global commodities with global pricing. The direct labor cost was developed with the VSM and it shows the variation in labor rate and process manpower observed by region. Burden cost from DFMA® is primarily driven by the new winding equipment. Standard rates were applied to SGA at 3%, Engineering at 3%, and Profit at 5% unless noted different. Overall we do not see significant variation by region for a specific type.

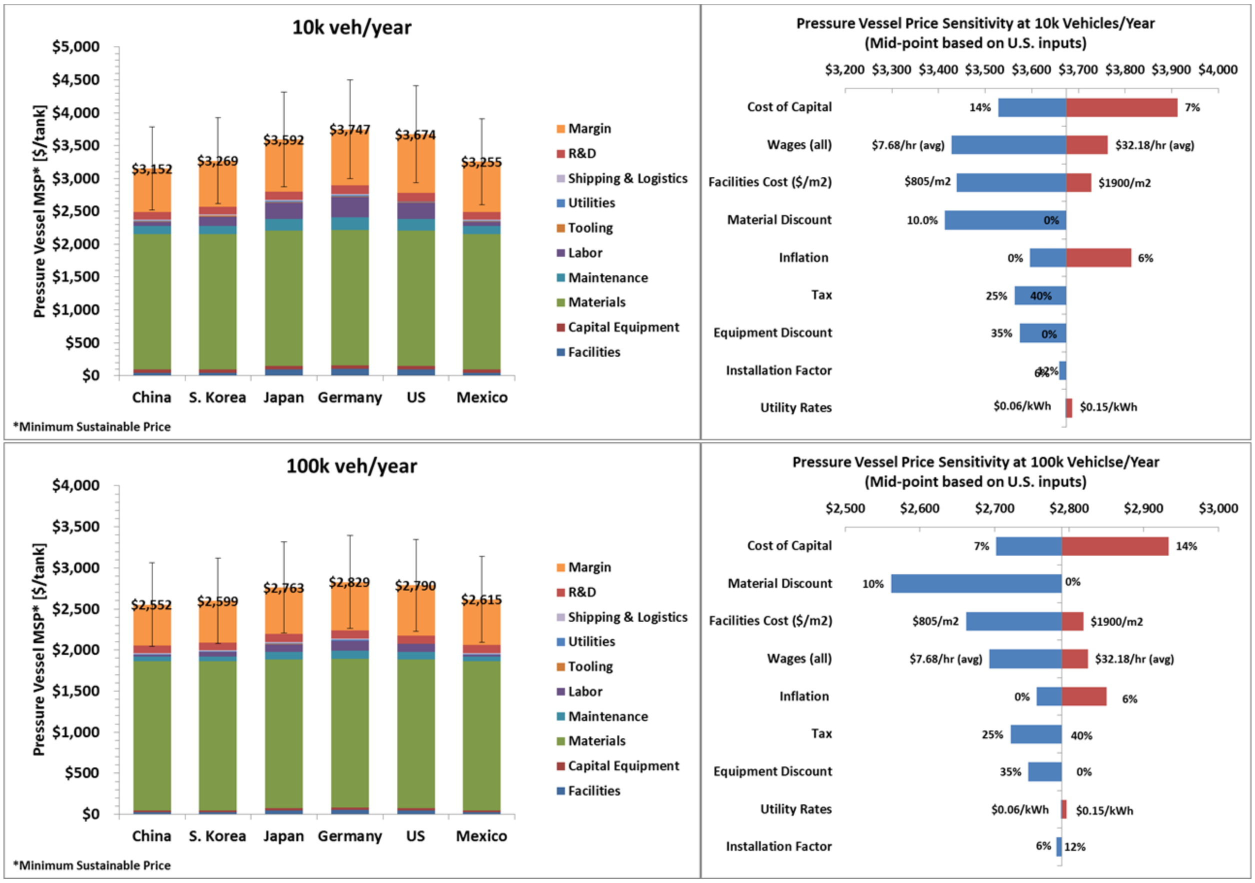

Figure 5-21: Summary pressure vessel discounted cash flow analysis

The two major cost components of the hydrogen storage system are the carbon fiber composite and the Hydrogen Balance of Plant (HBOP). The outer tank of the hydrogen storage system is made from a high strength carbon fiber composite able to withstand 2.25 safety factors over the 70 MPa nominal hydrogen pressure. Such fiber, for example Toray's T700S, is in high demand for military and aircraft applications. The high demand keeps the cost of the carbon fiber composite for the hydrogen storage system high. The winding of the carbon fiber composite to form the hydrogen storage tank is time-consuming and may limit production rates. The HBOP includes the valves, pressure regulators, and an integrated in-tank valve with temperature transducers, filters, flow valves, and solenoid valve. Many of the components in the HBOP are designed for very high-pressure storage (70 MPa) operation adding to the cost for these components.

H_2 Pressure Vessel Value Stream Mapping

The following Figure 5-22 is one of the H_2 vessel value stream maps based upon plant visits, data obtained in interviews with manufacturers, and prior project work. Table 5-11 shows H_2 vessel key process steps and labor cost. Additional VSMs are found in Appendix 4.5.

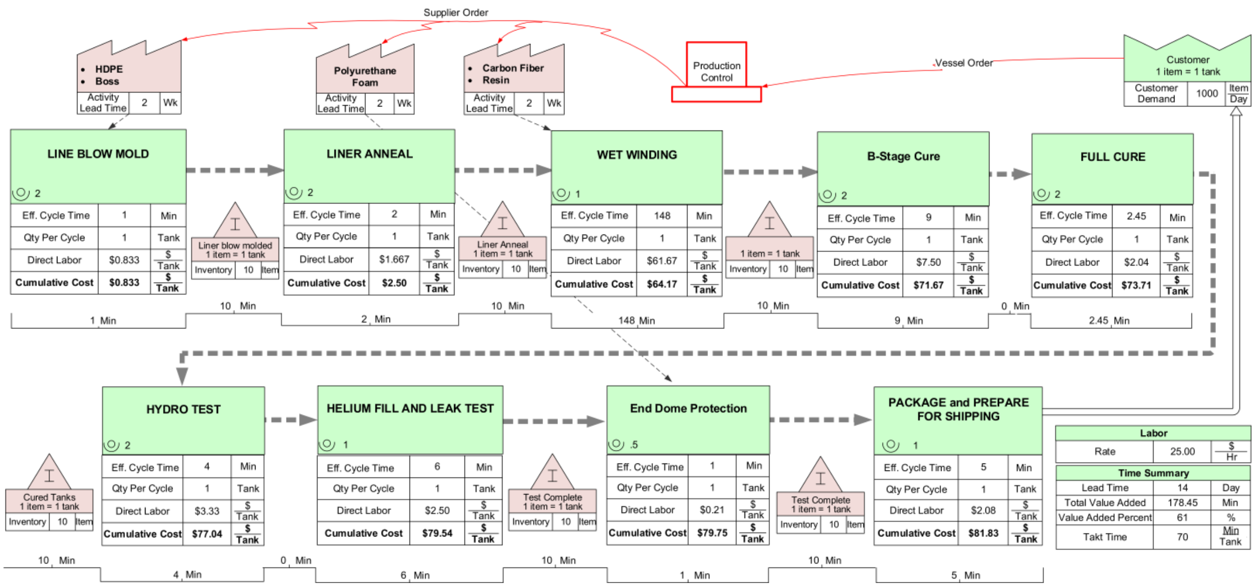

Figure 5-22: Pressure Vessel Manufacturing Value Stream Map

Table 5-11: H_2 Vessel labor cost by process

Process Specs	Line Blow Mold	Linear Anneal	Wet Winding	B-Stage Cure	Full Cure	Hydro Test	Helium fill & leak test	End Dome Protection	Pkge & Prepare to Ship
No of Operators	2	2	1	2	2	2	1	0.5	1
Cycle Time (min)	1	2	148	9	2.45	4	6	1	5
Qty per cycle (Tank)	1	1	1	1	1	1	1	1	1
Direct Labor	$0.83	$1.67	$61.67	$7.50	$2.04	$3.33	$2.50	$0.21	$2.08
Cumulative Labor	$0.83	$2.50	$64.17	$71.67	$73.71	$77.04	$79.54	$79.75	**$81.83**
Rate per hour	**$25.00**								
Rate per minute	$0.417								

5.8 Regional Fuel Cell Stack Cost Factors

The current fuel cell supply chain is in its early development or introduction stage as described in Figure 4-2. There are relatively few suppliers for each component, each selling components that fit within their core business capability to automotive OEMs, none of which are operating fuel cell component manufacturing at high utilization. The cost breakdown analyses for the key components reflect inputs from suppliers as the (fragmented) market currently exists. In contrast, the DFMA® and discounted cash flow (which derives from DFMA®) analyses reflect idealized suppliers that are highly optimized with lean operating expenses. This idealized manufacturing cost reflects what the market is expected to look like in the mature stage of the product-life-cycle as envisioned in Figure 4-2.

The key risks to U.S. competitiveness are from foreign sourced fuel cell stacks and hydrogen storage vessels. Balance of plant components are largely sourced from suppliers in a mature supply chain, although it is not yet optimized for the fuel cell market. The fuel cell stack, however, is an entirely new component that could, in principle, be sourced from a foreign or domestic supplier. The hydrogen storage vessel regional cost factors are shown in Figure 5-21 and represents a supply chain with core competencies that are completely different from the fuel cell system.

To better understand the underlying regional cost drivers, the relative regional cost advantages for a fuel cell stack were estimated by adding components purchased from a single country as modeled in the discounted cash flow analysis (e.g., all bipolar plates, GDL, catalyst, and membrane purchased from hypothetical Japanese suppliers). A simplifying assumption was made that the cost of stack assembly and testing will be a small fraction of the component costs and will have similar regional cost drivers as the components (i.e., tax, labor rates, etc.) It is also assumed that membrane electrode assembly integration and assembly, which is not expected to be a negligible cost, will have similar regional cost drivers. The balance of plant is neglected in this simplified analysis because, while it represents a large fraction of the fuel cell system cost, it will likely be sourced from an existing mature supply chain that is separate from the fuel cell stack supplier in all stages of the supply chain development as shown in Figure 4-12. The results of this partial stack cost estimate are presented relative to the cost of a stack made from U.S. components in Figure 5-23. This analysis suggests that the manufacturers' operating margin is the regional competitive driver for a stack at 10k vehicles per year, while other factors such as labor, utilities, and land cost have little impact on regional competitiveness. At 100k vehicles per year, the differences between countries are minor in this simplified analysis.

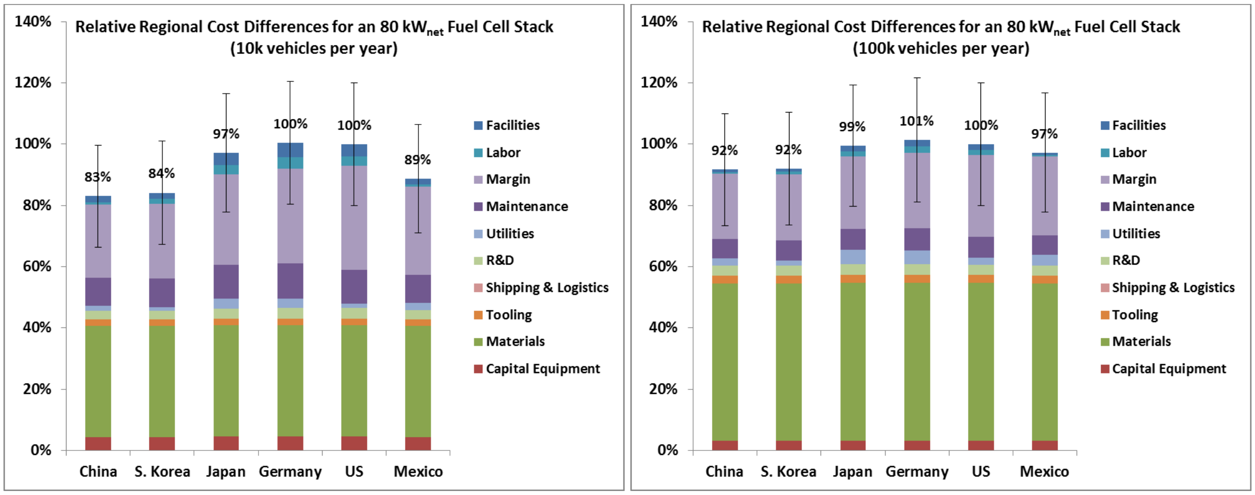

Figure 5-23: Regional fuel cell stack cost estimate based on component costs predicted by discounted cash flow analysis.

The value of estimating the regional cost of manufacturing a fuel cell stack is in its ability to illustrate that indigenous regional factors are not expected to dominate. In other words, low-cost labor, electricity, etc. are not the driving costs. Instead, this analysis suggests that the margin, which is strongly influenced by the assumed marginal tax rate, will determine regional competitiveness at low volume production (10,000 vehicles per year). We did not have access to representative U.S. companies' effective tax rates, but average effective tax rate is likely to be ~25% rather than our assumed 40%. At high volume (100,000 vehicles per year), margin has a smaller impact on regional cost competitiveness and the effect of marginal versus effective tax rate is expected to largely eliminate the cost differences between countries.

It is important to note one other limitation of this simplified regional stack cost analysis. In addition to the simple assumption that all components are sourced from a single country, no pass-through markup was applied. As discussed in Section 4: Supply Chain Evolution, supply chain optimization is a complex endeavor and automotive OEMs currently favor a tiered supply chain. It is probable that the stack will be supplied by a Tier one-half supplier who will manage supply of the stack components. Throughout the supply chain, components will be integrated at different stages organized around supplying components optimized for cost and quality. Studying the tradeoffs between supplier profit, quality control, shipping and logistics, and component certification is a complex study of its own.

6 Global Supply Chain Strategies

6.1 Introduction

The countries and regions that are developing fuel cell industries, the support they are providing to do so, and the wider availability of capital and other resources are strongly linked. Because of this they are reported together in this section of the study, rather than individually.

As we have seen in other sections of this report, very few automotive fuel cell suppliers and developers are approaching full mass-production capabilities, and in very few countries. This reflects the very large investment requirements, the complexity of the technology, and the continuing uncertainty of the market.

The countries leading in developing fuel cell industries usually demonstrate at least one of several characteristics which have led them to engage with the supply chain and its development. Broadly, these are:

- Strong automotive manufacturing history and supply base;
- Large corporations with specialized skills in fuel cells;
- A belief that fuel cells represent an opportunity and a strong government program to support it.

Some countries have more than one of these characteristics. Some countries with none of the characteristics may have one or two isolated specialist developers, but these tend to be special cases. In certain cases, it is a region rather than, or in addition to, a country that is particularly relevant.

To compete as a company in the automotive industry, size is important. In order to be an automotive OEM or a trusted supplier, it is essential to be capable of, *inter alia*:

- very high volume repeat manufacturing,
- complex supply chain management,
- exceptional levels of quality control,
- absorption of fluctuations in demand,
- large investments in buildings, capital and labor
- building plants internationally to service OEMs
- an established track recorded of meeting automotive component delivery schedules

These characteristics are very hard to achieve other than in large companies – one of our interviewees commented that their quality and supply chain compliance department alone was larger than most pure-play fuel cell companies.

Smaller companies also have or have had technology leadership – much of the fuel cell sector has been driven by small-scale entrepreneurial activity. But the information gathered for this report suggests that evolving from such a small company into a suitably qualified automotive supplier is both extremely hard and quite unlikely, as they will rarely have the opportunity or resources to develop the skills above. The small company, or its technology, is in practice more likely to be acquired by an existing supplier or to provide IP and technology insights under license.

Conversely, large companies with the requisite skills but who are not accustomed to playing the role of a conventional Tier 1 supplier may choose not to enter the market, or may leave it if it is seen to be either too small or too unprofitable. Specifically, this is because of a further requirement – not listed above as it is a strategic choice rather than a characteristic – which is the willingness to operate under a high-volume but low-profit regime. In order for cars to be competitively priced, margins throughout the supply chain are very low and relationships are typically either open-book or based on very stringent conditions. This contrasts strongly with many of the business approaches in industries that could supply specialist fuel cell components. Fine chemicals companies, for example, are accustomed to double-digit percentage margins on their goods and may not be prepared to accept the very small profits that have to be negotiated with automotive OEMs.

While the focus of this part of the study is on funding within those countries most relevant to the trade flow analysis, we have seen that trade flows are dominated by Asia, and often there is no ‘flow’ as it is internal to a single country (e.g., Japan to Japan). This leaves us with very few countries to consider, and so to add some perspective to what is happening there, some figures for fuel cell support more widely are included below. Support for stationary as well as transport fuel cells is outlined, both to offer context on the priorities of a region and also because the way that funding is split up or allocated varies widely by country.

6.2 Overall Strategies by Country

A very short list of countries and, to some extent, regions plays this leading role in the evolution of the automotive fuel cell industry.

Japan has all three of the characteristics listed at the start of this section: a strong automotive manufacturing history and supply base; large corporations with specialized skills in fuel cells; and a clear belief that fuel cells represent an opportunity – with a large and far-reaching government program to support it. **Korea** has a strong automotive history, albeit relatively recent, and a vision for fuel cells. It has developed some specialized skills, though remains behind the leaders in most areas in terms of supply chain capability. **Germany** has strong automotive manufacturing and several specialized corporations, but while Government support for fuel cells as a whole is amongst the largest, the automotive sector is less well supported than Japan. Elsewhere in Europe, the picture is primarily one of isolated specialty corporations, such as in the **UK, Sweden** and one or two other countries. **Canada** had a strong program at an earlier juncture, with a particular regional emphasis around Vancouver, because of Ballard’s role. The effects of this remain, with Vancouver now a development and manufacturing center for automotive fuel cell stacks, but Government support as a whole is small.

The **United States** is also represented – it also has a strong automotive history and large, specialized corporations. But while absolute spending is reasonably high for a fuel cell program, the support does

not have the end-to-end focus found in Japan, in particular, and the financial crisis in 2008 severely restricted U.S. automotive OEMs: while GM was at one stage close to Toyota and Honda as a global leader, it has since fallen back.
The final country with a strong ranking is **China**, which does not have especially strong automotive manufacturing, historically, nor corporations with specialist capabilities. It is however in the process of funding and otherwise supporting a nascent automotive fuel cell industry, under a strategic government initiative, and is likely to become a much more important player. Importantly for the findings of this report, **China's** approach highlights how the emerging supply chain can be influenced. Until recently China was considered to have excellent science and technology capability, but not the capacity or structures required to mass-produce high-quality automotive fuel cells. This remains largely true, but specific programs are now in place to support not only the science and technology base, as previously, but also local uptake of technology, and technology transfer for supply chain development. This support has come in the form of subsidies for fuel cells as part of the New Energy Vehicles program, and for hydrogen refueling infrastructure. The result is that Chinese companies are actively seeking joint ventures with leading suppliers (Ballard and Hydrogenics each supply stacks and systems for buses and light rail) and the country has a stated goal to develop an indigenous supply chain. Some capabilities will come through the technology transfer mentioned above, and others through ongoing R&D and scale-up support, and rapid iteration of technology.

This can be taken as a positive message, in that it shows that the automotive fuel cell supply chain is not yet locked down, and it suggests that judicious funding and other support mechanisms can influence its location and its development. It does however highlight some of the many forces pulling on those few companies that can currently satisfy demand, which will evolve as other countries or regions wish to acquire technology. It further emphasizes China's interest in capturing value from what it views as an imminent opportunity. In fact, China's willingness to support the development of supply chain expertise is akin to what Japan and Korea (and the U.S., historically) have done in other sectors. While Japan, and subsequently Korea, gradually worked their way into the upper echelons of the existing internal combustion engine development and production community, the advent of a new technology brings additional opportunity to disrupt the status quo and to become part of the new community supplying new technologies. Because the existing players and their supporting suppliers are firmly committed to existing technologies, some of them will find it hard to justify change. New entrants do not face this issue to the same extent.

An important point relevant to current and future supply chain development is the positioning of the broad-based Tier 1s. While much of this analysis has focused on specialist component suppliers, companies such as Denso in Japan are in the process of developing their own fuel cell capabilities. These are not widely discussed and their current status does not permit direct comparison with the entities detailed in this study, they could very likely act as they do now in a future supply chain, integrating much of the stack and system to supply to an OEM. It will be important to monitor this evolution, to enable strategic decisions to be taken.

6.3 Motivations for Developing a Fuel Cell Economy by Country

Several elements, or motivations, were reviewed as part of this study that have contributed to the advancement of fuel cell economies around the world including policies, incentives, government funding and new technologies being developed. The motivations for the different *countries* to engage strongly with the automotive fuel cell supply chain are partly, but not completely, linked to the characteristics described at the start of this section. In some cases governments have been part of the creation of the vision from the start, while in others the industrial players have either moved alone or partially convinced the governments to participate.

The big global drivers of:

- zero polluting emissions (in California and in some other regions), and
- reduced fleet-wide CO_2 requirements

are forcing *car companies* to adapt, and new technology in some form remains essential. The pressure they face is translated more or less directly into their government discussions. A very specific example of policy pressure was the attempt by Volkswagen to falsify their emissions from diesel engines, the fallout from which now appears to be leading them to much greater investments in both battery and fuel cell electric vehicles.

