Final Report: Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications (2012-2016)

September 2016

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STRATEGIC ANALYSIS

Sponsorship and Acknowledgements

This material is based upon work supported by the Department of Energy under Award Number DE-EE0005236. The authors wish to thank Dr. Dimitrios Papageorgopoulos, Mr. Jason Marcinkoski, Mr. Greg Kleen, and Dr. Adria Wilson of DOE's Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Office (FCTO) for their technical and programmatic contributions and leadership.

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Table of Abbreviations

AMR	Annual Merit Review (meeting)
ANL	Argonne National Laboratory
atm	atmospheres
BDI	Boothroyd Dewhurst Incorporated
BOL	beginning of life
BOM	bill of materials
BOP	balance of plant
CCM	catalyst coated membrane
CEM	integrated compressor-expander-motor unit (used for air compression and exhaust gas expansion)
DFMA®	design for manufacture and assembly
DOE	U.S. Department of Energy
DSM™	dimensionally stable membrane (Giner membrane support)
EERE	DOE Office of Energy Efficiency and Renewable Energy
ePTFE	expanded polytetrafluoroethylene
EW	equivalent weight
FCT	EERE Fuel Cell Technologies Program
FCTT	Fuel Cell Technical Team
FCV	fuel cell vehicle
GCTool	General Computational toolkit
GDL	gas diffusion layer
H_2	hydrogen
ICE	internal combustion engine
kN	kilo-Newtons
kW	kilowatts
kW_{e_gross}	kilowatts of gross electric power
kW_{e_net}	kilowatts of net electric power
kW_{th}	kilowatts of thermal power
LT	low temperature
MEA	membrane electrode assembly
NREL	National Renewable Energy Laboratory
NSTF	nano-structured thin-film (catalysts)
PEM	proton exchange membrane
Pt	platinum
PtCoMn	platinum-cobalt-manganese
QC	quality control
$Q/\Delta T$	heat duty divided by delta temperature
R&D	research and development

SA	Strategic Analysis, Inc.
USCAR	United States Council for Automotive Research LLC
U.S. DRIVE	Driving Research and Innovation for Vehicle efficiency and Energy sustainability partnership
V	volt

Foreword

Energy security is fundamental to the mission of the U.S. Department of Energy (DOE) and hydrogen fuel cell vehicles have the potential to eliminate the need for oil in the transportation sector. Fuel cell vehicles[1] can operate on hydrogen, which can be produced domestically, emitting less greenhouse gasses and pollutants than conventional internal combustion engine (ICE), advanced ICE, hybrid, or plug-in hybrid vehicles that are tethered to petroleum fuels. Transitioning from standard ICE vehicles to hydrogen-fueled fuel cell vehicles (FCVs) could greatly reduce greenhouse gas emissions, air pollution emissions, and ambient air pollution, especially if the hydrogen fuel is derived from wind-powered electrolysis or steam reforming of natural gas.[2,3] A diverse portfolio of energy sources can be used to produce hydrogen, including nuclear, coal, natural gas, geothermal, wind, hydroelectric, solar, and biomass. Thus, fuel cell vehicles offer an environmentally clean and energy-secure pathway for transportation.

This research evaluates the cost of manufacturing transportation fuel cell systems (FCSs) based on low temperature (LT) proton exchange membrane (PEM) FCS technology. Fuel cell systems will have to be cost-competitive with conventional and advanced vehicle technologies to gain the market-share required to influence the environment and reduce petroleum use. Since the light duty vehicle sector consumes the most oil, primarily due to the vast number of vehicles it represents, the DOE has established detailed cost targets for automotive fuel cell systems and components. To help achieve these cost targets, the DOE has devoted research funding to analyze and track the cost of automotive fuel cell systems as progress is made in fuel cell technology. The purpose of these cost analyses is to identify significant cost drivers so that R&D resources can be most effectively allocated toward their reduction. The analyses are annually updated to track technical progress in terms of cost and to indicate how much a typical automotive fuel cell system would cost if produced in large quantities (up to 500,000 vehicles per year).

Bus applications represent another area where fuel cell systems have an opportunity to make a national impact on oil consumption and air quality. Consequently, beginning with year 2012, annually updated cost analyses have been conducted for PEM fuel cell passenger buses as well. Fuel cell systems for light duty automotive and buses share many similarities and indeed may even utilize identical stack hardware. Thus, the analysis of bus fuel cell power plants is a logical extension of the light duty automotive power system analysis. Primary differences between the two applications include the installed power required (80 kilowatts of net electric power (kW_{e_net})[4] for automotive vs. ~160 kW_{e_net} for

[1] Honda FCX Clarity fuel cell vehicle: http://automobiles.honda.com/fcx-clarity/; Toyota fuel cell hybrid vehicles: http://www.toyota.com/about/environment/innovation/advanced_vehicle_technology/FCHV.html

[2] Jacobson, M.Z., Colella, W.G., Golden, D.M. "Cleaning the Air and Improving Health with Hydrogen Fuel Cell Vehicles," *Science*, 308, 1901-05, June 2005.

[3] Colella, W.G., Jacobson, M.Z., Golden, D.M. "Switching to a U.S. Hydrogen Fuel Cell Vehicle Fleet: The Resultant Change in Energy Use, Emissions, and Global Warming Gases," *Journal of Power Sources*, 150, 150-181, Oct. 2005.

[4] Unless otherwise stated, all references to vehicle power and cost ($/kW) are in terms of kW net electrical (kW_{e_net}).

a 40 foot transit bus), desired power plant durability (nominally 5,000 hours lifetime for automotive vs. 25,000 hours lifetime for buses), and annual manufacturing rate (up to 500,000 systems/year for an individual top selling automobile model vs. ~4,000 systems/year for total transit bus sales in the U.S.).[5]

The capacity to produce fuel cell systems at high manufacturing rates does not yet exist, and significant investments will have to be made in manufacturing development and facilities in order to enable it. Once the investment decisions are made, it will take several years to develop and fabricate the necessary manufacturing facilities. Furthermore, the supply chain will need to develop which requires negotiation between suppliers and system developers, with details rarely made public. For these reasons, the DOE has consciously decided not to analyze supply chain scenarios at this point, instead opting to concentrate its resources on solidifying the tangible core of the analysis, i.e. the manufacturing and materials costs.

The DOE uses these analyses as tools for R&D management and tracking technological progress in terms of cost. Consequently, non-technical variables are held constant to elucidate the effects of the technical variables. For example, the cost of platinum is typically held constant to insulate the study from unpredictable and erratic platinum price fluctuations. Sensitivity analyses are conducted to explore the effects of non-technical parameters.

To maximize the benefit of our work to the fuel cell community, Strategic Analysis Inc. (SA) strives to make each analysis as transparent as possible. The transparency of the assumptions and methodology serve to strengthen the validity of the analysis. We hope that these analyses have been and will continue to be valuable tools to the hydrogen and fuel cell R&D community.

[5] Total buses sold per year from American Public Transportation Association 2012 Public Transportation Fact Book, Appendix A Historical Tables, page 25, http://www.apta.com/resources/statistics/Documents/FactBook/2012-Fact-Book-Appendix-A.pdf. Note that this figure includes all types of transit buses: annual sales of 40' transit buses, as are of interest in this report, would be considerably lower.

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1 Overview

This report summarizes project activities for Strategic Analysis, Inc. (SA) Contract Number DE-EE0005236 to the U.S. Department of Energy titled "Transportation Fuel Cell System Cost Assessment". The project defined and projected the mass production costs of direct hydrogen Proton Exchange Membrane fuel cell power systems for light duty vehicles (automobiles) and 40 foot transit buses. In each year of the five year contract, the fuel cell power system designs and cost projections were updated to reflect technology advances.

Each year a detailed ~200 page report was generated documenting design and cost assumptions and results for each power system. The reader is advised to reference these five annual reports [1]–[5] for details of the analyses. The purpose of this final report is to summarize project activities and overview major assumptions and results. Because details are numerous and changed each year of the analysis, this report will focus primarily on the major design and cost changes from year to year.

A few key points regarding the project:

- Costs are typically reported in $/kW_{e\_net}$. The term "kW_{e_net}" represents the net electrical power available for vehicle supply above and beyond power for fuel cell system operation.
  - The fuel cell automotive system is rated at 80 kW_{e_net}.
  - The fuel cell bus system is rated at 160 kW_{e_net}.
- The fuel cell systems consist of the Proton Exchange Membrane (PEM) fuel cell stack(s) and its supporting balance of plant components (air compressor, expanders, sensors, cooling systems, controllers, etc.).
- Main traction batteries, electric drive motors, and the hydrogen storage subsystem were NOT included in the cost analysis.
- Costs were evaluated using a Design for Manufacture and Assembly (DFMA®) cost methodology. DFMA® is a process-based cost methodology meaning that it seeks to model the actual physical hardware and activities used in manufacture and assembly.
  - Main components of the stack were cost analyzed using the DFMA® methodology.
  - The costs of lesser components (fittings, valves, etc.) were based on vendor price quotations or other non-DFMA® methodologies.
- Costs are reported in nominal dollars. However, no effort was made to inflate prices from year to year due to inflation. Because there were too many price quotes (on materials, components, or capital equipment) to feasibly update each year, the price quotes were repeated each year until they were judged to grow "stale", at which time a new quotation was solicited. This results in a relatively up-to-date estimate of system cost in nominal year dollars.
- "Costs" are presented, not "prices". Thus the fuel cell costs represent the manufacturing and materials cost of the fuel cell system integrator without markup for profit, research and development, management overhead, warranty, non-recurring cost, or advertising. Consequently, the system costs do not represent the price the consumer would pay to purchase the fuel cell system.

- The annual reports are typically structured to report a "baseline" design and cost for the automotive and bus power systems. Additional side studies and analyses were conducted to explore alternatives. If the alternative resulted in lower cost (or other desirable attributes), then it was considered for incorporation into the baseline design.

The analysis was conducted in close cooperation with three key groups: Argonne National Laboratory (ANL), the National Renewable Energy Laboratory (NREL), and the DOE technical managers. Dr. Rajesh Ahluwalia's group at ANL provided cell and system performance modeling as well as general fuel cell power system expert consultation. Mr. Mike Ulsh of NREL provided manufacturing and quality control expertise, particularly in the area of roll-to-roll processing. Mr. Jason Marcinkoski, Dr. Dimitrios Papageorgopoulos, and Dr. Adria Wilson of DOE Headquarters provided invaluable technical guidance and assistance to the project. And finally, the project was briefed annually to the Fuel Cell Technical Team (FCTT). The FCTT is a public-private group formed under USCAR/U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability partnership) to allow pre-competitive cooperation on fuel cell technology topics of mutual interest. The FCTT provided extremely beneficial guidance, information, and perspective on a wide range of topics.

2 Project Tasks

The five year project was executed in four tasks, each one repeated each year of the project.

The four tasks are described below.

2.1 Task 1.0 Literature Review

SA conducted a continuous literature review throughout the project to stay apprised of the latest developments in PEM fuel cell, system configuration, and manufacturing technology. This primarily took the form of reading journal articles and other technical documents, attending the DOE Annual Merit Review (AMR) and other DOE project team meetings, and technical meetings (via phone) with experts from academia and industry.

2.2 Task 2.0 System Definitions and Bills of Materials

In association with ANL, SA defined the key features of the automotive and bus FC power systems so as to assess system and component performance and sizing. Flow schematics were used to identify major component functionality and provide a visual listing of relevant parameters (mass flow, pressure, temperature, etc.). System performance modeling calculations were conducted in Microsoft Excel and/or Aspen HYSYS® to validate the material and heat flows, and by ANL performance models generated in General Computational toolkit (GCTool).[6]

[6] http://www.anl.gov/technology/project/gctool-design-analyze-and-compare-fuel-cell-systems-and-power-plants

2.3 Task 3.0 Manufacturing Process Definition and Design for Manufacture and Assembly (DFMA®) Cost Estimation

SA conducted rigorous DFMA® analyses based on the current fuel cell technology in each year of the project so as to allow preparation of a detailed annual reference reports. A DFMA® costing methodology was applied for the main components of the system: stack (inclusive of bipolar plates, gas diffusion layers (GDL), catalyst, catalyst application, membrane, gaskets, and endplates), air compressor and integrated motor (and exhaust gas expander for the automotive system), and air humidifier.

Costs were assessed at a variety of annual system production rates:

- For the automotive FCS:
  - 1,000
  - 10,000
  - 30,000
  - 80,000
  - 100,000 and
  - 500,000 systems per year.
- For the bus FCS:
  - 200
  - 400
  - 800 and
  - 1,000 systems per year.

The analysis was based on the then-current technology for each year of the study. However, fuel cell systems are not currently produced at the rates of interest. Consequently, some extrapolation of current design and production methods was done to project to high production rates.

A variety of analysis activities and assessments were conducted under this task, including:

- projection of FCS component and production costs at multiple rates of production,
- examination of alternative manufacturing processes to determine the lowest cost production method,
- optimization of stack/system operating conditions that leads to the lowest system cost,
- examination of capital equipment and evaluation of equipment development maturity and risk so as to make recommendations for future R&D efforts,
- investigation and detailed specification of quality control equipment to ensure high yields and low costs,
- enumeration of all manufacturing/assembly/testing steps and identification of all cost and fabrication assumptions used in the cost analysis,
- evaluation of all end-of-life disposal/recycling processes and associated costs,
- lifecycle cost (LCC) analysis using a discounted cash flow methodology,
- development of mathematical functions to scale system component costs,
- tornado and Monte-Carlo sensitivity analysis, and

- utilization of design trade and optimization studies to determine a feasible path forward to reduce total system and lifecycle cost.

2.4 Task 4.0 Reporting

Transparent reporting of analysis methodology, assumptions, and results was the main objective of the project. Consequently, comprehensive written reports were prepared each year and made publically available. In addition, a series of reports and presentations were conducted each year to both vet and publicly report findings. These additional reporting activities included:

- Annual project presentation at the DOE Fuel Cell and Hydrogen Annual Merit Review (AMR),
- Annual presentation to the U.S. Drive Technical Team Meetings,
- Quarterly technical reports submitted to DOE,
- Periodic presentation at the Fuel Cell Seminar, and
- Publication of project findings in a peer-reviewed journal.

