U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FUEL CELL TECHNOLOGIES OFFICE

Pathways to Commercial Success:

Technologies and Products Supported by the Fuel Cell Technologies Office

December 2015

Prepared by Pacific Northwest National Laboratory
for the U.S. Department of Energy Fuel Cell Technologies Office

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* Appendices will be posted online in FY2016

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Summary

The purpose of the project described in this annual report is to identify and document the commercial and emerging (projected to be commercialized within the next 3 to 5 years) hydrogen and fuel cell technologies and products that resulted from U.S. Department of Energy support through the Fuel Cell Technologies Office (FCTO) in the Office of Energy Efficiency and Renewable Energy (EERE). Pacific Northwest National Laboratory (PNNL) undertook two efforts simultaneously to accomplish this project. The first effort was a patent search and analysis to identify patents related to hydrogen and fuel cells that are associated with FCTO-funded projects (or projects conducted by DOE-EERE predecessor programs) and to ascertain the patents' current status, as well as any commercial products that may have used the technology documented in the patent. The second effort was to identify FCTO-funded technologies by contacting the principal investigators or points of contact and FCTO personnel. PNNL also reviewed FCTO program annual reports, and examined grants made under the Small Business Innovation Research and Small Business Technology Transfer Programs that are related to hydrogen and fuel cells.

The patent analysis identified 589 patents associated with research supported by FCTO dating back to 1977. The 589 FCTO patents include: 299 fuel cell patents, 213 hydrogen production/delivery patents, and 77 hydrogen storage patents. Three types of organizations received the patents: national laboratories (227 patents), private companies (275 patents), and universities (87 patents). Private companies received the greatest number of patent awards in the fuel cell and production/delivery areas, accounting for 53% of the fuel cell patents and 48% of the production/delivery patents. The national laboratories had 60% of the awards in the storage area.

The patent award status by use indicated that 27 patents are currently used in commercial products and 67 are part of research now taking place on emerging technologies. In addition, 322 awarded patents are still being used via continuing research and/or active attempts to license the patents. Of all the patents reviewed, 71% are still actively being pursued through use in continuing research, emerging technologies, or commercially available products.

In addition, PNNL identified 46 technologies that have been commercialized. From 2000 through 2006, an average of 1.5 technologies entered the market per year. From 2007 through 2014, an average of 4.0 technologies per year entered the market. For 2015, one technology is known to have entered the market thus far. Commercial technologies also supported the creation/retention of 391 direct jobs in fiscal year 2015. This effort also identified 68 emerging technologies that are anticipated to be commercially available in 3 to 5 years. Of the 68 emerging technologies, 47% are in the fuel cell area, 43% are in the production/delivery area, and 10% are in the storage area.

This report documents the methodology and results of this study, including the specific patents as well as commercial and emerging technologies that resulted from FCTO funding.

1.0 Introduction

This report documents the methodology and results of an effort to identify and characterize commercial and emerging[1] technologies and products that resulted from the support of the Fuel Cell Technologies Office[2] (FCTO) within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). Commercialization of technologies that are cultivated in a government research and development (R&D) program is viewed as one measure of success. Pacific Northwest National Laboratory (PNNL) has been conducting similar technology tracking activities for other EERE offices for over two decades.

The results presented in this report represent the findings from the PNNL effort. The information presented on commercial and emerging technologies fulfills the primary objective—to assess the commercialization status of EERE-developed hydrogen and fuel cell technologies. The effort is expected to continue, with an updated report produced annually.

This chapter presents a brief overview of FCTO-funded R&D that is leading to commercial technologies and products, and a summary of the contents of this report.

1.1 Overview of the DOE Fuel Cell Technologies Office

FCTO is focused on key technical challenges associated with fuel cells and hydrogen production, delivery, and storage, as well as institutional barriers, such as hydrogen safety, codes and standards, technology validation, market transformation, and public awareness. FCTO is currently conducting applied research, technology development, and learning demonstrations, as well as safety research, systems analysis, and public outreach and education activities. The research involved in solving critical technological barriers is often high risk, and can benefit from leveraging resources and skills. Therefore, FCTO encourages public-private partnerships, which include the supply chain industry, automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, standards development organizations, other federal agencies, state government agencies, universities, national laboratories, and other national and international stakeholder organizations.

FCTO is currently conducting R&D, demonstration, analysis, and other efforts to support development of hydrogen and fuel cell technologies primarily for transportation (including materials handling equipment, fuel cell vehicles and hydrogen refueling infrastructure). Additional applications include stationary power (including backup emergency power and residential electric power generation), and portable power (including consumer electronics such as cellular phones, handheld computers, radios, and laptop computers) that can enable economies of scale and pave the way for transportation applications. FCTO subprograms that are relevant to technology development represented in this report include the following:

- Hydrogen Production
- Hydrogen Delivery
- Hydrogen Storage
- Fuel Cells
- Manufacturing R&D.

The first four subprograms are the primary focus of this report because they are focused on technology R&D that would result in patents and other intellectual property that could be incorporated into commercial technologies and products. Manufacturing R&D is a relatively new subprogram that is likely to lead to commercial technologies in the future.

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[1] "Commercial" technologies, as defined in this report, are those available for purchase and that have been sold to at least one party. "Emerging" technologies, as defined in this report, are technologies that are projected to be commercialized within the next 3 to 5 years, based on the opinion of the technology developer.

[2] Formerly the Hydrogen, Fuel Cells & Infrastructure Technologies Program, 2002-2009, and the Fuel Cell Technologies Program, 2009-2012.

The current goals of these four subprograms are briefly summarized below.