The motivations for developing particular *components* are generally most strongly linked to competitive advantage or to supply chain risk. Some materials and processes are complex or expensive to replicate, or safety requirements may be difficult to meet. In these cases, the legacy producers are usually best placed to compete, not new entrants.

6.3.1 Japan

Japan's development has been strongly shaped by its lack of natural energy resources. This means that it has needed to develop value-added technology, such as high energy efficiency, to bring in export revenue and high energy efficiency is valued within Japan because local natural energy resource prices are also high. Diversification from fossil fuel is also important. Fuel cells and hydrogen energy are seen as an opportunity to build on all of these areas, and have been adopted into the Government energy strategy. Because this strategy and many other aspects of policy are developed in close collaboration with industry, major Japanese corporations are investing alongside government to support the development and roll-out of FCEVs. This supports local emissions and employment objectives while also, they hope, developing export markets. Japan has the capability already to manufacture all of the fuel cell components considered in this report, though not yet at high volumes. Local technology remains under development however, exemplified by the Toyota Mirai's use of a membrane from Gore (produced in Japan). Local membrane suppliers do exist however, and it is likely that Japanese companies will strongly enter this space in the future.

To meet its objectives, Japan has probably the most comprehensive support program for fuel cell vehicles globally, within the larger context of support for fuel cells and hydrogen more broadly. Much of that support is through direct government grants and subsidies, from its fundamental research to its hydrogen refueling infrastructure and beyond. Government and industry roles and expectations are relatively clear, i.e., the government supports fuel cell and hydrogen programs while industry executes the programs.

The Ministry of Economy, Trade and Industry (METI) has reported an overall budget for fuel cell and hydrogen-related activities in FY2016 of $429 million (¥47.4 billion) of which $344 million is to support deployment related activities.[43] That funding is targeted at the following topics:

- Subsidies for residential FCs $86.1 million
- Subsidies for HRSs $56.2 million
- Support for FCEVs $136 million
- Demonstrations for a global H_2 supply chain $25.4 million
- Construction of a H_2 energy network $40.8 million

With the exception of the residential section above, all of the support can be linked at least in part to automotive activities. The global H_2 supply chain will allow bulk hydrogen supply for use in all sectors; the H_2 energy network activities will reflect both stationary and transport uses. Major corporations are heavily implicated in delivering on each of the topics.

Japanese industry in general is dominated by such major corporations, with relatively little space or funding available to start-up companies, especially in the engineering and technology sectors. So much of the technology is developed in-house in the big companies, though they are very comfortable to partner companies overseas or acquire their technology. And while the same is true to an extent in other countries, Japanese corporations are often noted for strong and visionary founders and leaders. Many of the major companies are comparatively young in global terms and Toyota's vision for hydrogen and fuel cells, for example, is driven in no small way by the views of its Chairman, part of the founding family.

6.3.2 Korea

Korean motivation is similar to the Japanese motivation. The country has a similar lack of natural resources and has industrialized in a way similar to Japan to address those concerns. As a more recent arrival on the global automotive scene, Korea also wishes to prove its ability to compete at the highest technology level, and is working to strengthen its indigenous supply capabilities for many of the FCEV components. Unlike Japan, it does not yet have the capability to produce all of the supply chain components itself, though components like pressure vessels and air handling are within existing capabilities. Korean companies are very aggressive in acquiring technology and technology rights as is evident from their investments in both the stationary fuel cell sector and in selected technologies.

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[43] Kawamura (METI), Japanese challenges for accelerating realization of a hydrogen society, FCHJU Stakeholder Forum 2016, November 2016, http://www.fch.europa.eu/sites/default/files/5.%20S.%20Kawamua%20%28ID%202891527%29.pdf

Korean companies have acquired all or part of FuelCell Energy, the erstwhile Rolls-Royce Fuel Cells, United Technology Corporation and ClearEdge's stationary fuel cell technologies, and recently Kolon bought license rights to Gore's fuel cell membrane technology.[44] It is clear, that in principle, Korea would like to produce as much as possible of the required components locally.

Government and industry are very closely linked and support programs and policies are again often designed with considerable consultation. Korea has had substantial support for fuel cells from the Government in the past, and maintains some funding. However, much of the focus is on stationary fuel cells, with less focus devoted directly to transport. Hyundai is, in practice, supplying many of its vehicles to overseas customers, particularly in Europe and in California. Hyundai, and many other major Korean corporations, have their own substantial internal funding devoted to the development of competitive fuel cell and hydrogen energy products. In Korea, more entrepreneurial activity in fuel cells has taken place than in Japan, for example, though the big corporations are still dominant. However, few entrepreneurs are active in the automotive space, either for vehicles or components.

More specifically, in terms of direct governmental funding, Korea planned for 2016 to invest US$5.4 million in FCEVs and hydrogen refueling stations, and US$5.3 million will be focused on household and building applications. The 2016 R&D budget is US$26 million.[45] Korea is also looking to replace CNG buses with fuel cell buses. The target is 26,000 buses, with an average rate of 2,000 per year.[46] There have been no announcements of support that this initiative may get.

On the stationary front, residential fuel cells are supported as part of the "One million Green Homes" program and the "Building subsidy Program", which includes not only fuel cells, but also other technologies, such as Solar PV, Solar Thermal, Geothermal, and Small Wind.[47] The main driver in Korea for deployment of stationary fuel cells is, however, the Renewable Portfolio Standard (RPS). Power producers with capacity of 500 MW or above are obligated to increase their share of new or renewable power generation (including fuel cells running on conventional fuels) incrementally to 10% in 2022 as shown in Table 6-1.

Table 6-1: Korea obligatory new or renewable energy supply ratio (RPS targets)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Ratio (%)	2	2.5	3	3.2	4	5	6	7	8	9	10

[44] http://www.businesskorea.co.kr/english/news/industry/16404-fuel-cell-technology-kolon-industries-secures-core-technology-fuel-cell
[45] http://www.iphe.net/docs/Meetings/SC25/25-SC-Statement-Republic-of-Korea.pdf
[46] http://www.intelligent-energy.com/news-and-events/industry-news/2016/03/22/south-korea-to-replace-cng-buses-with-hydrogen-fuel-cells/
[47] http://www.iphe.net/docs/Meetings/SC23/Korea_SC23.pdf

The obligation has resulted in more than 150 MW of installed stationary fuel cell capacity, also thanks to the double counting of fuel cells in the credit scheme of the standard.[48] The penalties of not meeting the requirements give an indication of the indirect incentive for fuel cell deployment, but should not be directly counted as a governmental subsidy.[49] The penalties are a maximum 150% of trading prices of renewable energy supply certificates. (In 2013, certificates are selling at KRW40 for €0.026-0.035/kWh.)[50] The amount of penalties varies depending on causes and frequency of the non-compliance.

6.3.3 European Union

In addition to funding delivered by and in individual Member States, the European Union has set up a public-private partnership called the Fuel Cell and Hydrogen Joint Undertaking. Now in its second phase of funding, it is known as FCH 2 JU, and it supports a wide range of projects and some underpinning activities. European Union motivation for fuel cells (as opposed to individual country motivation) is a function of industrial development and job creation, environmental impact reduction and energy import dependence. Support is therefore intended to support all applications. Transport figures strongly, but as part of a much broader picture.

The FCH 2 JU's 2016 call for proposals had a budget of $130 million (€117.5 million)[51] indicative of the broad scope of fuel cell applications: $63 million (€57 million) available in the Transport Pillar, and $62 million (€56 million) in the Energy Pillar. Although the call includes a few fundamental topics (e.g., development of processes for direct production of hydrogen from sunlight), the overwhelming majority target deployment with, e.g., demonstrations, development of manufacturing technologies, and standards, and support to industrialization efforts. The 2017 FCH2 JU call for proposals has a tentative budget of $139 million (€125 million).[52]

6.3.4 Germany

Germany has a strong commitment to both technology and to quality of life, including the environmental aspects of the latter. It has a strong automotive industry known for high quality and high technology products. German national and regional government supports its fuel cell developers through long-term programs, with specific policy objectives in mind – typically industrial strategy or environmental or economic benefit. Funding is relatively high in comparison with other global players.

The motivation for investing in part comes from Government and in part from industry itself. Government sees an opportunity to maintain a strong industrial position and provide high quality and

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[48] http://www.iphe.net/docs/Meetings/SC23/Korea_SC23.pdf
[49] http://www.energy.or.kr/renew_eng/new/standards.aspx
[50] http://www.renewableenergyfocus.com/view/31556/factfile-rps-framework-drives-south-korean-market/
[51] FCH2 JU, 2016 Annual Work Plan and Budget, http://www.fch.europa.eu/sites/default/files/documents/FCH2%20JU%202016%20AWP%20and%20Budget_en.pdf
[52] Drabicka, IPHE Country Update Nov 2016: European Commission, http://iphe.net/docs/Meetings/SC26/26-SC-Statement-European-Commission.pdf

increasingly 'green' jobs. At the same time, as in Japan, industry CEOs have chosen to support fuel cells, and hydrogen energy. Daimler and Linde are important examples representing the fuel demand side and the fuel supply side of the automotive fuel cell equation, with their investments at different times dependent heavily on the views of the CEO.

German *automotive* fuel cell support has in practice depended quite heavily on both government and industry inputs. Daimler was initially a very strong supporter of the new technology, partnering with Ballard and Ford very early on. It has since then slowed down its developments, though a vehicle is planned to be launched in 2017, and almost all of the initial supply chain is already in place – with much stack development and production expertise in Vancouver, Canada. Some components and materials for the stack come from outside Canada, however. Ballard also supplies expertise to Volkswagen, having sold it many patents and provided engineering services on a frequent basis. VW has a less advanced program than Daimler but has significantly increased investment in all of its alternative drivetrains following rulings on its emissions scandal. It is unclear what proportion of the increase from €3bn to €9bn is focused on fuel cells. BMW has stated that it sees 2020 as the earliest it may commercialize its own FCEV. Within Germany, suppliers can be found for all of the components considered here. Some of these are global leaders and they supply OEMs in other countries and regions.

Many German Bundeslaender, or states, have individually strong policies also. Certain amongst them depend on large automotive or other industrial strengths, and are willing and able to fund pilot and demonstration projects, or offer tax and other incentives to technology companies. The ecosystems that exist around the major automotive OEMs play an important role in the advancement of the German automotive fuel cell industry.

Germany's National Innovation Program for Fuel Cell and Hydrogen Technologies was prolonged in 2016 for another 10 years (Phase 2). The renewed program has a mandate to support deployment, not just R&D, unlike Phase 1. The overall budget was announced to be €1.5 billion over the ten-year period, but it is not possible yet to tell what fraction will go into deployment support. As one of the first deployment incentives, a program for residential fuel cells was launched in 2016: The German Federal Ministry for Economic Affairs and Energy (BMWi) is making €150 million available for the period 2016 to 2018 for efficiency measures in the building sector (Anreizprogramm Energieeffizienz, APEE). Residential CHP fuel cells of between 250 W and 5 kW electric output are supported with an upfront subsidy, depending on size. A 1 kW mCHP unit would get €10,200 for example.

While the German industrial situation allows and encourages entrepreneurial activity, in practice the vast majority of automotive fuel cell development takes place in the major corporations. While again this study focuses on the existing specialist suppliers, Bosch, like Denso is developing capabilities for fuel cell supply. Currently it is not working with components relevant to this study, but is likely to play an increasingly important role as the sector does mature.

6.3.5 UK and Sweden

The UK and Sweden do have some level of government support for fuel cells but do not have a major government vision and initiative comparable with those discussed above. And while the UK historically had a strong automotive industry, and retains manufacturing and components supply strengths, it is no longer equivalent to Japan and Germany, for example. Both countries have some fuel cell support initiatives, but these have tended to be comparatively low-key, and supply chain strength in automotive has come largely from existing corporations of the likes of Johnson Matthey and Sandvik. Specific motivations in these countries are less evident than in others, though industrial competitiveness and environmental issues play a role. The components being developed depend heavily on the specific strengths and positioning of the individual companies.

6.3.6 Canada

Canada, and in particular certain provinces, notably British Columbia, has historically supported fuel cell innovation and development, including one of the first fuel cell buses. Early in the 2000s, an enormous amount of investment was made into fuel cell developer Ballard by overseas companies, mainly Daimler and Ford. This combined with the local support to produce a significant strength in PEM fuel cells, including for automotive applications. The investment was driven by the potentially game-changing nature of the technology and the requirement for zero emissions in other jurisdictions, and focused on first-mover advantage and a wish to develop support innovation in general. The motivation was not because Canada had a strong automotive industry or necessarily wished to develop one. Ballard in fact exploited U.S. National Laboratory technology, in part, to achieve its high performance.

Although subsequently Ballard shrank in size and refocused its efforts, world-class expertise remained in the Vancouver area and led directly to the choice of location of the current AFCC fuel cell stack facility, which supplies Daimler. A few specialist suppliers and much relevant university activity are also in the region, while the Ballard diaspora is global and has influenced the fuel cell supply chain in all of the regions discussed. Canada continues to support fuel cells at a low level, and certainly for the time being the Vancouver cluster will remain important. This strongly illustrates the technological complexity of the fuel cell sector and the need for experience and data to support its development. New entrants will require external support or technology transfer in order to move rapidly, as is being clearly demonstrated by the engagement of Ballard expertise in China and by companies like VW.

6.3.7 China

China has spent many years building a foundation for fuel cell development. Government support for fuel cells was initially motivated by a wish to develop scientific skills, and some entrepreneurial companies have entered the space. China focused mainly on other, nearer-term technologies while building fuel cell competencies. Chinese conditions also allowed developers to produce vehicles which were not globally leading but nevertheless important prototype and pilot cars, and rapidly iterate these. The universities, which benefited from Government funding, are also traditionally strongly linked with automotive companies, acting in some cases as their *de facto* research and development divisions.

Chinese motivation has subsequently shifted and government programs are now focused on two major aspects of fuel cells – using them in certain vehicle classes (at present) to reduce air pollution problems in cities, and helping China move from a low-cost producer of commodities to a high value-added developer of solutions. This has four purposes: (1) to reduce reliance on overseas technology and expertise, and (2) to increase the potential for high-value jobs, (3) cleaner and better-performing industry and (4) high-value exports. A concomitant driver is the wish to exploit more indigenous non-fossil resources such as the very large amounts of solar and wind power already installed, which could potentially be turned into hydrogen and used in vehicles and other energy sectors.

The focus on air pollution has led China to re-prioritize its New Energy Vehicles program and give more emphasis to fuel cell vehicles. Battery electric vehicles have received support for a long period and are strongly represented. By supporting fuel cell vehicles, in particular buses in the near term, China is able to add a further option for air pollution reduction. China is also receiving support from the United Nations Development Program (UNDP) to expand its hydrogen and fuel cell expertise, including work with the City of Rugao, which intends to become a 'hydrogen city', and programs intended to bring in overseas experts to help with technology transfer and training for different parts of the supply chain. Unlike other countries and regions, it is plausible for China eventually to develop end-to-end automotive fuel cell supply capability, even starting with the raw materials for fluoropolymers.

New-energy vehicles subsidies were announced for the period 2016-2020 jointly by the Ministry of Industry and Information and the National Development and Reform Commission. Subsidy standards in 2016 will amount to 200,000RMB/unit (US$28,000/unit) for passenger cars, 300,000RMB/unit (US$42,000/unit) for light passenger vehicles and vans, and 500,000RMB/unit (US$70,000/unit) for large and medium buses and medium and heavy trucks. Subsidies for fuel cell vehicles will remain constant until 2020, whereas subsidies for pure electric vehicles and plug-in hybrid vehicles will be reduced by 20% in 2017-18 and 40% in 2019-20.[53]

In 2015, the Ministry of Industry and Information and State Administration of Taxation jointly issued an exemption from vehicle tax to new-energy vehicles. In a separate measure, the Ministry of Transport announced that it will be gradually decreasing the subsidy for fuel for conventional public buses (currently they cover the full cost of fuel) every year through 2019.[54] The government hopes that these initiatives together will bolster the number of clean-energy vehicles on the road to eventually hit a government-set growth target of 200,000 buses and 100,000 new-energy taxis and delivery vehicles on the road by 2020.[55]

Beijing also allocated nearly 100 billion yuan ($16 billion) to build charging facilities and appropriate infrastructure to popularize energy-efficient vehicles.[56] New hydrogen refueling stations are under construction in many areas.

[53] http://www.iphe.net/docs/Meetings/SC23/China_SC23.pdf
[54] http://www.iphe.net/docs/Meetings/SC23/China_SC23.pdf
[55] http://www.ibtimes.com/china-increases-subsidies-energy-efficient-vehicles-it-enough-alleviate-pollution-1929627
[56] http://www.ibtimes.com/china-increases-subsidies-energy-efficient-vehicles-it-enough-alleviate-pollution-1929627

6.3.8 United States

U.S. support for fuel cells has been long-standing and significant. Many enterprises have been developed because of and around such funding. Industrial – and defense – development is important. Much of the support has related to R&D, with national laboratories, universities, and companies all major contributors to progress. Some funding has also been available for infrastructure and for other market development activities. The U.S. automotive industry has historically played a big role, with both GM and Ford early investors – GM in fact producing the first fuel cell van in the 1960s. And the U.S. has major corporations with specialized skills which underpin many of the existing vehicles now emerging into the market. However, the U.S. vision for fuel cells has not been continuously strong. The Bush administration viewed it as an opportunity for indigenous energy but subsequent administrations saw it, at least initially, as a distraction. It has not been seen as a national priority in terms of either employment or environmental benefits. Nevertheless, California in particular has acted as a driver of the entire global industry, with its introduction of the ZEV mandate and subsequent addition of CO_2 regulations, unlike in other jurisdictions where CO_2 emissions reduction has never been a strong national motivation for fuel cells. Overall the U.S. and its individual states combine to show all three motivations of a strongly supportive country, but not always at the same time or in the same place.

Absolute levels of support have been comparable to other global leaders, and the continuity in some aspects has enabled the U.S. to build major competencies. Public information from the U.S. Department of Energy and others is used globally to set benchmarks and compare technology progress. Apart from California, however, only small demonstration fleets of vehicles have been put onto public roads, and this shows little sign of changing.

U.S. industry has been strongly engaged in fuel cells in the past, and some of it still is. UTC developed automotive stacks while GM and others were also working on them, and they subsequently helped Hyundai to make their first fuel cell vehicles. GM and Honda recently announced plans for a joint hydrogen fuel cell manufacturing facility in the Detroit Michigan area.[13] Ford's partnership with Daimler and what was once Ballard and is now AFCC was linked to major internal development efforts. Those programs appear to be smaller and less aggressive now than at that time, in part because of the impacts of the 2008 financial crisis.

Support for fuel cells and hydrogen technologies from the federal government in the U.S. go to a large extent into R&D activities as shown in Table 6-2. In total about 100 million USD are provided through DOE's Fuel Cell Technologies Office (FCTO), of which around 20% supports deployment through technology validation, work on safety, codes and standards, and through market transformation.[57]

[57] https://energy.gov/sites/prod/files/2016/11/f34/fcto_state_of_states_2016_0.pdf

Table 6-2: U.S. Federal funding for fuel cell and hydrogen activities[58]

Key Activity	FY 15	FY 16	FY 17
	($ in thousands)		
	Approp.	Approp.	Request
Fuel Cell R&D	$33,000	$35,000	$35,000
Hydrogen Fuel Cell R&D	$35,200	$41,050	$44,500
Manufacturing R&D	$3,000	$3,000	$3,000
Sustems Analysis	$3,000	$3,000	$3,000
Technology Validation	$11,000	$7,000	$7,000
Safety, Codes and Standards	$7,000	$7,000	$10,000
Market Transformation	$3,000	$3,000	$3,000
Technology Acceleration	$0	$0	$13,000
NREL Site-wide Facilities Support	$1,800	$1,900	N/A
TOTAL	**$97,000**	**$100,950**	**$105,500**

The major incentive at federal level to install fuel cell technologies is the investment tax credits of 30% for qualified fuel cell property or $3,000/kW of the fuel cell nameplate capacity (i.e., expected system output), whichever is less.[59] Although the tax credit benefits have been extended beyond Dec. 31, 2016 for many other technologies, it expired for fuel cells at the end of the year.[60]

Besides the federal funding and incentives available, many states support fuel cell technology:[14]

- 30 states include fuel cells or hydrogen as eligible resources in Renewable Portfolio Standards.
- 32 states permit net metering of fuel cells.
- 25 states offer funding for fuel cells in the form of rebates, grants, loans, bonds, PACE financing, or public benefits funding.
- 16 states provide personal, corporate, property and/or sales tax incentives for fuel cells.

California stands out with several policies in place:[14]

- CARB's Advanced Clean Cars Program builds upon the state's Zero Emission Vehicle (ZEV) Regulation, and the Clean Vehicle Rebate Project (CVRP) provides a $5,000 rebate for FCEVs.
- Assembly Bill 8, enacted in 2013, includes a provision to fund at least 100 hydrogen stations with a commitment of up to $20 million per year and the Energy Commission's Alternative and

[58] http://www.iphe.net/docs/Meetings/SC26/26-SC-Statement-United-States.pdf
[59] https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects
[60] http://www.fuelcellenergy.com/applications/financial-incentives/u-s-incentives/

Renewable Fuel and Vehicle Technology Program (ARFVTP) supplies funding for these hydrogen stations.