3 System Schematics

System schematics are a useful tool for identifying the main components within a system and understanding how they interact. As the analysis has evolved throughout the course of the annual updates, there has been a general trend toward system simplification. This reflects improvements in technology to reduce the number of parasitic supporting systems and thereby reduce system cost. The path to system simplification is likely to continue, and, in the authors' opinion, remains necessary to achieve or surpass cost parity with internal combustion engines.

System flow schematics for each of the systems in the current report are shown below. Note that for clarity, only the main system components are identified in the flow schematics.

3.1 2012-2016 Automotive System Schematic

The system flow schematic representing the 2012-2016 light duty vehicle (auto) fuel cell power systems appears in Figure 1 below. The system schematic did not substantively change over the five year project; however, some component technologies were altered:

- Replacement of the tubular membrane (air) humidifier with a plate frame membrane humidifier (2013).

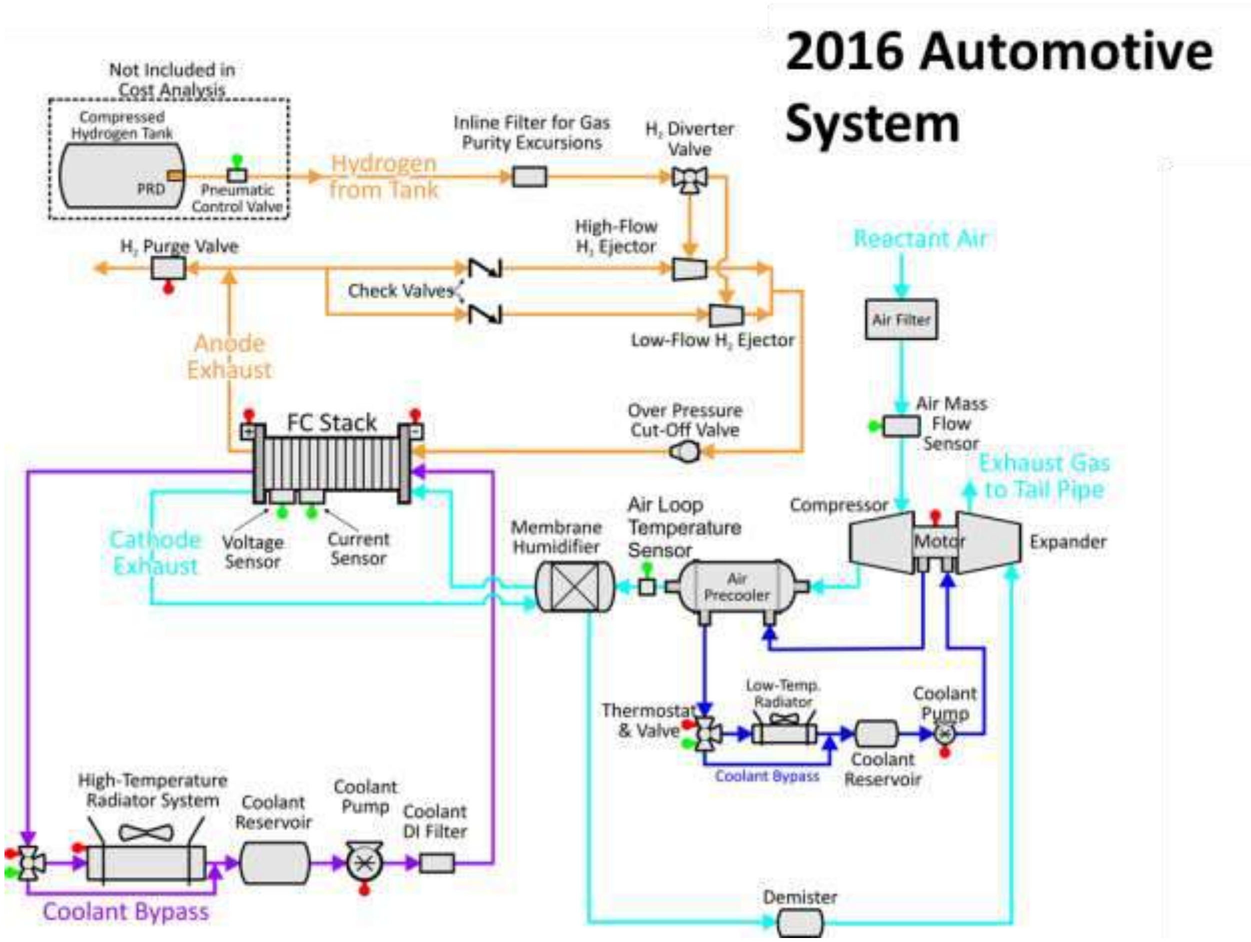

Figure 1. Flow schematic for the 2016 automotive fuel cell system

3.2 2012-2016 Bus System Schematic

The system flow schematic representing the 2012-2016 transit bus fuel cell power systems appears in Figure 2. Like the automotive systems, the schematics for the bus system did not change over the course of the project except to model component substitutions:

- Replacement of the tubular membrane (air) humidifier with a plate frame membrane humidifier (2013)
- Replacement of the centrifugal air compressor with an Eaton-style multi-lobe compressor (2013)

Bus power system hardware and layout are directly analogous to the automotive systems with the exception of two key differences. 1) The automotive system contains one 80 kW fuel cell stack as opposed to the bus system which contains two 80 kW stacks, and 2) the automotive system operates at a higher pressure than the bus system, leading to the automotive system's air supply subsystem employing a compressor, motor, and expander (CEM) unit while the bus system uses only a compressor and motor unit.

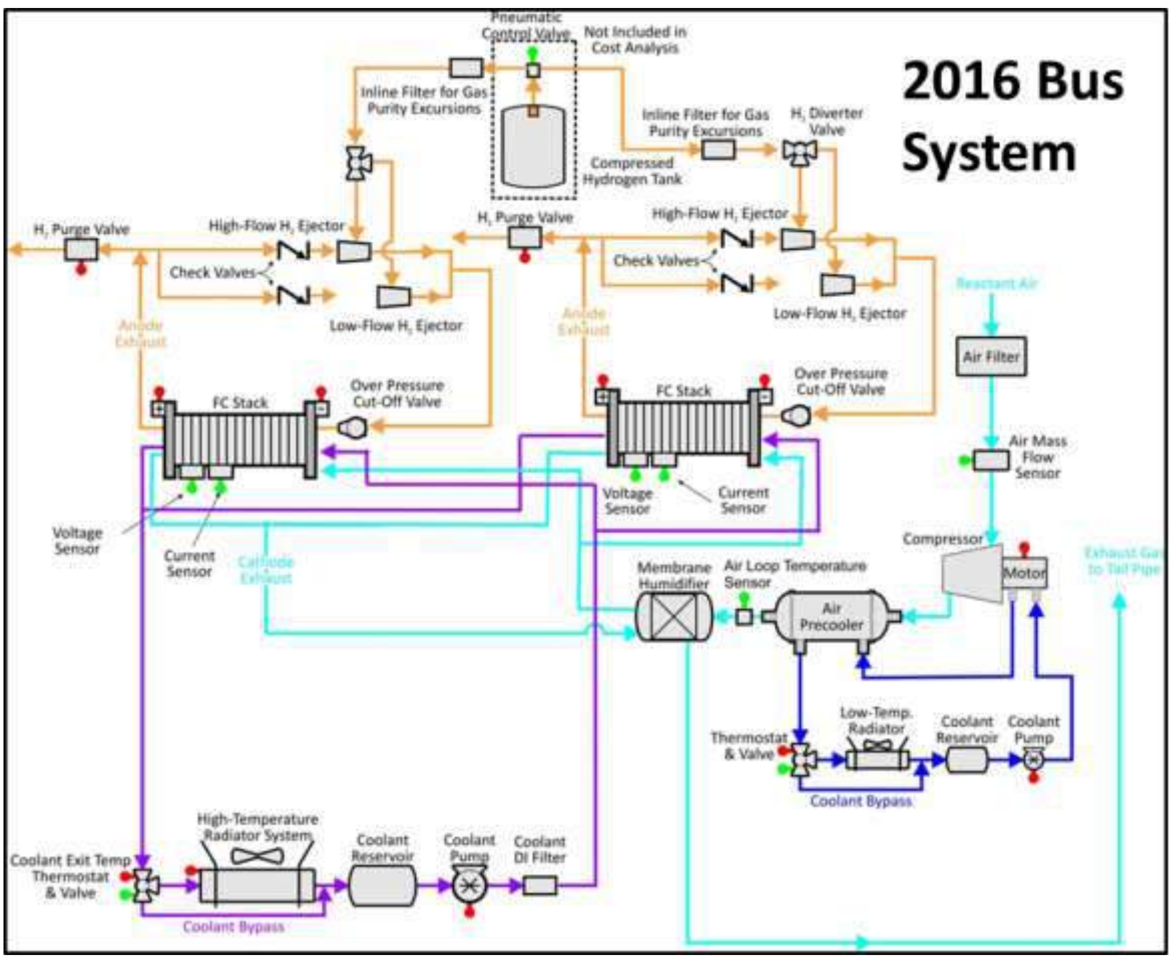

Figure 2. Flow schematic for the 2012-2016 bus fuel cell system

4 System Configurations, Fabrication Methods, and Operating Conditions

Each year of the project, the fuel cell power systems analyzed were examined to assess how the systems should be configured, manufactured, and operated to achieve lowest system cost. Changes to the system configurations were meant to capture technological changes from year to year but also reflected analysis improvements.

In general, three main types of re-evaluations and optimizations occurred each year of the project:

- System operating parameter optimization for lowest system cost: SA worked in association with ANL to select stack parameters (cell voltage, pressure, air stoichiometry, catalyst loading, air inlet humidity) that led to the lowest system cost while satisfying the $Q/\Delta T \leq 1.45$ kW/°C constraint, which was imposed in 2013.[7]
- System configuration and fabrication methods: consideration of optimal system components/configuration (e.g. plate frame vs. tubular membrane humidifiers, inclusion of a gas expander, hydrogen ejectors vs. electric recirculation pump) and manufacturing methods (e.g. stamping vs. hydroforming, NSTF™ vs. slot-die coating, PANI vs. Pt-based catalysts).
- Cost modeling analysis re-evaluation: improvements to the DFMA® analysis (e.g. updated material pricing, better estimates of maintenance costs, more accurate estimate of stamping forces, addition of quality control equipment).

While in theory each class of optimization is distinct, in reality they overlap due to the analysis constantly being improved and the system configuration often impacting the stack operating conditions. Consequently it is difficult to completely separate the cost impact of technological changes from analysis improvements (at least in some cases). The reader is referred to the detailed annual reports for a full description of annual changes and assumptions [1]–[5].

4.1 Summary of Key Annual Analysis Topics and Changes

As previously explained, the analysis was updated each year to define the system and project costs for the baseline automotive and bus fuel cell power systems. Additionally, in each year, one or more "side studies" were conducted to explore design or manufacturing aspects that were not incorporated in the baseline but might be in the future.

The following lists show the main topics explored in the each year of the project. The topics generally were investigated with the automotive system in mind, and then applied to the bus systems as applicable. For detailed cost changes from year to year, see Appendix C and D.

[7] $Q/\Delta T$ is defined as the kW of heat to be rejected by the radiator divided by the temperature difference between the radiator coolant (~90°C) and the outside air (estimated at 40°C to represent the worst case scenario). It is a short-hand numeric measurement of the size of the radiator: a high value indicating that a large radiator is required, and a low value indicating that only a small radiator is required.

2012 Analysis

- Initial analysis of the project establishing the automotive and bus baseline designs and cost projections
- The automotive analysis was based on a 2011 DFMA® cost analysis conducted by SA under a separate DOE contract
- The bus analysis was performed for the first time

2013 Analysis

- Low temperature cooling loop now modeled as a dedicated system (as opposed to being shared with the traction motor cooling loop)
- Updated polarization to reflect advancements in 2013
- Increase Pt cost to $1,500/troy ounce
- Imposition of $Q/\Delta T <= 1.45$ constraint
- Switch to Plate Frame humidifier (from tubular membrane humidifier)
- Analysis of low-cost Gore MEA fabrication (fabrication of 3-layer MEA (electrode-membrane-electrode) with slot-coating roll-to-roll process)
- Analysis of Eaton-style (multi-lobe Lysholm) air compressor (and expander)
- Revised modeling of factory quality control equipment/procedures
- Updated material prices
- Alignment of CEM status efficiencies (with DOT status and efficiencies used by ANL)

2014 Analysis

- Updated polarization to reflect advancements in 2014
- Analysis of de-alloyed binary catalyst synthesis
- Further evaluation of low cost Gore MEA fabrication
- Further evaluation of Eaton-style air compressor (and expander)
- Summary of quality control equipment
- Updated material prices
- Extension of Monte Carlo to all manufacturing rates
- Projection of a potential future pathway to $40/kW$_{e_net}$ system cost

2015 Analysis

- Discussion of the de-alloyed binary catalyst selection process
- Updated polarization to reflect advancements in 2015
- Re-evaluation of parasitic loads and gross power (to bring into alignment with ANL modeling)
- Re-evaluation of cell geometry (to reduce active to total cell area from 0.8 to 0.625 to bring into better alignment with industrial practice)
- Updates to the MEA sub-gasket processing assumptions (to correct an error in the assumed web width of the equipment)

- Exploration of low manufacturing rate production methods (to better define cost effective fabrication methods at low production rates)
- Side Studies:
    - Analysis of Giner Dimensionally Stable Membrane (DSM™) fabrication (as an alternative to ePTFE used to support the PEM membrane)
    - Analysis of Binary de-alloyed PtNi/C catalyst deposited via NSTF
    - Analysis of non-Pt Polyaniline (PANI)-Fe-C catalyst synthesis (as non-precious metal catalyst comparison to the baseline Pt-based catalyst)
    - Further analysis of low production fabrication methods that were not selected for the baseline system (bipolar plate material, forming, and coating methods)

2016 Analysis

- De-alloyed binary catalyst selection process discussion
- Updates to the binary catalyst synthesis analysis (for d-PtNi/C and d-Pt/C Johnson Matthey-style catalysts)
- Updated polarization to reflect advancements in 2016
- Re-evaluation of progressive die stamping for bipolar plates
- Re-evaluation of TreadStone Technologies BPP coating (incorporation of Gen2 system)
- Updated hydrogen sensor cost quote from FiS for model FH2-HY04 used in the Toyota Mirai
- Re-evaluation of laser welding coolant gasket (incorporation of multiple servos and welding stations)
- Analysis of the GDL production process (full DFMA®-style cost analysis as opposed to previous quote based estimates)
- Side Studies:
    - Updates to the Borit Hydrogate™ (hydroforming) BPP analysis
    - Analysis of the Toyota Mirai fuel cell system
    - Analysis of amorphous carbon BPP coating
    - Analysis of binary de-alloyed PtNi catalyst application using 3M NSTF

4.2 Automotive Fuel Cell System Configuration Comparison

Figure 3 contains a summary of the key configuration choices and manufacturing methods used for the automotive systems for each of the five analysis years.