Hydrogen Production. The goal of the Hydrogen Production subprogram is to develop low-cost, highly efficient hydrogen production technologies from diverse domestic sources, with a focus on renewable and low carbon sources. The subprogram objectives include lowering the cost of distributed production (at the pump) of hydrogen from electrolysis and biomass; developing high-temperature thermochemical cycles; and developing advanced renewable photo-electrochemical and biological hydrogen generation technologies. Hydrogen separation is a key technology that cross-cuts hydrogen production options, and various separation membranes are being developed as part of distributed and central hydrogen production systems. In addition, work in the subprogram includes developing better catalysts needed in production systems and coordinating with the Office of Science on basic research, such as hydrogen production from algae and other biological systems. The subprogram also coordinates with the Office of Fossil Energy (FE) on coal gasification (with sequestration) and separation processes, and with the Office of Nuclear Energy (NE) on hydrogen production from thermochemical processes. More recently, the subprogram has been coordinating with DOE's Joint Center for Artificial Photosynthesis (JCAP) funded by DOE's Office of Science.

Hydrogen Delivery. The goal of the Hydrogen Delivery subprogram is to develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power. Some of the current objectives include reducing the cost of compression, storage, and dispensing at refueling stations and stationary power facilities; reducing the cost of hydrogen transport from central and semi-central production facilities to the gate of refueling stations and other end users; and reducing the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units. Some of the technical challenges that must be addressed include resolving hydrogen embrittlement concerns and developing new and improved materials for pipeline delivery of hydrogen, developing novel liquid and solid carrier technologies, improving compression and bulk storage technologies, and improving hydrogen liquefaction approaches.

Hydrogen Storage. The goal of the Hydrogen Storage subprogram is to develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications, as well as early market applications, with the primary objectives focused on developing and verifying on-board hydrogen storage systems for transportation applications. Various research activities are being pursued, such as those related to lightweight composite tanks for high-pressure storage; conformability; high-capacity metal hydrides, including boron-based materials, adsorbent-based and nanostructured materials; chemical carriers; and other promising materials for low or medium pressure hydrogen storage. Coordination with the Office of Science is also noteworthy, particularly in developing a fundamental understanding of hydrogen-material interactions. More recently, the subprogram has been coordinating with the Advanced Research Projects Agency- Energy (ARPA-E) which is funding innovative materials and tank R&D for natural gas storage. Synergies between hydrogen and natural gas storage are being explored.

Fuel Cells. The goal of the Fuel Cells subprogram is to develop and demonstrate fuel cell power system technologies for transportation, stationary, and portable power applications. The subprogram emphasizes polymer electrolyte membrane or proton exchange membrane (PEM) fuel cells as replacements for internal combustion engines in light-duty vehicles as well as fuel cells for stationary power, portable power, and auxiliary power applications. Research focus areas include membranes, electrocatalysts and electrode design, membrane electrode assemblies, gas diffusion layers, bipolar plates, seals, and other aspects of fuel cell design including water management and balance-of-plant components. The subprogram has included small-scale solid oxide fuel cell (SOFC) R&D for several years to complement the FE's Solid State Energy Conversion Alliance (SECA) Program[3] on megawatt-scale SOFC power systems; however recently FCTO has shifted awayfrom SOFC R&D. The FCTO portfolio includes diverse non-SOFC fuel-cell technology such as alkaline fuel cells, and only includes solid oxide approaches as they relate to hydrogen production/electrolysis. Work on fundamental catalysis is coordinated with the Office of Science. More recently, coordination with ARPA-E has been initiated, particularly in innovative areas such as alkaline exchange membranes.

More information about program goals, objectives, research thrusts, and activities can be found in the FCTO Multi-Year Research, Development, and Demonstration Plan (http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22).

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[3] FE's SECA Program is supporting the development of large-scale SOFCs that can be mass produced in modular form at $400/kW. The objective of the SECA Program is to put reliable fuel cells into a more modular and affordable design to allow wide-spread penetration into stationary and utility-scale markets.

The objectives of, and R&D activities funded by, FCTO and its predecessor programs have changed over the years as the Office has become more focused on the goals described above and as advancements have been made in R&D. Because this report looks retrospectively at commercial successes over the history of hydrogen and fuel cell research within EERE, the patents and commercial/emerging technologies and products described in the remainder of this report may be broader than one would expect from examining the current FCTO efforts.

1.2 Contents of this Report

The remaining chapters explain in more detail the methodology used and provide the results of the effort in tables and charts. The appendices provide details related to the data-gathering techniques and descriptions of each of the commercial and emerging technologies and products that were identified during the study, as well as the list of patents resulting from the R&D efforts undertaken by FCTO and its predecessors. Note that in this report, the delivery technologies have been grouped with production technologies because of the overlap between the two categories. A new area tracked since fiscal year (FY) 2011 is an estimate of the number of jobs directly related to FCTO funding. These estimates are based on recipient interviews and may be refined as more information and validation become available.

2.0 Approach

Two efforts were undertaken simultaneously by PNNL, and initiated in August 2007 under FCTO's System Analysis subprogram, to start the FCTO technology tracking project. The first effort was a patent search and analysis to identify hydrogen- and fuel-cell-related patents that are associated with FCTO-funded projects (or projects conducted by DOE-EERE predecessor programs) and to ascertain the patents' current status, as well as any commercial products that may have used the technology documented in the patent. The second effort was a series of interviews and document reviews conducted to identify and characterize commercial and emerging technologies that have benefited in a direct way as a result of direct funding from FCTO (or funding from EERE predecessor programs) or from grants under programs such as the Small Business Innovation Research and Small Business Technology Transfer. These initial efforts resulted in the August 2009 EERE report entitled: *Pathways to Commercial Success: Technologies and Products Supported by the Hydrogen, Fuel Cells & Infrastructure Technologies Program*. PNNL has subsequently produced an annual update to this report from FY 2010 through FY 2015. The approach taken for these efforts is summarized in Sections 2.1 and 2.2 below.