- The Fleet Rule for Transit Agencies that established a demonstration and purchase requirement of ZEVs, including FCEVs, for large transit agencies.
- The Self Generation Incentive Program (SGIP), which provides grant funding to support the deployment of distributed power generation resources, including stationary fuel cells. However, the program was modified in 2016 to focus on energy storage and its allocation to generation technologies (including fuel cells, wind, waste heat to power, and combined heat and power technologies) to just 25% of the program's overall budget.
- California state grant money supported, in part, 18 fuel cell buses for transit service and more than 480 fuel cell systems (totaling more than 210 MW of power generation).

Other states offer purchase rebates:[14]

- A $5,000 rebate is offered to FCEV purchased through Connecticut's Connecticut Hydrogen and Electric Automobile Purchase Rebate (CHEAPR) program. A $2,500 rebates is offered to FCEV purchasers (Hyundai Tucson Fuel Cell and the Toyota Mirai) under the Massachusetts MOR-EV program (funded by DOER).
- A $1,000 rebate on the purchase of a hydrogen and/or fuel cell vehicle is offered under Pennsylvania's Alternative Fuels Incentive Grant Program.

New York has a specific purchase requirement: [14]

- New York requires at least half of new, administrative-use vehicles will be ZEVs/FCEVs as part of the Clean Fleets New York pilot program, New York's Department of Environmental Conservation, NYPA, NYSERDA, and other agencies and as part of a pilot program. [14]

Many other types of program exist:

Sales and Use Tax Exemptions [14]

- New York provides a sale and use tax exemption for fuel cell systems.
- New Jersey offers a sales tax exemption for ZEVs which, for 2016, includes the Toyota Mirai and Hyundai Tuscon FCEVs.
- Washington State extended their existing sales and use tax exemptions to include vehicles powered by hydrogen.

Low Interest Loans/Tax Credits/Loan Forgiveness [14]

- For the FuelCell Energy manufacturing facility expansion in Torrington, CT, the state is providing a financial package that includes $20 million of low interest long-term loans and up to $10 million of tax credits. Additionally, the state is including forgiveness of up to 50% of the loan principal if job retention and job creation targets are reached.

Establishment of Rules and Permits related to fuel cells

- Connecticut has a Siting Council to review and approve stationary fuel cell power installations.
- 2016 Connecticut legislation has the objective of preparing the state and its industries for the presence and operation of electric, zero-emission and fuel cell vehicles within the state. The new law addresses underground parking of hydrogen fuel vehicles and makes changes to labeling of vehicles that carry pressurized gas as fuel.
- Colorado has a mandate to promulgate rules by 2017 concerning retail hydrogen fuel for vehicles including rules relating to inspections, measurement, and specifications.
- NREL is active in the development of hydrogen codes and standards for buildings, components, systems, and vehicles.
- Various groups, such as the Colorado Hydrogen Coalition, have been formed to accelerate development of the hydrogen fuel cell technologies market.

Renewable Portfolio Standards [14]

- Thirty states include fuel cells among the eligible technologies under their Renewable Portfolio Standard.
- Hawaii has set a goal of 100% clean energy by 2045 is taking strong steps to become a leader in hydrogen.

Direct funding is further available in other states also: [14]

- Incentive grant funding is provided through Connecticut's DEEP's Fuel Cell Program via the Connecticut Green Bank's On-Site Distributed Generation Program, the Microgrid Grant and Loan Program, and the Low and Zero Emissions Renewable Energy Credit Program (LREC/ZREC).
- Grant funding to support the deployment of distributed power generation resources, including stationary fuel cells, is provided in California through the "The Self Generation Incentive Program".
- New York's NYSERDA has made $150 million in funding available for large-scale renewable energy projects.
- Connecticut runs a competitive Microgrid Grant and Loan Program. Additionally, the state offers incentives via its Low-Emission Renewable Energy Credits Program, for participants to sell renewable energy credits to the local utility.

6.4 Capital Availability and Support Mechanisms

Capital specifically linked to scaling-up fuel cell supply chains is rare to find. Large capital investments typically come from large company balance sheets, and occasionally from loans. Many jurisdictions do offer support for new factory build and relocation, but these cover a wide range of technology and other industries. It is therefore hard to identify or specify the type and amount of such capital that can be made available if required. Equally, capital availability will be largely decided on conventional financial risk metrics – the size and balance sheet of the organization, the amount of finance required, time period for payback, default risk, etc. It is relatively unlikely that finance will be made available for fuel cells in preference to other technologies under these mechanisms, as they are by definition for industrial scale-up and not for R&D. To date, scale-up capital for manufacturing has fallen almost exclusively into two types:

- Funds raised from investors either pre- or post-IPO for the larger fuel cell pure-play companies (Ballard, Hydrogenics, Plug Power etc.)
- Funds provided internally by major corporations (Toyota, Honda, Johnson Matthey, etc.)

Some support for relocation or reduced premises costs has been provided in some cases, usually for the smaller companies. Typical external support does vary somewhat by country, but also by region and by type of entity. A brief overview of types of additional support is provided below.

6.4.1 Local and state economic development support

Economic development support comes in many forms. Grants and subsidies can be allocated by a city, region or country looking to attract a certain type of industry or employer. Under European Union rules, it can also be allocated in the form of structural or other funds to marginalized or low-income areas (usually regions of countries), with no prescribed technology or other requirements for investment.

6.4.2 Preferential tax treatment

In many cases, companies investing significantly into new facilities can negotiate favorable taxation options. These may include rapid capital depreciation and offsetting, or lower overall tax rates on corporate profits, sometimes for a defined period. In some cases companies can negotiate lower taxes simply by moving some operations to a region – Switzerland has particularly competitive relocation rates in many cantons.

6.4.3 Development bank loans

While conventional bank loans are ubiquitous, those given out by development banks follow their rules and mandates. They can be given at preferential rates or under preferential conditions, but will always have a set of ‘development’ criteria to be met over and above those that a typical bank uses for financial risk management.

6.5 Supply Chain Segment Analysis

As seen in the other sections of this report, very few automotive fuel cell suppliers are approaching full mass production capabilities, and in very few countries. All suppliers are moving cautiously and making incremental investments to meet current automotive fuel cell needs as they want to minimize the risk of technology changes in the early introduction phase of the hydrogen fuel cell system.

This section will cover a component scorecard of the 5 key components of this study in the respective region and provide a map of current global suppliers. It will also include the manufacturing gaps, opportunities, and vulnerabilities, potential tipping points, and U.S. strengths and weaknesses.

6.5.1 Active and Potential Component Suppliers and OEMs Global Map

Figure 6-1 below reflects the number of OEMs and suppliers by region that are actively producing or could potentially produce bipolar plates, catalyst, gas diffusion layers, H_2 vessels, membrane, and other BOP at the quality and volume required by an automotive OEM. In the European region, we see a concentration of suppliers within the current German supply base. In the Asian region, we see suppliers primarily in China and Japan, with a few in Korea. In the U.S. and Canada region, we see suppliers throughout the U.S, and in Canada in the Vancouver BC area.

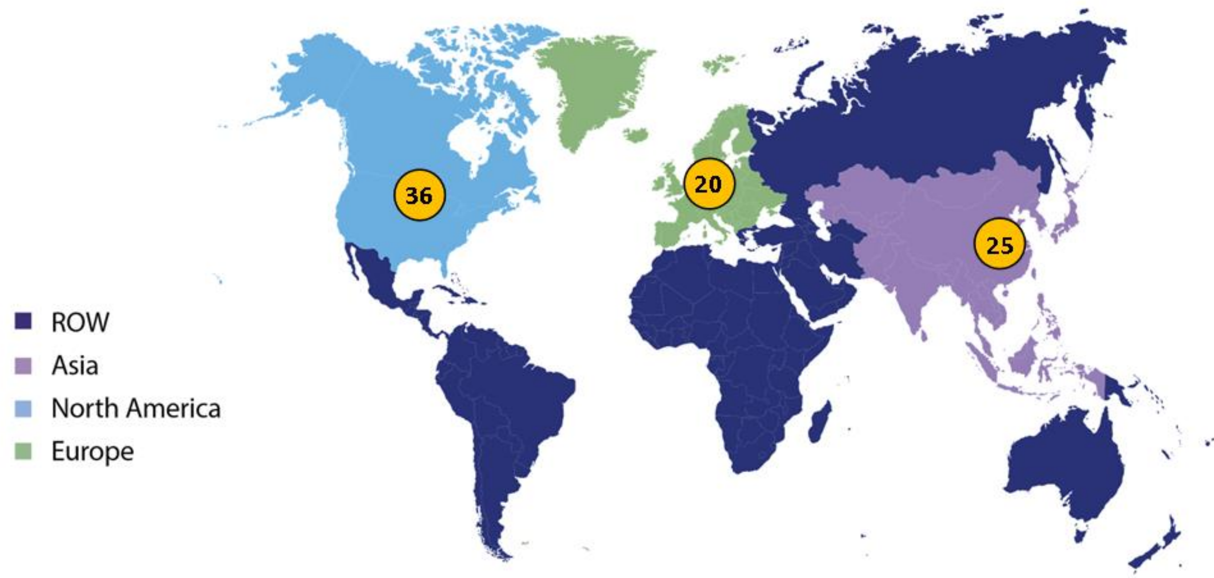

Figure 6-1: OEM and Suppliers by Region - Active and Potential

6.5.2 Component Scorecard – Technology and Manufacturing Readiness

The scorecard shown in Figure 6-2 shows the current global state of technology and manufacturing readiness at two volume levels, 1 -10,000 and 100,000 annual vehicles. At the 1-10,000 volume level both Asia and Europe reflect a green high capability that technology is currently sufficient to produce to stated demand for the 4 fuel cell stack components and the hydrogen pressure vessel. Although U.S. manufacturers at the 1-10,000 volume level are rated high to moderate manufacturing capability and capacity, since current production has not been demonstrated due to minimum demand from U.S. OEMs to date.

At the 100,000 volumes, we see a broad mix of capability although overall not capable of meeting the technology or manufacturing readiness needs at the 100,000 volume. No OEM orders exist at that level. Overall EU and Japan are in the best position for both technology and manufacturing readiness. In the Asia region, China lags Japan in technology and manufacturing for the four fuel cell stack components. For bipolar plates, major advancements in technology and manufacturing processes and major capital investment will be required. Europe is in the best position as they have three suppliers that have made bipolar plates at the lower volumes and could ramp up with major investment. For catalyst, Europe and Asia have manufacturers with the capability and capacity to operate at 100,000 units per year once the volumes are forthcoming. For gas diffusion layers, advancements in technology and manufacturing processes and capital investment will be required. For membranes, the technology exists although major advancements in manufacturing processes and major capital investments to produce to stated demand at cost and quality levels. For hydrogen pressure vessels, the technology exists and manufacturing capability could be added to meet the 100,000 unit volume. H_2 vessels have benefitted from the high demand of similar CNG (compressed natural gas) vessels that have been manufactured in volume over the last 5 years.

	Technology Readiness																			
	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	MOD	MOD	MOD	MOD	LOW	H-M	H-M	H-M	H-M	H-M	H-M	H-M	H-M

	Manufacturing Readiness																			
	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	LOW	M-L	MOD	MOD	LOW	LOW	MOD	M-L	LOW	M-L	M-L	M-L	M-L

Figure 6-2: Component Technology and Manufacturing Readiness Scorecard

Readiness Legend:

HIGH	Currently sufficient to produce to stated demand
HIGH TO MODERATE	Capability and capacity exist, although no current production demonstrated at stated demand
MODERATE	Requires some advancements or capital investment to produce to stated demand
MODERATE TO LOW	Requires some advancements capital investment, and no current production demonstrated at stated demand
LOW	Requires major advancements or major capital investments to produced to stated demand

7 U.S. Competitiveness Analysis and Suggested Actions

The U.S. has a long history of automotive manufacture, of innovation in manufacturing processes and in fuel cells of all types. However, it does not currently have a strong position in the supply chain for AFCSs with the notable exception of hydrogen storage systems.

7.1 Manufacturing Breakpoints and Tipping Point

As discussed in Section 1, automotive FC systems and components are currently produced in relatively small quantities commensurate with the currently low production rate of fuel cell vehicles. Current production rates stand at between a few hundred and 3,000 vehicles/year depending on the supplier. The manufacturing methods currently in use are generally pilot scale equipment or semi-automated, smaller versions of high-rate equipment. Examples of current manufacturing methods include web lines with narrow width, and stamping machines forming one part, when use of a larger pressure could form multiple parts simultaneously. In many cases, high-rate, fully automated equipment can be envisioned but has not been demonstrated, both because there is not yet product demand to justify the investment and also because some associated aspect of the technology has not yet reached maturity – such as QA systems for high-speed web processes.

The typical manufacturing lifecycle, consistent with production of an internal combustion engine vehicle , consists of the following stages: (See Section 4.2 for further details.)

- Development Stage: < 1,000 AFCS per year
- Introduction Stage: 1,000 – 20,000 AFCS per year
- Growth Stage: 20,000 – 100,000 AFCS per year
- Mature Stage: 100,000 – 500,000 AFCS per year
- Decline Stage: <500,000 APFS per year (and declining)

In practice, until at least tens and usually hundreds of thousands of units are being produced, costs are too high for the OEMs to make a profit. So there is often a large jump in production between the Development and Introduction Stages, representing a transition between a local/regional test program and an actual national product. This large jump is feasible because production methods are, in general, already fully developed and there is an existing infrastructure of production facilities. However, neither of these conditions applies to the current fuel cell vehicle market; thus the FCEV manufacturing breakpoints may not be the same as for ICEVs.

A typical method of assessing automotive production rates is through the “takt time”[61]. Takt time represents the time available to produce each unit to meet customer demand. (For example: if 365 units per year was required, the takt time would be merely 365 days/365 units = 1 day/unit.)[62] This style

[61] The name comes from the German word for an orchestra leader’s baton used to keep musical time.
[62] Sometime the reciprocal of Takt time is reported, parts per hour.

of analysis is appropriate for high rate production, where manufacturing methods at a variety of production rates are fully developed, and the issue is mainly about selection of the appropriate method.

A takt time computation is of value to the production of fuel cell components as it gives an indication of what production rate needs to be achieved to meet demand. However, other analysis methods and considerations associated with an emerging technology such as FCEV also influence manufacturing breakpoints. Such factors may include:

- The natural breakpoints for specific types of manufacturing processes to achieve full utilization (and presumably good economics). These will differ dramatically depending on the process and the part being produced, e.g., BPP production will be fully utilized long before the chemical plant for ionomer. (How many vehicles can a fully utilized manufacturing line support?)

- The level of capital investment needed to achieve the next level of production. (If capital investment is very high, a company may decline to commit to facility development until a very large and assured FCEV market is demonstrated or other guarantees are in place.)

- The general technical maturity of the process. (Production rate can be increased by use of parallel production lines. However, there is a practical upper limit on the number of parallel lines beyond which management of tolerances and inventory control become prohibitive. At that point, a new approach or manufacturing process may be required to achieve higher capacities. The new technology can only be implemented when it is fully proven.)

During the OEM and supplier interview sessions, each company was asked about their current level of technology and manufacturing accomplishment and what elements were needed to achieve the next level or production. Table 7-1 summarizes their responses as related to manufacturing breakpoint, defined here as the logical “next step” in manufacturing capability taking all of the above factors into consideration. The breakpoint potentially varies by component and thus is examined individually for each of the five key system components.

A “Tipping Point” is further defined as the manufacturing breakpoint that enables the conditions that precipitate a significant change to the status quo. Tipping points may take several forms and generally we desire to identify the tipping points that lead to favorable outcomes. Examples of tipping points include:

- Industry use of a high-rate manufacturing process that achieves lower cost, which by virtue of its low-cost increases demand, thereby creating a virtuous cycle of declining cost and potentially wider FCEV adoption.
- A company, region, or nation being first to implement a substantial production capability such that it creates a competitive price advantage over its rivals and thus creates the conditions wherein they become a dominant global or regional supplier.

Of course, this assumes a market for the product and not just an excess production capacity.

It is further noted that car companies will no doubt have multiple FCEV models within their portfolio of vehicles, and these vehicles may or may not use the same components coming off the production line, though in the early years it seems highly likely that parts will be common as far as possible. Consequently, a distinction is made between vehicles/year of a specific model, and vehicles/year of total manufacturers' production. Furthermore, it is likely that Tier 1 suppliers will (for some components at least) supply to multiple OEMs and so a further distinction is made between a manufacturer's total vehicles/year, and the total vehicles/year supported by a given supplier production line.

While the interviewees were queried about manufacturing breakpoints for their respective components, their responses were not always quantitative. Consequently, the manufacturing breakpoints are assessed below by combing the interviewee input with results of the DFMA® analyses. The result is a semi-quantitative assessment of the project manufacturing breakpoints that could be tipping points in favor of increased U.S. competitiveness.

Bipolar Plates (subdivided into forming, welding/joining, and coating)

Forming: A single high-speed stamping machine operating around the clock can produce BPPs for approximately 15,000 vehicles/year. Interviewees report existing capacity to support 1,000 to 15,000 vehicles/year (0.4 M to 5.6 M welded BPP/year). They further report the ability to scale up to ~100,000 vehicles per year with additional capital investment and (most likely) with use of larger and possibly stiffer presses to achieve greater dimensional tolerances.

Welding/Joining: Welding of the BPPs generally remains a production bottleneck with interviewees looking to improve capacity by increasing the level of welding automation and/or decreasing the required weld length. Welding can also cause thinning of material, affecting performance or durability. Of note are approaches that use adhesives to join the BPP halves, which obviates welding and hold the potential for short cycle times.

Coating: Physical vapor deposition (PVD) approaches are currently most prevalent with cycle times ranging from 3[63] to 30[64] minutes. These processes are typically conducted in batch operations. Consequently, batch size becomes a critical scaling parameter. To achieve an effective cycle time of 4 seconds per welded BPP assembly (to match that of stamping) for a 3-30 minute batch time, requires batch sizes of 45-450 parts per batch. This translates to ~15,000 – 150,000 systems per year at full utilization. Non-PVD approaches such as sol-gel-coating[65] or organic binder coating[66] hold potential for short cycle times and lower cost.

[63] 3 minutes is representative of the total system cycle time for vacuum draw-down, cleaning, deposition (up to ~30 μm), and re-pressurization for a conventional PVD process (magnetron sputtering or similar).
[64] 30 minutes is representative of a total cycle time of an amorphous carbon deposition system.
[65] European COBRA project – http://www.cobra-fuelcell.eu/objectives-2/
[66] U.S. Patent 8,053,141 B2 (2011).

Catalyst

Current FCEV catalysts are predominantly Pt-based, produced in batch processes, and applied by roll-to-roll inking. Interviewees report that batch catalyst processing is likely to remain for the long term, and Pt-based catalysts and roll-to-roll inking for at least the near to mid future, although work continues in non-precious metal catalysts and vapor deposition methods. While the specific procedures of catalyst powder synthesis vary considerably between suppliers and between types of catalyst, the process is in general a series of batch processes consisting of alternating applications of the following steps: precipitation/reaction, washing, drying/heat-treating, and acid-etching (optional). Batch sizes vary but are currently typically <10 L/batch and are not expected to exceed ~1,000 L batch volume even at full production (due to difficulties achieving both high catalyst quality and complete reactions in very large volume reactors). Based on DFMA® analysis, this suggests that batch sizes will be no greater than ~50 kg catalyst powder and a single fully utilized, large-scale system will support ~70,000 vehicles/year. However, we note that the knee in the production cost curve occurs much lower (closer to 10,000 vehicles/year) and that costs at low volume are driven primarily by business markup costs (R&D, physical security, and quality control/assurance). Scale-up procedure is well understood and there does not appear to be a clear-cut step change in catalyst manufacturing rate, as a continuum of equipment sizes exists for each processing step. While reductions in precious metal content will be very important, greater market demand appears to be the primary requirement to achieve reduced cost.

Membrane

Fuel cell membrane material is currently fabricated from PFSA ionomer on an ePTFE support material. Interviewees report that PFSA membranes are expected to be used into the foreseeable future, as is an ePTFE support, though multiple researchers are exploring lower-cost alternatives. Consideration of the manufacturing breakpoint requires consideration of both the membrane raw materials and of the membrane synthesis methods.

Ionomer: Demand for PFSA ionomer, even at high FCEV production rates, is expected to be low by industrial chemical standards: only ~50 metric tons per year of ionomer is needed for 500k vehicles/year compared to a typical polymer processing plant which can produce ~1,000 metric tons per day. Consequently, PFSA ionomer is likely to be produced in small tonnage plants for many years, with no obvious manufacturing breakpoints.

ePTFE Support: ePTFE is likewise produced in large quantity, at least for textile products. ePTFE suitable for fuel cell applications reportedly requires custom and proprietary processing steps but, as currently understood, such steps utilize processing equipment currently in existence. Consequently, no clear ePTFE manufacturing breakpoint is observed.

