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Manufacturing process assumptions used in fuel cell system cost analyses

Jason Marcinkoski[a,*], Brian D. James[b], Jeff A. Kalinoski[b], Walt Podolski[c], Thomas Benjamin[c], John Kopasz[c]

[a] *United States Department of Energy, Washington, DC, USA*
[b] *Directed Technologies Inc., Arlington, VA, USA*
[c] *Argonne National Laboratory, Argonne, IL, USA*

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ABSTRACT

This paper is a summary of the manufacturing processes used in recent automotive fuel cell system cost analyses funded by the U.S. Department of Energy (DOE). Through these analyses, DOE examines the projected cost of an 80-kW polymer-electrolyte fuel cell system manufactured at a rate of 500,000 systems per year. Directed Technologies Inc. (DTI) and TIAX LLC (TIAX) have been contracted independently to perform such analysis since 2006, and both have prior experience. This paper addresses the most recent fuel cell configurations envisioned by DTI and TIAX. DTI has recently presented their 2010 analysis results and TIAX has recently presented their 2009 results with preliminary 2010 results. Since these presentations do not document in full, the underlying details and assumptions, DTI and TIAX's most recent comprehensive written reports are used for the present discussion. DTI's most recent report detailed 2009 technology, and TIAX's most recent report detailed 2008 technology. The summary of manufacturing process assumptions is meant to impart a sense of the rigor of the cost analyses funded by the DOE, and to provide the reader with an overview of the manufacturing processes used for fuel cells.

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1. Introduction

Fuel cell systems will have to be cost-competitive with other 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 U.S. Department of Energy (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 how R&D resources can be most effectively allocated for cost reduction, to track annually the 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).

Because the DOE uses these analyses to track technological progress in terms of cost, non-technical variables are held constant to elucidate the effects of the technical variables. For example, the cost of platinum is held at US$ 1100 per troy ounce (US$ 35.37 per g) to insulate the study from unpredictable and erratic platinum price fluctuations. Sensitivity analyses are conducted to explore the effects of these non-technical parameters. To maximize the benefit of our work to the fuel cell community, we strive to disseminate the details of the assumptions and methodology, which also serves to strengthen the validity of the analysis by enabling opportunities for feedback from the fuel cell R&D community.

The system design and material and component fabrication models used in these analyses are updated annually to reflect estimates of the status of developing fuel cell technology, and in general, are based on non-proprietary public presentations by fuel cell companies and other researchers, along with extensive review of the patent literature. Consequently, the presented information may lag what is being done "behind the curtain" in fuel cell companies. Nonetheless, identification and analysis of largely open-source current-technology systems provides a benchmark against which the impact of future technologies may be compared. For practical reasons, the technology used in the analyses will continue to be validated through feedback from industry and the fuel cell system R&D community. As the hypothesized systems begin to converge on a more stable form, emphasis of the analysis will shift from validating the technology to validating the roots of the cost analysis assumptions—the material costs, labor assumptions, and capital cost of the manufacturing equipment used to fabricate the system.

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* Corresponding author at: EE-2H, Fuel Cell Technologies, Rm. 5G082, 1000 Independence Ave., Washington, DC 20585, USA. Tel.: +1 202 586 7466.
E-mail addresses: jmarcinkos@gmail.com, jason.marcinkoski@hq.doe.gov (J. Marcinkoski).

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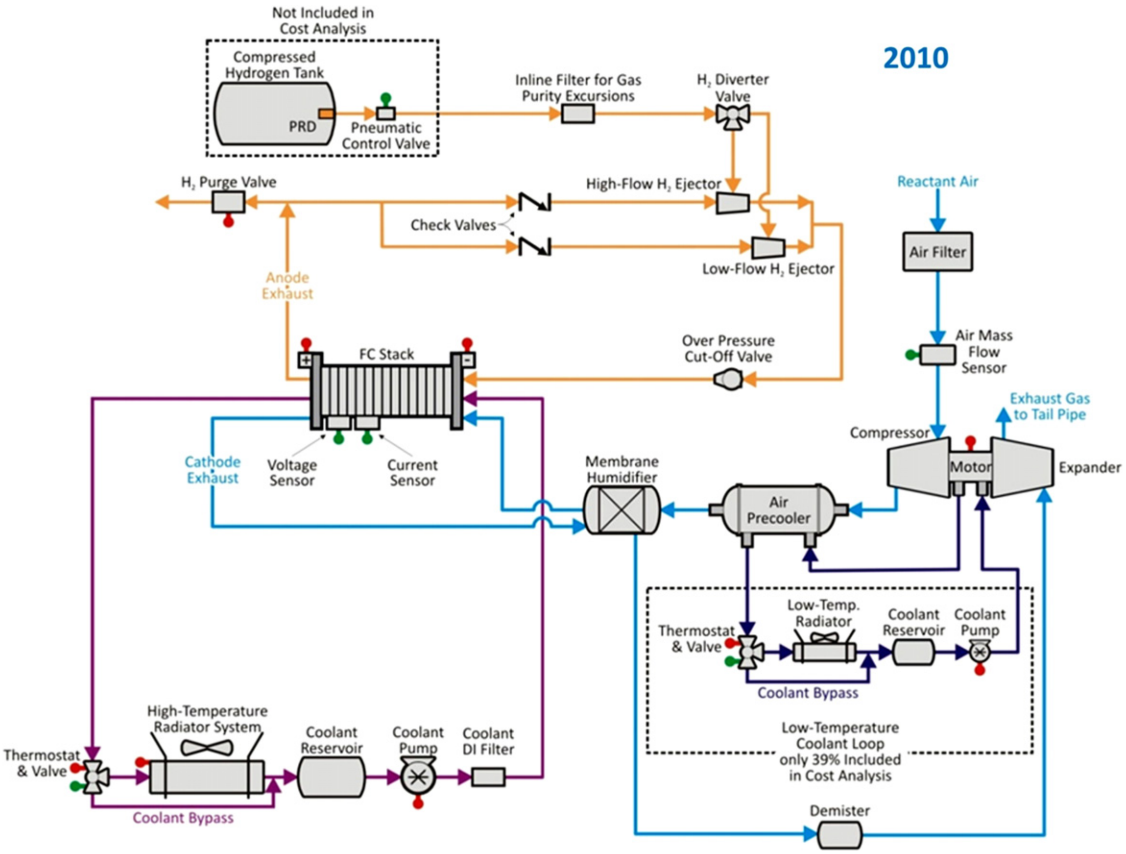

Fig. 1. DTI 2010 fuel cell system schematic.

Each annual assessment covers the material and manufacturing cost of complete 80-kW$_{net}$ direct hydrogen polymer electrolyte membrane (PEM) fuel cell systems suitable for powering light-duty vehicles. The analyses include all fuel cell system components required to convert hydrogen and air into electricity and water, including mounting hardware and cooling system. The vehicle traction motor, motor inverter/controller, and hydrogen storage system are not included in these cost analyses. Figs. 1 and 2 show the fuel cell systems schematically.