2.1 Patent Search and Analysis

PNNL conducted several patent searches using the United States Patent and Trademark Office (USPTO) database. The searches included key words related to the hydrogen program[1] and focused exclusively on patents for which DOE had a "Government Interest."[2] The resulting list contained 118 fuel cell patents (mostly related to PEMs) and 239 hydrogen production, storage and delivery patents dating back to 1977. The PNNL team then conducted an initial screening analysis to winnow the patent list to those likely to be associated with EERE research. (Other parts of DOE, including the FE, NE, and Office of Science, also conduct research on hydrogen and fuel cells, but those patents were not included in this study.)

In addition, PNNL obtained the list of patents that were cited in the Hydrogen and Fuel Cells Program's Annual Progress Reports for 2002 – 2007[3] and included them in the patent list. The list was sent to FCTO staff to review, and some patents were removed or recategorized (e.g., from fuel cells to production). The resulting list contained patents for 77 fuel-cell-related and 103 hydrogen-related technologies or inventions (180 total).

The next step was to obtain more information about the government's role in developing the patent and to determine its current status. The PNNL team contacted patent holders by phone or email. For large organizations (e.g., national laboratories, universities, and multinational corporations), PNNL team members were often referred to a central office within the organization, such as a technology transfer, commercialization, or legal affairs office.

The PNNL team members asked the patent holders or central offices whether FCTO or EERE (or its predecessors) funded the research resulting in the patent. Patents not related to FCTO or EERE funding were removed from the list. If a patent had received such funding, the PNNL team attempted to ascertain the current status of the patent and placed it in one of the following categories: no longer being pursued for commercialization nor used in research, still being used in research, used in a commercial product, or licensed to another company. If the patent is still being used in research, PNNL asked if it was part of an emerging technology for which PNNL was gathering data. If the technology was licensed to another company, PNNL asked for the name of the company and tried to ascertain whether a commercial product had resulted from the patent. As PNNL gathered technology data, other patents associated with FCTO/EERE funding were sometimes identified and added to the list. Figure 2.1 depicts the initial patent analysis process for the hydrogen and fuel cell technologies.

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[1] One search used the following search terms: "hydrogen" AND "storage" OR "transport" OR "delivery" OR "dispensing" AND "government/energy." The other search used the following search terms: "fuel cell" AND "pem" OR "membrane" AND "government/energy."

[2] Note that the patent database has a separate field that designates whether there is a "Government Interest" in the patent. If DOE has an interest, that field says, for example, "The United States Government has rights in this invention pursuant to Contract No. […] between the United States Department of Energy and [….a national laboratory or other party]." It is possible that not all of the parties with EERE-related patents correctly indicated that their patents had a "Government Interest."

[3] These reports can be found at http://www.hydrogen.energy.gov/annual_progress.html.