Membrane Synthesis: Creation of the ePTFE-supported PFSA membrane is currently achieved via roll-to-roll processing wherein the primary limiting factors are web speed, web width, and high-speed quality control systems. Interviewees did not report current production capacity but DFMA® analysis suggests that a single line running pilot-scale equipment can supply approximately 500,000 m^2/year, suitable for

~30,000 vehicles/year, while a production-scale facility can produce 1.5M m^2/year (or around 100k vehicles/year). DFMA® analysis also suggests that the primary step changes come from increasing web width: lab-scale equipment at ~0.25 m web width is suitable for 1k vehicles/year, pilot-scale equipment at ~0.5 m is suitable for 10,000-50,000 vehicles/year, and production-scale equipment at ~1 m is suitable for 80,000-500,000 vehicles/year. Web speed is obviously an important parameter but is traded-off with oven length to achieve the required residence time (typically ~3 minutes); web speed can be readily increased but comes at the expense of longer, more expensive drying ovens.

Gas Diffusion Layer

Currently, the GDL is produced by coating and oxidizing a precursor felt or woven paper of chopped PAN-based carbon fibers. PAN (polyacrylonitrile) is a global commodity, produced from ACN (acrylonitrile), which is primarily produced in Europe and Asia.[67] Conversion of PAN into carbon fiber (CF) (see below) is conducted at scale in Europe and Japan, and the United States Conversion of CF into a felt or paper roll-good suitable for GDL is reportedly conducted by only a few global suppliers, but at production rates well in excess of fuel cell demand for many years. Thus there are no apparent manufacturing breakpoints as the precursor materials (all the way up to the CF felt roll good) are expected to be supplied as a minor slipstream from current vendor production. In contrast, the additional processing to convert the felt precursor into fully functional FC GDL is expected to be done at bespoke facilities dedicated to FC GDL production. DFMA® analysis suggests that GDL price highly correlates with facility throughput, which in turn depends on roll width and speed, and on effective quality control (QC) processes for high speeds. Because optimal line speed is expected to remain approximately constant regardless of facility output, the critical parameter is web width. Interviewees were not willing to share facility capacities. Based indirectly on observed processes and input from OEMs, we estimate current manufacturing processes will support 300,000 m^2/year (equivalent to ~10k vehicles/year) with an implied web width of ~0.5-0.8 m. In contrast, facilities with a ~1 m web width could double capacity and, based on DFMA® analysis, achieve significantly better economics. Thus the GDL manufacturing breakpoint is estimated at approximately 80k vehicles/year.

Pressure Vessels

Carbon-composite wound pressure vessels are currently produced in high quantity (~100,000 vessels per year)[68] for compressed natural gas ICEVs. While the pressure for CNG storage tanks (typically 250 bar) is lower than the target pressure for H_2 tanks (700 bar), the methods and materials of construction are very similar. Consideration of manufacturing breakpoints for the pressure vessel requires separate consideration of the carbon fiber and the vessel fabrication process.

[67] http://www.icis.com/resources/news/2012/02/27/9535512/chemical-profile-acrylonitrile/

[68] The estimate of ~100,000 vessels per year takes into consideration the range of tank sizes currently being produced and attempts to normalize them to FCEV-sized tank equivalents.

Carbon Fiber: Pressure vessels are currently fabricated by wrapping high-strength continuous strands of carbon fiber (e.g,. Toray T-700 carbon fiber) around a gas-impermeable liner (aluminum or polymer). Interviewees report that suitable grades of carbon fiber are currently produced in high quantity (3,000 tonnes/year) at plants running two parallel lines at or near capacity. Reduction in cost due to economies of scale is therefore not expected as any increased capacity would be supplied by merely replicating processing lines with the same economics. Interviewees also report that carbon fiber is likely to be used into the foreseeable future (as opposed to replacement with other lower-cost materials). Innovation is likely to come in the form of improved quality control for the material and manufacturing processes so as to enable a reduction in carbon fiber usage. For these reasons, no carbon fiber manufacturing break-points are currently projected.

Vessel Fabrication: Pressure vessels are currently fabricated via "wet-winding" using multiple-spindle filament winding machines.[69] The process is identical to that used to fabricate CNG vessels but is adjusted for the additional fiber winding needed to achieve a higher composite wall thickness to contain the higher H_2 pressure. Consequently, the H_2 pressure vessel winding times are generally longer than CNG vessel times. Despite the longer winding times, DFMA® analysis suggests that winding cost is not a cost driver of the system (carbon fiber price is the dominant cost driver). However, high numbers of parallel winding process trains would be needed to complete 500k vehicles per year (at approximately 5 hours of winding time per vessel). This requires substantial factory floor space, but more importantly, creates potential quality control issues due to management of high numbers of parallel lines. Thus, while no obvious vessel fabrication manufacturing breakpoints are observed, there still exists a desire for higher capacity winding machinery.

Table 7-1: Summary of Manufacturing Breakpoints and Potential Tipping Point

Component	Current Capacity (per facility)	Next Manufacturing Breakpoint
Bipolar Plates	~1k veh/year, ~700k plates/year	20k- 100k veh/year
Catalyst	~2k+ veh/year	10k-70k veh/year
Membrane	~2k+ veh/year	10k-30k veh/year, then 80k-100k veh/year
Gas Diffusion Layer	10k veh/year	30k – 80k veh/year
Pressure Vessel	80k veh/year	80k veh/year

[69] Wet-winding refers to the impregnating the dry carbon fiber with liquid resin just prior to winding onto the tank. It is in contrast to the use of "pre-preg" wherein the carbon fiber is pre-impregnated with resin at a remote factory, transported to the winding site, and wrapped onto the tank in a predominately "dry" process.

7.2 General U.S. Strengths and Weaknesses

The United States possesses strengths that could aid it to become a global player in the future automotive fuel cell market. However, no single nation is clearly dominant regarding prospects for the long-term fuel cell market, and in relative terms, the U.S.'s strengths and weaknesses are generally slight in comparison to other nations. Consequently, the question is not if the U.S. will (in the long-term) be a significant global competitor (it clearly will be), but rather success or failure will be measured primarily by the rapidity and extent of U.S. participation in the global fuel cell marketplace.

The following U.S. strengths are generally applicable to all five of the key FCS components.

- Presence of a high-technology domestic automotive industry
  - The fuel cell supply chain is expected to build-out in the same manner as the internal combustion engine vehicle supply chain has developed. Consequently, the existence of a domestic precursor auto manufacturing capability is a significant advantage. Indeed, the FCEV is a direct replacement for the ICEV, and to a very large extent, the fuel cell supply chain is expected to be developed by many of the existing auto supply chain participants and OEMs, in the same locales. The U.S., like many European countries, Japan, Korea, and China, has a vibrant auto manufacturing infrastructure, capable of producing millions of vehicles per year, with advanced technology, and sophisticated Just-in-Time supply chain management techniques.

- R&D/Innovation
  - **The U.S. is a leader in innovation:** According to a recently published report on global manufacturing competitiveness by Deloitte[15], the U.S. is the largest spender on basic research with expenditure of US$64.4 billion. Japan is a distant second with spending of US$16.0 billion. Based on patents issued (in 2014), the U.S. is on top overall with 61,492 patents, representing 29 percent of patents filed by all countries.[70]

  - **Superb innovation ecosystem:** As succinctly stated in the Deloitte report: *"The United States has a superb innovation ecosystem where industry, start-ups, labs, and universities collaborate on R&D work to enhance manufacturing competitiveness, e.g., automotive cluster in Detroit. High productivity: The United States has one of the highest labor productivity in the world, at $110,050 (constant 2011 PPP international dollars) per person engaged in 2014."*

  - **Robust research funding at national laboratories and universities, which is exploited by the private sector:** Also from the Deloitte Report: *"Department of Energy's national labs, representing 17 facilities, are known to be pioneers in carrying out basic research, have created*

[70] Patents are an indirect, and flawed, measure of innovation. However, based on a preliminary assessment, Asian companies are currently dominating in terms of world-wide issued fuel cell patents.

an annual impact to the tune of US$21 billion from their path breaking technologies, e.g., development of Web, advanced cathode technology helping battery manufacturing industry."

- Infrastructure
    - While the U.S. physical infrastructure is aging, the U.S. road, rail, and coastal port infrastructure remains one of the best in the world for moving freight. Infrastructure is key to moving supplies and finished goods. While infrastructure is not a distinguishing factor compared to Europe or Japan, the U.S. infrastructure has some advantages over Mexico/Central-America and China (some regions).

- Educated Workforce
    - Access to an educated workforce is increasing a critical factor for manufacturing jobs. In general, the U.S. ranks high in this category although regional availability of sufficient employees may be a factor.

- Reliable and low-cost electricity supply
    - The U.S. has a comparative advantage in the reliable supply of low-cost electricity. While rates vary considerably across the US, average U.S. rates ($0.07/kWh) are significantly lower than those in Japan ($0.15/kWh, Germany ($0.15/kWh), and Mexico ($0.11/kWh). (But comparable to those in Korea ($0.06/kWh) and China ($0.08/kWh).
    - While low-cost electricity is obviously an advantage, electricity cost is, in general, a low fraction of total fuel cell system cost. However, for some high electricity-consuming components (GDL and carbon fiber), the savings may be appreciable.

While these U.S. strengths all generally apply to fuel cells, the R&D/Innovation aspects merit additional attention. Fuel cell related R&D is robust in the U.S. with notable work being conducted at the U.S. National Labs (Los Alamos, Pacific Northwest, National Renewable Energy Lab, Argonne National Lab, Sandia, and Brookhaven) and in the private sector (e.g., W.L. Gore & Associates (Gore), 3M). In principle, U.S.-based R&D could lead to increased U.S.-based manufacturing and U.S. competitiveness; this is a long-term trend, rather than a near-term accomplishment, and is consistent with the timescale required to achieve big changes in technology. However, R&D alone will not lead to U.S. manufacturing if there is no domestic market. The following facts are further noted:

- Manufacturing tends to follow the customer/market. This is evident in Japan where new fuel cell component manufacturing facilities have been erected to support the local FCEV automotive industry, and new manufacturing facilities are being planned and built in China to support local FCEV bus production.

- Gore is headquartered in Newark, DE and while their FC membrane technology was jointly developed in the U.S. (Elkins, MD) and Japan, Gore fuel cell membrane production facilities were recently consolidated in Japan, presumably to be closer to their automotive customers.

- While AFCS catalyst production currently appears to be dominated by Johnson Matthey, Umicore, and Tanaka, Brookhaven National Laboratory recently developed low-Pt catalysts and licensed the technology to N.E. Chemcat Corporation, a leading Japanese catalyst and precious metal compound manufacturer[16]. Production is presumably to be in Japan, close to the catalyst application and fuel cell vehicle assembly facility.

- 3M has devoted considerable resources to development of vacuum deposited low-Pt catalysts on nanostructured thin films. While such catalysts may ultimately come into widespread use, there have been no public acknowledgments of their use by any fuel cell developers.

The U.S. also has some disadvantages compared to other nations.

- **Growth in the Asian automotive and bus fuel cell market will come before growth in the U.S./rest-of-world. Demand will most likely be met by Asian suppliers, who then will use their manufacturing economies of scale to outcompete U.S. suppliers.** However, new manufacturing capability is being developed by U.S. companies in Japan capable of supplying markets in Japan, South Korea, and China. Meanwhile, China is actively pursuing partnerships with foreign fuel cell manufacturers[17], has programs in place aimed at developing indigenous supply chain capability, and is providing subsidies to consumers to stimulate a local fuel cell market [18]. Given low-cost shipping, there appears to be a risk that entire fuel cell systems (but perhaps not the bulky H_2 storage tanks) could be shipped worldwide, much as automotive Li-batteries are shipped today. While production near the automotive assembly plant may be the ultimate supply chain structure in a mature market, a supply chain with manufacturing bases in locations that are first to market could persist for several decades until the FCEV market reaches maturity.

- **Lack of Coordinated Incentives/Facilitation:** Other countries use incentives or mandates to create domestic demand. Domestic demand, combined with specific programs to develop their domestic fuel cell supply chain, will significantly accelerate a domestic manufacturing infrastructure. While such programs, to some degree, exist in the U.S., the U.S. has made no national long-term commitment to fuel cell technology. Consequently, potential supply chain participants (and OEMs) may be hesitant to commit to facility investment due to uncertainty.

- **High-cost labor:** Average U.S. labor costs are significantly higher than in Korea, China, and Mexico. (Labor rates are moderately higher in Germany and U.S. rates are comparable to those in Japan.) This would be a competitive disadvantage for the U.S. for labor-intensive manufacturing, but fuel cell component manufacture will be highly automated. In addition, the talent pool is China is rising due to China's enormous population and increasing access to higher education by the average citizen. These factors represent risks to U.S. competitiveness.

- **High corporate tax rate:** The U.S. currently has one of the highest marginal corporate tax rates in the world, posing a burden on manufacturers and making products less competitive. However, there appears to be less disparity in the "country effective tax rates" (vs. marginal rates), thereby lessening the impact of tax policy differences.

- **Increasing R&D investments outside of the US:** As summarized in the Deloitte report[15]: "*US-based manufacturing companies are also increasing their R&D efforts in Asia to take advantage of favorable R&D incentives and also to be closer to their markets so that they can bring out products to suit their localized needs. From 2000 to 2010, R&D performed by subsidiaries of U.S. MNCs [multinational corporations] in locations outside of the United States grew at an annual rate of 4.4 percent (in constant dollars) compared to growth of 2.3 percent in R&D spent by U.S. MNCs in the United States.*"

7.3 Assessment of U.S. Competitiveness in Each of the Five Key Components

The strengths and weaknesses described above applied to the U.S. manufacturing and the supply chain in general. However, the U.S. may have differing levels of inherent competitiveness among the five key components. Consequently, each key component is discussed individually below and a summary table indicating current and future competitiveness is given at the end.

Bipolar Plates: Since the BPP component is ultimately expected to be manufactured in close proximity to the AFCS assembly site, BPPs are expected to be produced in the U.S. as long as there is AFCS demand in the U.S. Currently, Europe and Asia hold the lead in BPP technology. However, given the U.S. capacity for innovation, there is a substantial opportunity for the U.S. to innovate in the areas of plate formation, coatings, and joining. U.S. suppliers are currently not willing to invest in upfront R&D since they do not perceive a favorable business case.

The BPP component is broken down into three sub-elements:

> BPP Formation: The U.S. is currently behind Europe in BPP formation and will likely import manufacturing technology for at least the near-term. It is less costly in import than to innovate. The prospects for U.S. formation production are low in the near-term and high in the far-term. The prospects for U.S. innovation are low to moderate.
>
> BPP Coating: The U.S. is lagging behind Europe and Asia in coating technology and production but there remains a substantial gap between coating technology available and what is needed. The prospects for U.S. coating production are low in the near-term and high in the far-term. The prospects for U.S. innovation is low to moderate.
>
> BPP Joining: There is no clear front-runner in terms of BPP welding (or other joining technology); new systems are needed to improve cycle times. Given the U.S. capabilities in non-BPP welding applications, U.S. production prospects are low in the near-term and high in the far-term. U.S. innovation prospects are high for both near and far-term.

Membrane: The U.S. currently holds the global lead in membrane technology and should continue to innovate. The membrane component is broken down into three sub-elements:

> *Ionomer*: The ionomer is likely to be produced in the future in large quantities at remote foreign sites (probably China). The prospect for U.S. production competitiveness is low while innovation

competitiveness (developing new, better-performing, or intrinsically lower-cost ionomers) is high.

Membrane support: U.S.-based W.L. Gore Inc. is currently the world leader in ePTFE support, although production and R&D (for FC membrane) currently occurs in Japan. Other U.S.-based companies (e.g., 3M and Giner) have development efforts in non-ePTFE supports. The prospect for U.S. production is moderate and innovation competitiveness is high.

Roll-to-Roll/Casting membrane fabrication techniques: High-speed fabrication techniques, derived from slot-die coating, are expected to be used in the future. While the U.S. has a strong competitive position in this generic field, Europe and Asia are also strong. Additionally, localized production of the CCM/MEA may be favored over remote centralized production with shipping of value added components. Consequently, prospects for U.S. production and innovation competitiveness are moderate to high.

Catalyst: Europe (Umicore, Johnson Matthey, Heraeus) and Asia (Tanaka) are currently the world leaders in fuel cell catalyst technology. Given the long development lead time and other barriers to market entry, this is likely to continue for many years. A few U.S. companies have the potential to be competitive suppliers but either currently have no development programs or no market position. However, due to the high cost of Pt-based catalyst, there may be negative tariff consequences for cross-border transport; this may favor U.S.-based production to supply U.S. demand. Conversely, stringent quality control requirements and ease of shipping due to the limited volume of catalyst material (even to support high vehicle production rates) argues for catalyst production remaining with its parent company. Overall prospects for U.S. catalyst production competitiveness are low in the near-term and low to moderate in the far-term. U.S. innovation competitiveness is moderate.

GDL: Four main competitors predominate and are divided among Europe (SGL, Freudenberg), Asia (Toray), and the U.S. (AvCarb). GDL is a roll-good and thus can theoretically be easy to ship. However, the GDL properties are manufacturer dependent, with some manufacturers reporting somewhat brittle GDLs while others indicate that brittleness is not a factor. Consequently, a remote centralized GDL production facility may develop, unencumbered by long-distance shipping concerns. The U.S. does not seem to enjoy any clear advantages over other regions. Overall, the outlook for U.S. GDL production and innovation competitiveness is rated moderate.

Pressure Vessel: Pressure vessel competitiveness is divided into carbon fiber production and vessel fabrication. Both areas are ripe for technology advancement and the U.S. is active in both.

Carbon Fiber: Toray (Japan) is a dominant supplier of intermediate modulus continuous carbon fiber most appropriate for pressure vessels. However, Toray has production facilities in the U.S. with new capacity planned (South Carolina) and existing capacity available through Toray's Zoltec acquisition (Missouri and Texas). The outlook for carbon fiber production in the U.S. is improving (although most likely through foreign-owned companies with U.S. production facilities focused on aerospace applications). Carbon fiber availability is limited by production rate. As automotive fuel cell demand develops, new facilities will develop. This affords an opportunity for these new facilities to be in the U.S. The outlook for U.S. fiber production is rated moderate to high. Innovation competitiveness is also rated moderate to high based on ongoing national laboratory and industrial R&D.

Vessel Fabrication (CF winding): Europe, Asia, and the U.S. all have substantial high technology capabilities. The prospect for U.S. production and innovation competitiveness is rated high.

Figure 7-1 summarizes the U.S. prospects described above for each of the five key components.

<table>
<tr><th></th><th colspan="2">BPP</th><th colspan="2">Membrane</th><th colspan="2">Catalyst</th><th colspan="2">GDL</th><th colspan="2">Vessel</th></tr>
<tr><th></th><th>Near</th><th>Far</th><th>Near</th><th>Far</th><th>Near</th><th>Far</th><th>Near</th><th>Far</th><th>Near</th><th>Far</th></tr>
<tr><td rowspan="6">Manuf. Potential</td><td rowspan="2">Forming Low</td><td rowspan="2">Forming High</td><td rowspan="2">Ionomer Low</td><td rowspan="2">Ionomer Low</td><td rowspan="6">Low</td><td rowspan="6">Mod-Low</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="3">Fiber High-Mod</td><td rowspan="3">Fiber High-Mod</td></tr>
<tr></tr>
<tr><td rowspan="2">Coating Low</td><td rowspan="2">Coating High</td><td rowspan="2">Support Mod</td><td rowspan="2">Support Mod</td></tr>
<tr><td rowspan="3">Fabricate High</td><td rowspan="3">Fabricate High</td></tr>
<tr><td rowspan="2">Joining Low</td><td rowspan="2">Joining High</td><td rowspan="2">R2R High-Mod</td><td rowspan="2">R2R High-Mod</td></tr>
<tr></tr>
<tr><td rowspan="6">Innov. Potential</td><td rowspan="2">Forming Mod-Low</td><td rowspan="2">Forming Mod-Low</td><td rowspan="2">Ionomer High</td><td rowspan="2">Ionomer High</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="3">Fiber High-Mod</td><td rowspan="3">Fiber High-Mod</td></tr>
<tr></tr>
<tr><td rowspan="2">Coating Mod-Low</td><td rowspan="2">Coating Mod-Low</td><td rowspan="2">Support High</td><td rowspan="2">Support High</td></tr>
<tr><td rowspan="3">Fabricate High</td><td rowspan="3">Fabricate High</td></tr>
<tr><td rowspan="2">Joining High</td><td rowspan="2">Joining High</td><td rowspan="2">R2R High-Mod</td><td rowspan="2">R2R High-Mod</td></tr>
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Figure 7-1: Summary of U.S. Competitiveness in Manufacturing and Innovation

7.4 Specific Actions to Improve U.S. Competitiveness

Based on the examples of other countries' attempts to improve competitiveness (Section 6.2 and 6.3), and with recognition of U.S. strengths and weakness (Section 7.3), the following actions are suggested for consideration to improve the competitiveness of the U.S.-based FCS supply chains. The options are not mutually exclusive, nor are they completely independent of each other.

In general, the options fall into three main categories: *Actions to Increase Demand, Actions to Support Manufacturing Scale-Up (i.e., increase supply),* and *Actions to Support Component Development.* FCEV demand is a fundamental requirement for a successful AFCS supply chain, and is likely to influence its location. Consequently, the *Increase Demand* options focus on lowering cost or otherwise increasing vehicle sales. AFCS supply must of course be technologically feasible and economically favorable. Consequently, the *Support Manufacturing Scale-up* options focus on creating the supply chain conditions wherein suppliers have sufficient technological and business confidence to invest in production facilities. Finally, the *Support Component Development* options are critical because the AFCS suppliers must be technologically able to produce the parts at quantity while meeting cost and performance targets, and as previously discussed, there are currently many technology/manufacturing shortfalls.