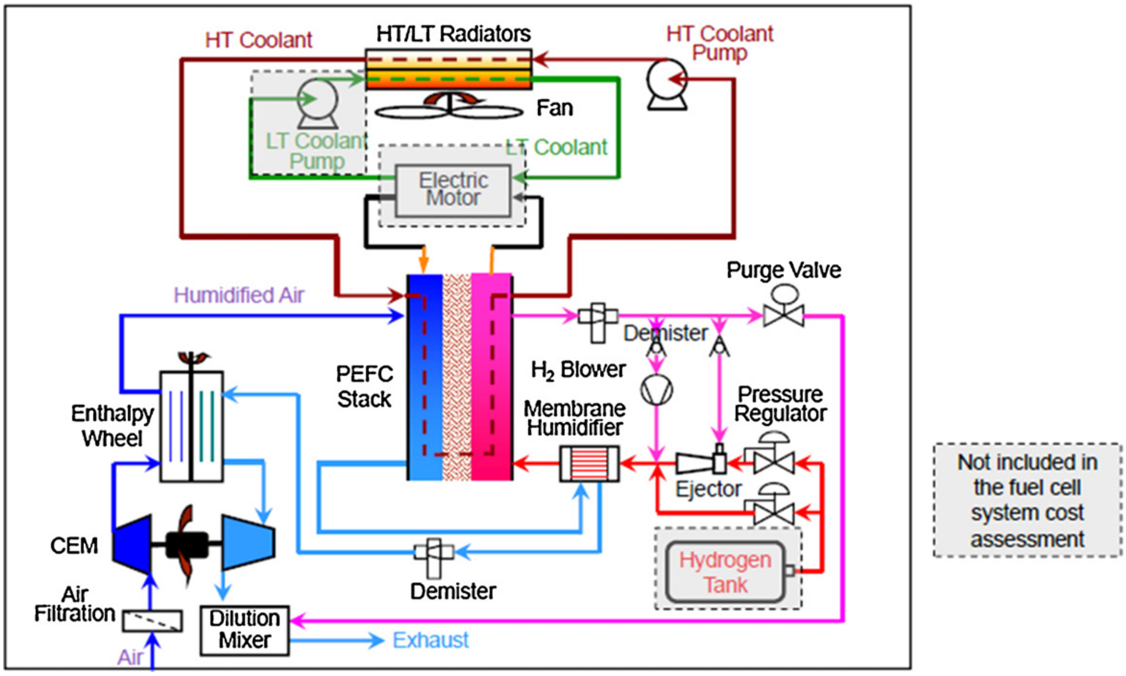

Fig. 2. TIAX 2008 fuel cell system schematic.

This paper is a summary of manufacturing processes and assumptions used by Directed Technologies Inc. (DTI) [1] and TIAX LLC (TIAX) [2] in two recent presentations and their most recent written reports. DTI and TIAX both presented their latest work at the DOE Fuel Cell Technologies Program Annual Merit Review and Peer Evaluation (AMR) meeting held in Washington DC in June 2010. DTI's AMR presentation [1] covers 2010 technology, and TIAX's AMR presentation [2] covers 2009 technology and also includes a preliminary assessment of 2010 technology. Because TIAX's 2010 technology assessment is preliminary, it will not be discussed. The presentations from DTI [1] and TIAX [2] contain the latest system designs and cost projections from each company, but do not document all of the important underlying details and assumptions. Consequently, written reports from DTI and TIAX are the focus for the present discussion. DTI's most recent comprehensive written report [3] is an assessment of 2010 technology (DTI's projections for 2015 technology will not be discussed within this paper), and TIAX's most recent comprehensive report [4] is an assessment of 2008 technology. The presentation from DTI [1] corresponds to their most recent comprehensive report [3] assessing 2010 technology, and the presentation from TIAX [7] corresponds to their most recent comprehensive report [4] assessing 2008 technology.

2. Cost analysis methodology and general assumptions

The primary costing methodology employed for the cost analyses is the Design for Manufacture and Assembly (DFMA®) technique pioneered by Boothroyd and Dewhurst. The DFMA® process is a systematic means for the design and evaluation of cost-optimized components and systems. These techniques are powerful and yet flexible enough to incorporate accumulated historical cost data and manufacturing acumen.

The cost for any component analyzed via DFMA® techniques includes direct material costs, manufacturing costs, assembly costs, and markup. Direct material costs are determined from the exact type and mass of material employed in the component. This cost is usually based upon either historical volume prices for the material or vendor price quotations. In the case of materials not widely used at present, the manufacturing process must be analyzed to determine the probable high-volume price for the material. The manufacturing cost is based upon the required features of the part and the time it takes to generate those features in a typical machine of the appropriate type. The cycle time can be combined with the "machine rate," the hourly cost of the machine based upon amortization of capital and operating costs, and the number of parts made per cycle to yield an accurate manufacturing cost per part. Assembly costs are based upon the amount of time required to complete the given operation and the cost of either manual labor or of the automatic assembly process train. The piece cost derived in this fashion is quite accurate as it is based upon an exact physical manifestation of the part and the technically feasible means of producing it as well as the historically proven cost of operating the appropriate equipment and amortizing its capital cost.

A percentage markup is applied to the material, manufacturing, and assembly cost to account for profit, general and administrative (G&A) costs, research and development (R&D) costs and scrap costs. This percentage typically varies with production rate to reflect the efficiencies of mass production. It also changes based on the business type and on the amount of value that the manufacturer or assembler adds to the product. For purposes of cost summation, it was necessary to establish a notional business structure so that markup could be applied appropriately. DOE's fuel cell systems cost analyses assume a business scenario of considerable vertical integration where the stack manufacturer is also the final system integrator. Consequently, most stack components are produced and assembled in-house, most balance-of-plant (BOP) components are manufactured by lower-tier vendors, and final system assembly is also conducted in-house. In accordance with past DOE assumptions, a markup rate to the fuel cell manufacturer/system-assembler is not currently included in the cost estimates. Thus there is no markup on the vast majority of fuel cell stack components whereas there is a manufacturing markup applied to most of the (purchased) BOP components, resulting in cost estimates more closely representing the fuel cell company's direct cost rather than the sales price to the public. Costs for warranties, non-recurring engineering, and sales taxes are not included in either of the cost estimates. Additionally, while the cost of the buildings in which manufacturing and assembly occur are not included in the DTI analysis, they are included in the TIAX analysis.

Since fuel cell system production requires some manufacturing processes not normally found in automotive production, the formal DFMA® process and the manufacturing knowledge of DTI and TIAX are buttressed with budgetary and price quotations from experts and vendors in other fields. In general, all stack components were analyzed using the DFMA® costing procedures which estimate cost based on the specific component dimensional design, materials, manufacturing method, and assembly method. The DFMA® costing methodology was also applied to major BOP components such as the air compressor and humidifier, whereas the costs of smaller components were estimated using quotations or other costing techniques. Through the combination of historical knowledge and technical understanding of fuel cell system functionality, multiple component designs and manufacturing processes were evaluated to lead to an accurate cost assessment of the fuel cell system.

To assess the cost benefits of mass manufacturing, DTI examined five annual production rates: 1000; 30,000; 80,000; 130,000; and 500,000 systems per year. However, emphasis in this paper is placed on the highest manufacturing rate, typical for auto manufacturers. The reader is directed to Ref. [3] for full cost details at other annual manufacturing rates.

3. System definition

DTI and TIAX were required to cost 80-kW$_{net}$ systems, but were given freedom to define fuel cell system configuration and component specifications. DTI's design, shown in Fig. 1, does not reflect the design of any one manufacturer but rather is a composite of elements from a number of designs. TIAX relies mostly on a fuel cell model developed at Argonne National Laboratory (ANL) [5], shown in Fig. 2. Based on the power requirements, the design specifications were developed to facilitate the appropriate sizing of the system components. The basic design specifications are shown in Table 1 below. The status of power density and platinum loading are typically provided to DTI, TIAX and ANL each year after consensus is reached by the FreedomCAR and Fuel Partnership Fuel Cell Tech Team, a team of DOE, the U.S. Council for Automotive Research LLC, and 5 energy companies. The technology does not necessarily meet all design criteria, but reflects the state of the art for a given year. For instance, stack durability and operation in freezing environments are issues that are addressed independent of fuel cell cost assessment. DTI and TIAX were also required to incorporate state-of-the-art component technology into the fuel cell system designs they used for developing the manufacturing processes and costs. The latest cost assessments included component technologies as shown in Table 2.