	Automotive Fuel Cell Systems				
	2012 System	2013 System	2014 System	2015 System	2016 System
Power Density (mW/cm^2)	984	692	834	746	749
Total Pt loading ($mgPt/cm^2$)	0.196	0.153	No change	0.142	0.134
Total Pt Loading (g/ kW_{e_gross})	0.205	0.229	0.189	0.204	0.191
Net Power (kW_{e_net})	80	No change	No change	No change	No change
Gross Power (kW_{e_gross})	88.24	89.4	92.75	88.22	87.7
Cell Voltage (V)	0.676	0.695	0.672	0.661	0.659
Operating Pressure (atm)	2.5	No change	No change	No change	No change
Stack Temp. (Coolant Exit Temp) (°C)	87 (“peak stack”)	92.3	95	94	No change
Air Stoichiometry	1.5	No change	2.0	1.5	1.4
Q/ΔT (kW_{th}/°C)	1.80	1.45	No change	No change	No change
Active Cells	369	359	372	378	379
Membrane Material	Nafion on 25-micron ePTFE	No change	No change	No change	Nafion on 17-micron ePTFE
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	No change	No change	No change	No change
Bipolar Plates	Stamped SS 316L with TreadStone LiteCell™ Coating (Gen1)	No change	No change	No change	Stamped SS 316L with TreadStone LiteCell™ Coating (Gen2)
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	No change	No change	No change	No change
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer (Ballard Cost)	No change	No change	No change	Carbon Paper Macroporous Layer with Microporous Layer (DFMA® cost of Avcarb GDL)
Catalyst & Application	3M Nanostructured Thin Film (NSTF™) Pt/Co/Mn: Cath: 0.146 $mgPt/cm^2$ Anode: 0.05$mgPt/cm^2$ Pt	3M NSTF™ Pt/Co/Mn: Cath: 0.103 $mgPt/cm^2$ Anode: 0.05$mgPt/cm^2$ Pt	No Change	Slot Die Coating of: Cath.: Dispersed 0.092 $mgPt/cm^2$ d-PtNi on C Anode: Dispersed 0.05$mgPt/cm^2$ Pt on C	Slot Die Coating of: Cath.: Dispersed 0.116 $mgPt/cm^2$ d-PtNi on C Anode: Dispersed 0.018$mgPt/cm^2$ Pt on C
CCM Preparation	None	None	None	None	Acid washing
Air Humidification	Tubular Membrane Humidifier	Plate Frame Membrane Humidifier	No change	No change	No change
Hydrogen Humidification	None	None	None	None	None
Exhaust Water Recovery	None	None	None	None	None
Hydrogen Recirculation	2 passive ejectors operating in parallel (low flow, high flow)	No change	No change	No change	No change
MEA Containment	Screen Printed Seal on MEA Sub-gaskets, GDL crimped to CCM	No change	No change	Screen Printed Seal on MEA Sub-gaskets, GDL hot pressed to CCM	No change
Coolant & End Gaskets	Laser Welded(Cooling)/ Screen-Printed Adhesive Resin (End)	No change	No change	No change	No change
Freeze Protection	Drain Water at Shutdown	No change	No change	No change	No change
Hydrogen Sensors	2 for FC System[8]	No change	No change	No change	No change
End Plates/ Compression System	Composite Molded End Plates with Compression Bands	No change	No change	No change	No change
Stack Cond, (hour)	5	No change	No change	2	No change

Figure 3. Summary comparison of automotive fuel cell system configurations

[8] There are a total of 4 hydrogen sensors on-board the FC vehicle: 2 under the hood in the power system (within cost estimate), 1 in the passenger cabin (not in cost estimate), and 1 in the fuel system (not in cost estimate).

Key trends over the project include:

- Power Density: The power density started high and fluctuated a bit due to the switch from NSTF to dispersed catalyst (undertaken due to lifetime concerns of NSTF catalysts) and differing guidance from the FCTT regarding representative value (partially based on differences between Best of Class (BOC) and average polarization performance).
- Catalyst loading: Trending downward.
- Membrane Material: Trending toward thinner membranes (of lower equivalent weight).
- Catalyst and Application: Trending toward dispersed, de-alloyed, binary catalysts.

4.3 Bus Fuel Cell System Configuration Comparison

Figure 4 contains a summary of the key configuration choices and manufacturing methods used for the bus systems for each of the five analysis years.

Key trends over the project include:

- Membrane Material: Trending toward thinner membranes (of lower equivalent weight).
- Catalyst and Application: Trending toward dispersed Pt/C.

	Bus Fuel Cell Systems				
	2012 System	2013 System	2014 System	2015 System	2016 System
Power Density (mW/cm^2)	716	601	No change	739	No change
Total Pt loading (mgPt/cm^2)	0.4	No change	No change	0.5	No change
Total Pt Loading (g/ kW_{e_gross})	0.576	0.689	0.689	0.720	No change
Net Power (kW_{e_net})	160	No change	No change	No change	No change
Gross Power (kW_{e_gross})	177.1	186.2	187.6	194.7	194.7
Cell Voltage (V)	0.676	No change	No change	0.659	No change
Operating Pressure (atm)	1.8	No change	No change	1.9	No change
Stack Temp. (Coolant Exit Temp) (°C)	74	No change	No change	72	No change
Air Stoichiometry	1.5	2.1	No change	1.8	No change
Q/ΔT (kW_{th}/°C)	4.38	4.65	4.66	5.4	No change
Active Cells	739	No change	740	758	No change
Membrane Material	Nafion on 25-micron ePTFE	No change	No change	Nafion on 20-micron ePTFE[9]	No change
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	No change	No change	No change	No change
Bipolar Plates	Stamped SS 316L with TreadStone Litecell™ Coating (Gen1)	No change	No change	No change	Stamped SS 316L with TreadStone Coating (Gen2)
Air Compression	Centrifugal Compressor, Without Expander	Eaton-Style Multi-Lobe Compressor, Without Expander	No change	No change	No change
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer (Ballard Cost)	No change	No change	No change	Carbon Paper Macroporous Layer with Microporous Layer (DFMA® cost of Avcarb GDL)
Catalyst & Application	3M Nanostructured Thin Film (NSTF™) Pt/Co/Mn: Cath: 0.35mgPt/cm^2 Anode: 0.05mgPt/cm^2 Pt	No change	No change	Slot Die Coating of: Cath.: Dispersed 0.4mgPt/cm^2 Pt on C Anode: Dispersed 0.1mgPt/cm^2 Pt on C	No change
CCM Preparation	None	None	None	None	Acid washing
Air Humidification	Tubular Membrane Humidifier	Plate Frame Membrane Humidifier	No change	No change	No change
Hydrogen Humidification	None	None	None	None	None
Exhaust Water Recovery	None	None	None	None	None
Hydrogen Recirculation	2 passive ejectors operating in parallel (low flow, high flow)	No change	No change	No change	No change
MEA Containment	Screen Printed Seal on MEA Sub-gaskets, GDL crimped to CCM	No change	No change	Screen Printed Seal on MEA Sub-gaskets, GDL hot pressed to CCM	No change
Coolant & End Gaskets	Laser Welded (Cooling), Screen-Printed Adhesive Resin (End)	No change	No change	No change	No change
Freeze Protection	Drain Water at Shutdown	No change	No change	No change	No change
Hydrogen Sensors	2 for FC System	No change	3 for FC System[10]	No change	No change
End Plates/ Compression System	Composite Molded End Plates with Compression Bands	No change	No change	No change	No change
Stack Conditioning (hrs)	5	No change	No change	2	No change

Figure 4. Summary comparison of bus fuel cell system configurations

[9] 2015 polarization performance based on 20 micron thickness, but cost was assessed based on 25 microns. 2016 cost was updated to reflect 20 micron thick membrane.

[10] Additional sensor added to bus system due to the larger fuel cell compartment.

5 Cost Results

Fuel cell stack and balance of plant cost estimates were generated for both automotive and bus fuel cell systems for each analysis year. Cost breakdown of subsystem costs are too expansive to detail here. Consequently, top level summaries of the cost results are shown in Figure 5 below showing both reported values and adjusted values (normalized $1,500/tr.oz Pt price, CEM efficiency, and Q/ΔT requirement). Further cost details[11] appear in Appendix A and B, and full details are available in the individual annual update reports.

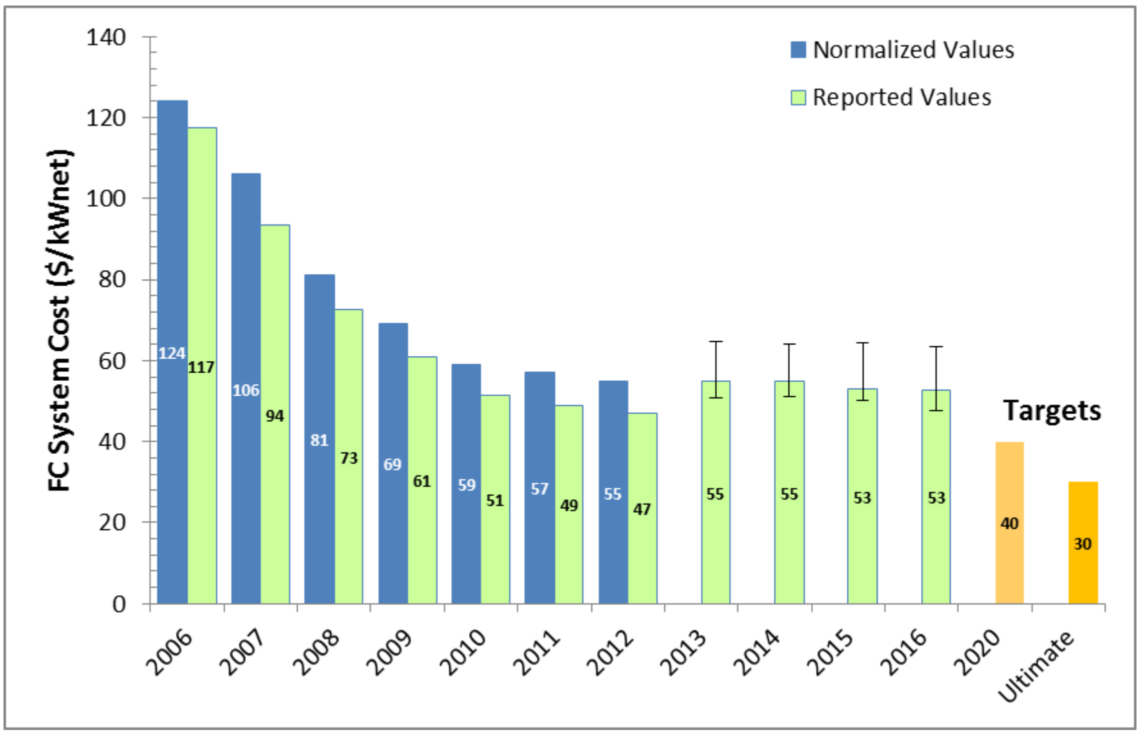

Figure 5. Modeled cost of an 80-kW$_{e_net}$ PEM fuel cell system based on projection to high-volume manufacturing (500,000 units/year). Reported values from 2012 and earlier were adjusted to account for the higher platinum price, the realigned compressor and expander efficiencies, and the Q/ΔT requirement introduced in 2013 (see 2013 DOE cost record[7]).

Figure 5 displays the annual automotive fuel cell systems costs as computed each analysis year (all at 500k systems/year). Cost results are shown for projections going back to 2006 since SA conducted similar analyses prior to this project starting in 2012. Monte Carlo analysis was first applied in 2013, thus error bars indicating the 90% confidence band of projected costs are not available before then. The DOE system cost target of $40/kW$_{e_net}$ and ultimate target of $30/kW$_{e_net}$ are also shown on the graph.

[11] It should be noted that cost values in Appendix A (SA's final year values reported at the end of the calendar year) may not match up exactly with values in Figure 5 (DOE Record values reported at the end of the fiscal year [6]–[9]) due to the difference in time when values are reported.

Note that three significant changes were made in 2013 which prevent a direct comparison in system cost for the entire range of years. Prior to 2013, the assumed price of Pt in the analyses was $1,100/troy ounce (rather than $1,500/troy ounce), higher compressor and expander efficiencies were used, and $Q/\Delta T$ was not constrained to $\leq$ 1.45 kW/°C. Consequently, the blue bars in the graph correspond to the cost of the early year systems with these three parameters normalized to post 2013 levels. This provides a more equitable assessment of the cost impact of technology changes from year to year.

Several conclusions may be drawn from the graph:

- Projected system cost (at 500k systems/year) decreased rapidly between 2006 and 2010.
- Since 2012, system cost has been fairly flat. Slight fluctuations in cost are within the 90% confidence error bounds.

Although not shown in the graph, the cost elements composing the system cost are roughly equally split between stack cost and balance of plant cost (at high production rates). Furthermore, three cost elements make up the majority of stack cost: bipolar plates, catalyst and its application, and membrane.

At lower manufacturing rates, the automotive system cost shows a general trend toward lower cost with each analysis year, as seen in Figure 6. The cost of the system is always lower at higher production rates. In 2013, the updates to Pt Cost, CEM efficiencies, and $Q/\Delta T$ constraint heavily impacted cost, particularly at 1,000 systems per year. In 2015, re-evaluation of low volume manufacturing methods was conducted to ensure proper sized equipment was fully utilized. This reduced the cost for the 2015 low volume cases. In 2016, the addition of >400% markup on catalyst synthesis (excluding markup on Pt material cost) at 1,000 systems per year increased the cost more than $\$30/kW_{e\_net}$.