We note that in the long term (i.e., in a mature AFCS economy governed by a Tier One-Half supply chain), AFCS manufacturing is expected to be located in the U.S. as is currently the case for the analogous production of ICEs and ICEVs. Thus, there will be North American production (for at least some components) and assembly for the North America FCEV marketplace. While this may be the inevitable outcome in the far-term, industry/DOE action to improve U.S. manufacturing capability in the near-term may hasten the process and may deepen the extent to which design of the vehicles occurs in the U.S., and whether U.S. companies own the eventual design/production facilities.

Options to increase U.S. competitiveness hence include:

- **Actions to Support Demand**
  - **Increase Demand by Lowering Cost to Consumer:** Developing the U.S. as a location of strong demand will help to determine the manufacturing process selection and how the supply chain will be structured and located. Increasing demand can come through lowering cost, so any actions that reduce the total cost of components/system/sub-system produced in the U.S. should improve competitiveness. These actions include:
    - Direct FCS/component consumer subsidies for U.S. produced components.
    - Loan guarantees for production plants/equipment.
    - Low-cost loans for capital equipment.
    - Investment tax credits.
    - R&D tax credits.
    - Other tax reductions.
    - Research and development on manufacturing processes (to reduce cost).
    - Lower Corporate tax.

  - It is noted that increased demand has the potential benefit of increasing supply. In the nearer-term, the market for FCEVs is quite limited. However, in some cases production close to the demand source is valuable. For example, Gore membrane/MEA production is situated in Japan, close to the Japanese demand (Toyota's AFCS production facilities). Consequently, if there were increased U.S. demand for FC components, there would be a much higher likelihood for U.S.-based production of the components. [It is further noted that Toyota Mirai fuel cell vehicles are produced in Japan but are sold both in Japan and worldwide (U.S., Europe). Thus, in this near-term scenario, a production facility supplies outside the region, but in the long-term, production and end-user demand locations are expected to be highly correlated.]

  - **Increase Demand by Guaranteed Purchase Plan:** The government could guarantee to purchase a certain number of vehicles every year so as to stimulate the supply chain. For instance, the U.S. government could buy up to 10k vehicular power plants per year for five years. This would cost up to $80M/year for five years but would create an assured market that would allow suppliers to invest in production facilities. (Note that the guaranteed purchase is of the FC power plant only, not the entire FCEV. The auto OEM's presumably would arrange production of the remainder of the vehicle and H_2 supply infrastructure.)

- **Actions to Support Manufacturing Scale-up**
  - **Go big:** Economies of scale is a potent strategy to reduce cost and destroy competition. In fact, China's competitive advantage in both photovoltaics and automotive Li-ion batteries has been largely attributed to economies of scale built by the related glass and small electronics industries, respectively [12], [19]. And since cost is a key factor in component selection, having a large plant capable of low-cost production is a large advantage.

    We note the relationship between "being first" and "being big"; they are not the same but are often related. The company who is first to market, at scale with a low-cost product, has a competitive advantage and may be able to pool orders from a variety of worldwide small demands and thus become a dominant global supplier. They may be able to enter the virtuous cycle of large production -> low cost -> higher demand-> lower cost, etc. This strategy is most applicable in the near-term, less-mature H_2 economy. However, the company that is first to market may suffer the "first-mover disadvantage" wherein they end up spending capital to develop technology, which is then largely utilized by competitors unencumbered by development cost. This is what happened with Chinese photovoltaics, which mostly bought-in older tech but at enormous scale. Alternately, the first mover may find that they invested heavily in innovation only to be surpassed by the rapidly evolving technology marketplace. Thus we conclude that "Going Big" is more important than being first, but that being first possibly allows you the option to "Go Big".

  - **Encourage Fuel Cell Hubs:** The objective would be to encourage a vibrant community of fuel cell related businesses so that the supply chain impact would be greater than the sum of its parts. This option is based on the following tenants:
    - The OEMs interviewed for this study have expressed a desire/requirement for 3-5 viable and at least partially interchangeable suppliers of each component so as to ensure a vibrant marketplace and reliable supply. Since different OEMs will not want to rely on the same 3 suppliers, this means a slightly larger pool.
    - The current ICEV supply chain illustrates the advantages of supplier co-location with automotive assembly plants for many components, at very large scale. [20]
    - FC businesses become anchors for additional FC business. Establishment of a FC business promotes additional related business to be located in the same region. For example, Ballard Power Systems' location in Vancouver was the anchor for co-located AFCC and Mercedes facilities. Another example is Silicon Valley which attracts many internet related start-ups due to the high density of related

businesses in the region. Likewise, establishment of a (large and successful) U.S.-based FC company can be a draw for additional business.

- Future U.S. FC manufacturing facilities are likely to be at or near existing ICEV manufacturing facilities. Thus existing U.S. ICEV manufacturing centers are prime candidates for future fuel cell hubs. There has been a trend for automotive assembly plants to go to locales outside of the Detroit area, typically in labor cost or tax beneficial locations. For example:
  - Honda in Marysville, OH
  - VW in Cleveland, TN
  - Toyota Motor Manufacturing, Mississippi, Inc. (TMMMS) in Blue Springs, MS
  - Toyota Motor Manufacturing, Kentucky, Inc. (TMMK) in Georgetown, KY
  - Toyota Motor Manufacturing, Texas, Inc. (TMMTX) in San Antonio, TX
  - Toyota Motor Manufacturing, Indiana, Inc. (TMMI) in Gibson County, IN
- Taken together, the above points argue for development of regional FC technology hubs in current ICEV production zones to enhance competitiveness by creating the conditions most amenable to OEMs. Consequently, actions taken to create FC business hubs in the U.S. would enhance U.S. competitiveness.

- **Encourage local development:** U.S. OEMs and manufactures need to re-start local development as they have fallen behind Japan and Europe in BPP, membrane, GDL, and catalyst (and are on par in H_2 vessels). Federal, state, or regional efforts, working with manufacturers to address any issues and increase engagement would maintain or improve the U.S. capacity to capitalize on market growth

- **Actions to Support Component Development**
  - **Invest in R&D:** The U.S. has a robust and exemplary history of innovation, thus encouraging FC-related U.S. R&D will increase the chances of U.S.-based production in the early years. However, technology is global, and a production process invented in one company can often be readily transferred to another country for production. Nonetheless, there is an increased likelihood that new production technology will be first used in the country of origin in the early years. And even if the U.S.-developed technology is exported, there still is a substantial U.S. benefit through royalties, technology spin-off affects, and through the potential increase of local AFCS demand. It is noted that fuel cell related technology gaps exist (see Section 2.7.2) and additional R&D is needed to fill them. Consequently, R&D is needed just needed at the fundamental level (for long term improvements) but also at manufacturing development level (in the near-term).

- **Component Specific Manufacturing Development Projects:** Manufacturing-related actions to enhance U.S. competitiveness can be taken for specific fuel cell system components. These manufacturing opportunities are divided into two categories: a high priority category representing nearer-term applied research, and a lower priority category representing longer-term basic research.

High Priority Manufacturing Opportunities (generally applied research)

MEA

- Opportunity #1: Development of a (near-)continuous, high-speed process for MEA fabrication
  - Processing of membrane, catalyst application, GDL, and gasket, all in continuous, high-speed line.
  - In-line quality control for the above.
  - Roll-to-roll processing (or other) that minimizes handling of individual parts by delay of part singulation as long as possible.
  - Process capable of MEA fabrication of ~1/second (~1.8 m^2/minute (based on active area))
- Opportunity #2: Development of low-cost methods for gasket application
  - Simplified, low-cost, high-speed application of the gasket material to the BPP or MEA.
  - Design and/or selection of materials to facilitate the above.
  - Gasket application or methods to serve function of gaskets

Vessels

- Opportunity #3: Development of high production rate pressure vessel fabrication lines
  - Winding process is currently well understood but is time-consuming. Multi-hour wind times leads to very large numbers of parallel winding machines needed for high rate vessel production.
  - Develop alternate winding approaches to dramatically reduce the number of parallel lines needed.
  - Develop alternate curing systems to simplify furnace requirements (dwell time and furnace length).
- Opportunity #4: Development of new, low-cost fibers as alternatives to carbon fiber
  - Carbon fibers are currently the major cost element of the H_2 storage system.
  - Develop alternative fibers, from alternative non-PAN precursors, that are inherently less costly but of equal modulus and tensile strength performance.
  - Develop simplified, low-cost processing of these alternative fibers.

Bipolar Plates

- Opportunity #5: Development of (near-)continuous, high-speed process for BPP fabrication
  - Sequential, roll-to-roll formation, coating, and joining of BPP assemblies

  - Delay of part singulation so as to minimize part handling
  - Develop processes capable of <1 s per plate processing time (~3 m^2/min (based on total plate area))
- Opportunity #6: Program to characterize and assess the problem of thinning of metal in BPP
  - Investigate limitation of conventional sheet metal stamping due to metal elongation limits and thinning issues.
- Opportunity #7: Development of alternate forming techniques that solve the metal thinning limitations of conventional stamping.
  - Identify/Devise solutions to these limits so as to enable advanced BPP designs consistent with expected future stack performance (high power density, improved water management, low-pressure drop, low stoichiometric flow rates, etc.).

Industry standardization of some balance of plant components

- Opportunity #8: Standardization of the compressor/expander/motor
  - Facilitate strategic partnership or joint venture between OEM and CEM supplier
  - Facilitate creation of a consortium of CEM manufacturers to develop standard requirements and/or designs

Manufacturing R&D/Demonstrations

- Opportunity #9: Demonstration of high-speed, high accuracy, geometry-neutral fuel cell stacking system
  - Equipment is needed by all vendors
  - Provides quality control at high processing rates.
- Opportunity #10: Demonstration of low-cost, high-speed, high-accuracy, geometry-neutral BPP welding systems
  - Equipment is needed by multiple vendors.
  - Current systems are costly due to low welding and indexing speeds.
  - Desired system would leverage existing U.S. capabilities in welding and system automation to develop high-speed, high-accuracy automated systems that could be used by any fuel cell vendor.

<u>Lower priority manufacturing opportunities: (generally basic research)</u>

Catalyst

- While Pt-based catalysts are fairly well-understood, there is always a desire for development of catalysts with superior polarization performance and/or lower cost.
- Opportunity #10: Optimize the structure of ultra-thin catalyst layers (e.g., NSTF with water-management/flooding problems solved)

Membrane

- Opportunity #11: Understanding and performance of Nafion™ PFSA membranes is fairly advanced.

- Opportunity #12: Improvements for increased durability.
- Opportunity #13: Improvement for lower cost.

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9 Appendices

Appendix 1 Project Team, Objectives, and Deliverables

- Identification of Team, Duration, Goal
  The project prime awardee was Global Wind Network (GLWN) (Patrick Fullenkamp PI, Dee Holody, Renee Anderson). The working project partners were Strategic Analysis, Inc. (Brian James, Cassidy Houchins); DJW Technologies (Douglas Wheeler); E4tech (David Hart, Franz Lehner). Two independent sub-contractors were Brent Fourman and Bowen Liu. The work was carried out in close collaboration with DOE EERE (Nancy Garland); DOE Golden Office (Jesse Adams, Chris Werth, Nicholas Oscarsson); The project duration was from June 1, 2015 to December 1, 2016 for the Competitiveness Analysis and through May 31, 2019 for the 4 years of annual fuel cell metrics of units, megawatts by country, and by application.

  The goal of the project was to identify and develop a greater understanding of the five key components of the automotive PEM hydrogen and fuel cell system. And determine the current state of supply chain readiness at four production levels 1,000, 10,000, 100,000, and 500,000 annual vehicle volume from both the automotive OEM's and Tier 1's perspective. Also establish the key factors determining fuel cell systems component manufacturing costs and pricing on a global basis in order to enhance the competitiveness of U.S. manufacturers, and to reduce installed systems cost. Multiple stakeholders including DOE, automotive OEMs, and component manufacturers will all benefit by better understanding the factors determining domestic competitiveness in the emerging automotive PEM hydrogen and fuel cell system industry.

- Major objectives of this project were:
  - Project Team will carry-out a detailed manufacturing (1) Global Competitiveness Analysis of hydrogen and fuel cell systems and components manufactured including 700 bar compressed hydrogen storage system in the U.S., Europe, Asia, and other key areas to be identified to determine the global cost leaders, the best current manufacturing processes, the key factors determining competitiveness, and the potential means of cost reductions. This objective, in close conjunction with the National Renewable Energy Laboratory, will be completed in Period 1 (M1-M18) and the report issued in M18.
  - In parallel, GLWN will also carry-out an (2) Analysis to assess the status of global hydrogen and fuel cell markets. The analysis of units, megawatts by country and by application will focus on polymer electrolyte membrane (PEM) fuel cell systems (automotive and stationary). This objective will be completed annually and all data for the designated reports will be reported during M12, M24, M36 and M48.

- Lists of Deliverables
  This initiative to conduct a global hydrogen and fuel cell manufacturing competitiveness analysis will provide key data that will assist the DOE FCTO to prioritize strategic investments to strengthen American competitiveness in domestic and global markets of hydrogen and fuel cell components and systems. The following outcomes from this analysis will further support the FCTO's mission to enable commercialization of a portfolio of hydrogen and fuel cell technologies, and reduce institutional and market barriers that may impede future commercialization of associated technologies:

  1. Identification of the global cost leaders of the systems and major components
  2. Identification of the best global manufacturing processes of the systems and major components
  3. Identification of the key factors determining competitiveness
  4. Identification of the potential means of cost reductions
  5. Annual 4 year Global Market Analysis of Hydrogen and Fuel Cell Systems

Appendix 2 Additional Images

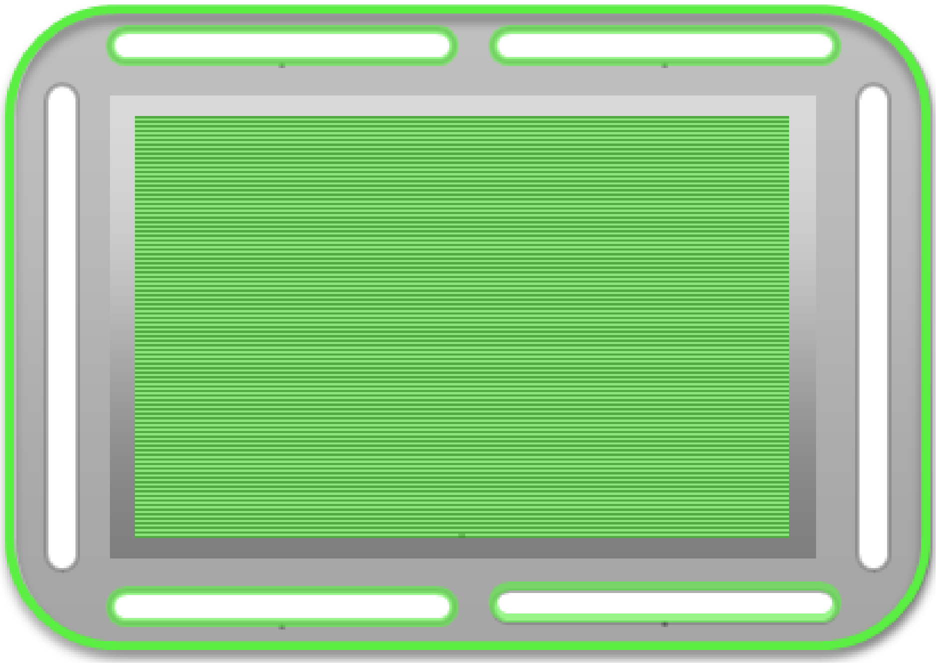

Figure 9-1: Schematic of a bipolar plate showing critical features (reactant and cooling manifolds, and flow fields) in gray. Green areas indicated potential weld points.

Figure 9-2: Bipolar plates shown by Borit at the 2016 Hannover Messe convention in Hannover, Germany.

Photo taken by Patrick Fullenkamp.

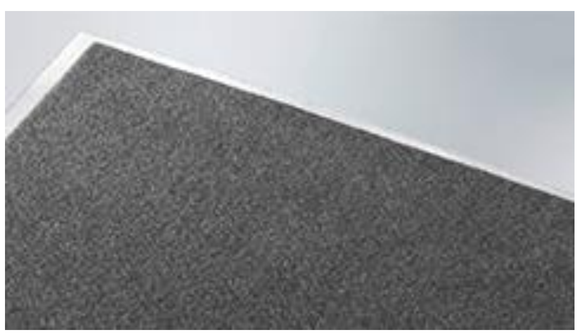

Figure 9-3: Image of a gas diffusion layer

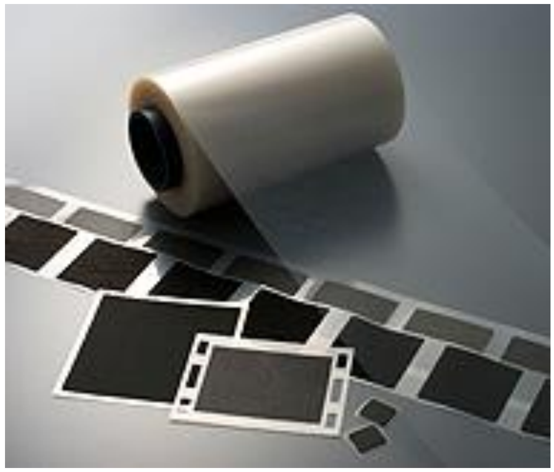

Figure 9-4: Image of catalyst coated membrane

Figure 9-5: One of two 700 bar Type IV H_2 pressure vessels on the Toyota Mirai

(source: Patrick Fullenkamp).

Appendix 3 Cost Model Assumptions

Table 9-1: Regional cost assumptions used in discounted cash flow analysis.

Unskilled Wages	\$/hour	18.73	10.88	18.55	3.34	3.34	23.97
Skilled Wages	\$/hour	26.95	15.65	26.70	6.60	6.30	34.50
Supervisor Wages	\$/hour	50.85	0.00	0.00	13.41	13.41	65.09
Facilities Cost	\$/m^2	1,700	805	1,700	805	805	1,904
Utility Rates	\$/kWh	0.07	0.06	0.15	0.08	0.11	0.15
Installation Factor (% of capital cost)	%	12	6	12	6	6	12
Real Cost of Capital	%	10	10	10	10	10	10
Marginal Corporate Tax	%	40	24	36	25	30	30
Cost Inflation (cost of labor, util., materials)	%	2.5	3.2	0.0	2.8	5.9	1.7
Expected MSP Inflation	%	2	2	2	2	2	2
Property Tax and Insurance Rate	%	2	2.0	2	2	2	2.0
SG&A (% of Revenue)	%	12.3	12.3	12.3	12.3	12.3	12.3
R&D (% of Revenue)	%	3.5	3.5	3.5	3.5	3.5	3.5

Table 9-2: Fuel cell stack assumptions used in DFMA® analysis.

Stack power	80 kW_{net}
Operating temperature	100°C
Peak operating pressure	2.5 atm
Relative humidity (stack inlet)	67%
Power Density @ rated power	746 mW/cm^2 (1,128 mA/cm2 @ 661 mV/cell)
Cathode stoichiometry	1.5
Cathode Catalyst	Dispersed de-alloyed PtNi
Cathode Pt Loading	0.092 mgPt/cm^2
Membrane	17 µm, ePTFE support, PFSA, 12.7 m^2/stack
GDL	23.65 m^2/stack
Plates	Stamped 0.0762 mm (3 mil) 316L SS
Coating	TreadStone proprietary materials and process

Table 9-3: Hydrogen storage system assumptions used in DFMA® analysis.

Design pressure	700 bar
Safety factor	2.25
Usable H_2	5.6 kg
Carbon Fiber	Toray T-700S
Resin	Vinyl Ester
Total Composite Mass	97 kg
CF Volume Fraction	64.7%
Liner Material	HDPE

Appendix 4 Component Value Stream Maps

The following are the value stream maps for each component, for each of the three regions based upon plant visits and or data obtained in interviews with manufacturers or equipment suppliers.