3.1. Polymer electrolyte membrane

DTI bases fabrication of the polymer electrolyte membranes on the process described in a W.L. Gore & Associates Inc. (Gore) patent

Table 1
Fuel cell system specifications.

	Units	DTI 2010 Technology	TIAX 2008 Technology	TIAX 2009 Technology
Rated system power	kW_{net}	80	80	80
System voltage @ rated power	V	250	300	300
System efficiency @ rated power	%	50	50	47.3
Stack power	kW_{gross}	87.9	86.9	91.8 (scenario 5)
Stack efficiency @ rated power	%	55	54	54.6
Cell voltage @ rated power	V/cell	0.676	0.685	0.693
Active cells per stack		369	219 (2 stacks)	217 (2 stacks)
Total Pt loading	$\text{mg}_{\text{Pt}}\,\text{cm}^{-2}$	0.15	0.25	0.15 (scenario 5)
MEA areal power density @ rated power	$\text{mW}\,\text{cm}^{-2}$	833	716	700
Active area per cell (cm^2)	cm^2	286	277	304
Current density @ rated power	$\text{mA}\,\text{cm}^{-2}$	1233	1045	1010
Stack pressure @ rated power	atm abs.	1.69	2.5	2.5
H_2 flow rate	$\text{kg}\,\text{h}^{-1}$	4.8	4.8	5.1
Air flow rate	$\text{kg}\,\text{h}^{-1}$	411	329	348
H_2 Stoichiometric ratio		1.5	1.4	1.4
Oxygen stoichiometric ratio		2.5	2.0	2.0
Peak stack temperature	°C	90	90	90
Ambient temperature	°C	40	27	27
Ambient relative humidity	%	67	50	50

(US Patent 5,547,551) in which Nafion® ionomer coats and fills the pores of a highly porous expanded polytetrafluorethylene (ePTFE) substrate. Based on the patent literature and discussion with Gore and other industry experts, an 8-step roll-to-roll fabrication process is postulated: (1) unwinding of a $25\,\mu\text{m}$ thick ePTFE substrate, (2) dipping of the ePTFE in a first Nafion® ionomer bath, (3) drying of the substrate in a first infra-red (IR) oven, (4) dipping of the substrate in a second Nafion® ionomer bath, (5) drying of the substrate in a second IR oven, (6) submersion of the now-occluded ePTFE film in a boiling water hydration bath for 5 min, (7) air drying, and (8) rewind onto a spool for transport to the catalyst application process line. Material cost of the Nafion® ionomer was not estimated from the ground-up but rather is based on discussion with industry experts, quotations on products similar to Nafion®, and lower volume quotations on Nafion®. DTI uses an ePTFE price of $5.62\ \text{US\$}\ \text{m}^{-2}$ based on a dated high-volume, industry quotation. The estimated Nafion® ionomer price ranges from $\sim 2000\ \text{US\$}\ \text{kg}^{-1}$ at 1000 vehicles per year to $\sim 112\ \text{US\$}\ \text{kg}^{-1}$ at 500,000 vehicles per year. The capital cost of the processing equipment was based originally on scaled component quotations from U.S. Webcon for similar web handling equipment but was then substantially increased after feedback from industry membrane experts. Web yields at various manufacturing rates are based on input from Gore. Also based on feedback from Gore, substantial plant under-utilization is built into the cost estimates to reflect the expected substantial year-to-year growth rates. The manufacturing process was last analyzed in detail in 2008 and would benefit from a re-examination to update procedures and processes.

For their 2009 and 2010 cost studies, TIAX assumed a $20\,\mu\text{m}$ unsupported 3M perfluorosulfonic acid (PFSA) membrane and a $20\,\mu\text{m}$ ePTFE-reinforced membrane, respectively; a decrease in thickness from the 2008 study which assumed a 30-μm thick 825 equiv.-wt 3M PFSA membrane. In addition, they have preliminarily increased the ionomer cost from their 2009 estimate of $80\ \text{US\$}\ \text{lb}^{-1}$ ($176\ \text{US\$}\ \text{kg}^{-1}$) (the cost referenced in their 2005 report [6]) by 20%, due to higher cost risk for shorter side chain PFSA. This is still to be verified by industry feedback in 2010, as is the ePTFE cost assumption of $5\ \text{US\$}\ \text{m}^{-2}$. The preliminary 2010 cost estimate for the membrane is $18.73\ \text{US\$}\ \text{m}^{-2}$ ($318.42\ \text{US\$}\ \text{kg}^{-1}$), with materials representing ~85% of the cost.

For membrane manufacturing, details from the 2008 study indicate TIAX assumed a high-volume low-cost process for the manufacture of “second generation” dispersion-cast PFSA membranes developed by DuPont™ in 2003. In this process, dispersion

Table 2
Component and material technologies.

	DTI 2010 technology	TIAX 2008 technology system (as documented in the 2008 technology report draft)	TIAX 2009 technology updates (as presented at the 2010 AMR)
Membrane material	$25\,\mu\text{m}$ Nafion® on ePTFE	$30\,\mu\text{m}$ 3M PFSA	$20\,\mu\text{m}$ PFSA
Catalyst application	Nanostructured thin film (NSTF)	Nanostructured thin film (NSTF)	Nanostructured thin film (NSTF)
Gas diffusion layers	Carbon paper macroporous layer with microporous layer	Woven carbon cloth coated with DuPont™ T-30 PTFE and Cabot carbon black powder	Woven carbon fiber
MEA containment	Insert molded frame/seal	Injection molded frame/seal + gasket formed in bipolar plate	Injection molded frame/seal
Bipolar plates	Stamped SS 316L with TreadStone coating	Embossed expanded graphite resin	Embossed expanded graphite resin
End plates	Composite molded end plates	Aluminum end plates and current collectors with PFSA insulator sheet	Not addressed in 2009 update presentation.
Compression system	Metal compression bands	Tie bolts	
Stack conditioning	5 h	Not included	Not addressed in 2009 update presentation
Air compression	Centrifugal compressor, with radial inflow expander	Centrifugal compressor, with radial inflow expander	Centrifugal compressor, with radial inflow expander
Fuel recirculation	Two ejectors	Two ejectors and blower	Two ejectors and blower
Air humidification	Tubular membrane humidifier	Enthalpy wheel	Planar membrane humidifier
H_2 humidification	None	Tubular Nafion® membrane humidifier	Planar membrane humidifier
H_2 sensors	2	1	Not addressed in 2009 update presentation
Cooling system	High temperature cooling loop and 39% of low-temperature cooling loop attributed to fuel cell system.	Aluminum automotive radiator, 25 fins per inch, $75\,\mu\text{m}$ thickness, 2.8 cm depth	HT and LT automotive tube-fin radiators

cast films are formed directly from solutions of PFSA in water and alcohol by a coating process onto an inert polytetrafluorethylene (PTFE) backing film. In 2008 TIAX assumed a 40% solids content PFSA dispersion, consistent with the Nafion® dispersion used in their 2005 study [6]. They assumed a two-step drying process similar to that specified in the Liquion™ product bulletin (30 min at 50 °C followed by 15 min at 100–120 °C), followed by 5 min of cooling at 20 °C. The process equipment definition was based on conversations with original equipment manufacturers and the cycle time was based on a line speed of 20 ft per minute (6 m per minute), based on industry feedback.