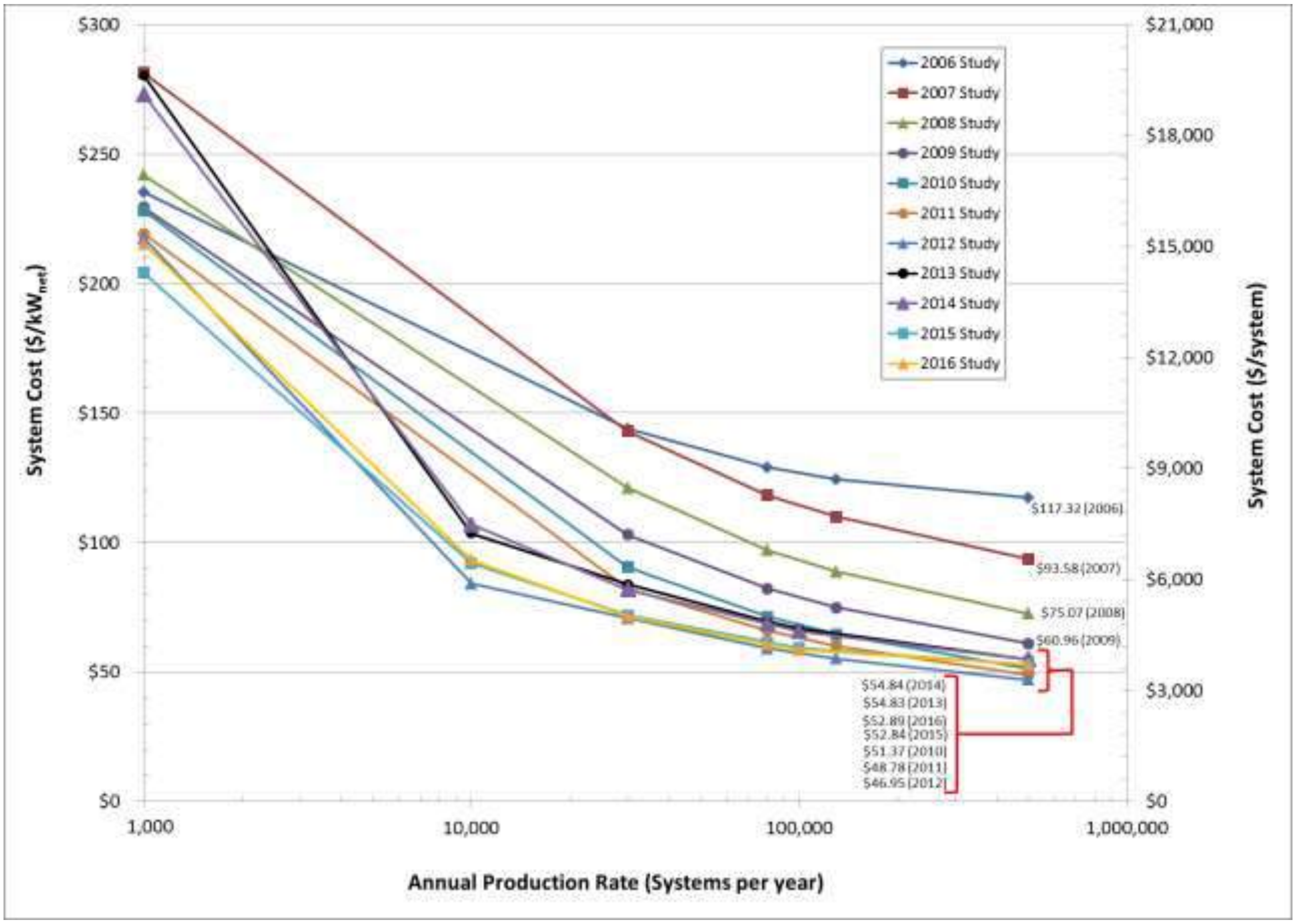

Figure 6. Automotive cost at all years and production volumes studied

6 Future System Cost Projection to $40/kW_{e\_net}$

As shown in Figure 5, there is a substantial cost gap between the current projected automotive system cost and achievement of the DOE cost targets. In addition to the cost target, the DOE has postulated individual component cost and performance targets. These component target values were applied to the baseline analysis and the resulting system cost assessed.

Figure 7 illustrates an example pathway to $40/kW_{e-et}$ (at 500,000 systems per year) in the form of a waterfall chart, with each step corresponding to a system cost parameter improvement. At the left end of the waterfall chart is the $80kW_{e\_net}$ 2016 baseline system cost ($53/kW_{e\_net}$). By varying the input values in the DFMA® model for power density, Pt content, air CEM cost, and bipolar plate (BPP) cost, the combined improvements result in $40/kW_{e\_net}$, DOE 2020 cost target. The target values used in this waterfall chart are taken from the Fuel Cell Technical Team U.S. Drive 2013 Roadmap.[12] The most significant steps in reducing cost are the system power density (delta $6/kW_{e\_net}$, based on an increase

[12] http://energy.gov/sites/prod/files/2014/02/f8/fctt_roadmap_june2013.pdf

from 749 to 1,000 mW/cm^2) and the BPP cost reduction (delta $\$4/kW_{e\_net}$, based on a decrease from \$8.17 to $\$3/kW_{e\_net}$). Additional performance or component cost parameters will need to be improved to meet or beat the ultimate DOE system cost target of $\$30/kW_{e\_net}$.

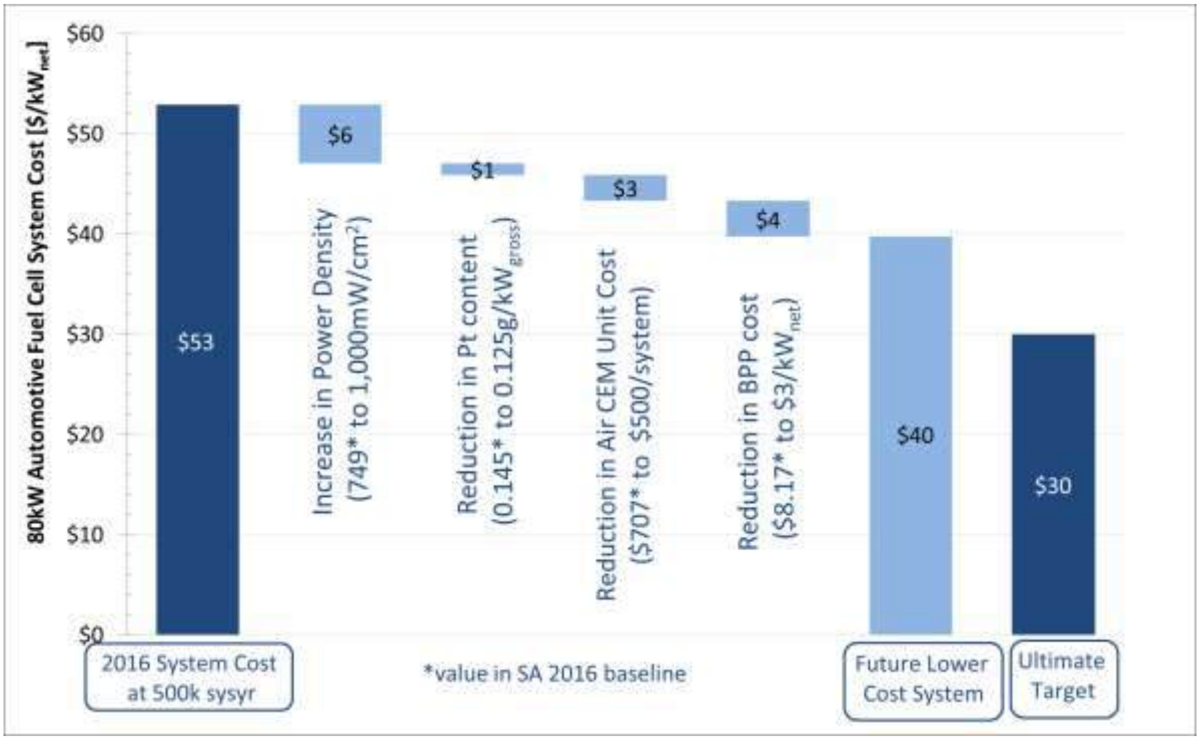

Figure 7. Waterfall chart for projection of automotive fuel cell system cost down to $\$40/kW_{e\_net}$, and DOE ultimate target $\$30/kW_{e\_net}$

7 Research and Cost Challenges and Recommendations

Analysis of the automotive and bus fuel cell systems over subsequent years has shed light on technology and cost shortfalls in achievement of the DOE cost targets. The following is a top level list of recommendations for further research.

Bipolar Plates

- Plate Forming: Despite the ability to produce bipolar plates at fast rates in progressive stamping presses (a few seconds per plate), the rates are not fast enough for the millions of plates needed per year. High numbers of parallel forming lines would be required, leading to infeasible factory setups and difficult quality control issues. Faster bipolar plate forming systems are needed.
- Plate Coating: There is no clearly identified pathway to a low cost, high volume-feasible bipolar plate coating (for corrosion resistance and electrical contact improvement).
- Laser welding: (to seal and create a cooling cell between the plates).
    - Laser welding lengths needs to be minimized to achieve low cost. Systems with low effective welding cycle times need to be demonstrated.

    - High rate, low cost, alternates to laser welding should be explored.
    - Clamping of the BPPs to ensure plate contact while welding is identified as a key parameter for welding success. Additional research is needed for optimization.
- Material: Metal plates (as opposed to graphite, Grafoil, or composite materials) appear to be preferred for automotive applications. Alternate alloys with both lower cost and inherent ant-corrosion properties should be explored.

Membranes

- Increased power density remains the number one pathway to reduced system cost.
- Ionomer costs at high production rates remain uncertain.
- While ePTFE has proven to be an effective membrane support, its cost is high. Fabrication (at production level) and performance assessment of alternate supports (such as the Giner DSM) should be conducted.

Catalysts

- Non-Pt based catalysts: Pt based catalysts have been demonstrated to be most cost effective. To achieve competitiveness, non-Pt catalysts need to substantially improve their power density.
- Pt Usage: Substantial strides have been achieved in reducing Pt usage (and improving kW/gPt). Nonetheless, Pt cost is one of the largest cost elements within the fuel cell system. Efforts to further reduce Pt while maintaining performance and durability should continue.
- Catalyst Synthesis: Synthesis is complicated but appears to be relatively inexpensive (excluding Pt cost), particularly at high rate production. It appears to be a favorable tradeoff to exchange synthesis complexity (possibly higher cost) for high polarization performance.
- Durability: Catalyst (and membrane) durability has not been explicitly factored in the cost analyses. However, it is clear that durability improvements are needed to meet minimum customer requirements.

Gas Diffusion Layers

- There is a wide distribution in GDL costs seemingly due to a combination of production scale, material wastage, and GDL company markup. More investigation is warranted to better understand these cost drivers.

Manufacturing Research

- Numerous components can be produced in quantities suitable for 1,000 vehicle systems per year but require manufacturing process development to achieve 100k vehicles per year production capability. They require not only a high-confidence market demand (to allow confidence in capital investment) but also substantial R&D dollars to develop the high speed production systems.

References

[1] B. D. James and A. B. Spisak, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2012 Update," Strategic Analysis, Inc., 2012.

[2] B. D. James, J. M. Moton, and W. G. Colella, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2013 Update," Strategic Analysis, Inc., 2013.

[3] B. D. James, J. M. Moton, and W. G. Colella, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2014 Update," Strategic Analysis, Inc., 2014.

[4] B. D. James, J. M. Huya-Kouadia, and C. Houchins, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2015 Update," Strategic Analysis, Inc., 2015.

[5] B. D. James, J. M. Huya-Kouadia, and C. Houchins, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2016 Update," Strategic Analysis, Inc., 2016.

[6] J. Marcinkoski and J. Spendelow, "Fuel Cell System Cost 2012," DOE Fuel Cell Technologies Office, Record# 12020, Sep. 2012.

[7] J. Marcinkoski and J. Spendelow, "Fuel Cell System Cost 2013," DOE Fuel Cell Technologies Office, Record# 14012, Jun. 2014.

[8] J. Marcinkoski and J. Spendelow, "Fuel Cell System Cost 2014," DOE Fuel Cell Technologies Office, Record# 14014, Oct. 2014.

[9] J. Marcinkoski, J. Spendelow, A. Wilson, and D. Papageorgopoulos, "Fuel Cell System Cost 2015," DOE Fuel Cell Technologies Office, Record# 15015, Oct. 2015.

8 Appendix A: Tabular Summary of Automotive Fuel Cell System Cost Results

2012 Auto Cost

			2012 Automotive System					
Annual Production Rate		**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)		**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)		**kWgross**	88.24	88.24	88.24	88.24	88.24	88.24
Stack Components								
	Bipolar Plates (Stamped)	**$/stack**	$1,819	$437	$411	$395	$396	$392
	MEAs							
	Membranes	**$/stack**	$3,519	$882	$495	$337	$277	$171
	d-PtNi Catalyst Ink & Application (Disp	**$/stack**	$1,453	$817	$771	$765	$763	$760
	GDLs	**$/stack**	$2,137	$639	$359	$215	$166	$82
	M & E Hot Pressing	**$/stack**	$0	$0	$0	$0	$0	$0
	M & E Cutting & Slitting	**$/stack**	$487	$51	$18	$8	$6	$3
	MEA Sub-Gaskets	**$/stack**	$1,487	$235	$115	$91	$95	$87
	Coolant Gaskets (Laser Welding)	**$/stack**	$213	$42	$29	$27	$27	$26
	End Gaskets (Screen Printing)	**$/stack**	$149	$15	$5	$2	$1	$1
	End Plates	**$/stack**	$97	$33	$29	$25	$23	$17
	Current Collectors	**$/stack**	$53	$11	$8	$6	$5	$5
	Compression Bands	**$/stack**	$10	$9	$8	$6	$6	$5
	Stack Housing	**$/stack**	$61	$10	$7	$6	$5	$4
	Stack Assembly	**$/stack**	$76	$59	$41	$35	$34	$32
	Stack Conditioning	**$/stack**	$171	$57	$54	$47	$41	$28
Total Stack Cost		**$/stack**	$11,731	$3,296	$2,349	$1,963	$1,844	$1,613
Total Stacks Cost (Net)		**$/kWnet**	$146.64	$41.20	$29.37	$24.54	$23.05	$20.17
Total Stacks Cost (Gross)		**$/kWgross**	$132.94	$37.35	$26.62	$22.25	$20.90	$18.28