Appendix 4.1 Bipolar Plate VSM

Example 1

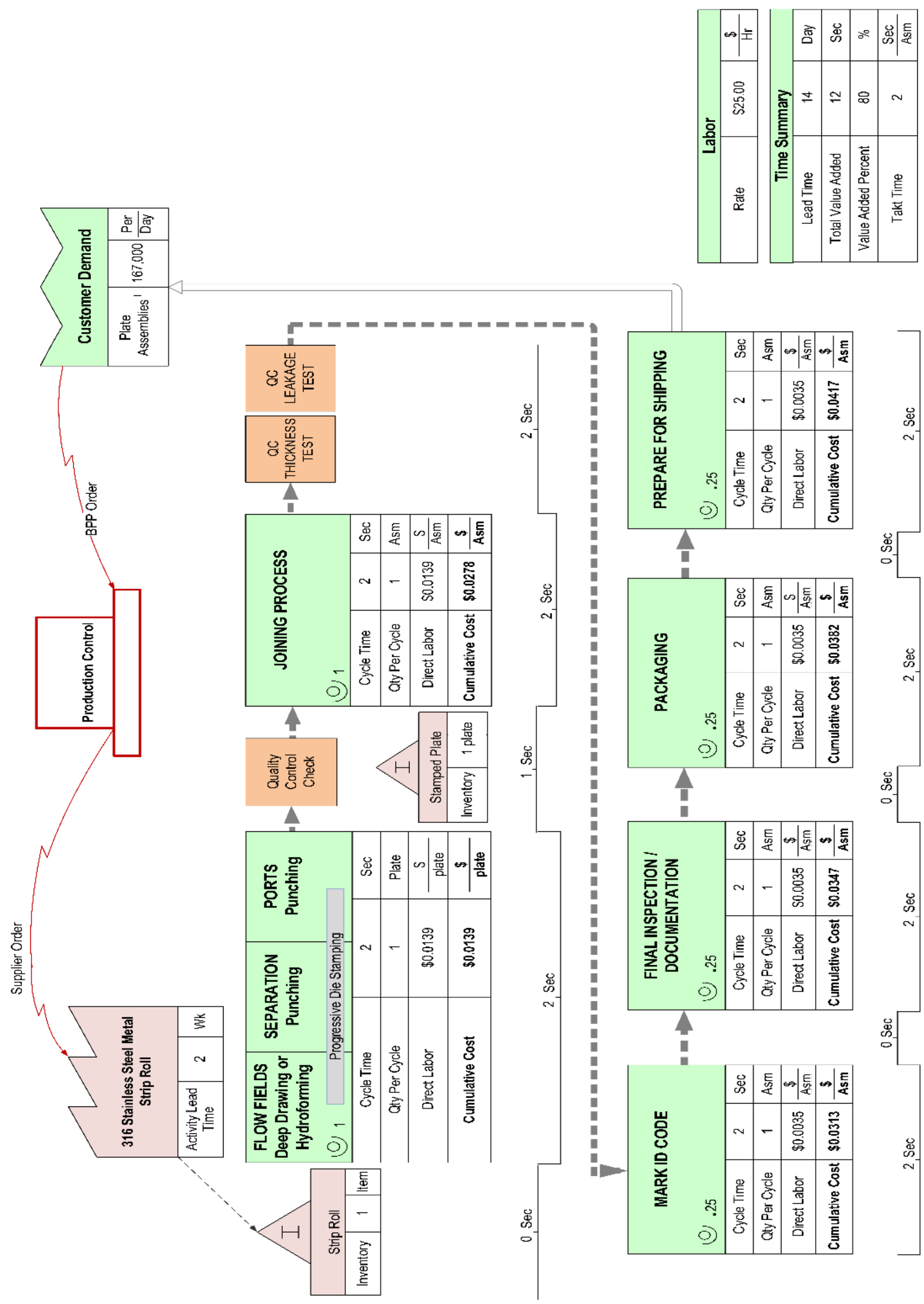

Figure 9-6: Bipolar Plate Manufacturing Value Stream Map (100k vehicles per year) - Example 1

Example 2

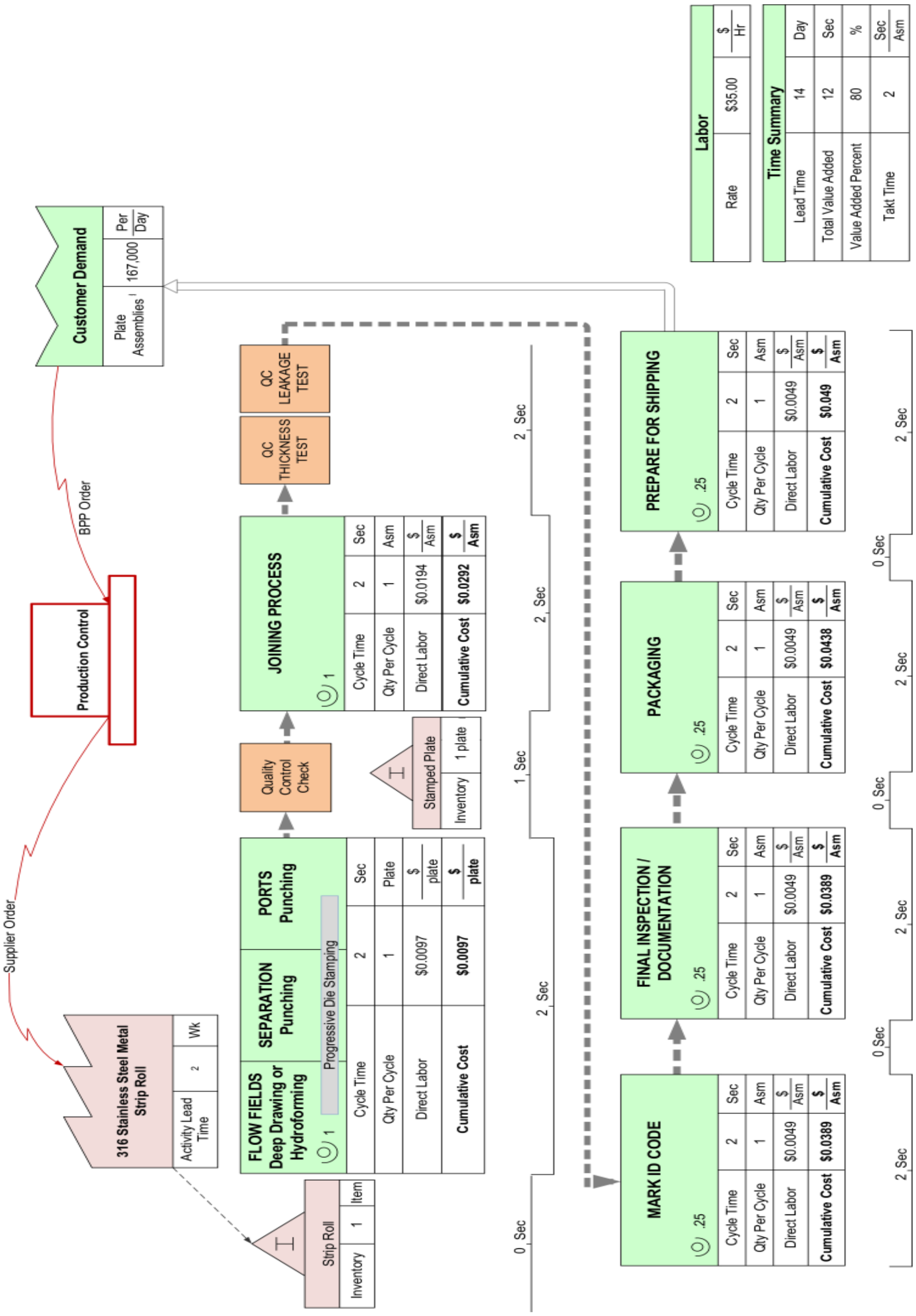

Figure 9-7: Bipolar Plate Manufacturing Value Stream Map (100k vehicles per year) – Example 2

Example 3

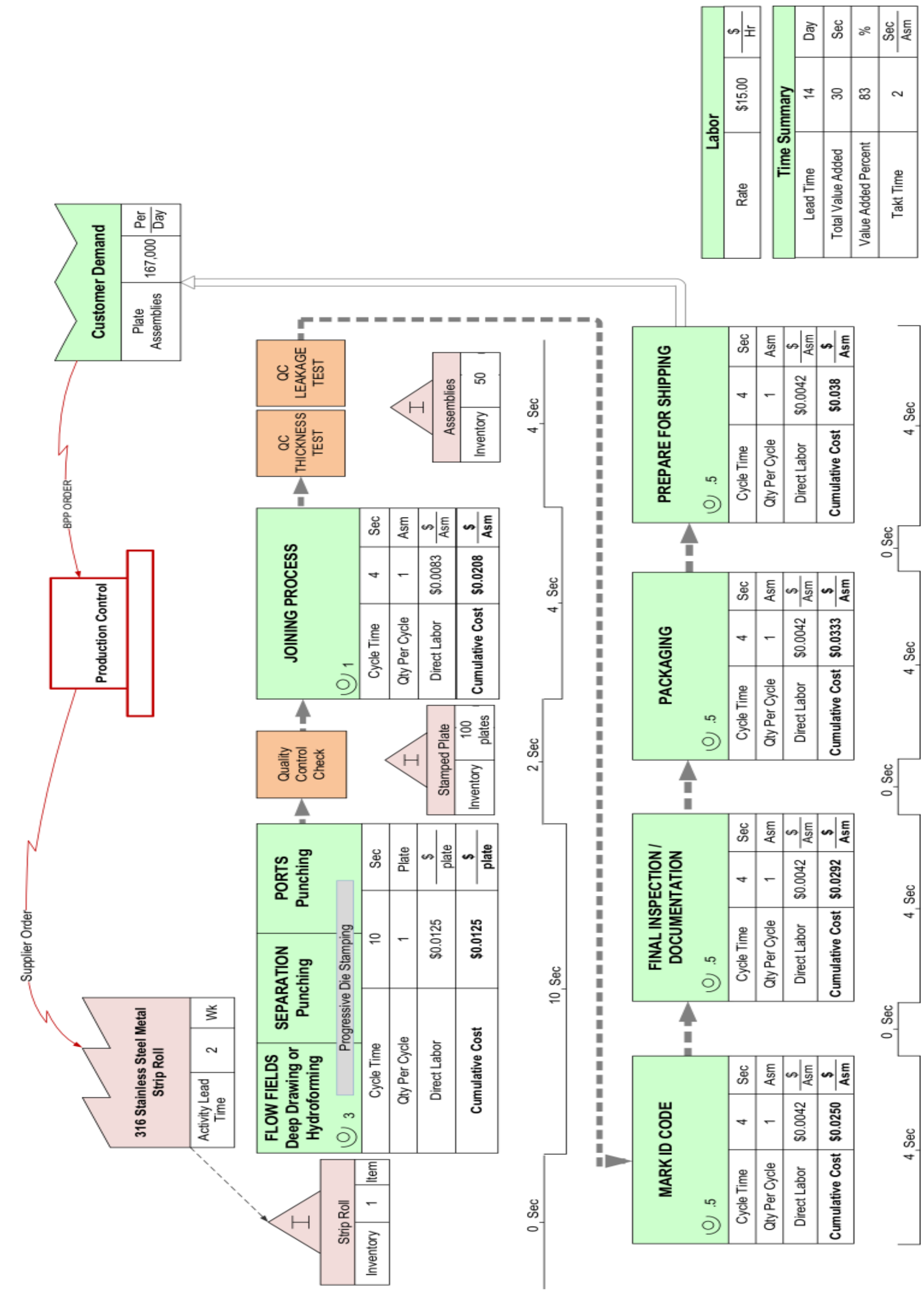

Figure 9-8: Bipolar Plate Manufacturing Value Stream Map (100k vehicles per year) – Example 3

Appendix 4.2 Cathode Catalyst VSM

Example 1

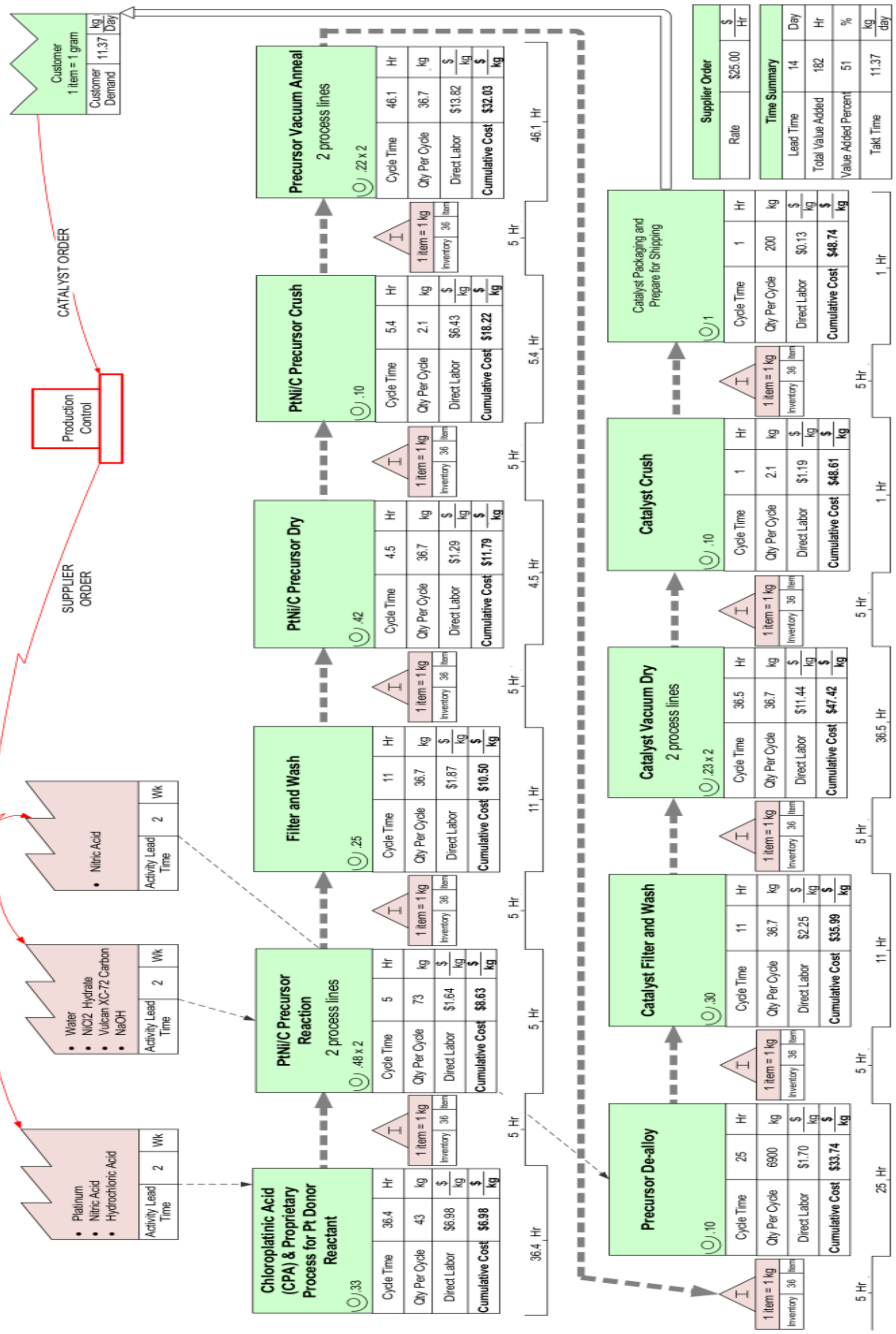

Figure 9-9: Cathode Catalyst Manufacturing Value Stream Map (100k vehicles per year) – Example 1

Example 2

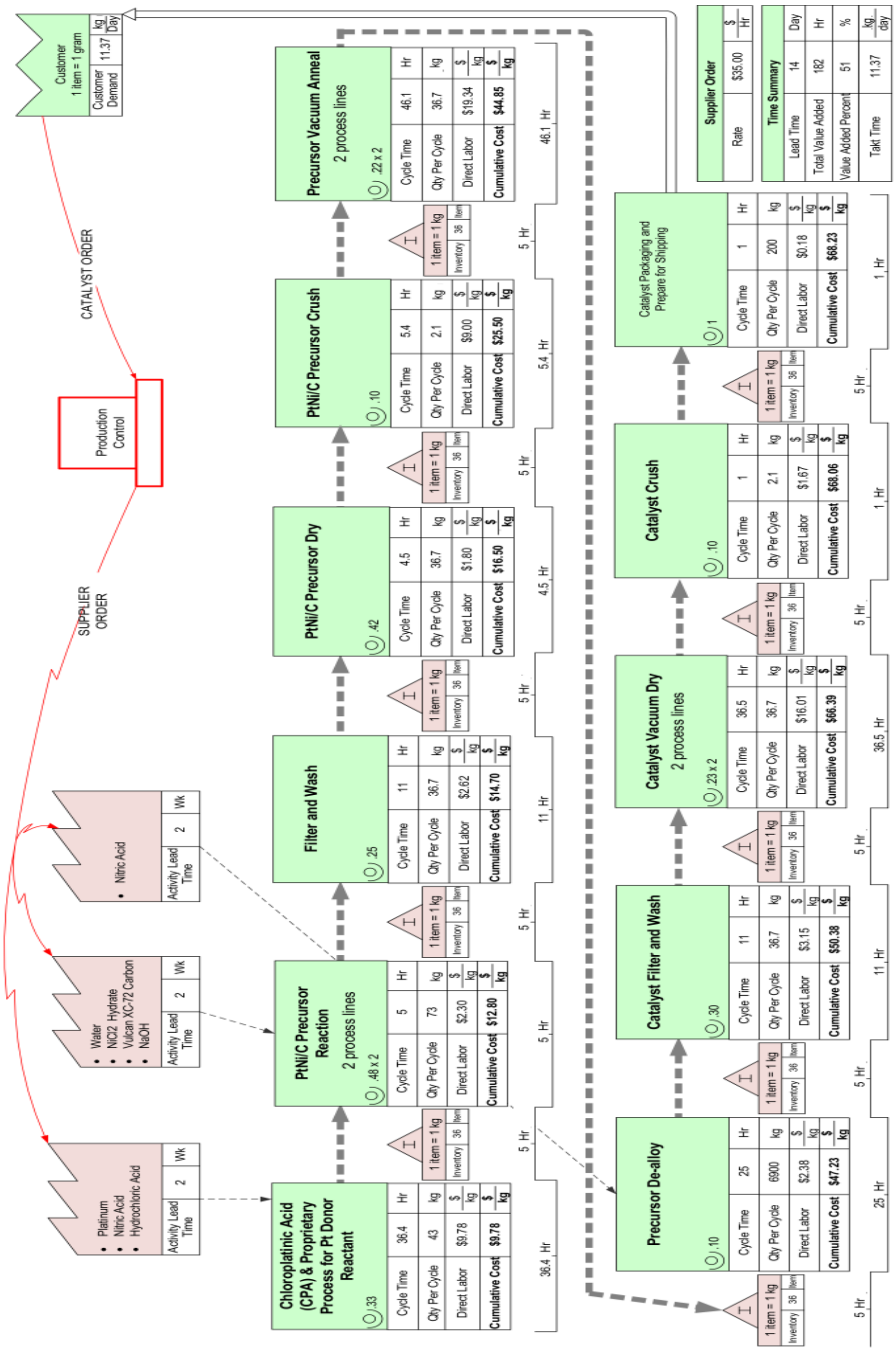

Figure 9-10: Cathode Catalyst Manufacturing Value Stream Map (100k vehicles per year) – Example 2

Example 3

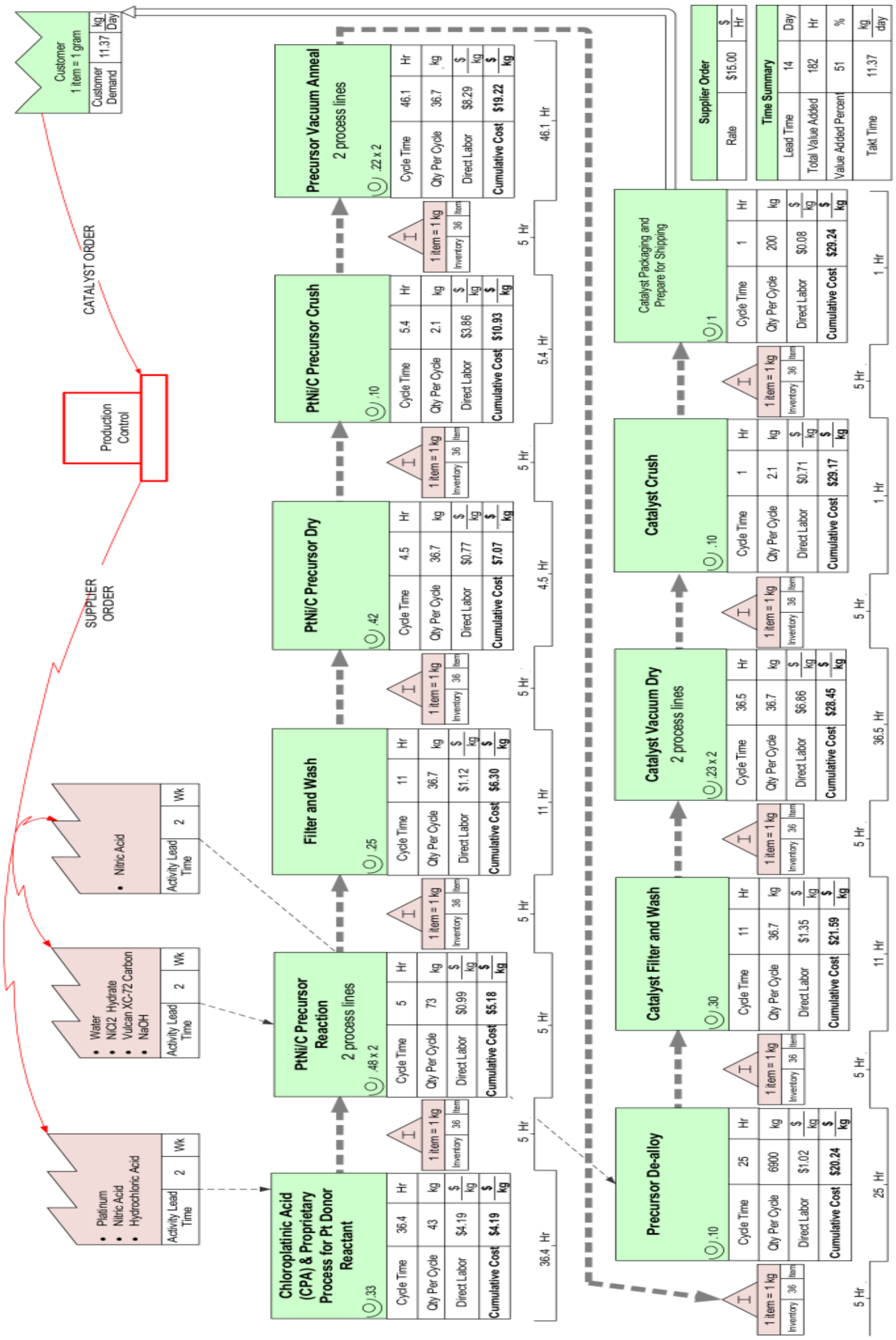

Figure 9-11: Cathode Catalyst Manufacturing Value Stream Map(100k vehicles per year) – Example 3