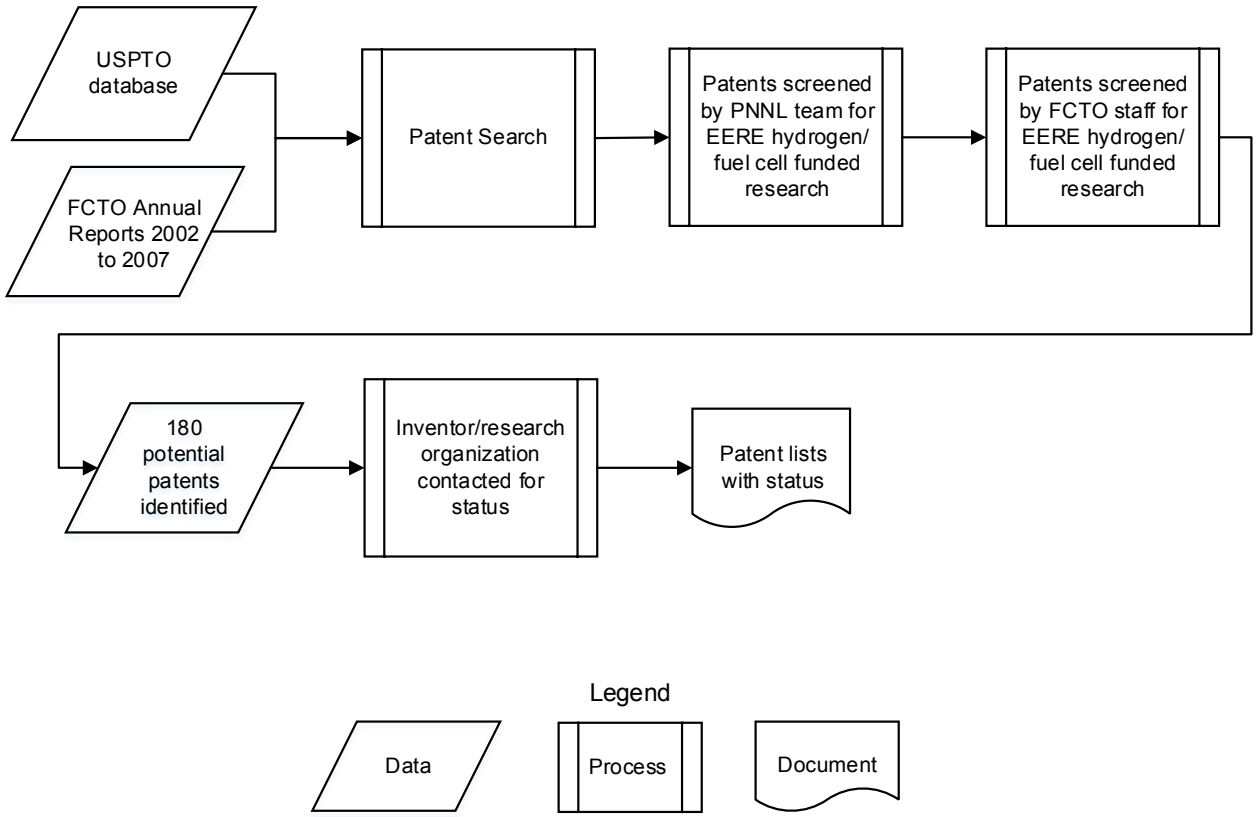

Figure 2.1. Initial Patent Analysis Process for Hydrogen and Fuel Cell Technologies

In FY 2010, PNNL began updating the August 2009 *Pathways to Commercial Success* report. As part of the updating process, the PNNL team conducted a search through FY 2008 and 2009 Hydrogen and Fuel Cells Program Annual Progress Reports to identify any new patents issued during those years. In addition, principal investigators for FCTO-funded emerging technologies and commercial products were asked if they had been awarded any new patents as a result of their R&D work. In June 2010, EERE launched a Technology Commercialization Portal on its website (http://techportal.eere.energy.gov/), which features a portfolio of EERE-funded technologies available for licensing, including patents. Using the EERE Portal, the PNNL team conducted a search for patents that employed screening strategies similar to those used in the original USPTO database searches. The PNNL team contacted patent holders via phone and e-mail to determine whether or not the underlying research associated with a patent was FCTO-funded. If a patent had received such funding, its current status was obtained. In subsequent years, PNNL conducted patent searches using the same methodology as in FY 2010.

The combined results of all the patent searches are discussed in Chapter 3. Some of the intellectual property in the patents on the list was used in technologies or products that were commercialized or that are soon to be commercialized. The section below describes the effort, conducted in parallel with the patent analysis, to identify and describe commercialized and emerging technologies. Chapter 3 provides information about these technologies and the patents related to them.

2.2 Technology Tracking to Identify and Describe Commercial and Emerging Technologies

The PNNL team also identified FCTO-funded projects that may have led to commercial or emerging technologies. To accomplish this, a series of one-on-one meetings was first held with current and former FCTO personnel during which the lists of all FCTO-funded projects, obtained from the Hydrogen and Fuel Cells Program Annual Progress Reports for 2002 through 2007, were reviewed. Also, PNNL reviewed earlier annual reports from FCTO predecessor programs. From these meetings, the PNNL team obtained a preliminary list of projects that FCTO personnel indicated may have led to commercial or emerging technologies. The government personnel also provided information about points of contact (POCs) or principal investigators (PIs) at each relevant research organization and, where available, hard copies of reports or presentations pertinent to the technologies. The resulting list of projects from these meetings was separated into three categories according to the following research areas: fuel cells, hydrogen production/delivery, and hydrogen storage.

The PNNL team contacted the POCs or PIs for the technologies to determine whether they were commercially available, emerging, still in the research stage but more than 3 to 5 years from commercialization, or no longer being pursued. For technologies identified as commercial or emerging, the POCs/PIs for each technology were contacted to gather data about the technology.

The Hydrogen and Fuel Cells Program Annual Progress Report also includes descriptions of hydrogen and fuel cell projects from the annually funded Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants. The SBIR grants are funded in two phases: Phase 1 grants focus on the feasibility of an idea and are funded at a low level (typically $100K to $150K), and Phase 2 grants focus on principal R&D and are funded at a higher level (typically up to $500K, and more recently $1 million). To receive a SBIR Phase 2 grant, a small business would have to have successfully completed a Phase 1 grant and have been selected to continue their research. The STTR grants are similar to SBIR grants as far as having small business participation, but a nonprofit research institution, such as a university or national laboratory, must also be involved. The PNNL team focused on the SBIR Phase 2 and STTR grant projects and contacted the associated PIs to determine the status of the technologies being developed under these grants. Any technologies identified as commercial or emerging were added to the technology tracking list. In FY 2013 and FY 2014, FCTO piloted a SBIR/STTR Technology Transfer Opportunity (TTO) Funding Opportunity Announcement (FOA). This was the first TTO FOA conducted by DOE through EERE and entailed offering specific national laboratory patents to small businesses for commercialization. The results of these FCTO-funded TTOs will be tracked in future PNNL reports.

Data gathered about the technologies were then entered into a FCTO Technology Tracking Database. The database is divided into commercial and emerging technology sections and into three types of research within each section: fuel cells, production/delivery, and storage. In addition, hard copy files are kept that include the template (database) information and other supporting data such as annual progress reports, presentations, and information from the organization's website. The database was created and populated by PNNL and is stored at PNNL, and FCTO personnel have access to it. Periodically, PNNL transmits an updated version of the database to DOE to replace the older version on the DOE system.

For each of the commercial and emerging hydrogen technologies in the database, the PNNL team prepared and edited a summary description and sent it to the industry/research organization POC for review and subsequent approval before sending it to FCTO personnel to review. Figure 2.2 depicts the initial technology tracking process. In subsequent years, the PNNL team used a similar technology tracking process to identify new emerging and commercially available technologies and ascertain the current status of technologies identified in previous years. Beginning in FY 2011, the PNNL team also asked commercial technology POCs to estimate the number of jobs created or retained by the sales of their technologies. The current listing of commercially available and emerging technologies is shown in Appendix A. The results of the technology tracking effort are discussed in Chapter 3.