3.2. Catalyst ink and application

DTI and TIAX both assume a nano-structured thin film (NSTF) catalyst based on open literature descriptions of a 3M process.

DTI's NSTF catalyst application consists of a four-step roll-to-roll method. The steps are sublimation of PR-149 (Perylene Red pigment 149) onto DuPont™ Kapton® polyimide web, vacuum annealing of the PR-149 for 10 min at 270 °C to grow crystalline, high surface area whiskers, vapor deposition of elemental platinum, cobalt, and manganese onto the crystalline nanostructures, and the transfer of the catalyst nanostructure from the Kapton® substrate to the fuel cell membrane via a hot rolling operation. DTI-specified capital equipment necessary for the operation consists of: evacuation chambers, sublimation unit, magnetron sputter unit, annealing ovens, and a re-pressurization chamber. The line rate is 5.84 m per minute. Previous analysis modeled catalyst application as a die-slot roller technique. While roller application is simple, rapid, and inexpensive, MEA's created using this technique have not been shown to yield the high power density achievable by the NSTF catalyst. Cost comparison indicates very similar manufacturing cost between NSTF and roller application at high production volumes but when the projected difference in power density (833 mW cm^{-2} vs. 715 mW cm^{-2}) is taken into account, the NSTF catalyst achieves a 10.28 US$ kW$_{\mathrm{net}}^{-1}$ advantage.

TIAX describes the same process with some variation. They specify two "pre-soak" phases, in which the PR-149 material is heated to set temperatures in a vacuum furnace, and they also specify that a class 10,000 clean room is required. TIAX specifies varying line speed, 10 ft per minute (3 m per minute) for the anode and 5 ft per minute (1.5 m per minute) for the cathode as well as carrier web width, vacuum pressure, presoak and annealing temperatures, and time durations for the process. TIAX indicates they have obtained feedback from 3M indicating the process assumptions for the organic whisker and NSTF process are reasonable. TIAX denotes US$ 5M in equipment for the process (vacuum chambers, diffusion pumps and high-vacuum valves, mechanical pumps, web handling, control systems, other mechanical systems, assembly and quality control), but does not show the source for the equipment costs.

3.3. Gas diffusion layer

DTI assumes a dual-layer gas diffusion layer as developed at the University of South Carolina. Cost of the base macro-porous GDL carbon paper is not analyzed from the ground up but rather is based on industry price projection (9 US$ m^{-2} in high volumes from SGL Group). A five-step process is used to create the micro-porous layer: (1) dip macroporous GDL in PTFE solution of methanol and DI water, (2) dry in IR oven for 10 min at 280 °C, (3) spray application of micro-porous emulsion consisting of PTFE, solvent, and carbon powder (Vulcan® XC72), (4) dry in IR oven for 10 min at 280 °C, and (5) cure in IR oven for 30 min at 350 °C. Capital cost of the equipment is based on modified industry quotations for similar industrial equipment.

TIAX assumed a woven carbon fiber cloth coated with DuPont™ PTFE T-30 and Cabot carbon black powder. They based the GDL specification on E-Tek low-temperature ELAT® GDL, LT 1200-W. The source for the raw material cost quotations for various quantities of materials needed for various production levels was not specified. The fabrication process involves measuring and mixing the PTFE and carbon black, spraying the solution onto the woven cloth, and a three-stage heat treatment of the sprayed cloth. TIAX specifies and references a detailed list of processing parameters from TIAX's 2005 study [6], but does not identify the source of the information. The capital cost for equipment is broken down by the process steps (mix, spray, dry, heat-treat, and sinter) and the cost of the capital equipment is based on conversations with unspecified industrial equipment manufacturers. TIAX provides a coarse breakdown of sintering furnace components, but does not offer this level of detail for the other process equipment.

3.4. Catalyst coated membrane, GDL and frame assembly

DTI outlines a three-step process to fabricate the MEA/seal assembly. The anode and cathode gas diffusion layers and catalyst coated membrane are fed into a hot press in layers (90 s dwell time at 160 °C, US Pat. 5,187,025). A large platen area (~0.75 m^2) is used to achieve high through-put and low cost. The MEA sheet is cut to size, and the frame/gasket is insertion molded around the MEA pieces. DTI specifies the equipment for these processes: unwind and rewind stands, hot press, slitter, cutter, stacker, and insert molding machine. Capital cost of the equipment is based on modified industry quotations for similar equipment. It also appears that there may be opportunities to reduce the cost of capital equipment by reducing the number of rewind and unwinding operations. DTI has examined five sealing materials (a generic silicone, Henkel Loctite® silicone, DuPont™ Viton® GBL-6005 and GF-S, and Henkel Loctite® LIM Hydrocarbon) to determine a durable option which could be insertion molded at temperatures the membrane material can tolerate. Four of the five materials are commercial products with well established pricing. However, the selected material (Henkel Loctite® Liquid Injection-Moldable (LIM) hydrocarbon) is a recently developed product designed specifically for this application. Based on recommendation from Henkel, the Henkel LIM Hydrocarbon cost is set at a 20% premium over bulk Viton®.

TIAX uses a similar method for assembling the MEA (based on a detailed study of several patents), except that they form the frame seal with Viton®, and they include an additional gasket which is formed in-place in the bipolar plates. TIAX provides a thorough breakdown of process parameters, but neglects to mention the source of capital equipment quotations. TIAX uses a transfer molding process to form the gasket in-place in a groove located on the bipolar plate. They reference a US patent as well as a website for Molding Solutions. They assume DuPont™ Viton® as a gasket material, claiming longer life than the nitrile rubber assumed in their previous studies. They do not address the compatibility requirements of the Viton® material with the transfer molding process and although the capital equipment is common, they do not specify the source of the quotation.

3.5. Bipolar plates and coatings/surface treatments

DTI assumes a four-stage progressive die stamping of 3 mil (25 μm) thick 316 L stainless steel sheet metal for the bipolar plates. The progressive die is assumed to operate at 66 strokes per minute and has a press force based on the plate area, plate thickness, deformation pattern, and material tensile strength. The costs of the stamping presses, associated coil handling equipment, and expendable dies are based on DFMA® historical correlations and consultation with vendors. The anode plate is laser welded to the cathode plate around the plate perimeter to create a coolant flow cavity between the plates. A laser-welding speed of 25 cm per second is used (other methods for bonding the bipolar plates were also considered: insertion molding of a polymer gasket and screen printing a gasket, but laser welding was determined to be the most cost effective). Fully robotic placement of the plates is used to achieve a high laser utilization and quality control. Post-stamp washing of the plates is not included in the analysis but its cost is expected to be very low. DTI assumes an anti-corrosion coating is applied to the bipolar plates based on the TreadStone LiteCell process, as derived from open literature references (US Patent 7,309,540) and confidential conversations with TreadStone. DTI is unable to report full detail of the process. The postulated coating application follows a three-step process. The major step is the deposition of non-continuous layer of gold dots (~1% surface coverage) via a low-cost patented process to impart low contact resistance. The plate coating is applied after bipolar plate stamping. The gold layer is only applied to one side of the plates because only one side requires low contact resistance.