			2012 Automotive System					
Annual Production Rate		**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)		**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)		**kWgross**	88.24	88.24	88.24	88.24	88.24	88.24
BOP Components								
	Air Loop	**$/system**	$1,736	$1,040	$1,038	$897	$869	$842
	Humidifier & Water Recovery Loop	**$/system**	$646	$227	$153	$118	$108	$92
	High-Temperature Coolant Loop	**$/system**	$537	$462	$462	$405	$383	$357
	Low-Temperature Coolant Loop	**$/system**	$96	$86	$86	$80	$76	$71
	Fuel Loop	**$/system**	$349	$303	$294	$264	$254	$240
	System Controller	**$/system**	$171	$151	$137	$103	$96	$82
	Sensors	**$/system**	$1,707	$893	$893	$660	$543	$225
	Miscellaneous	**$/system**	$286	$167	$158	$144	$139	$135
Total BOP Cost		**$/system**	$5,528	$3,328	$3,221	$2,671	$2,468	$2,045
Total BOP Cost		**$/kW (Net)**	$69.10	$41.60	$40.26	$33.39	$30.85	$25.56
Total BOP Cost		**$/kW (Gross)**	$62.64	$37.72	$36.50	$30.27	$27.97	$23.17

			2012 Automotive System					
Annual Production Rate		**systems/year**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)		**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)		**kWgross**	88	88	88	88	88	88
Component Cost/System								
	Fuel Cell Stacks	**$/system**	**$11,731**	**$3,296**	**$2,349**	**$1,963**	**$1,844**	**$1,613**
	Balance of Plant	**$/system**	**$5,528**	**$3,328**	**$3,221**	**$2,671**	**$2,468**	**$2,045**
	System Assembly & Testing	**$/system**	**$145**	**$101**	**$99**	**$99**	**$98**	**$98**
Total System Cost		**$/system**	$17,404	$6,725	$5,669	$4,733	$4,411	$3,756
Total System Cost		**$/kWnet**	$217.55	$84.06	$70.86	$59.17	$55.13	$46.95
Cost/kWgross		**$/kWgross**	$197.23	$76.21	$64.24	$53.64	$49.98	$42.57

2013 Auto Cost

		2013 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	89.44	89.44	89.44	89.44	89.44	89.44
Stack Components							
Bipolar Plates (Stamped)	**$/stack**	$1,976	$572	$506	$489	$489	$486
MEAs							
Membranes	**$/stack**	$4,530	$1,251	$757	$500	$455	$236
Catalyst Ink & Application (NSTF)	**$/stack**	$2,242	$1,168	$1,126	$1,080	$1,082	$1,051
GDLs	**$/stack**	$2,661	$795	$447	$267	$238	$102
M & E Cutting & Slitting	**$/stack**	$533	$55	$20	$9	$8	$4
MEA Frame/Gaskets	**$/stack**	$1,493	$265	$146	$137	$145	$130
Coolant Gaskets (Laser Welding)	**$/stack**	$219	$43	$43	$33	$31	$31
End Gaskets (Screen Printing)	**$/stack**	$153	$15	$5	$2	$2	$0
End Plates	**$/stack**	$177	$70	$60	$52	$51	$45
Current Collectors	**$/stack**	$57	$14	$10	$9	$8	$7
Compression Bands	**$/stack**	$10	$9	$8	$6	$6	$5
Stack Housing	**$/stack**	$63	$11	$8	$6	$6	$5
Stack Assembly	**$/stack**	$76	$32	$32	$32	$32	$32
Stack Conditioning	**$/stack**	$176	$58	$55	$48	$42	$29
Total Stack Cost	**$/stack**	$14,368	$4,361	$3,224	$2,672	$2,594	$2,164
Total Stacks Cost (Net)	**$/kWnet**	$179.60	$54.51	$40.31	$33.40	$32.42	$27.05
Total Stacks Cost (Gross)	**$/kWgross**	$160.65	$48.76	$36.05	$29.87	$29.00	$24.20

		2013 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	89.44	89.44	89.44	89.44	89.44	89.44
BOP Components							
Air Loop	**$/system**	$1,818	$1,108	$1,106	$963	$933	$903
Humidifier & Water Recovery Loop	**$/system**	$2,915	$441	$252	$180	$170	$133
High-Temperature Coolant Loop	**$/system**	$512	$420	$420	$365	$345	$323
Low-Temperature Coolant Loop	**$/system**	$97	$88	$88	$78	$74	$70
Fuel Loop	**$/system**	$350	$304	$295	$265	$255	$241
System Controller	**$/system**	$171	$151	$137	$103	$96	$82
Sensors	**$/system**	$1,755	$1,190	$921	$680	$625	$231
Miscellaneous	**$/system**	$292	$170	$161	$147	$143	$138
Total BOP Cost	**$/system**	$7,909	$3,872	$3,380	$2,781	$2,640	$2,121
Total BOP Cost	**$/kW (Net)**	$98.87	$48.40	$42.24	$34.76	$33.00	$26.52
Total BOP Cost	**$/kW (Gross)**	$88.43	$43.29	$37.79	$31.09	$29.52	$23.72

		2013 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	89.44	89.44	89.44	89.44	89.44	89.44
Component Costs/System							
Fuel Cell Stacks	**$/system**	$14,368	$4,361	$3,224	$2,672	$2,594	$2,164
Balance of Plant	**$/system**	$7,909	$3,872	$3,380	$2,781	$2,640	$2,121
System Assembly & Testing	**$/system**	$149	$103	$102	$101	$101	$101
Cost/System	**$/system**	$22,426	$8,336	$6,706	$5,554	$5,335	$4,387
Total System Cost	**$/kWnet**	$280.33	$104.20	$83.82	$69.42	$66.68	$54.83
Cost/kWgross	**$/kWgross**	$250.74	$93.20	$74.97	$62.10	$59.65	$49.05

2014 Auto Cost

		2014 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	92.75	92.75	92.75	92.75	92.75	92.75
Stack Components							
Bipolar Plates (Stamped)	**$/stack**	$1,952	$556	$489	$474	$479	$472
MEAs							
Membranes	**$/stack**	$4,119	$1,086	$644	$419	$380	$208
Catalyst Ink & Application (NSTF)	**$/stack**	$2,078	$1,009	$925	$924	$913	$899
GDLs	**$/stack**	$2,474	$739	$416	$248	$221	$95
M & E Cutting & Slitting	**$/stack**	$532	$55	$20	$9	$7	$4
MEA Frame/Gaskets	**$/stack**	$1,479	$254	$135	$126	$121	$116
Coolant Gaskets (Laser Welding)	**$/stack**	$219	$43	$30	$33	$31	$29
End Gaskets (Screen Printing)	**$/stack**	$153	$15	$5	$2	$2	$0
End Plates	**$/stack**	$161	$60	$51	$44	$43	$37
Current Collectors	**$/stack**	$55	$13	$9	$8	$7	$6
Compression Bands	**$/stack**	$10	$9	$8	$6	$6	$5
Stack Housing	**$/stack**	$63	$12	$8	$7	$6	$5
Stack Assembly	**$/stack**	$79	$61	$42	$36	$35	$33
Stack Conditioning	**$/stack**	$176	$58	$55	$48	$42	$29
Total Stack Cost	**$/stack**	$13,550	$3,971	$2,836	$2,383	$2,293	$1,940
Total Stacks Cost (Net)	**$/kWnet**	$169.37	$49.63	$35.45	$29.79	$28.66	$24.25
Total Stacks Cost (Gross)	**$/kWgross**	$146.09	$42.81	$30.58	$25.70	$24.72	$20.92

		2014 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	92.75	92.75	92.75	92.75	92.75	92.75
BOP Components							
Air Loop	**$/system**	$2,083	$1,653	$1,336	$1,185	$1,146	$1,111
Humidifier & Water Recovery Loop	**$/system**	$2,959	$475	$284	$209	$197	$164
High-Temperature Coolant Loop	**$/system**	$468	$443	$414	$366	$349	$327
Low-Temperature Coolant Loop	**$/system**	$103	$97	$93	$88	$84	$80
Fuel Loop	**$/system**	$346	$306	$291	$261	$251	$238
System Controller	**$/system**	$171	$151	$137	$103	$96	$82
Sensors	**$/system**	$1,752	$1,188	$919	$679	$625	$231
Miscellaneous	**$/system**	$263	$165	$136	$123	$119	$115
Total BOP Cost	**$/system**	$8,145	$4,477	$3,610	$3,015	$2,867	$2,346
Total BOP Cost	**$/kW (Net)**	$101.81	$55.97	$45.13	$37.68	$35.84	$29.33
Total BOP Cost	**$/kW (Gross)**	$87.82	$48.28	$38.93	$32.50	$30.91	$25.30

		2014 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	92.75	92.75	92.75	92.75	92.75	92.75
Component Costs/System							
Fuel Cell Stack (High Value)	**$/system**	$15,106	$4,856	$3,650	$3,132	$3,043	$2,626
Fuel Cell Stack (Nominal Value)	**$/system**	$13,550	$3,971	$2,836	$2,383	$2,293	$1,940
Fuel Cell Stack (Low Value)	**$/system**	$12,860	$3,604	$2,547	$2,120	$2,053	$1,699
Balance of Plant (High Value)	**$/system**	$8,492	$4,918	$3,853	$3,233	$3,080	$2,553
Balance of Plant (Nominal Value)	**$/system**	$8,145	$4,477	$3,610	$3,015	$2,867	$2,346
Balance of Plant (Low Value)	**$/system**	$7,790	$4,063	$3,354	$2,777	$2,638	$2,124
System Assembly & Testing	**$/system**	$148	$103	$101	$101	$101	$101
Cost/System (High Value)	**$/system**	$23,380	$9,525	$7,379	$6,266	$6,029	$5,096
Cost/System (Nominal Value)	**$/system**	$21,843	$8,551	$6,548	$5,499	$5,261	$4,387
Cost/System (Low Value)	**$/system**	$21,070	$8,026	$6,177	$5,156	$4,943	$4,065
Total System Cost	**$/kWnet**	$273.04	$106.89	$81.85	$68.74	$65.77	$54.84
Cost/kWgross	**$/kWgross**	$235.51	$92.20	$70.60	$59.29	$56.73	$47.30

2015 Auto Cost

		2015 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	88.22	88.22	88.22	88.22	88.22	88.22
Stack Components							
Bipolar Plates (Stamped)	**$/stack**	$1,607	$632	$593	$571	$565	$558
MEAs							
Membranes	**$/stack**	$3,213	$994	$615	$410	$374	$206
d-PtNi Catalyst Ink & Application (Dispersion)	**$/stack**	$2,527	$1,129	$980	$952	$940	$913
GDLs	**$/stack**	$2,509	$750	$422	$252	$224	$96
M & E Cutting & Slitting	**$/stack**	$0	$22	$10	$5	$4	$3
MEA Sub-Gaskets	**$/stack**	$917	$274	$153	$126	$124	$116
Coolant Gaskets (Laser Welding)	**$/stack**	$219	$43	$43	$33	$31	$30
End Gaskets (Screen Printing)	**$/stack**	$1	$1	$1	$1	$1	$0
End Plates	**$/stack**	$100	$81	$71	$65	$64	$56
Current Collectors	**$/stack**	$8	$7	$7	$7	$7	$6
Compression Bands	**$/stack**	$10	$9	$8	$6	$6	$5
Stack Housing	**$/stack**	$64	$12	$8	$7	$7	$6
Stack Assembly	**$/stack**	$80	$61	$42	$36	$35	$34
Stack Conditioning	**$/stack**	$60	$18	$18	$16	$17	$13
Total Stack Cost	**$/stack**	$11,360	$4,049	$2,985	$2,496	$2,407	$2,052
Total Stacks Cost (Net)	**$/kWnet**	$142.00	$50.62	$37.32	$31.20	$30.09	$25.64
Total Stacks Cost (Gross)	**$/kWgross**	$128.77	$45.90	$33.84	$28.29	$27.28	$23.25

		2015 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	88.22	88.22	88.22	88.22	88.22	88.22
BOP Components							
Air Loop	**$/system**	$1,850	$1,438	$1,143	$998	$966	$936
Humidifier & Water Recovery Loop	**$/system**	$1,209	$298	$181	$147	$137	$107
High-Temperature Coolant Loop	**$/system**	$476	$443	$414	$366	$349	$327
Low-Temperature Coolant Loop	**$/system**	$76	$72	$70	$66	$63	$60
Fuel Loop	**$/system**	$346	$306	$291	$261	$251	$238
System Controller	**$/system**	$171	$151	$137	$103	$96	$82
Sensors	**$/system**	$437	$331	$291	$260	$253	$212
Miscellaneous	**$/system**	$263	$165	$136	$123	$119	$115
Total BOP Cost	**$/system**	$4,828	$3,204	$2,662	$2,323	$2,234	$2,075
Total BOP Cost	**$/kW (Net)**	$60.35	$40.05	$33.28	$29.04	$27.92	$25.94
Total BOP Cost	**$/kW (Gross)**	$54.73	$36.32	$30.18	$26.33	$25.32	$23.52

		2015 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	88.22	88.22	88.22	88.22	88.22	88.22
Component Costs/System							
Fuel Cell Stack (High Value)	**$/system**	$12,597	$4,870	$3,742	$3,231	$3,140	$2,757
Fuel Cell Stack (Nominal Value)	**$/system**	$11,360	$4,049	$2,985	$2,496	$2,407	$2,052
Fuel Cell Stack (Low Value)	**$/system**	$10,174	$3,498	$2,497	$2,072	$1,995	$1,663
Balance of Plant (High Value)	**$/system**	$5,341	$3,650	$2,908	$2,545	$2,447	$2,278
Balance of Plant (Nominal Value)	**$/system**	$4,828	$3,204	$2,662	$2,323	$2,234	$2,075
Balance of Plant (Low Value)	**$/system**	$4,474	$2,740	$2,468	$2,155	$2,071	$1,835
System Assembly & Testing	**$/system**	$148	$103	$101	$101	$101	$101
Cost/System (High Value)	**$/system**	$17,750	$8,297	$6,570	$5,714	$5,529	$4,982
Cost/System (Nominal Value)	**$/system**	$16,336	$7,357	$5,749	$4,920	$4,742	$4,228
Cost/System (Low Value)	**$/system**	$15,149	$6,644	$5,242	$4,486	$4,321	$3,825
Total System Cost	**$/kWnet**	$204.20	$91.96	$71.86	$61.50	$59.27	$52.84
Cost/kWgross	**$/kWgross**	$185.18	$83.39	$65.16	$55.77	$53.75	$47.92