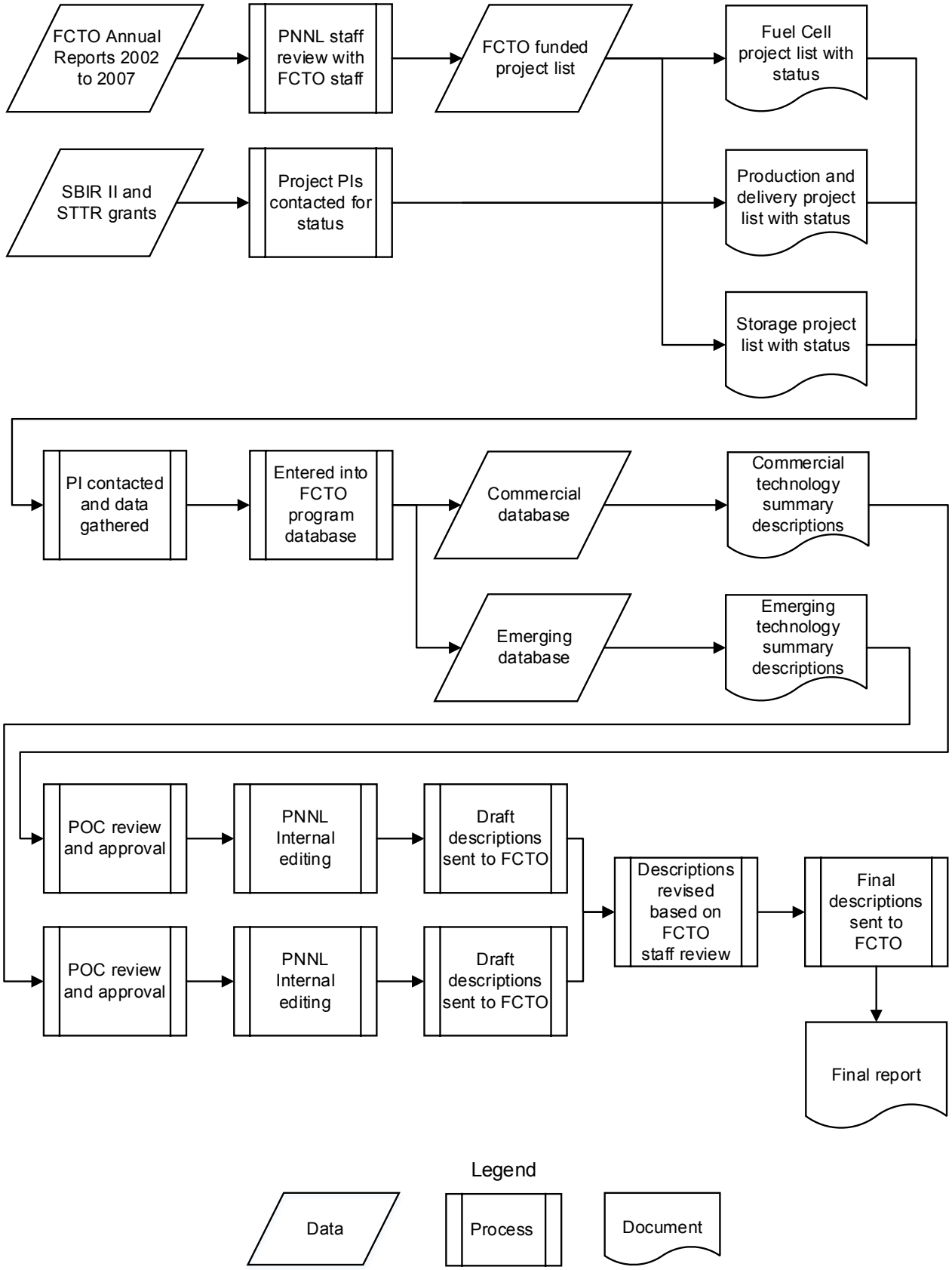

Figure 2.2. Initial Technology Tracking Process for Hydrogen and Fuel Cell Technologies

3.0 Results

The results of the efforts undertaken in the FCTO technology tracking project are summarized in this chapter. Section 3.1 describes the patent search and analysis and Section 3.2 describes the results of the commercial and emerging technology identification and tracking effort.

3.1 Patent Search and Analysis

The results of the patent search are shown in tables in Appendix B; the 299 fuel cell patents are listed in Appendix B.1, the 213 hydrogen production/delivery patents are listed in Appendix B.2, and the 77 hydrogen storage patents are listed in Appendix B.3. The patents are listed in chronological order from the most recent to the oldest patent for each group. The tables list the patent number, award date, organization receiving the patent, patent title, patent description, and patent status.

Figure 3.1 shows the cumulative number of patents awarded over time, starting with 2007 patent awards through 2015 (at the time of this report, data for 2015 were only partially available). From 2007 through 2014, an average of 46 patents per year were awarded. During the same time frame, fuel cell, production/delivery, and storage patents were awarded at an average rate of 23, 17, and 7 patents per year, respectively. As the figure shows, the number of patents awarded per year increased significantly in 2009 and 2010. To date, 2010 had the largest number of patents awarded in an individual year: 37 fuel cell patents, 24 production/delivery patents, and 11 storage patents.