Recently TIAX has updated their analysis (for a 2010 status system) to include thermally nitrided metallic bipolar plates under development at Oak Ridge National Laboratory, but have yet to fully document the details of their recent work. The process begins by unwinding a roll of Fe–20Cr–4V foil into a seven-stage progressive die stamp. The anode and cathode plates are laser welded together and placed in batches into three stages of furnaces—a heat-up furnace for 30 min, vacuum nitridation furnace for 90 min, and cool-down furnace for 60 min. TIAX references discussions with Minster Press Inc. for the capital cost (US$ 400,000) of the 300-ton (2667 kN) press and coil feeding, the cycle time of the press (30 parts per minute) and the tooling cost (US$ 300,000).

The 2008 report from TIAX includes an analysis of flexible graphite foil bipolar plates, which were the largest weight and size contributors to the stack. TIAX relies on three US patents and feedback from GrafTech for the process of making the plates. Although patents describe how to process raw graphite flake, TIAX begins with expanded graphite flake (assumes US$ 2 per lb or US$ 4.4 per kg). The expanded graphite flake is mixed with carbon fiber and roll-pressed into a thin graphite foil of thickness <1 mm. The foil is impregnated with a resin (including vinyl ester, polydimethyl siloxane, methyl ethyl ketone peroxide and cobalt napthenate) in a vacuum chamber. The source for the resin cost is not provided. The impregnated foil is calendered and passed through a series of embossing rollers to emboss the plate features into the impregnated foil. A roller die cuts the bipolar plates which are cured in a conveyer oven for 10 min at 90–120 °C to cure the resin. Two plates are bonded together to form a bipolar plate with cooling channels. TIAX specifies the capital costs for roll pressing, resin impregnation, calendering, embossing, compression molding, die cutting, and curing stations, but does not specify sources for capital equipment cost. Further component detail for the embossing station was provided, but this level of detail was not provided for any of the other stations.

3.6. Endplates and current collectors

The DTI endplates are based on a UTC Power fuel cell concept (US Patent 6,764,786) utilizing compression-molded composite endplates mated to metal current collectors. The endplates are made out of a non-conductive composite (Lytex® 9063 glass fiber reinforced epoxy resin). Use of endplates that are not electrically conductive allows elimination of electrical insulator plates. A 5-min compression mold cycle-time is assumed based on Lytex® literature. Capital cost of the compression mold is based on part size, Quantum Composites recommended injection and cure pressure, and correlation to conventional injection molding machines. The Lytex® material cost (11 US$ kg^{-1} in high volume) is based on a price quotation. The endplates are ribbed for added stiffness and low weight. Metal bands are used to provide stack compression. The DTI current collectors are also based on the UTC Power fuel cell concept (US Patent 6,764,786) in which a flat metal current collector is attached to two metal studs which protrude through the endplate to provide load extraction terminals. The current collector components are fabricated from a copper sheet by a stamping process. The metal studs are merely copper rods cut to the desired length and brazed to the current collectors. Since the part shapes (sheets and rods) and attachment mechanism (brazing) are so simple, the components are assumed to be purchased as finished parts with little fabrication detail specified.

TIAX assumes that the endplates are made from aluminum and are die-cast to final dimensions. A die-cut PTFE sheet is used to insulate the endplate from the aluminum current collector. TIAX's 2008 report does not specify any processing associated with the current collector.

3.7. Assembly of stack

DTI assumes manual assembly of stack repeating cells at low-volume manufacturing (1000 units per year) and automated robotic assembly at all higher-volume rates. Non-repeating stack components are assembled by manual operations at all rates. The stacks are leak-checked, and full testing occurs during stack conditioning. The process is straight-forward and requires some special material handling, fixtures, and tools. Capital costs are estimated by the summation of standard components of industrial robotic machinery as defined in the industrial literature. The only additional material is the compression band. DTI does not specify whether a clean-room and its associated equipment and supplies are required.

TIAX assumed three steps for the stack assembly process; assembly of the major (repeated) stack components, manufacturing and assembly of balance-of-stack components, and overall stack quality control (QC). They assumed a fully-automated assembly center equipped with a pick-and-place robot for the MEA, a pick-and-place robot for the bipolar plates, and a specialized assembly station. The use of two pick-and-place robots significantly reduces the assembly time. TIAX assumed a 6-s cycle time with a 1-s idle time between pick-and-place actions and 3-s delay between the MEA and bipolar plate placement cycles, resulting in a 10-s cycle time for assembling an MEA and bipolar plate. For the 2008 system, this resulted in a 38-min assembly time for each stack of 220 MEAs. The assembly of balance-of-stack hardware was assumed to be manual operation and involves installing the stack manifold, endplates, endplate insulators, outer wrap, current collectors, and tie bolts. The balance-of-stack assembly time was 10 min, and quality control time was 15 min. Based on industry feedback, TIAX set the overall yield for the stack production line at 94%. Process equipment cost estimates were based on conversations with original equipment manufacturers.

3.8. Stack conditioning

DTI follows a prescribed process outlined in a UTC Fuel Cell patent (US Patent 7,078,118) for stack conditioning. Three stacks are conditioned at a time (5 h per stack), staggering the start time to reduce the peak load. Conditioning cost is calculated by estimating the capital cost of a programmable load bank and hydrogen required. DTI obtained a rough order of magnitude price quotation of US$ 210,000 to US$ 280,000 per bank in quantities of 10–20 from FuelCon Systems Inc. and scales this value to US$ 145,000 for the 145 systems needed to condition 500,000 stacks per year. DTI believes the benefit of recovering electricity generated during fuel cell conditioning is small and electrical infrastructure required is considerable. Electricity recovery is not included in their estimates.

TIAX does not include the cost of stack conditioning in their analyses. They claim the duration, number of parallel stations and capital cost of the equipment will not be significant.

3.9. Air compressor/expander/motor (CEM) unit

In collaboration with Honeywell, DTI conducted an all-new, extremely detailed CEM cost estimate. It is a bottom-up cost analysis based directly on the blueprints from an existing Honeywell design, which pairs a centrifugal compressor and radial-inflow expander and has a permanent-magnet motor running at 100,000 rpm on air bearings. This base design was then simplified and improved by DTI and Honeywell engineers to increase performance and lower cost. Ultimately, six different configurations were examined; three main configurations, plus a version of each without an expander.

The analysis was conducted utilizing a combination of DFMA® methodology and price quotations from established Honeywell vendors. Excluding repeat parts, the design has over 120 different components and assemblies. Each of these components was categorized into one of three different tiers, ranging from the 26 largest or most-significant “Tier 1” components, representing parts in need of the most careful cost analysis, to the minor “Tier 3” components such as screws and adhesives, representing minor parts for which educated guesses are sufficient in lieu of vendor quotations.

The new analysis also examined the motor controller, for which the same design was deemed applicable to control all six compressor designs. Unlike the compressor, the motor controller uses almost exclusively off-the-shelf parts that are already manufactured at high volume. As such, there is limited value in conducting a detailed DFMA® analysis, so the cost analysis is primarily based on vendor quotation. The original Honeywell controller design was based on a stand-alone boxed unit with air or water cooling. However, during the cost analysis, it was decided to integrate the CEM controller with the overall fuel cell controller, thereby saving on enclosure and cooling system cost.