Appendix 4.3 Gas Diffusion Layer VSM

Example 1

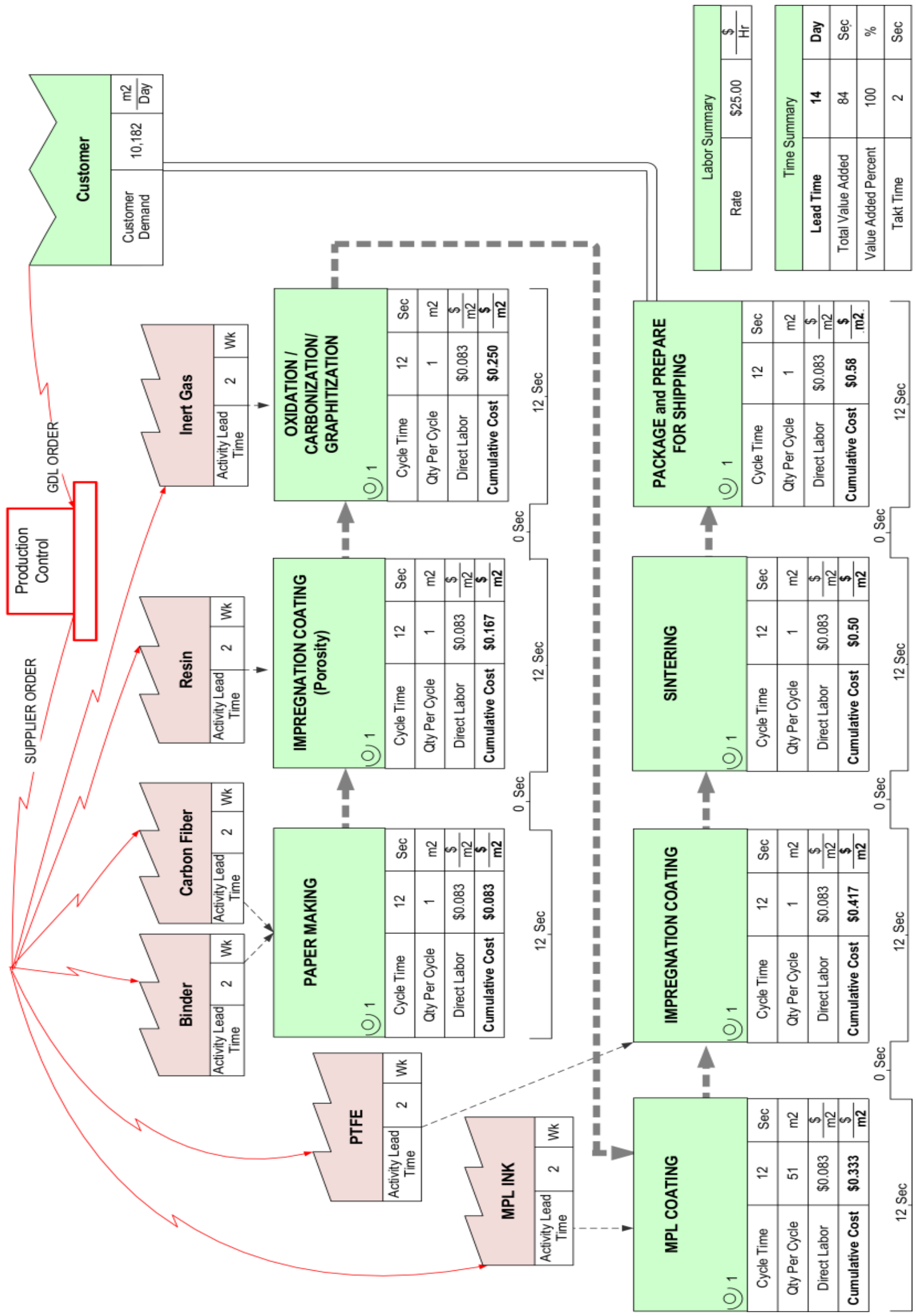

Figure 9-12: Gas Diffusion Manufacturing Value Stream Map (100k vehicles per year) – Example 1

Example 2

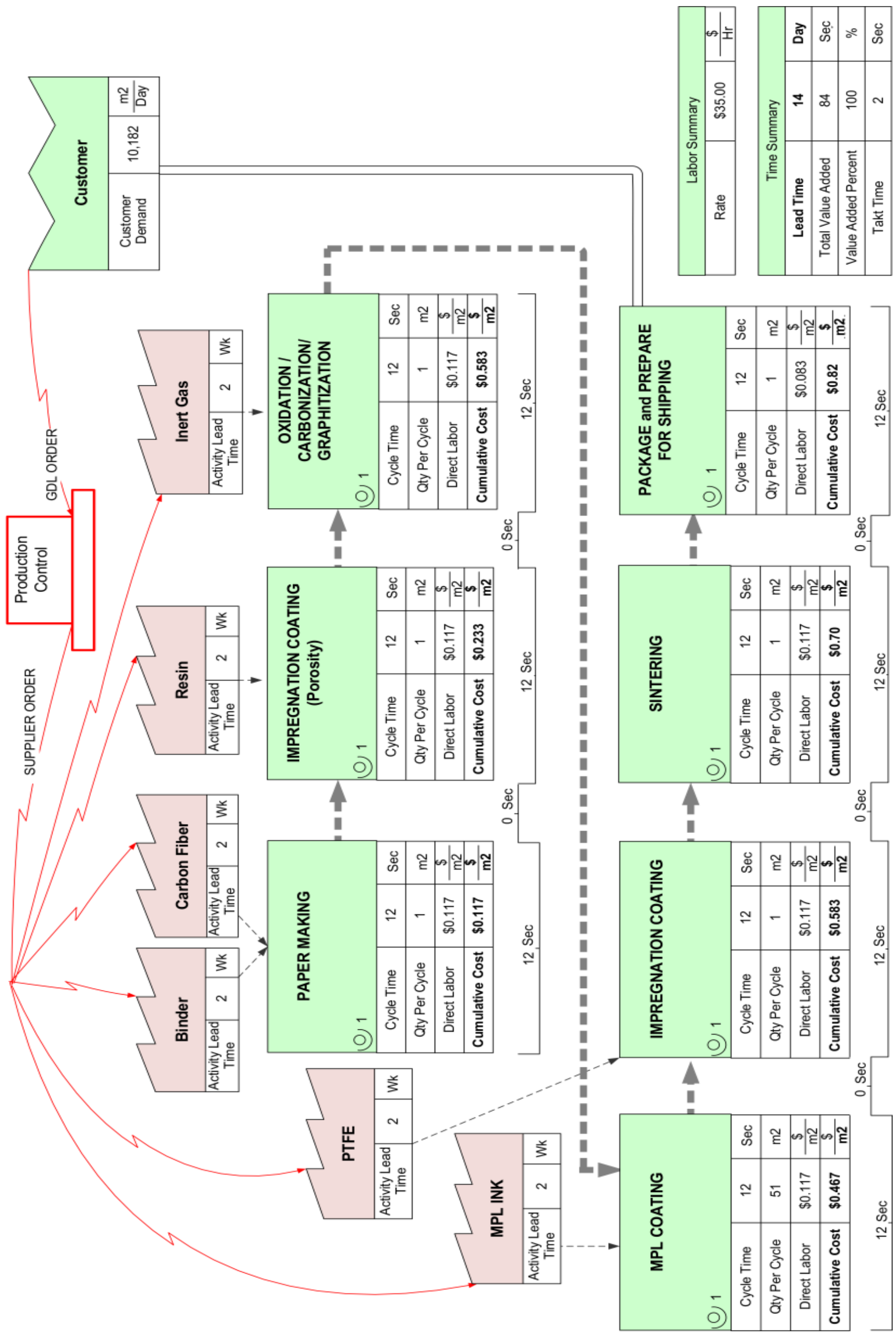

Figure 9-13: Gas Diffusion Layer Manufacturing Value Stream Map (100k vehicles per year) – Example 2

Example 3

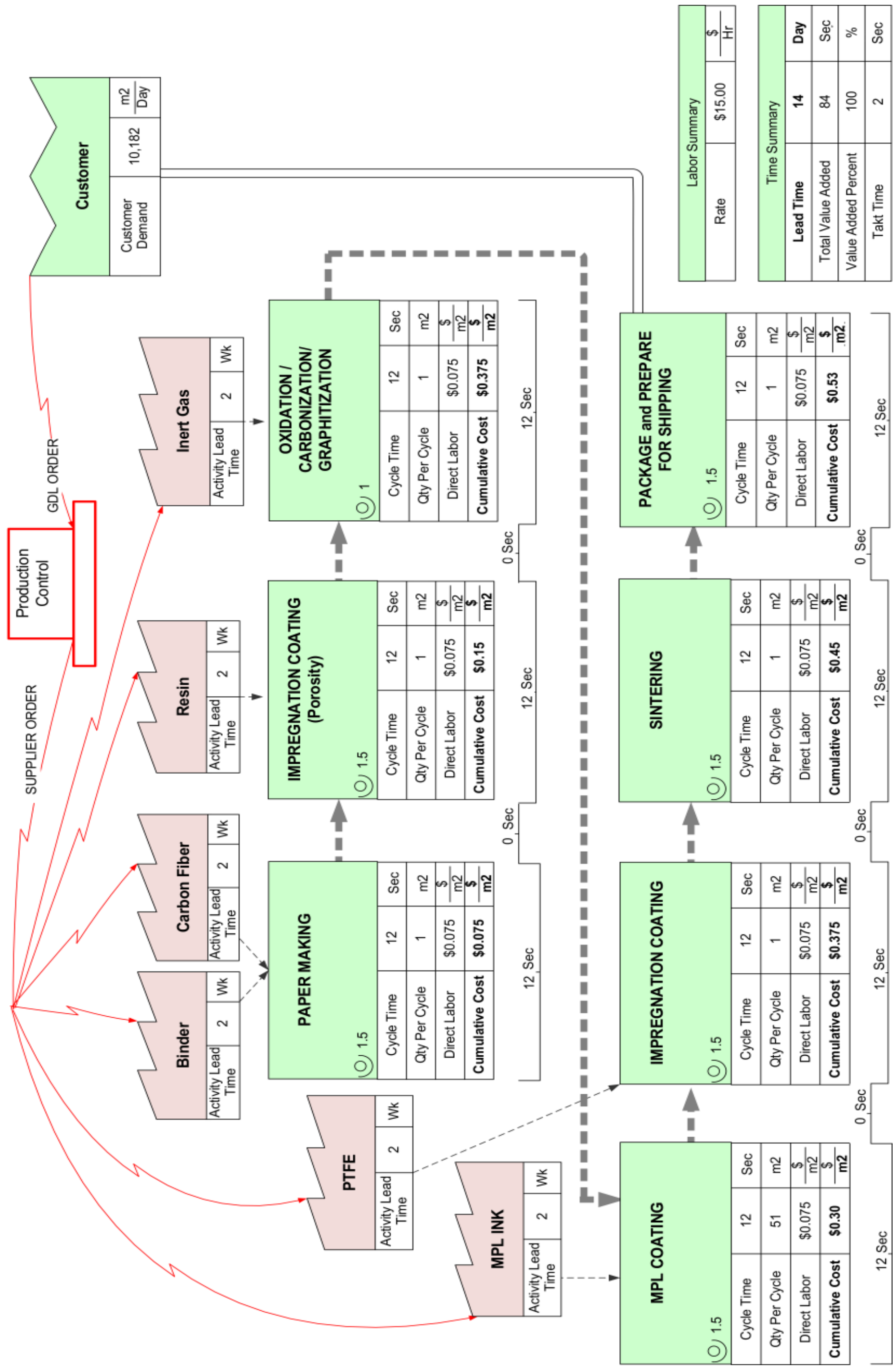

Figure 9-14: Gas Diffusion Layer Manufacturing Value Stream Map (100k vehicles per year) – Example 3

Appendix 4.4 Membrane VSM

The following are the membrane value stream maps from the three regions based upon plant visits and or data obtained in interviews with manufacturers or equipment suppliers.

Example 1

Figure 9-15: Membrane Manufacturing Value Stream Map (100k vehicles per year) - Example 1

Example 2

Figure 9-16: Membrane Manufacturing Value Stream Map (100k vehicles per year) – Example 2

Example 3

Figure 9-17: Membrane Manufacturing Value Stream Map (100k vehicles per year) – Example 3

Appendix 4.5 H_2 Storage Vessel

The following are the hydrogen vessel value stream maps from the three regions based upon plant visits and or data obtained in interviews with manufacturers or equipment suppliers.

Example 1

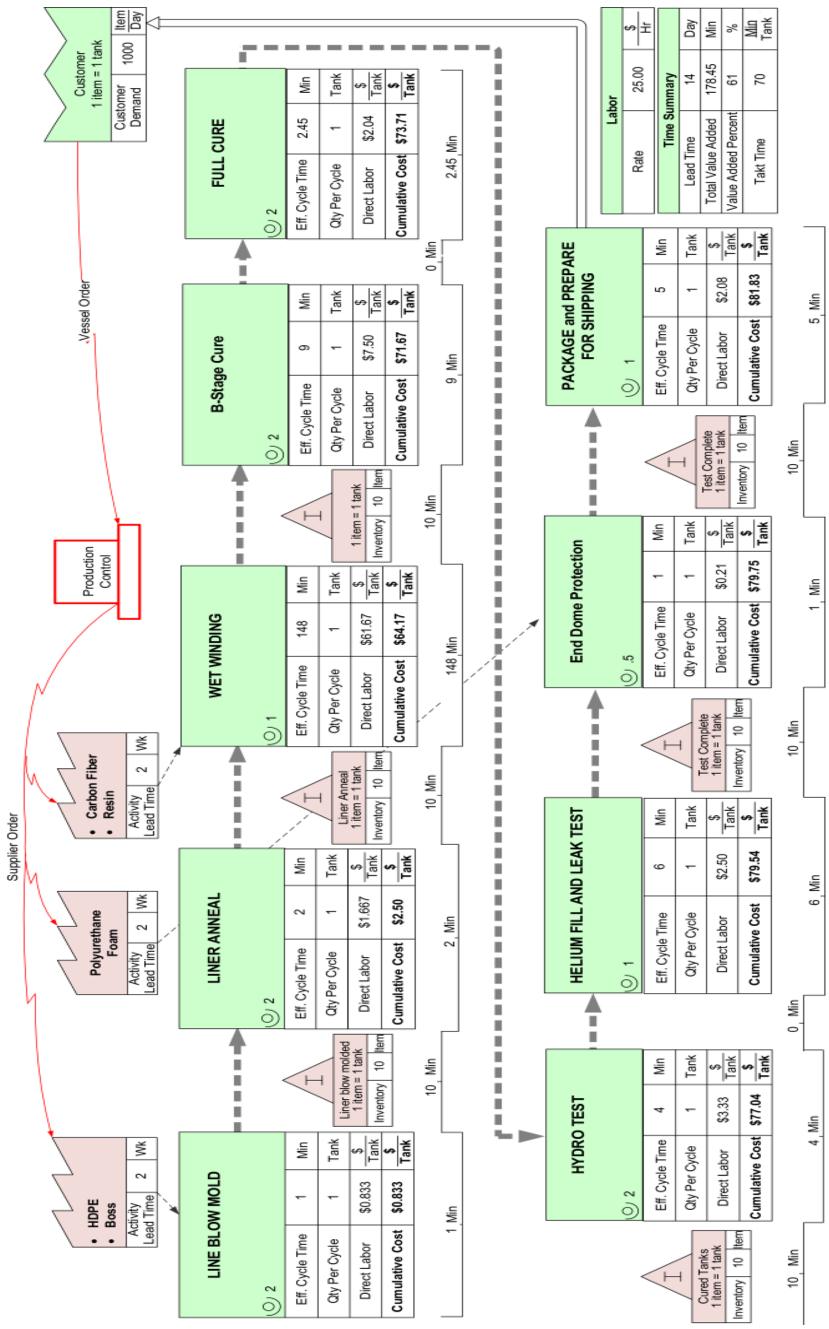

Figure 9-18: H_2 Storage Vessel Value Stream Map (100k vehicles per year) – Example 1

Example 2

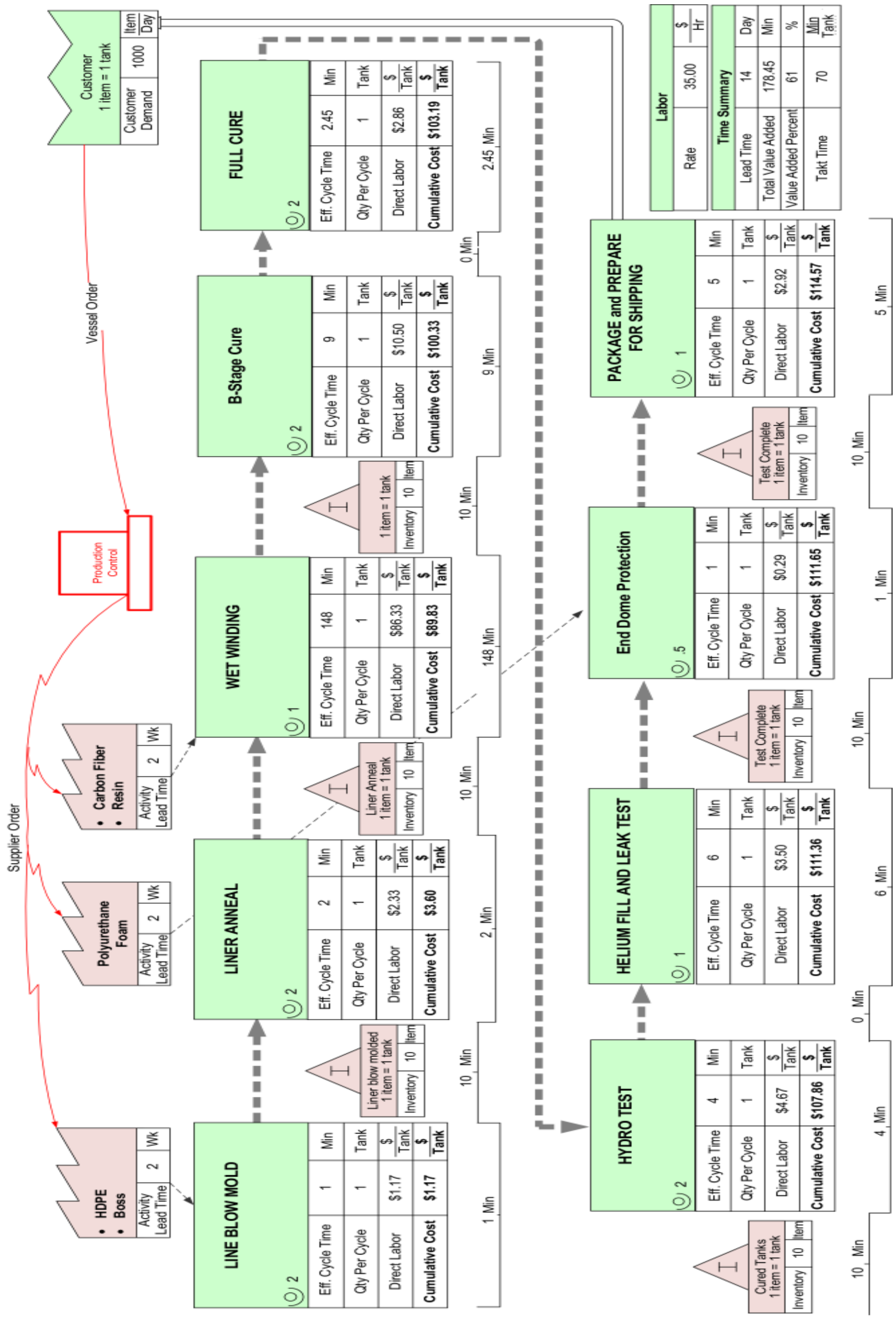

Figure 9-19: H_2 Storage Vessel Value Stream Map (100k vehicles per year) - Example 2