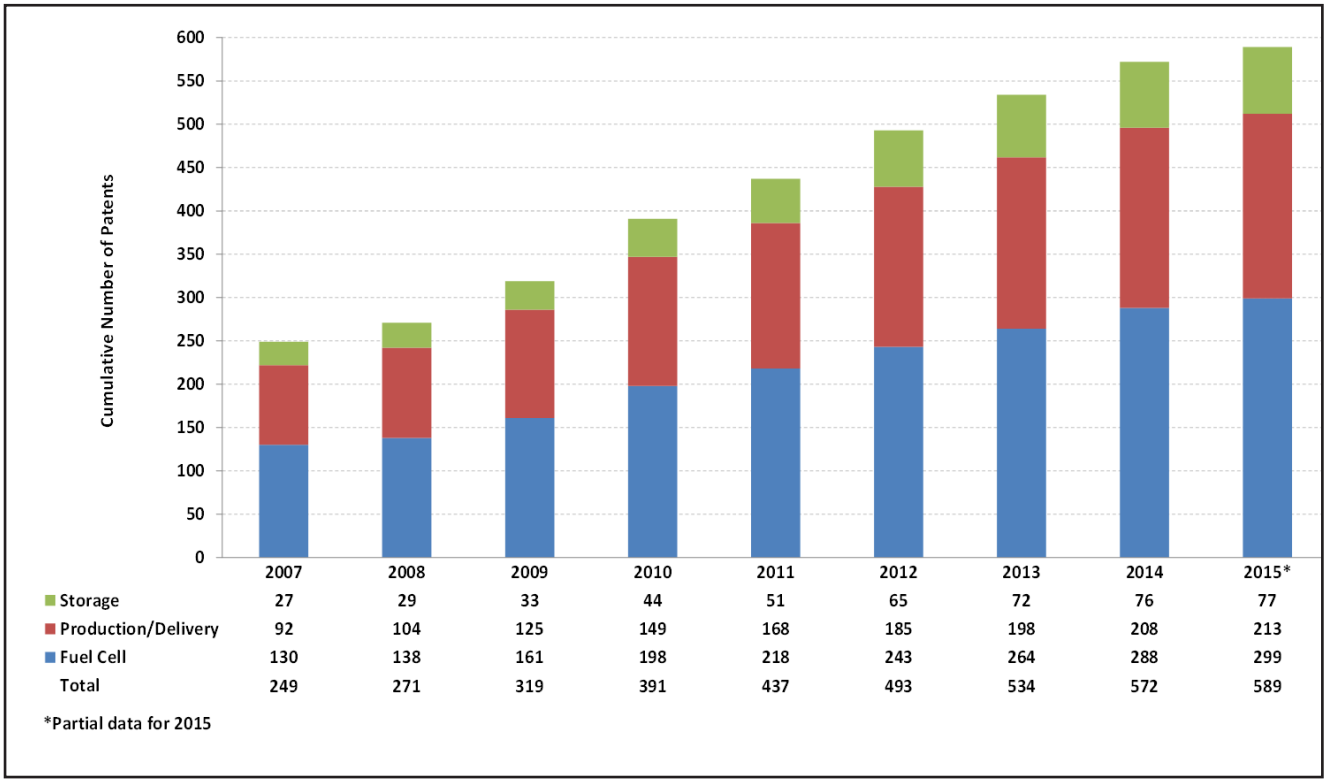

Figure 3.1. Cumulative Number of Patents Awarded over Time

Another way to view the patent awards, shown in Figure 3.2, is by the type of organization that received the patent or the inventor's employer. Three types of organizations were identified: national laboratories (227 patents), private companies (275 patents), and universities (87 patents). National laboratories and private companies account for 91% of all patents awarded for fuel cell technologies; private companies receive 53% of the awards. Private companies had more patent awards in the production/delivery area (47%) than national laboratories (32%), while universities had 21% of the production/delivery patents. National laboratories account for 60% of the storage patents, followed by universities and private companies each with 19%.