TIAX based their cost estimate of the CEM on the design developed by Honeywell as described in the patent literature and in Honeywell/DOE project presentations. The major components of the CEM are electric motor, variable-nozzle turbine, unison ring, air foil journal rings, power electronics, and motor controller. The sizing and specifications of the CEM were developed by ANL through a detailed system model [5]. The analysis was conducted utilizing a combination of DFMA® methodology and price quotations from established Honeywell vendors. The detailed bill-of-materials (BOM), including dimensions and materials for the manufactured parts, was developed from a review of publically available catalogs, patents, and DOE reports, and vetted through discussions with vendors. TIAX estimated the high-volume cost of fabrication for 16 components with the Boothroyd–Dewhurst DFMA® software package. The manufacturing processes for the fabricated components are described in the TIAX 2008 update report [4]. A capital equipment cost breakdown is presented for a die casting machine. A total capital equipment cost is provided without further break-down.

TIAX estimates for purchased parts were obtained from vendor quotations for low-volume which were then scaled for high-volume production. The major purchased components are the motor controller, motor stator, NdFeB magnets for the rotor, turbine wheel, compressor wheel, and air foil bearings. The motor controller and motor sub-assembly are the largest contributors to the CEM cost (US$ 5.00 out of US$ 6.68 per kW_{net} fuel cell power). TIAX’s bottom-up cost estimate that was reported is expected to be more accurate than their previous estimates which were based on vendor feedback for very low-volume production scaled to high volume.

3.10. Fuel circulation system

DTI assumes dual static ejectors to re-circulate hydrogen from the anode exhaust to the anode inlet to achieve target flow rates and hence high stack performance. The ejectors operate on the Bernoulli principle wherein high pressure H_2 gas from the fuel tank (>250 $\mathrm{lb\,in^{-2}}$ or 1724 kPa) flows through a converging-diverging nozzle to entrain lower-pressure anode exhaust gas. Two ejectors, high flow and low flow, are operated in parallel to achieve a wide turn-down range. Design of the ejectors is based on concepts from Graham Manufacturing and the patent literature (US Patent 5,441,821). Fabrication of each ejector consists of stainless steel investment casting of a two-part assembly, followed by machining, welding, and polishing. DTI is also investigating ejectors with variable geometry for future systems and, as indicated by ANL modeling [5], whether a hydrogen recirculation blower is needed during very low part-power system operation.

TIAX’s fuel management system consists of a hydrogen blower, ejectors, purge valve, check valve, and solenoid valves. The hydrogen blower cost was developed using bottom-up technology-based manufacturing cost models. The hydrogen blower cost was based on published information and patents on the Parker Hannifin Model 55™ Univane compressor. Sizing and specifications of the fuel management system were specified by the ANL detailed system model [5]. The blower includes several components such as a DC motor, motor shaft rotor, vane, housing and manifold. The rotor and single vane structure are referenced from U.S. Patent 5,374,172. A BOM was developed for the blower which consisted of purchased and fabricated parts. The high-volume cost for fabricated parts was estimated by DFMA® software. The manufacturing processes for the fabricated parts included casting, turning, drilling, milling, surface hardening, grinding, and tapping. All other components were assumed to be purchased, and their cost was determined by scaling low-volume prices from catalogs. Purchased items include ejectors, as well as solenoids, purge, and check valves.

3.11. Humidification system

DTI bases their membrane air humidifier on a scaled version of the FC200-780-7PP membrane humidifier from Perma Pure LLC. It consists of a two-part injection-molded Noryl® housing, which contains four Viton® O-rings, a nylon mesh filter, and an array of 1660 1-mm diameter Nafion® membrane tubes potted at each end with a polyurethane coating. The halves of the housing are then vibration-welded together and secured by a pair of steel C-clips. The capital costs for the nine steps in the process train (extrusion, de-ionized water bath, tube cutting, quality control, polyurethane dipping, end cap trimming, injection molding, final assembly, and vibration welding) are primarily derived from previous DTI work involving similar machinery and sum to US$ 4M per line.

The TIAX presentation at the 2010 DOE Hydrogen Program Review described a 2009 system with a membrane air humidifier (MAH) and a membrane hydrogen humidifier (MHH). TIAX’s preliminary 2010 system retains the MAH but eliminates the MHH (presumably, the MAH fabrication is unchanged). The 2009 humidifiers are planar units comprised of Nafion® membranes and nickel foam and are based on Nuvera (US patents 6,737,183 and 6,835,477) and Ballard (US patents 6,864,477 and 7,078,117) technology.

For the 2008 system, TIAX used an enthalpy wheel for air humidification and a tubular membrane humidifier was used for the hydrogen. The sizing and specifications of the water management system were developed by ANL [5]. The cathode enthalpy wheel (CEW) humidifier consists of a cordierite core with γ-alumina desiccant coating, a motor driving unit, housing, and two end manifolds. The cathode enthalpy wheel manufacturing process was based on Emprise US patents (2002/0071979 and 6,780,277), white papers, and personal communications. The CEW cordierite core is similar to the cordierite core in an automotive catalytic converter so the CEW core cost estimate assumed a 1.15× markup over the factory cost. The manufacturing process is comprised of standard manufacturing techniques. The cordierite core is formed by extrusion followed by drying and sintering at 1200 °C. The γ-alumina is applied by slurry coating and the core is sintered again at 1200 °C to fuse the γ-aluminate coating. The core is then assembled with end plates, seals, housing, motor, etc. The drive motor cost was based on scaled quotations or catalog-based estimates.

The 2008 MHH consisted of 960 Nafion® tubes assembled in a package following the geometrical dimensions and materials choices of the Perma Pure LLC FC2000-780-7PP Series™. The number of tubes was determined by ANL's model [5] and Perma Pure LLC was consulted to verify that the specifications would provide the mass transfer required for fuel humidification. Discussions with Perma Pure LLC provided the basis for the manufacturing process. Tubes are extruded and subjected to chemical conditioning and

Table 3
DTI 2010-technology cost results.

Category	Item	US$ per system	US$ per kW$_{net}$
Membrane	Polymer electrolyte membrane	231	2.88
Catalyst ink and application	Catalyst ink and application	695	8.69
Gas diffusion layer	GDLs	243	3.03
Catalyst coated membrane, GDL and frame assembly	Hot pressing GDLs to membrane	8.16	0.10
	Cutting and slitting	2.82	0.04
	MEA frame/gaskets	301	3.77
Bipolar plates and coatings	Bipolar plates and laser welding	455	5.68
Assembly of stack	End gaskets (screen printing)	0.54	0.01
	End plates	19.9	0.25
	Current collectors	5.07	0.06
	Compression bands	5.00	0.06
	Stack housing	5.16	0.06
	Stack assembly	32.1	0.40
Stack conditioning	Stack conditioning	28.1	0.35
Air compression system	CEM and motor controller	645	8.07
	Air mass flow sensor	30.0	0.38
	Air filter and housing	49.5	0.62
	Air ducting	45.6	0.57
Fuel circulation system	Inline filter for gas purity excursions	18.2	0.23
	Hydrogen high-flow ejector	30.6	0.38
	Hydrogen low-flow ejector	24.2	0.30
	Flow diverter valve	15.2	0.19
	Over-pressure cut-off valve	12.0	0.15
	Check valves	10.0	0.13
	Hydrogen purge valve	12.0	0.15
	Hydrogen piping	30.7	0.38
Humidification system	Membrane air humidifier	94.3	1.18
	Air precooler	52.8	0.66
	Demister	6.26	0.08
High-temperature cooling system	HTL coolant reservoir	6.30	0.08
	HTL coolant pump	69.5	0.87
	HTL coolant DI filter	37.8	0.47
	HTL thermostat and valve	5.04	0.06
	HTL radiator	160	2.00
	HTL radiator Fan	45.6	0.57
	HTL coolant piping	32.5	0.41
Low-temperature cooling system	LTL coolant reservoir (39%)	0.77	0.01
	LTL coolant pump (39%)	12.6	0.16
	LTL thermostat and valve (39%)	1.18	0.01
	LTL radiator (39%)	46.0	0.58
	LTL coolant piping (39%)	10.2	0.13
System controls	System controller	82.1	1.03
	Current sensors	20.0	0.25
	Voltage sensors	8.00	0.10
	Hydrogen sensors	197	2.47
System assembly	Wiring	83.9	1.05
	Belly pan for fuel cell system	4.24	0.05
	Mounting frames	30.0	0.38
	Fasteners for wiring and piping	38.5	0.48
	System assembly and testing	111	1.38
Total		4110.12	51.38