2016 Auto Cost

		2016 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	87.68	87.68	87.68	87.68	87.68	87.68
Bipolar Plates (Stamped)	**$/stack**	$1,985	$772	$698	$668	$658	$653
MEAs							
Membranes	**$/stack**	$3,167	$961	$589	$386	$351	$191
d-PtNi Catalyst Ink & Application (Disp	**$/stack**	$2,307	$1,326	$1,052	$973	$957	$928
CCM Acid Wash	**$/stack**	$506	$51	$34	$17	$19	$14
GDLs	**$/stack**	$2,602	$596	$328	$213	$196	$129
M & E Hot Pressing	**$/stack**	$39	$17	$17	$10	$10	$9
M & E Cutting & Slitting	**$/stack**	$0	$22	$10	$5	$4	$3
MEA Sub-Gaskets	**$/stack**	$917	$272	$152	$126	$124	$115
Coolant Gaskets (Laser Welding)	**$/stack**	$410	$53	$53	$40	$38	$37
End Gaskets (Screen Printing)	**$/stack**	$1	$1	$1	$1	$1	$0
End Plates	**$/stack**	$99	$80	$70	$64	$63	$55
Current Collectors	**$/stack**	$8	$7	$7	$7	$7	$6
Compression Bands	**$/stack**	$10	$9	$8	$6	$6	$5
Stack Housing	**$/stack**	$64	$13	$9	$8	$7	$6
Stack Assembly	**$/stack**	$80	$61	$42	$36	$35	$34
Stack Conditioning	**$/stack**	$60	$18	$18	$16	$16	$13
Total Stack Cost	**$/stack**	$12,255	$4,259	$3,087	$2,575	$2,493	$2,199
Total Stacks Cost (Net)	**$/kWnet**	$153.19	$53.23	$38.58	$32.19	$31.16	$27.49
Total Stacks Cost (Gross)	**$/kWgross**	$139.77	$48.57	$35.20	$29.37	$28.43	$25.08

		2016 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	87.68	87.68	87.68	87.68	87.68	87.68
BOP Components							
Air Loop	**$/system**	$1,813	$1,394	$1,095	$951	$920	$891
Humidifier & Water Recovery Loop	**$/system**	$1,176	$274	$158	$128	$119	$90
High-Temperature Coolant Loop	**$/system**	$480	$446	$417	$369	$352	$330
Low-Temperature Coolant Loop	**$/system**	$71	$68	$65	$61	$59	$56
Fuel Loop	**$/system**	$346	$306	$291	$261	$251	$238
System Controller	**$/system**	$172	$152	$138	$103	$97	$83
Sensors	**$/system**	$512	$290	$226	$184	$176	$131
Miscellaneous	**$/system**	$263	$165	$136	$123	$119	$115
Total BOP Cost	**$/system**	$4,833	$3,094	$2,527	$2,181	$2,092	$1,932
Total BOP Cost	**$/kW (Net)**	$60.41	$38.68	$31.58	$27.27	$26.15	$24.14
Total BOP Cost	**$/kW (Gross)**	$55.12	$35.29	$28.82	$24.88	$23.86	$22.03

		2016 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	87.68	87.68	87.68	87.68	87.68	87.68
Component Costs/System							
Fuel Cell Stack (High Value)	**$/system**	$15,093	$5,377	$3,981	$3,398	$3,317	$2,965
Fuel Cell Stack (Nominal Value)	**$/system**	$12,255	$4,259	$3,087	$2,575	$2,493	$2,199
Fuel Cell Stack (Low Value)	**$/system**	$10,818	$3,694	$2,575	$2,122	$2,050	$1,755
Balance of Plant (High Value)	**$/system**	$5,364	$3,558	$2,791	$2,422	$2,324	$2,153
Balance of Plant (Nominal Value)	**$/system**	$4,833	$3,094	$2,527	$2,181	$2,092	$1,932
Balance of Plant (Low Value)	**$/system**	$4,542	$2,715	$2,374	$2,051	$1,965	$1,808
System Assembly & Testing	**$/system**	$148	$103	$101	$101	$101	$101
Cost/System (High Value)	**$/system**	$20,226	$8,702	$6,696	$5,760	$5,585	$5,070
Cost/System (Nominal Value)	**$/system**	$17,236	$7,456	$5,715	$4,858	$4,686	$4,232
Cost/System (Low Value)	**$/system**	$15,858	$6,814	$5,217	$4,422	$4,259	$3,800
Total System Cost	**$/kWnet**	$215.45	$93.20	$71.43	$60.73	$58.57	$52.89
Cost/kWgross	**$/kWgross**	$196.58	$85.04	$65.18	$55.41	$53.44	$48.26

9 Appendix B: Tabular Summary of Transit Bus Fuel Cell System Cost Results

2012 Bus Cost

	2012 Bus System
Annual Production Rate	1,000
System Net Electric Power (Output)	160
System Gross Electric Power (Output)	177.10
Bipolar Plates (Stamped)	$1,141.17
MEAs	
Membranes	$2,595.88
Catalyst Ink & Application (NSTF)	$2,466.74
GDLs	$2,959.34
M & E Cutting & Slitting	$245.32
MEA Gaskets	$799.98
Coolant Gaskets (Laser Welding)	$111.62
End Gaskets (Screen Printing)	$74.80
End Plates	$77.51
Current Collectors	$32.20
Compression Bands	$10.00
Stack Housing	$66.55
Stack Assembly	$73.63
Stack Conditioning	$170.88
Total Stack Cost (single stack)	$10,825.62
Total Stack Cost ($/kW$_{net}$)	$135.32
Total Stack Cost ($/kW$_{gross}$)	$122.25

	2012 Bus System
Annual Production Rate	1,000
System Net Electric Power (Output)	160
System Gross Electric Power (Output)	177.10
Air Loop	$2,355.14
Humidifier and Water Recovery Loop	$964.62
High-Temperature Coolant Loop	$1,187.73
Low-Temperature Coolant Loop	$142.73
Fuel Loop	$641.99
System Controller	$342.14
Sensors	$2,573.98
Miscellaneous	$498.71
Total BOP Cost	$8,707.03
Total BOP Cost ($/kW$_{net}$)	$54.42
Total BOP Cost ($/kW$_{gross}$)	$49.16

	2012 Bus System
Annual Production Rate	1,000
System Net Electric Power (Output)	160
System Gross Electric Power (Output)	177.10
Fuel Cell Stacks	$21,651.24
Balance of Plant	$8,707.03
System Assembly & Testing	$152.34
Total System Cost ($)	$30,510.60
Total System Cost ($/kW$_{net}$)	$190.69
Total System Cost ($/kW$_{gross}$)	$172.28

2013 Bus Cost

		2013 Bus System			
Annual Production Rate	**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)	**kWnet**	160	160	160	160
System Gross Electric Power (Output)	**kWgross**	186.22	186.22	186.22	186.22
Stack Components					
Bipolar Plates (Stamped)	**$/stack**	$1,155	$1,086	$1,027	$1,008
MEAs					
Membranes	**$/stack**	$10,884	$6,974	$4,603	$4,051
Catalyst Ink & Application (NSTF)	**$/stack**	$4,852	$4,739	$4,653	$4,625
GDLs	**$/stack**	$8,399	$5,674	$3,839	$3,386
M & E Cutting & Slitting	**$/stack**	$15	$13	$12	$12
MEA Gaskets (Frame or Sub-Gasket)	**$/stack**	$769	$695	$675	$625
Coolant Gaskets (Laser Welding)	**$/stack**	$207	$175	$135	$194
End Gaskets (Screen Printing)	**$/stack**	$1	$1	$1	$1
End Plates	**$/stack**	$143	$133	$124	$121
Current Collectors	**$/stack**	$15	$14	$14	$14
Compression Bands	**$/stack**	$17	$16	$15	$14
Stack Insulation Housing	**$/stack**	$274	$145	$81	$69
Stack Assembly	**$/stack**	$155	$139	$129	$127
Stack Conditioning	**$/stack**	$797	$389	$371	$296
Total Stack Cost	**$/stack**	$27,680	$20,194	$15,679	$14,545
Total Cost for all 2 Stacks	**$/2 stacks**	$55,361	$40,387	$31,358	$29,089
Total Stacks Cost (Net)	**$/kWnet**	$346.01	$252.42	$195.99	$181.81
Total Stacks Cost (Gross)	**$/kWgross**	$297.29	$216.89	$168.40	$156.21

		2013 Bus System			
Annual Production Rate	**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)	**kWnet**	160	160	160	160
System Gross Electric Power (Output)	**kWgross**	186.22	186.22	186.22	186.22
BOP Components					
Air Loop	**$/system**	$6,689	$5,995	$5,433	$5,274
Humidifier & Water Recovery Loop	**$/system**	$1,420	$1,170	$1,007	$966
High-Temperature Coolant Loop	**$/system**	$1,741	$1,685	$1,631	$1,614
Low-Temperature Coolant Loop	**$/system**	$213	$207	$201	$199
Fuel Loop	**$/system**	$1,006	$959	$914	$900
System Controller	**$/system**	$584	$533	$488	$474
Sensors	**$/system**	$4,545	$4,155	$3,771	$3,649
Miscellaneous	**$/system**	$1,117	$908	$792	$765
Total BOP Cost	**$/system**	$17,316	$15,614	$14,238	$13,841
Total BOP Cost	**$/kW (Net)**	$108.22	$97.58	$88.98	$86.51
Total BOP Cost	**$/kW (Gross)**	$92.99	$83.85	$76.46	$74.33

		2013 Bus System			
Annual Production Rate	**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)	**kWnet**	160	160	160	160
System Gross Electric Power (Output)	**kWgross**	186.22	186.22	186.22	186.22
Component Costs/System					
Fuel Cell Stacks	**$/system**	$55,361	$40,387	$31,358	$29,089
Balance of Plant	**$/system**	$17,316	$15,614	$14,238	$13,841
System Assembly & Testing	**$/system**	$464	$339	$275	$262
Cost/System	**$/system**	$73,141	$56,340	$45,870	$43,192
Total System Cost	**$/kWnet**	$457.13	$352.12	$286.69	$269.95
Cost/kWgross	**$/kWgross**	$392.77	$302.55	$246.33	$231.94

2014 Bus Cost

			2014 Bus System			
Annual Production Rate		**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)		**kWnet**	160	160	160	160
System Gross Electric Power (Output)		**kWgross**	187.63	187.63	187.63	187.63
Stack Components						
	Bipolar Plates (Stamped)	**$/stack**	$1,208	$1,139	$1,079	$1,060
	MEAs					
	Membranes	**$/stack**	$10,902	$6,988	$4,612	$4,060
	Catalyst Ink & Application (NSTF)	**$/stack**	$5,198	$4,847	$4,715	$4,680
	GDLs	**$/stack**	$8,429	$5,695	$3,853	$3,398
	M & E Cutting & Slitting	**$/stack**	$15	$13	$12	$12
	MEA Gaskets (Frame or Sub-Gasket)	**$/stack**	$909	$759	$706	$650
	Coolant Gaskets (Laser Welding)	**$/stack**	$208	$175	$136	$194
	End Gaskets (Screen Printing)	**$/stack**	$1	$1	$1	$1
	End Plates	**$/stack**	$144	$133	$124	$122
	Current Collectors	**$/stack**	$15	$15	$14	$14
	Compression Bands	**$/stack**	$17	$16	$15	$14
	Stack Insulation Housing	**$/stack**	$275	$147	$83	$70
	Stack Assembly	**$/stack**	$155	$139	$129	$127
	Stack Conditioning	**$/stack**	$797	$389	$371	$296
Total Stack Cost		**$/stack**	$28,272	$20,456	$15,851	$14,700
Total Cost for all 2 Stacks		**$/2 stacks**	$56,545	$40,912	$31,702	$29,400
Total Stacks Cost (Net)		**$/kWnet**	$353.40	$255.70	$198.14	$183.75
Total Stacks Cost (Gross)		**$/kWgross**	$301.36	$218.05	$168.96	$156.69

			2014 Bus System			
Annual Production Rate		**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)		**kWnet**	160	160	160	160
System Gross Electric Power (Output)		**kWgross**	187.63	187.63	187.63	187.63
BOP Components						
	Air Loop	**$/system**	$8,947	$7,499	$6,514	$6,260
	Humidifier & Water Recovery Loop	**$/system**	$1,471	$1,219	$1,056	$1,014
	High-Temperature Coolant Loop	**$/system**	$1,786	$1,729	$1,673	$1,656
	Low-Temperature Coolant Loop	**$/system**	$224	$217	$211	$209
	Fuel Loop	**$/system**	$997	$950	$905	$891
	System Controller	**$/system**	$584	$533	$488	$474
	Sensors	**$/system**	$4,545	$4,155	$3,771	$3,649
	Miscellaneous	**$/system**	$1,118	$909	$792	$766
Total BOP Cost		**$/system**	$19,671	$17,211	$15,411	$14,919
Total BOP Cost		**$/kW (Net)**	$122.94	$107.57	$96.32	$93.24
Total BOP Cost		**$/kW (Gross)**	$104.84	$91.73	$82.13	$79.51

			2014 Bus System			
Annual Production Rate		**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)		**kWnet**	160	160	160	160
System Gross Electric Power (Output)		**kWgross**	187.63	187.63	187.63	187.63
Component Costs/System						
	Fuel Cell Stacks (High Value)	**$/system**	$69,264	$52,177	$42,142	$39,393
	Fuel Cell Stacks (Nominal Value)	**$/system**	$56,544	$40,912	$31,702	$29,399
	Fuel Cell Stacks (Low Value)	**$/system**	$51,383	$36,798	$28,226	$26,075
	Balance of Plant (High Value)	**$/system**	$21,224	$18,547	$16,603	$16,075
	Balance of Plant (Nominal Value)	**$/system**	$19,671	$17,211	$15,411	$14,919
	Balance of Plant (Low Value)	**$/system**	$18,133	$15,891	$14,253	$13,805
	System Assembly & Testing	**$/system**	$464	$339	$275	$262
Cost/System (High Value)		**$/system**	$89,549	$69,819	$57,890	$54,639
Cost/System (Nominal Value)		**$/system**	$76,679	$58,461	$47,388	$44,580
Cost/System (Low Value)		**$/system**	$71,314	$54,181	$43,747	$41,107
Total System Cost		**$/kWnet**	$479.25	$365.38	$296.17	$278.62
Cost/kWgross		**$/kWgross**	$408.68	$311.58	$252.56	$237.60