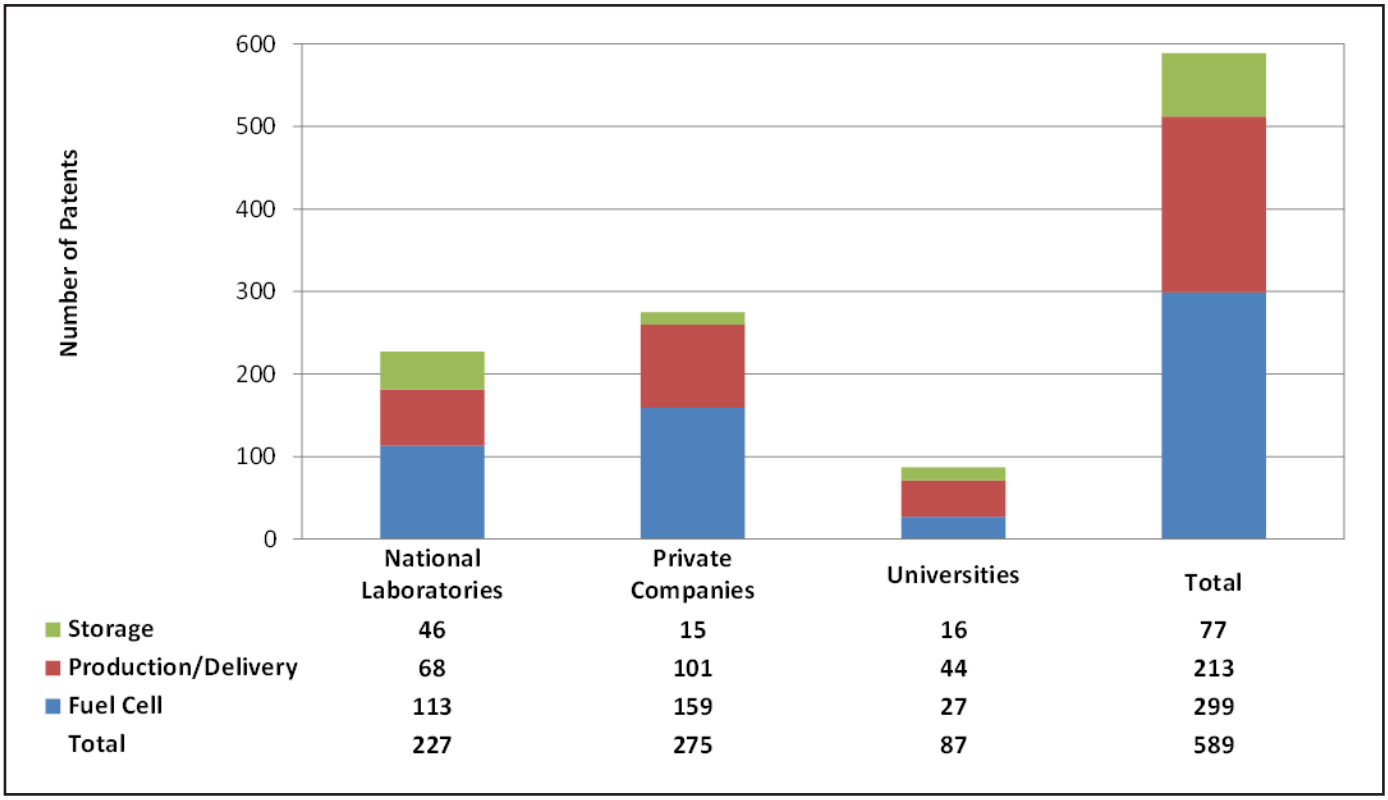

Figure 3.2. Types of Organization Receiving Patent Awards

Figure 3.3 shows the patent award status by use. As the figure shows, 27 patents are used in commercially available products. These 27 patents are associated with the 13 commercial technologies as listed below:

- Cathode Catalysts and Supports for PEM Fuel Cells, 3M Company – Patent number 8,227,140 (2012)
- Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells, Dynalene, Inc. – Patent number 7,138,199 (2006)
- Conductive Compound for Molding Fuel Cell Bipolar Plates, LANL – Patent number 6,248,467 (2001)
- Corrosion Test Cell for PEM Bipolar Plate Materials, LANL – Patent number 6,454,922 (2002)
- FARADAYIC® ElectroEtching of Stainless Steel Bipolar Plates, Faraday Technology, Inc. – Patent number 8,329,006 (2012)
- Hydrogen Generation from Electrolysis, Proton OnSite[1] – Patent numbers 7,850,838 (2010), 7,744,733 (2010), 7,678,251 (2010)
- H2 ProGen: A Total Supply Solution for Hydrogen Vehicles, Gas Technology Institute – Patent number 7,059,364 (2006)
- HRS-100™ Hydrogen Recycling System, H2Pump, LLC – Patent numbers 8,734,632 (2014) and 8,663,448 (2014)

- Intellipigment™: Visible Hydrogen Gas Leak Detection Material, University of Central Florida – Patent numbers 8,703,642 (2014), 8,652,993 (2014), 8,623,662 (2014), 8,591,818 (2013), 8,268,392 (2012), 8,048,384 (2011), 8,003,055 (2011)
- Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions, 3M Company – Patent numbers 8,481,227 (2013), 8,323,809 (2012), 7,838,138 (2010), 7,572,534 (2009), 7,517,604 (2009)
- Portable Reformed Methanol Fuel Cells, LLNL – Patent number 6,960,235 (2005)
- Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production, Catacel Corporation – Patent numbers 8,721,973 (2014), 7,906,079 (2011)

Sixty-seven patents are part of research now taking place on emerging technologies identified in the technology tracking list in Appendix A. In addition, 322 awarded patents are still being used via continuing research and/or active attempts to license the patent. Of all the patents reviewed, 71% are still actively being pursued through use in continuing research, emerging technologies, or commercially available products.

[1] Formerly Proton Energy Systems, Inc.