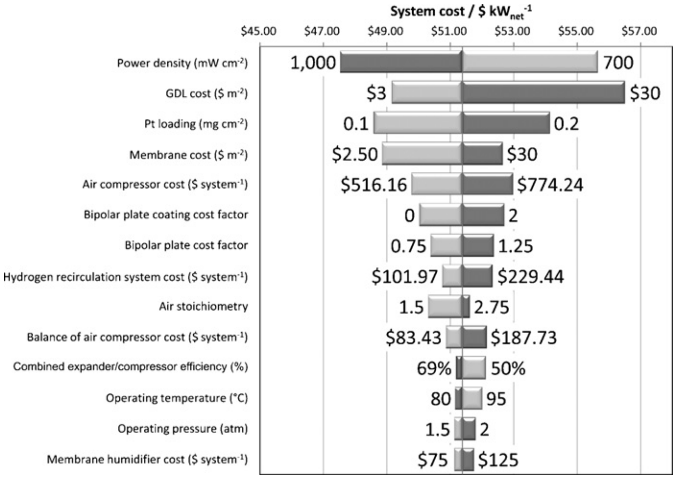

Fig. 3. DTI 2010-technology sensitivity analysis.

drying. Quality checks are performed and the tubes are wound to from a tube bundle. The ends of the bundle are cut off to provide a through path. The membrane humidifier assembly is completed by attaching in/out ducting, manifolds, seals, and filters. Major equipment includes a Nafion® tube extruder, chemical conditioning baths, dryers, tube winders and cutters, and final assembly equipment. The source for the cost estimates for the materials and equipment was not stated.

3.12. *Air cooler and demister*

DTI assumes an air cooler between the air compressor and the membrane humidifier to cool the hot compressed air to the humidifier's optimal inlet temperature of 55 °C. The design is based on a compact liquid/air cross-flow intercooler from Frozenboost.com. It is 100% aluminum, and uses an array of 0.08-mm-thick fins spaced at 24 fins per inch (9.4 fins per cm) to cool the air with a low pressure drop (0.05 lb in^{-2} or 0.35 kPa). Because the cost impact of the air cooler is small, a full DFMA® analysis was not conducted. Rather mass and volume of the radiator core were determined by heat transfer calculations conducted by ANL [5] and the material cost was estimated based on the cost of aluminum (7.70 US$ kg^{-1}). Materials cost was then simply doubled to account for the cost of manufacturing.

DTI employs a demister to remove liquid water droplets from the cathode exhaust stream and thereby prevent erosion of the turbine blades. Designed by DTI, the demister housing consists of two threaded, hollow 2 mm-thick polypropylene frustums that unscrew from one another to allow access to the filter inside. The filter is a nylon mesh Millipore product designed for water removal and costed at US$ 5.84 each at high volume (assuming 81 cm^2 per demister). The polypropylene adds only US$ 0.10 of material cost per part, and at high volume the injection molding process is only US$ 0.15 per part. Because the housing is so inexpensive, the filter dominates the total demister cost (US$ 6.12, or 0.08 US$ kW$_{net}^{-1}$).

Table 4
DTI 2010-technology sensitivity analysis inputs.

Variable	Min.	Max.	Base case
Power density (mW cm^{-2})	700	1000	833
GDL cost (US$ m^{-2})	3	30	11
Pt loading (mg cm^{-2})	0.1	0.2	0.15
Membrane cost (US$ m^{-2})	2.5	30	20.7
Air compressor cost (US$ system^{-1})	516	774	645
Bipolar plate coating cost factor	0	2	1
Bipolar plate cost factor	0.75	1.25	1
H_2 recirculation system cost (US$ system^{-1})	102	229	153
Air stoichiometry	1.5	2.75	2.5
Balance of air compressor cost (US$ system^{-1})	83	188	125
Combined compressor/expander efficiency (%)	50	69	64
Operating temperature (°C)	80	95	90
Operating pressure (atm)	1.5	2	1.69
Membrane humidifier cost (US$ system^{-1})	75	125	94

The 2008 TIAX cost analysis does not include the cost of the air demister or air cooler as TIAX claimed that these components are not expected to make a significant contribution to system cost at the current state of the technology. As the costs of the stack and current major BOP components were reduced, their importance was re-evaluated. In 2009, TIAX uses a Parker Hannifin quotation for the demister and scales it to volume.

3.13. *System controllers*

DTI recently updated the analysis of the system controllers. The controllers were broken down into 17 input and output circuits. For each input or output circuit it was estimated that approximately US$ 0.50 in electronic components (referencing catalog prices) would be needed. Additionally, input and output connectors, an embedded controller, and housing cost were estimated by catalog pricing. Hall Effect transducers and voltage sensors were added as well, but input power conditioning circuitry was not addressed. A quotation was used for the assumed dual-layer 6.5″ × 4.5″ circuit board. Assembly of 50 parts was based on robotic pick and place methods, but soldering operations were not discussed. DTI's recent controller analysis is currently undergoing industry vetting and refinement to validate their analysis. A 10% cost contingency is added to cover any unforeseen cost increases. The bottom-up analysis is considered to be more accurate than the previously hypothesized controller cost estimates.

In their 2008 report, TIAX partially addressed the system controller within the system assembly section. They listed the following components: main control board, control board power regulator and circuit breaker; four processors; a memory chip; four FET circuits for solenoid valves; and five solid-state relays for coolant pump, CEM motor, radiator fan, H_2 blower and enthalpy wheel. They also mention an electrical and controls sub-assembly station, but provide no further detail of the equipment at the sub-assembly station.

3.14. *Wiring*

DTI recently updated their wiring cost estimates. Wiring was selected by examining the length and maximum current required by each electrical component. Electrical connectors were specified for each wire/component. All wires and connectors were assumed to be outsourced with price quotations obtained from Waytek Inc. Assembly of the wiring harness was included in system assembly.

TIAX used engineering judgment, conversations with original equipment manufacturers, and scaled catalog prices to develop costs for the balance-of-system components (including wire harnesses) and system assembly processes. Estimates for thermistor wiring, on/off valve wiring, motor control wiring, power wiring, and other sensor wiring are included. Some of the wiring assumptions (wire gauge, connectors, etc.) are not discussed. The cost of assembling the wire harness is not discussed, so it is unclear whether it is included as part of the electrical and controls subassembly workstation.

3.15. *System assembly*

DTI estimates system assembly time by tabulation of all components to be assembled and then summation of the estimated acquisition, placement, and fastening times of each component.

Components included stack, motors, pumps, vessels, instruments, sensors, heat exchanger, piping, hoses and wiring. Total assembly time was estimated to be 177 min including a 10-min basic functionality test. For 1000 systems per year only one workstation is needed. For the higher production rates analyzed, a more efficient 10-workstation configuration is used. DTI assumes that the 10-workstation configuration will be 20% faster than the single-workstation configuration used in the 1000-unit-per-year scenario.