2015 Bus Cost

		2015 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	88.22	88.22	88.22	88.22	88.22	88.22
Stack Components							
Bipolar Plates (Stamped)	**$/stack**	$1,607	$632	$593	$571	$565	$558
MEAs							
Membranes	**$/stack**	$3,213	$994	$615	$410	$374	$206
d-PtNi Catalyst Ink & Application (D	**$/stack**	$2,527	$1,150	$987	$954	$941	$914
GDLs	**$/stack**	$2,509	$750	$422	$252	$224	$96
M & E Hot Pressing	**$/stack**	$43	$17	$17	$10	$10	$9
M & E Cutting & Slitting	**$/stack**	$0	$22	$10	$5	$4	$3
MEA Sub-Gaskets	**$/stack**	$917	$274	$153	$126	$124	$116
Coolant Gaskets (Laser Welding)	**$/stack**	$219	$43	$43	$33	$31	$30
End Gaskets (Screen Printing)	**$/stack**	$1	$1	$1	$1	$1	$0
End Plates	**$/stack**	$100	$81	$71	$65	$64	$56
Current Collectors	**$/stack**	$8	$7	$7	$7	$7	$6
Compression Bands	**$/stack**	$10	$9	$8	$6	$6	$5
Stack Housing	**$/stack**	$64	$12	$8	$7	$7	$6
Stack Assembly	**$/stack**	$80	$61	$42	$36	$35	$34
Stack Conditioning	**$/stack**	$60	$18	$18	$16	$17	$13
Total Stack Cost	**$/stack**	$11,360	$4,071	$2,994	$2,498	$2,409	$2,053
Total Stacks Cost (Net)	**$/kWnet**	$142.00	$50.88	$37.42	$31.23	$30.11	$25.66
Total Stacks Cost (Gross)	**$/kWgross**	$128.77	$46.14	$33.93	$28.32	$27.31	$23.27

		2015 Automotive System					
Annual Production Rate	**Sys/yr**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	88.22	88.22	88.22	88.22	88.22	88.22
BOP Components							
Air Loop	**$/system**	$1,850	$1,438	$1,143	$998	$966	$936
Humidifier & Water Recovery Loop	**$/system**	$1,209	$298	$181	$147	$137	$107
High-Temperature Coolant Loop	**$/system**	$476	$443	$414	$366	$349	$327
Low-Temperature Coolant Loop	**$/system**	$76	$72	$70	$66	$63	$60
Fuel Loop	**$/system**	$346	$306	$291	$261	$251	$238
System Controller	**$/system**	$172	$152	$138	$103	$97	$83
Sensors	**$/system**	$437	$331	$291	$260	$253	$212
Miscellaneous	**$/system**	$263	$165	$136	$123	$119	$115
Total BOP Cost	**$/system**	$4,829	$3,205	$2,663	$2,324	$2,235	$2,076
Total BOP Cost	**$/kW (Net)**	$60.37	$40.06	$33.29	$29.05	$27.93	$25.95
Total BOP Cost	**$/kW (Gross)**	$54.74	$36.33	$30.19	$26.34	$25.33	$23.53

		2015 Automotive System					
Annual Production Rate	**systems/year**	1,000	10,000	30,000	80,000	100,000	500,000
System Net Electric Power (Output)	**kWnet**	80	80	80	80	80	80
System Gross Electric Power (Output)	**kWgross**	88	88	88	88	88	88
Component Cost/System							
Fuel Cell Stacks	**$/system**	**$11,360**	**$4,071**	**$2,994**	**$2,498**	**$2,409**	**$2,053**
Balance of Plant	**$/system**	**$4,829**	**$3,205**	**$2,663**	**$2,324**	**$2,235**	**$2,076**
System Assembly & Testing	**$/system**	**$148**	**$103**	**$101**	**$101**	**$101**	**$101**
Total System Cost	**$/system**	$16,337	$7,379	$5,758	$4,924	$4,745	$4,229
Total System Cost	**$/kWnet**	$204.22	$92.23	$71.98	$61.54	$59.31	$52.86
Cost/kWgross	**$/kWgross**	$185.19	$83.64	$65.27	$55.81	$53.78	$47.94

2016 Bus Cost

		2016 Bus System			
Annual Production Rate	**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)	**kWnet**	160	160	160	160
System Gross Electric Power (Output)	**kWgross**	194.71	194.71	194.71	194.71
Stack Components					
Bipolar Plates (Stamped)	**$/stack**	$1,873	$1,632	$1,422	$1,876
MEAs					
Membranes	**$/stack**	$9,563	$6,475	$4,467	$3,980
Catalyst Ink & Application (dispersed l	**$/stack**	$6,759	$6,167	$5,669	$5,504
GDLs	**$/stack**	$6,641	$5,340	$3,406	$2,952
M & E Hot Pressing	**$/stack**	$121	$100	$97	$81
M & E Cutting & Slitting	**$/stack**	$14	$14	$13	$13
MEA Gaskets (Frame or Sub-Gasket)	**$/stack**	$621	$503	$481	$432
Coolant Gaskets (Laser Welding)	**$/stack**	$482	$383	$423	$340
End Gaskets (Screen Printing)	**$/stack**	$2	$1	$1	$1
End Plates	**$/stack**	$168	$156	$145	$142
Current Collectors	**$/stack**	$13	$13	$12	$12
Compression Bands	**$/stack**	$17	$16	$15	$14
Stack Insulation Housing	**$/stack**	$275	$146	$83	$70
Stack Assembly	**$/stack**	$158	$142	$132	$130
Stack Conditioning	**$/stack**	$290	$151	$146	$120
Total Stack Cost	**$/stack**	$26,995	$21,239	$16,516	$15,669
Total Cost for all 2 Stacks	**$/2 stacks**	$53,989	$42,478	$33,032	$31,338
Total Stacks Cost (Net)	**$/kWnet**	$337.43	$265.49	$206.45	$195.86
Total Stacks Cost (Gross)	**$/kWgross**	$277.28	$218.16	$169.65	$160.95

		2016 Bus System			
Annual Production Rate	**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)	**kWnet**	160	160	160	160
System Gross Electric Power (Output)	**kWgross**	194.71	194.71	194.71	194.71
BOP Components					
Air Loop	**$/system**	$8,863	$7,421	$6,445	$6,193
Humidifier & Water Recovery Loop	**$/system**	$1,278	$1,043	$896	$859
High-Temperature Coolant Loop	**$/system**	$1,935	$1,873	$1,813	$1,794
Low-Temperature Coolant Loop	**$/system**	$222	$216	$209	$207
Fuel Loop	**$/system**	$997	$950	$905	$891
System Controller	**$/system**	$283	$275	$268	$266
Sensors	**$/system**	$1,087	$992	$905	$879
Miscellaneous	**$/system**	$1,118	$909	$792	$766
Total BOP Cost	**$/system**	$15,784	$13,679	$12,234	$11,856
Total BOP Cost	**$/kW (Net)**	$98.65	$85.49	$76.46	$74.10
Total BOP Cost	**$/kW (Gross)**	$81.06	$70.25	$62.83	$60.89

		2016 Bus System			
Annual Production Rate	**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)	**kWnet**	160	160	160	160
System Gross Electric Power (Output)	**kWgross**	194.71	194.71	194.71	194.71
Component Costs/System					
Fuel Cell Stacks (High Value)	**$/system**	$69,339	$55,009	$45,471	$42,810
Fuel Cell Stacks (Nominal Value)	**$/system**	$53,989	$42,478	$33,032	$31,338
Fuel Cell Stacks (Low Value)	**$/system**	$45,405	$35,209	$27,662	$26,296
Balance of Plant (High Value)	**$/system**	$17,267	$14,955	$13,374	$12,961
Balance of Plant (Nominal Value)	**$/system**	$15,784	$13,679	$12,234	$11,856
Balance of Plant (Low Value)	**$/system**	$14,260	$12,370	$11,083	$10,748
System Assembly & Testing	**$/system**	$464	$339	$275	$262
Cost/System	**$/system**	$85,688	$69,105	$58,073	$54,982
Cost/System	**$/system**	$70,237	$56,495	$45,541	$43,456
Cost/System	**$/system**	$61,447	$49,088	$40,029	$38,293
Total System Cost	**$/kWnet**	$438.98	$353.10	$284.63	$271.60
Cost/kWgross	**$/kWgross**	$360.72	$290.15	$233.89	$223.18

10 Appendix C: Automotive Fuel Cell System Changes

2012 Auto Changes (from 2011 Analysis)

Change	Reason	Change from previous value	Cost (500k systems/year, $/kW)
Final Value for 2011			***$47.71***
Piping configuration/costing updated and expanded	Response to industry review	$0.76	$48.47
Purge valve upgraded to multi-function model	Response to industry review	$0.34	$48.81
Hot pressing process removed and replaced with crimping roller process prior to cutting and slitting	Hot pressing incompatible with NSTF catalyst deposition, new method required for combining membrane & GDL layers	-$0.05	$48.76
Ionomer cost curve reduction	Ionomer cost curve changed to reflect industry estimated value at high production	-$0.23	$48.53
Pressure, platinum loading, power density, and temperature updated to 2012 ANL optimization values	New release of ANL optimization curves for performance parameters	$1.83	$50.36
Membrane air humidifier design change	Air humidifier changed to tubular design (effect offset by ionomer cost reduction)	$0.25	$50.61
Gaskets changed from frame gaskets to sub-gaskets with screen-printed seals	New manufacturing process modeled in response to industry discussions	-$2.14	$48.47
GDL Analysis Replaced with values from Ballard Analysis	Response to Tech Team review	-$1.52	$46.95
Final Value for 2012		***-$0.76***	***$46.95***

2013 Auto Changes

Change	Reason	Change from previous value	Cost (500k sy/year, $/kW)
2012 Final Cost Estimate		**NA**	**46.95**
Plate Frame Humidifier	**Switch to a much lower volume plate frame humidifier (as opposed to previous membrane tube humidifier).**	**$0.51**	**$47.46**
Improved Catalyst Deposition Modeling	**Re-examination of NSTF application including wastage and Pt recycling.**	**($0.20)**	**$47.26**
Realigned Compressor and Expander Efficiencies	**Adjusted the air compressor (75% to 71%), exh. gas expander (80% to 73%), and motor (85% to 80%) efficiencies to match the status values modeled by ANL.**	**$1.87**	**$49.13**
Updated Material Costs	**Obtained new stainless steel and other material price quotations.**	**$0.13**	**$49.26**
Updated Quality Control System	**Re-examined quality control systems to ensure full functionality and improve cost realism.**	**$0.00**	**$49.26**
Increased Platinum Cost	**Increase in Pt base cost from $1100/troy once to $1500/troy ounce.**	**$3.19**	**$52.45**
Other Misc. Changes	**Updates made to improve and correct model i.e. LT and HT loop, CEM, and membrane adjustments.**	**($0.86)**	**$51.59**
Updated Polarization Data, Stack Operating Condition Optimization, and Imposition of Radiator Area Constraints	**Improved membrane electrode assembly (MEA) performance data based on expanded 3M NSTF experimental results. Performed stack condition optimization to achieve lowest system cost. Limited radiator Q/DT for volume management within the auto.**	**$3.24**	**$54.83**
Final 2013 Value		**$7.88**	**$54.83**

2014 Auto Changes

Change	Reason	Change from previous value	Cost ($/kW) (@ 500k sys/yr)
2013 Final Cost Estimate		NA	$54.83
Updated Polarization Data, and Stack Operating Condition Optimization	Performed independent stack condition optimization to achieve lowest system cost.	($0.37)	$54.46
Efficiency Calculation	Improved efficiency calculation to be based on the LHV of H2.	$0.27	$54.73
Other Misc. Changes	Updates made to improve material costs (including cost per kg of manganese gold, & polypropylene, and ePTFE qty needed annually, improvements to radiator system).	$0.11	$54.84
2014 Value (Preliminary)		$0.01	$54.84

2015 Auto Changes

Change	Reason	Change from previous value ($/kW)	Cost ($/kW) (@ 500k sys/yr)
2014 Final Cost Estimate		NA	$54.84
Polarization and Catalyst System	Reduction in power density from 834 to 746mW/cm^2 in switching from ternary PtCoMn NSTF catalyst to JM dealloyed PtNi dispersed catalyst on cathode, reduction of O_2 stoich from 2 to 1.5, and lower Pt loading (0.153 to 0.142mgPt/cm^2).	($1.04)	$53.80
Parasitic Load	Re-evaluated air pressure drop within system components. Reduced coolant pump and cooling fan power to align with ANL's modeling assumptions.	($0.92)	$52.88
Geometry Changes	Modification to catalyzed area of membrane and reduced the active to total area ratio from 0.8 to 0.625, and reduction of total catalyzed area to align with the thickness the subgasket is covering.	$0.87	$53.75
Subgaskets	Updated assumptions for subgasket equipment configuration.	($0.46)	$53.29
H2 Sensors	Updated price quote for H2 sensors.	($0.23)	$53.06
Minor Changes	Changed humidifier membrane area calaculation from scaling to using inlet and outlet air flow conditions. Updated stack conditioning assumptions.	($0.21)	$52.84
2015 Value		($1.99)	$52.84

2016 Auto Changes

Change	Reason	Change from previous value ($/kW)	Cost ($/kW) (@ 500k sys/yr)
2015 Final Cost Estimate		NA	$52.84
Polarization and Catalyst System	Increase of power density from 746 to 749mW/cm^2, reduction of air stoich from 1.5 to 1.4, reduction of catalyst loading from 0.142 to 0.134mg/cm^2, and reduction in membrane humidfier membrane area from 1.2 to 0.7m^2.	($0.93)	$51.91
BPP	Bipolar Plate stamping assumption changes (press force increase from 1,000 to 1,800 tons, capital from $530k to $2M, tooling cost increase from $100k to $600k and increase in tool lifetime of 600k to 10M cycles).	$1.72	$53.63
BPP Coating	Updated Treadstone Coating to Generation 2 materials and process.	($0.81)	$52.82
H2 Sensor	Updated H2 Sensor cost based on FiS model FH2-HY04, used in Toyota Mirai	($1.02)	$51.80
Dispersed Catalyst Synthesis	Numerous updates to dispersed catalyst synthesis based on feedback from catalyst material supplier. (11 changes including limited batch sizes, longer thermal cycle times, increase markups, etc.)	$0.83	$52.63
GDL	Conducted DFMA™ analysis based on Avcarb process and included a 25% markup for profit.	$0.38	$53.01
Coolant Gasket Laser Welding	Added extra laser welding length over the active area of the BPPs, reduced laser welding speed, and increased the number of simultaneous weld heads per station.	$0.05	$53.06
Minor Changes	Re-evaluated air compressor assembly cost to account for automation.	($0.24)	$52.82
2016 Value		($0.02)	$52.82