Example 3

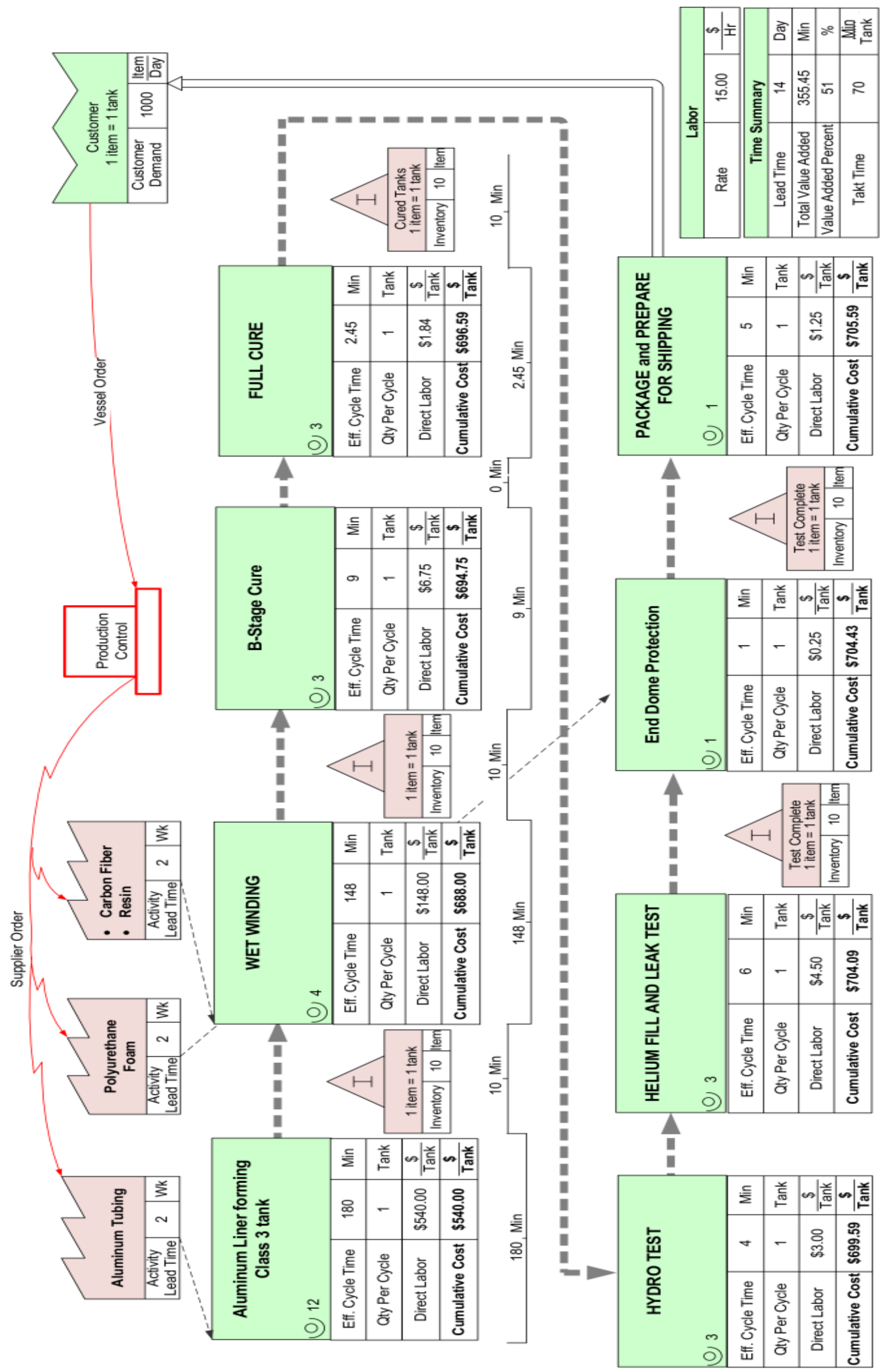

Figure 9-20: H_2 Storage Vessel Value Stream Map (100k vehicles per year) – Example 3

Appendix 5 Component Specifications for Supplier Quotes

Appendix 5.1 Bipolar Plates

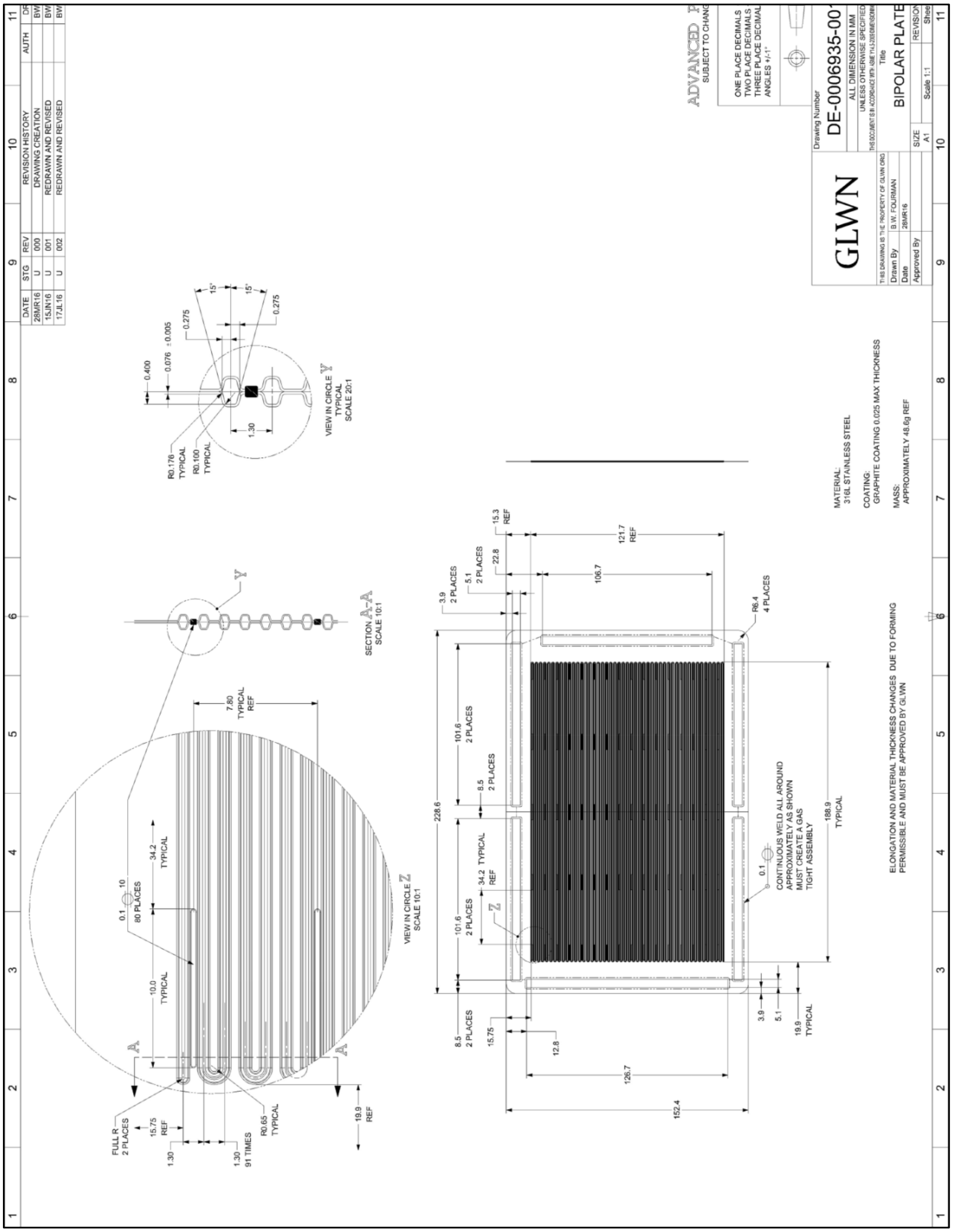

Figure 9-21: Bipolar plate specifications used for global supplier requests for quotes.

Appendix 5.2 Cathode Catalyst

DE-0006935-005 Catalyst Specification

Please provide a quote using your process and materials for a dispersed catalyst with loadings of 0.1mgPt/cm2 (cathode) and 0.05 mgPt/cm2 (anode).

We additionally would like to know how your quoted catalyst differs from our modeled catalyst. We model the catalysts and inks as:

- Cathode : 0.1 mgPt/cm2 de-alloyed Pt_3Ni on carbon (based on Johnson-Matthey catalyst)
- Anode: 0.05 mgPt/cm2 dispersed Pt on carbon.
- Ink Formula: 32 wt.% catalyst, 20 wt.% PFSA and 48wt.% Vulcan XC72.

Platinum Usage

Active Dimensions		Plate Outer Dimensions		Active Area	Total Plate Area						Annual mg @ annual vehicle volume			
Width	Height	Width	Height			cathode	anode	total mg Pt	# MEA for 80kW	total mg per				
cm	cm	cm	cm	cm2	cm2	0.1mgPt/cm2	.05mgPt/cm2	per MEA		80kw stack	1000	10000	100000	500000
21.7	14.4	26.3	19.0	312.5	500	32.42	16.21	48.63	379	18,430.4	18,430,378	184,303,783	1,843,037,829	9,215,189,144
											18.4 kg	184.3 kg	1,843. kg	9,215.2 kg

GDL Usage

GDL= carbon paper substrate with hydrophobic coating and MPL.

109.152 linear meters of GLD in stack (with at least 23cm of roll width)

Annual linear meters of GDL roll length required (with at least 23 cm roll width) @ annual vehicle volume				
1,000 veh/year	10,000 veh/year	100,000 veh/year	500,000 veh/year	
109,152	1,091,520	10,915,200	54,576,000	Linear meters at 23cm width
3119	31186	311863	1559314	Number of rolls at 35m x 23cm width **DE-0006935-003**

Figure 9-22: Cathode catalyst specifications used for global supplier request for quotes.

Appendix 5.3 Gas Diffusion Layer

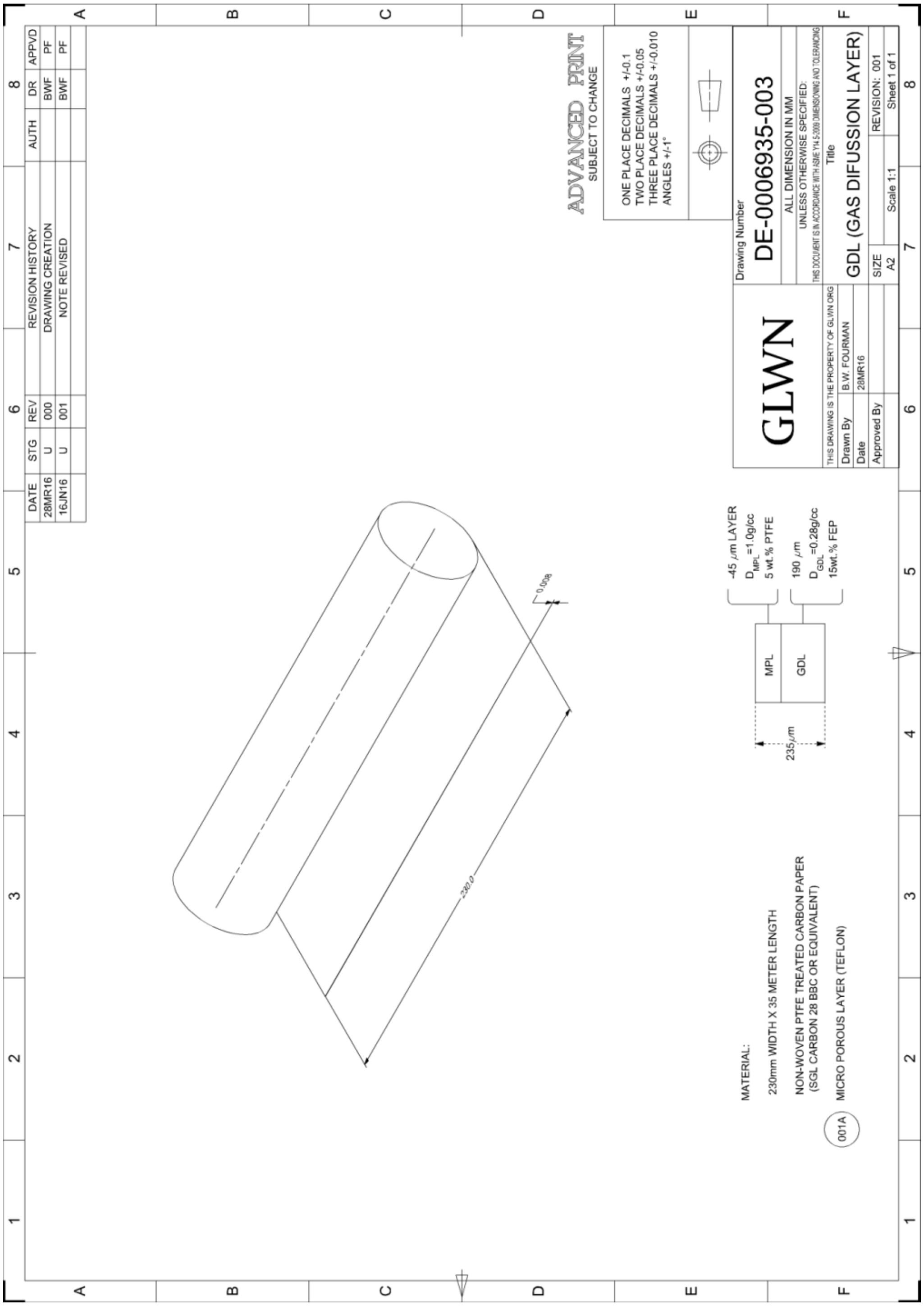

Figure 9-23: Gas diffusion layer specifications

Appendix 5.4 Membrane

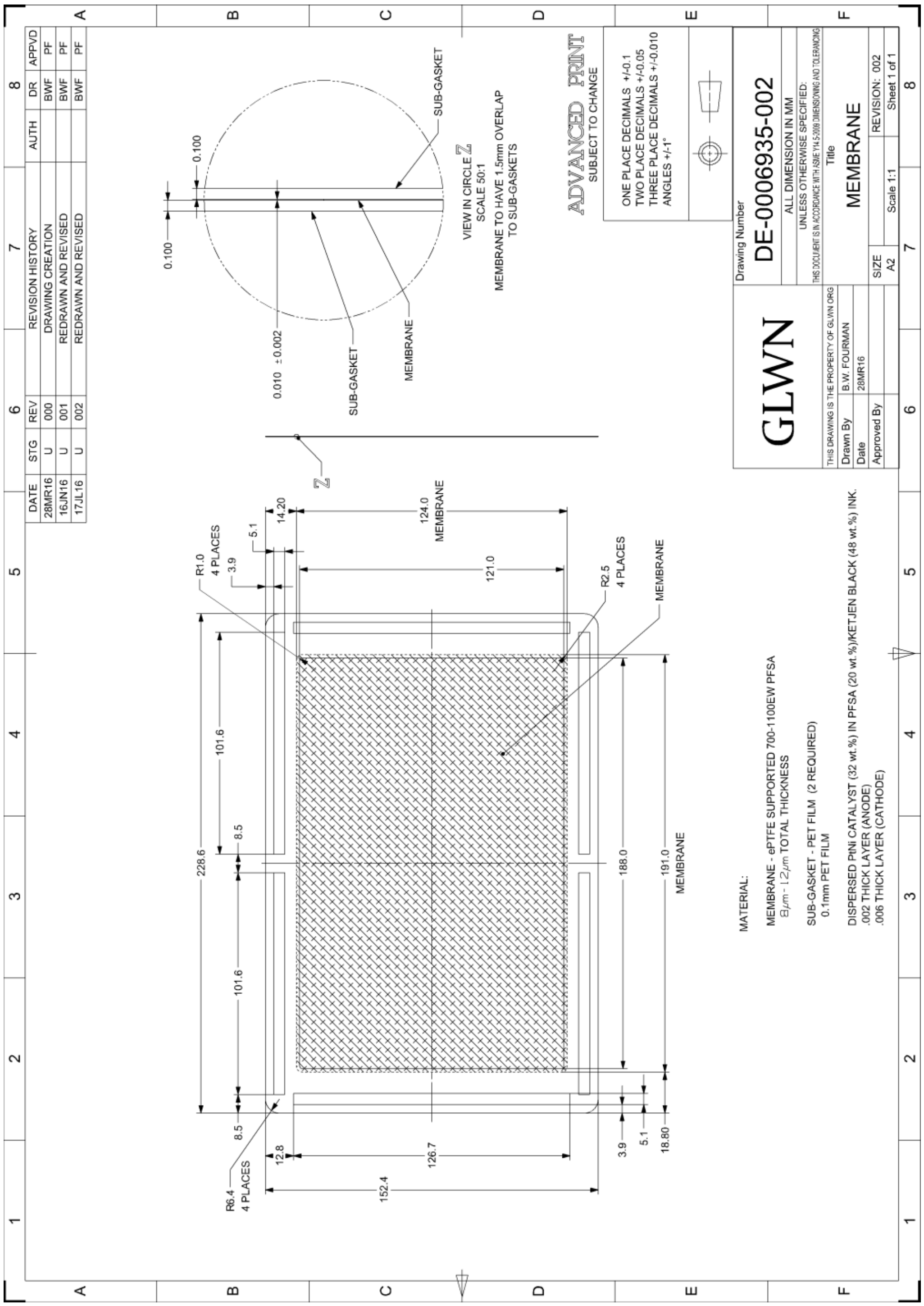

Figure 9-24: Membrane specifications used for supplier request for quotes

Appendix 5.5 700 Bar Type IV Pressure Vessel

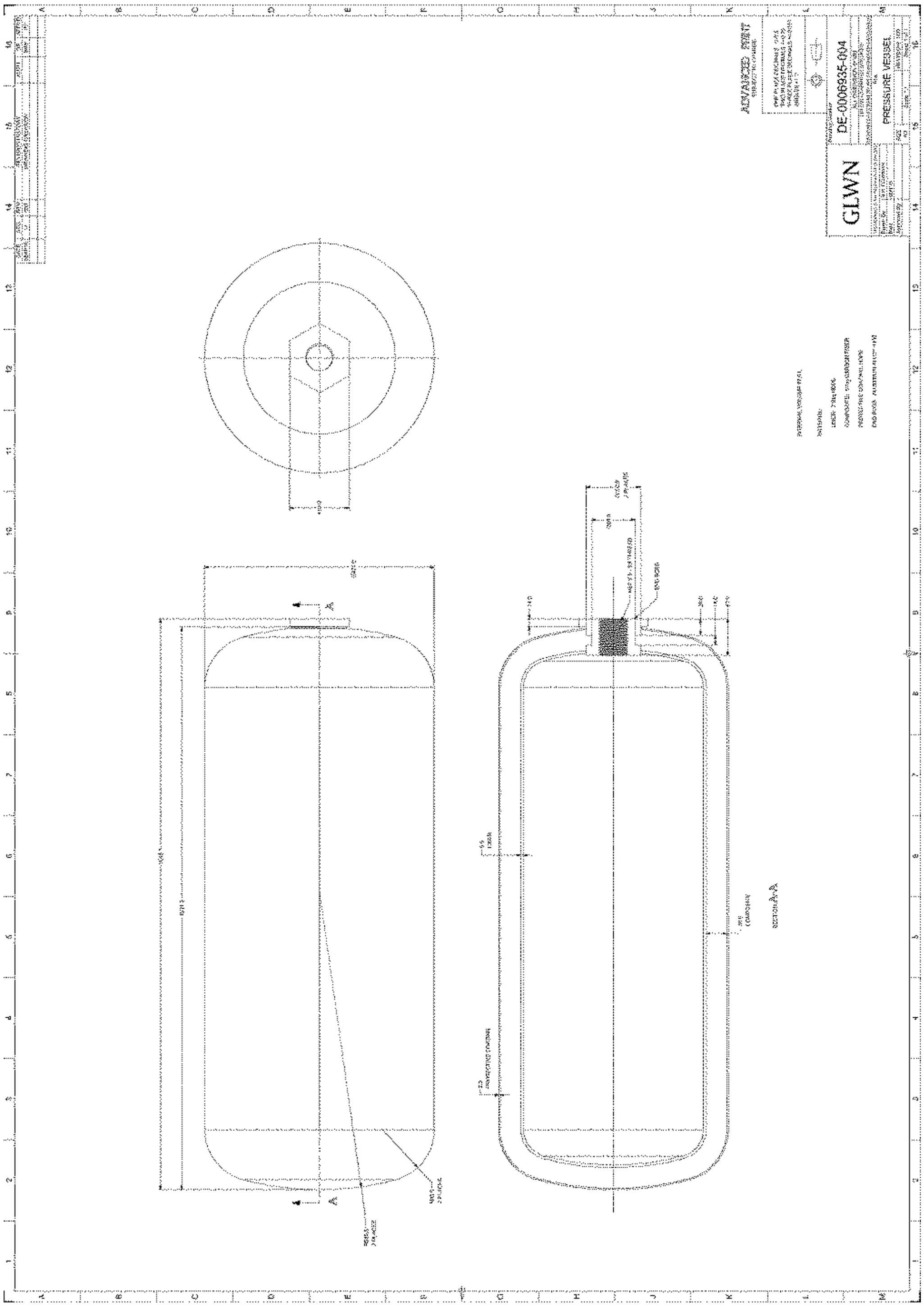

Figure 9-25: 700 bar type IV pressure vessel specifications for supplier request for quotes.