TIAX assumes four steps for the system assembly; BOP subsystem assembly, balance of system assembly, final system assembly and system quality control. The system assembly included the assembly of the BOP subsystems for thermal, water, air and fuel management, as well as the assembly of balance-of-system components. The system QC included visual inspection, power-on test, and voltage and leakage inspection. System assembly was assumed to be a manual operation including six stations: fuel management sub-assembly station, air management sub-assembly station, thermal management sub-assembly station, water management sub-assembly station, electrical and controls sub-assembly station, and final assembly station. Each assembly station is equipped with conveyers, rotating assembly fixtures, automatic power tools. The same equipment costs, labor, space, and power requirements were assumed for each of the six sub-assembly stations. The total system assembly time (not including stack assembly time and system quality control time) was estimated to be approximately 207 min. The equipment cost estimates were based on conversations with the original equipment manufacturers and TIAX's engineering judgment. The system production line overall yield was assumed to be 100%.

4. Results and concluding remarks

A table summarizing the results of each cost analysis, followed by the corresponding sensitivity analysis, is presented for refer-

Table 5
TIAX 2008-technology cost results.

Category	Item	US\$ per kW_{net}
Membrane	Polymer electrolyte membrane	2.38
Catalyst	Electrode	15.43
Gas Diffusion Layer	GDLs	2.04
Catalyst coated membrane, GDL and frame assembly	Catalyst membrane lamination	0.55
	Peeling support layers	0.01
	GDL electrode lamination	0.01
	Die cut MEA	0.65
	MEA frame seal	1.34
Bipolar plates and coatings	Bipolar plate	2.72
	Gasket	1.12
Assembly of stack	End plate insulator	0.22
	End plates	0.12
	Current collectors	0.04
	Tie bolts	0.30
	Outer wrap/stack manifold	0.28
	Stack assembly	1.28
Stack conditioning	Stack conditioning	0.00
Air compression system	Compressor expander module	7.69
	Two solenoid valves	0.77
	Air filter	0.06
Fuel circulation system	Hydrogen blower	3.15
	Two hydrogen ejectors	0.50
	Check valve	0.16
	Hydrogen purge valve	0.16
	Two solenoid valves	0.58
Humidification system	Membrane air humidifier	2.29
	Enthalpy wheel humidifier	0.84
	Four inlet and outlet fittings	0.13
Cooling system	HTL coolant pump	1.50
	HTL radiator	0.81
	HTL radiator fan	0.43
	Two coolant temperature sensors	0.07
System controls	Control Electronics Components	1.18
	One hydrogen sensor	0.50
	Humidity sensor	0.13
	Flow meter	0.13
	Two differential pressure transducers	0.25
	Two thermistors	0.06
	Stack CO sensors	0.13
System assembly	Wiring	0.81
	Safety contactor	0.37
	System mounting	0.63
	Ten pieces piping	0.04
	Ten fittings	0.30
	Startup batteries	1.31
	System assembly and QC	4.03
Total		57.48

Table 6
TIAX 2008-technology sensitivity analysis inputs.

Variable	Min.	Max.	Base	Comments[a]
Pt loading ($mg\,cm^{-2}$)	0.2	0.57	0.25	Minimum: DOE 2015 target[b]; maximum: TIAX 2005 report[c]
Pt Cost (US\$ tr.oz^{-1})	450	2250	1100	Minimum: ~108-year min. in 2007 US\$[d]; maximum: 12-month maximum LME price[e]
Power density ($mW\,cm^{-2}$)	350	1000	716	Maximum: industry feedback; minimum DOE 2015 target[b]
Membrane cost (US\$ m^{-2})	10	50	16	Minimum: GM study[f]; maximum: DuPont projection from 2002[g]
Interest rate (%)	8	20	15	Based on industry feedback
Bipolar plate cost (US\$ kW_{net}^{-1})	1.8	3.4	2.7	Based on component single variable sensitivity analysis
GDL cost (US\$ kW_{net}^{-1})	1.7	2.2	2	Based on component single variable sensitivity analysis
Viton® cost (US\$ kW_{net}^{-1})	39	58	48	Based on industry feedback

[a] High-volume manufactured cost based on a 80 kW_{net} power PEMFC system. Does not represent how costs would scale with power. Assumes a percentage mark-up to automotive OEM for BOP components.

[b] http://www1.eere.energy.gov/hydrogenand fuelcells/mypp/pdfs/fuel_cells.pdf.

[c] Ref. [8].

[d] www.platinum.matthey.com.

[e] www.metalprices.com.

[f] Ref. [9].

[g] Ref. [10].

ence. Results tables include items that were not discussed, as this paper pertains to those items that were costed in a bottom-up fashion, requiring the definition of a manufacturing process. Common components that already have significant market and supply-base did not require a bottom-up costing methodology (Figs. 3 and 4; Tables 3–6).

The summary of manufacturing process assumptions is meant to impart a sense of the current rigor of the cost analyses funded by the DOE. They are on-going efforts under continuous refinement, but they are constrained by practical limitations. Financial resources are limited and thus limit parallel efforts that may take place. After completely defining and costing a system technology, technical progress causes portions of the analysis to become obsolete, consequently new components or manufacturing methods must be analyzed. The cost estimators are also limited by lack of access to the advanced components and materials being developed by so many that have interest in protecting their trade secrets. Given these challenges, the estimators have made significant progress in defining the systems and understanding all of the fabrication processes required to manufacture and assemble the materials and component into a state-of-the-art system. They have built "bottom-up" models in terms of the manufacturing process to replace quotation-based assumptions for major components of the fuel cell system. Now that fuel cell systems and components are approaching technical targets, system designs have simplified, and the manufacturing processes are well understood, the focus of the analysis can proceed with further refinement—"bottom-up" analyses on the minor components and materials where the market forces of a large supplier base and customer base have not yet driven costs to their minimum. In addition to updating the analyses for technical advances, methodical quality control of the analyses will be implemented to ensure equipment costs are reasonable and every assumption is valid.

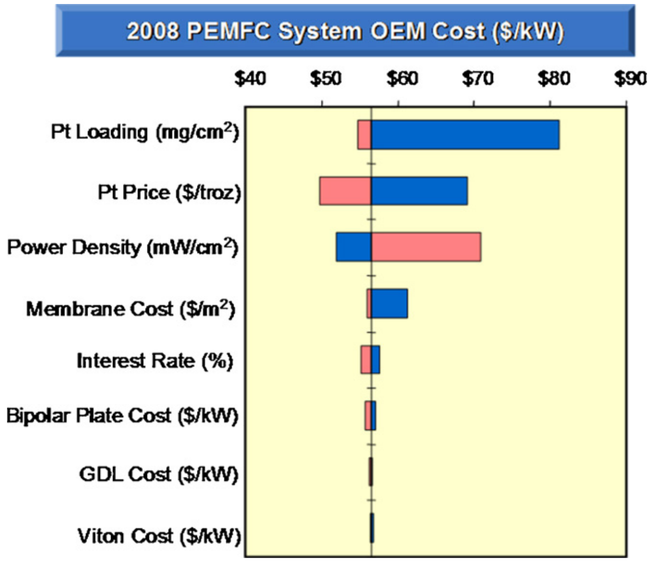

Fig. 4. TIAX 2008-technology sensitivity analysis.

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