11 Appendix D: Bus Fuel Cell System Changes

2013 Bus Changes (2012 was the first year of the bus analysis)

Change	Reason	Change from previous value ($/kW)	Cost ($/kW) (@ 1k sys/yr)
2012 Final Cost Estimate		NA	$190.69
Updated polarization and operating conditions	Reduction in power density: from 716 to 601mW/cm^2; Increase in air stoich from 1.5 to 2.1; cell voltage 0.676V; 74°C coolant exit temp; and total Pt loading of 0.4mg/cm^2	$14.02	$204.71
Air Compressor	Switch from Honeywell centrifugal compressor to Eaton-style multi-lobe roots compressor	$14.13	$218.84
Re-evaluation of Low Volume	Incorporated job-shop logic into model in addition to bus system integrator markup	$45.75	$264.58
Adjustment of Pt Price	Changed Pt price from $1,100/tr.oz to $1,500/tr.oz	$8.22	$272.80
Other Changes	Switched from tubular membrane humidifier to plate frame Gore/Dpoint membrane humidifier and small changes to QC and subgaskets	($2.85)	$269.95
2013 Value		$79.26	$269.95

2014 Bus Changes

Change	Reason	Change from previous value	Cost ($/kW$_{e_net}$) (@ 1,000 sys/yr)
2013 Final Cost Estimate		NA	$269.95
Updated Material Costs	Updates made to improve material costs (including cost per kg of manganese gold, & polypropylene, and ePTFE quantity needed annually, improvements to radiator system).	$1.10	$271.05
Efficiency Calculation	Improved efficiency calculation to be based on the LHV of H_2.	$1.15	$272.20
Compressor Changes	Updated Eaton-style compressor rotor machining and changed rotor housing process from sand casting to permanent mold.	$1.49	$278.37
Compressor-Motor Efficiency Changes	Updated compressor efficiency from 71 to 58% and the motor/motor controller combined efficiency from 80 to 95%.	$4.68	$278.37
Other Misc. Changes	Addition of clean room costs for the membrane humidifier processing station, improvement in power requirements for membrane humidifier etched plates process, minor correction to maintain the same number of cells in a stack, etc.	$0.25	$278.62
2014 Value		$8.67	$278.62

2015 Bus Changes

Change	Reason	Change from previous value	Cost ($/kW) (@ 1,000 sys/yr)
2014 Final Cost Estimate		NA	$278.62
Operating Conditions	Voltage: 0.676 to 0.659V Power Density: 601 to 739mW/cm2 Pressure: 1.8 to 1.9atm, Temp: 74 to 72.2C Catalyst Loading: 0.4 to 0.5mg/cm2 (0.1 anode and 0.4 cathode) O2 stoic: 2.1 to 1.8 Air Humidifier Membrane Area: 5 to 3.9m2	($4.83)	$273.80
Catalyst and Application to Membrane	Switched from PtCoMn NSTF to dispersed Pt on carbon using slot die coating. Includes addition of XRF to quality control equipment.	$1.07	$274.87
Parasitic Loads	Re-evaluated parasitic loads.	$5.02	$279.89
Quality Control Systems	Membrane QC from XRF to ODS MEA Cutting and Slitting QC from XRF to ODS Membrane Humidifier Membrane Fabrication QC change with increased anomaly detection size to 100 microns.	($4.83)	$275.06
H2 Sensors	Updated H2 sensor costs with NTM Sensor quotation.	($15.84)	$259.22
Geometry	Changed active to total area ratio from 0.8 to 0.625.	$8.00	$267.22
Miscellaneous	Updated stack conditioning time based on GM patent from 5hrs to 2hrs. Includes change in load bank and testing equipment capital cost. Switch from subgasket with roll-to-roll process to robotic stacking process.	($5.25)	$261.97
2015 Value		($16.66)	$261.97

2016 Bus Changes

Change	Reason	Change from previous value ($/kW)	Cost ($/kW) (@ 1k sys/yr)
2015 Final Cost Estimate		NA	$261.97
BPP	Bipolar Plate stamping assumption changes (press force increase from 1,000 to 1,800 tons, capital from $530k to $2M, tooling cost increase from $100k to $600k and increase in tool lifetime of 600k to 10M cycles).	$11.52	$273.49
BPP Coating	Updated Treadstone Coating to Generation 2 materials and process	($1.49)	$272.00
GDL	Changed to DFMA analysis of GDL and added 25% markup for profit	($1.63)	$270.38
Coolant Gasket Laser Welding	Added extra laser welding length over the active area of the BPPs, reduced laser welding speed, and increased the number of simultaneous weld heads per station.	$1.84	$272.22
Dispersed Catalyst Synthesis	Numerous updates to dispersed catalyst synthesis and catalyst material markup based on feedback from catalyst material supplier.	$2.90	$275.11
Minor Changes	Updated membrane thickness from 25 microns to 20 microns and minor changes to QC on slot die coating.	($3.51)	$271.60
2016 Value		$9.63	$271.60

12 Appendix E: Contract Publications and Presentations

(Listing does not include quarterly technical status reports)

1. "Fuel Cell Transportation Cost Analysis, Preliminary Results," Brian D. James, Annual Merit Review 2012, 15 May 2012.
2. "Fuel Cell Transportation Cost Analysis, Preliminary Results", Brian D. James, Strategic Analysis Inc., 18 July 2012, presented to the Fuel Cell Tech Team.
3. "Fuel Cell Transportation Cost Analysis, Preliminary Results", Brian D. James, Strategic Analysis Inc., 15 August 2012, presented to the Fuel Cell Tech Team.
4. "Mass-Production Cost Estimation for Automotive Fuel Cell Systems", Brian D. James, Kevin Baum, Andrew B. Spisak, Whitney G. Colella, DOE 2012 Annual Report.
5. "Summary of Fuel Cell Transportation Analysis Results at the Year 1 Go/No-Go Decision Point", Brian D. James, Strategic Analysis Inc., 29 November 2012, presented at DOE Headquarters.
6. "Fuel Cell Transportation Cost Analysis", Brian D. James (Primary Contact), Andrew B. Spisak, 7 November 2012, 2012 Fuel Cell Seminar at the Mohegan Sun in Connecticut.
7. "Hydrogen-fueled proton exchange membrane (PEM) fuel cell vehicles (FCVs) -- Conceptual and Physical Design and Capital Cost Estimates," James, B. D., Spisak, A. B., Colella, W. G. (presenter), ASME 2012 International Mechanical Engineering Congress & Exposition, Houston, Texas, Nov. 9th-15th, 2012, IMECE2012-88990.
8. "Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update", Brian D. James, Andrew B. Spisak, 2013.
9. "Simplified Automotive Fuel Cell system Cost Model", Brian D. James, Jennie M. Moton, submitted to ANL, May 24, 2013.
10. "Report on Automotive Fuel Cell System Cost at 10k and 200k Systems per year", Brian D. James, Jennie M. Moton, submitted to NREL, June 13, 2013.
11. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Presented at U.S. Department of Energy's 2013 Annual Merit Review and Peer Evaluation Meeting for the Hydrogen and Fuel Cell Technologies Program in Arlington, Virginia, May 17, 2013.
12. James, B. D., Moton, J.M., Colella, W. G., "Fuel Cell Vehicle Design for Manufacturing and Assembly (DFMA) Analysis," *ASME 2013 11th Fuel Cell Science, Engineering and Technology Conference*, Minneapolis, MN, July 14-19th, 2013, ESFuelCell2013-18420.
13. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis Update," Presented to Fuel Cell Tech Team (FCTT), July 17, 2013.
14. James, B.D., Moton, J.M., Colella, W.G., "2013 Auto Fuel Cell System Cost Update to FCTT (changes since July presentation)," Presented to Fuel Cell Tech Team (FCTT) at USCAR in Southfield, Michigan, September 18, 2013.
15. James, B.D., Moton, J.M., "2013 Auto Fuel Cell System Cost Summary," Presented to DOE at DOE headquarters, September 19, 2013.
16. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Annual Progress Report (APR), submitted to DOE, September, 2013.
17. James, B.D., Moton, J.M., Colella, W.G., "Design, Manufacture, and Cost Analysis of Fuel Cell Vehicles," *Proceedings of the European Fuel Cell Technology & Applications Conference – Piero Lunghi Conference (EFC2013)*, Rome, Italy, Dec. 11^{th}-13^{th}, 2013 (EFC13-183).

18. Colella, W.G., James, B.D., Spisak, A.B., Moton, J.M., "Next Generation Electrochemical Systems," *American Institute of Chemical Engineers (AIChE) Annual Meeting*, San Francisco, CA, Nov. 3th-8th, 2013.
19. James, B.D., Moton, J.M., Colella, W.G., "Technical Developments & Manufacturing Cost Assessment of Automotive Fuel Cell Systems," *2013 Fuel Cell Seminar*, STA44-2 High Temperature Fuel Cells, Paper Number 270, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.
20. James, B.D., Moton, J.M., Colella, W.G., "Design, Manufacture, and Cost Analysis of Fuel Cell Vehicles," *Fifth European Fuel Cell Technology & Applications Conference – Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-183).
21. Colella, W.G., "Resolving Bottlenecks in Transportation Supply Chains with Next Generation Fuel Cell and Hydrogen Energy Systems," *2013 Fuel Cell Seminar*, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.
22. James, B.D., Spisak, A.B., Colella, W.G, "Design for Manufacturing and Assembly Cost Estimation Methodology for Transportation Fuel Cell Systems," *J. Manuf. Sci. Eng 136(2), 024503 (Feb 19, 2014) doi:10.1115/1.4025624.*
23. James, B.D., Moton, J.M., Colella, W.G., "Design for Manufacturing and Assembly Analysis of Zero Emission Vehicular Power Plants," *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference (ESFuelCell2014)*, Boston, Massachusetts, June 30th – July 2nd, 2014 (ESFuelCell2014-6656).
24. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Presented at U.S. Department of Energy's 2014 Annual Merit Review and Peer Evaluation Meeting for the Hydrogen and Fuel Cell Technologies Program in Washington, D.C., June 16th - 20th, 2014.
25. James, B.D., Moton, J.M., Colella, W.G., "Cost Analysis of Fuel Cell and H_2 Storage System for Transportation," Presentation for the International Energy Agency (IEA) Advanced Fuel Cells Annex 26 at the U.S. Department of Energy's DOE's 2014 FCT AMR in Washington, D.C., June 17th, 2014.
26. James, B.D., Moton, J.M., Colella, W.G., "Definition and Cost Evaluation of Fuel Cell Bus and Passenger Vehicle Power Plants," *Presentation at the ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference (ESFuelCell2014)*, Boston, Massachusetts, June 30th – July 2nd, 2014
27. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Presentation for Fuel Cell Technology Team, USCAR office in Southfield MI, Virginia, July 16th, 2014.
28. James, B.D., Moton, J.M., "Status Update: 2014 Polarization Examination," Presentation to DOE, via webinar, August 7th, 2014.
29. James, B.D., Moton, J.M., "Review of Proposed 2014 Final Values: Automotive Fuel Cell System Cost," Presentation for DOE Fuel Cell Technologies Program Team, presented at DOE Headquarters, Washington, D.C., September 4th, 2014.
30. James, B.D., Moton, J.M., "Review of Proposed 2014 Final Values: Automotive Fuel Cell System Cost," Presentation for Fuel Cell Technology Team, presented remotely from SA Office in Arlington, Virginia, September 10th, 2014.
31. James, B.D., Moton, J.M., Colella, W.G., "Fuel Cell Transportation Cost Analysis," Annual Progress Report (APR), submitted to DOE, August 8th, 2014.

32. Moton, J.M., James, B.D., Colella, W.G., "Engineering and Economic Advances in Proton Exchange Membrane (PEM) Fuel Cell Vehicle (FCV) Design," Presentation at Fuel Cell Seminar, Los Angeles, CA, Nov 13th, 2014.
33. James, B.D., "2015 DOE Hydrogen Fuel Cell Program Review: Fuel Cell Vehicle and Bus Cost Analysis," Presentation given at the 2015 DOE Annual Merit Review Meeting, Arlington, VA, June 10th, 2015.
34. James, B.D., Houchins, C., Moton, J.M., "2015 Polarization Update Meeting," Presentation given to DOE FCTO, presented remotely from SA Headquarters in Arlington, VA, June 30th, 2015.
35. James, B.D., Houchins, C., Moton, J.M., "Transportation Fuel Cells Cost Analysis Update: Automotive Cost Analysis," Presentation given to Fuel Cell Technical Team, presented at US CAR in Southfield, MI, July 15th, 2015.
36. James, B.D., Moton, J.M., DeSantis, D.A., Houchins, C., "Fuel Cell Vehicle and Bus Cost Analysis", Annual Progress Report (APR) submitted to DOE July, 2015.
37. Moton, J.M., James, B.D., Houchins, C., DeSantis, D.A., " Re-evaluation of Cost and Identification of Risk for Low Volume Manufacturing Techniques Applied to Automotive Fuel Cell Systems," Presentation given at the 2015 Fuel Cell Seminar, Los Angeles, CA, November 17th, 2015.
38. Houchins, C., Moton, J.M., DeSantis, D.A., James, B.D., "Assessment of Polymer Electrolyte Fuel Cell Catalyst Cost, Performance and Manufacturability," Presentation given at the 2015 Fuel Cell Seminar, Los Angeles, CA, November 17th, 2015.
39. James, B.D., Houchins, C., Huya-Kouadio, J.M., "Transportation Fuel Cells Cost Analysis Update Automotive Cost Analysis", Presented to the Fuel Cell Technical Team, Southfield, MI, May 18th, 2016.
40. James, B.D., Huya-Kouadio, J.M., Houchins, C., DeSantis, D.A., "2016 DOE Hydrogen and Fuel Cells Program Review: Fuel Cell Vehicle and Bus Cost Analysis", Presented at the 2016 DOE FCTO Annual Merit Review Meeting, Washington, DC, June 9th, 2016.
41. James, B.D., Huya-Kouadio, J.M, Houchins, C., DeSantis, D.A., "Fuel Cell Vehicle and Bus Cost Analysis", Annual Progress Report (APR) submitted to DOE July, 2016.