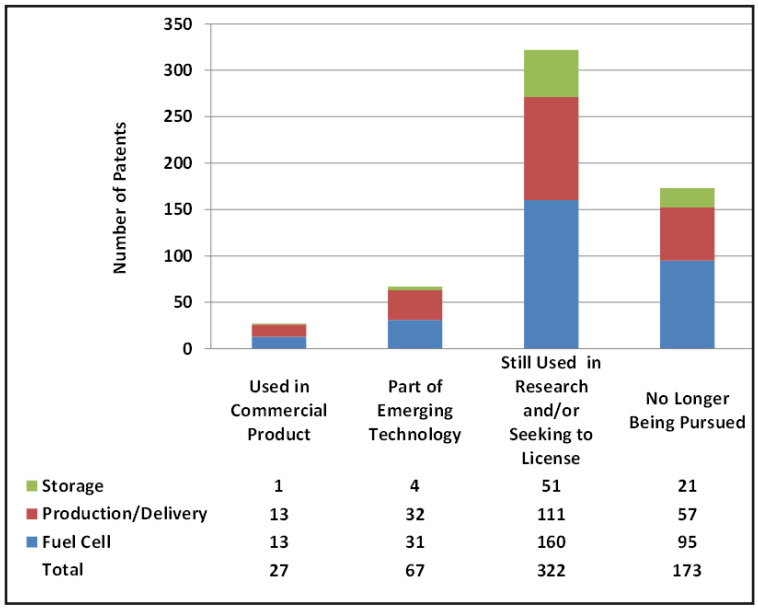

Figure 3.3. Status of Awarded Patents

3.2 Commercial and Emerging Technology Identification and Tracking Results

The FCTO Technology Tracking Database is updated annually and currently contains 32 commercially available technologies, all of which are described in Appendix C. Because some patents or technologies may no longer be in use in out years, the number of active commercial technologies may change from year to year. These descriptions were reviewed and approved by the industry POC for each technology. Figure 3.4 shows the cumulative number of commercial technologies entering the market. Of the 46 technologies that have entered the market 12 of them are no longer commercially available and 2 companies decided not to continue to participate in the technology tracking effort. From 2000 through 2014, three technologies per year entered the market. The years 2000 through 2006 showed a steady addition of technologies entering the market of 1.5 per year. For 2007 through 2014, an average of 4 technologies per year entered the market. In 2015, one technology has entered the market to date.

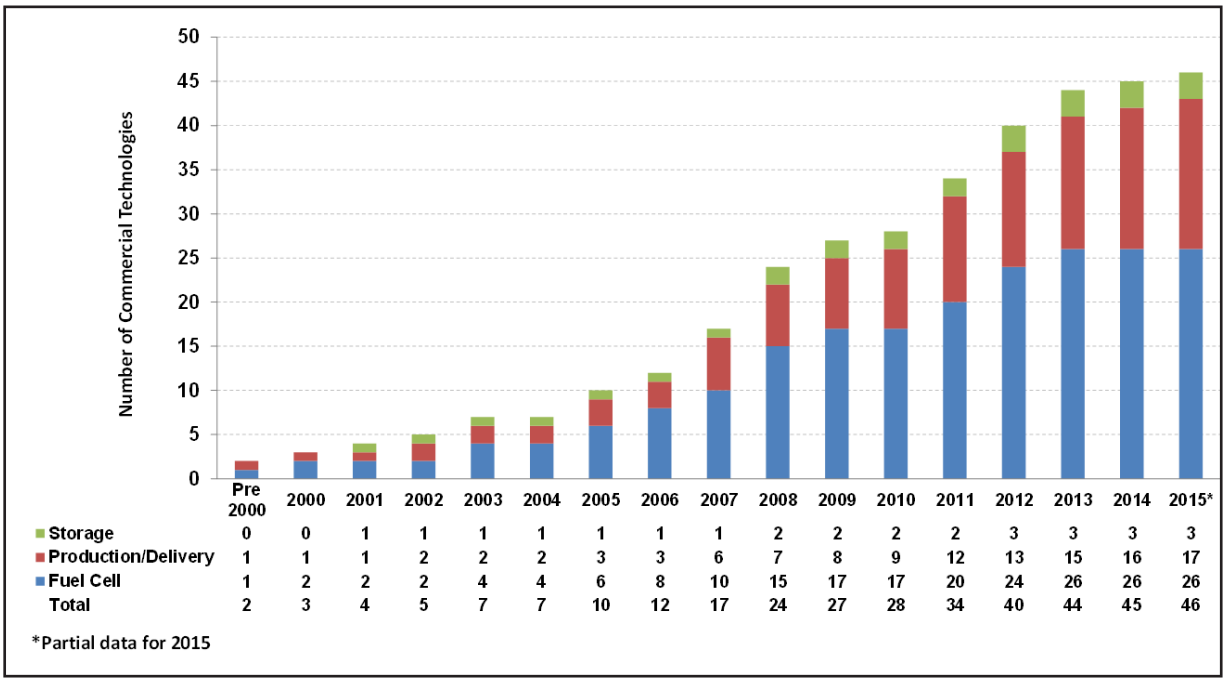

Figure 3.4. Cumulative Number of Commercial Technologies Entering the Market

Table 3.1 briefly describes each of the 18 commercially available fuel cell technologies and their benefits. All tables are included at the end of this chapter. The full descriptions of these technologies are provided in Appendix C.1. These technologies range from an analysis tool to manufacturing processes for fuel cells and their components, to entire fuel cell systems that can be used in vehicles or stationary applications.

Table 3.2 briefly describes each of the 13 commercially available production/delivery technologies and their benefits. The full descriptions of these technologies are provided in Appendix C.2. These technologies include improved catalysts, hydrogen generation systems for fueling vehicles, and technologies for providing high-purity hydrogen.

Table 3.3 briefly describes the one commercially available storage technology and its benefits. The full description of this technology is provided in Appendix C.3. The technology is a composite tank.

FCTO's Multi-Year Research, Development and Demonstration Plan, which was last updated in FY 2015, was examined to see how the commercially available technologies align with FCTO's objectives and goals. The plan lists challenges, tasks, and technology pathway items for the research areas funded by FCTO. The fuel cell area listed 10 tasks. The 18 commercially available technologies in Table 3.1 are aligned with 7 of these tasks, as shown in Table 3.4. Similarly, the 13 commercially available production/delivery technologies in Table 3.2 were found to align with 4 of the 11 challenges/items in that area, as shown in Table 3.5. The commercially available storage technology in Table 3.3 was found to align with 1 of the 3 storage challenges, as shown in Table 3.6.

The technology tracking database currently contains 68 emerging technologies for which descriptions are provided in Appendix D. These were reviewed and approved by the industry POC for each technology. Figure 3.5 shows the number of emerging technologies in each FCTO research area over the past 7 years of the technology tracking effort. Since 2009, the number of fuel cell emerging technologies has been about half of the total, with emerging storage technologies making up a very small percentage. Figure 3.6 shows the FY 2015 distribution of the emerging technologies in the three FCTO research areas.

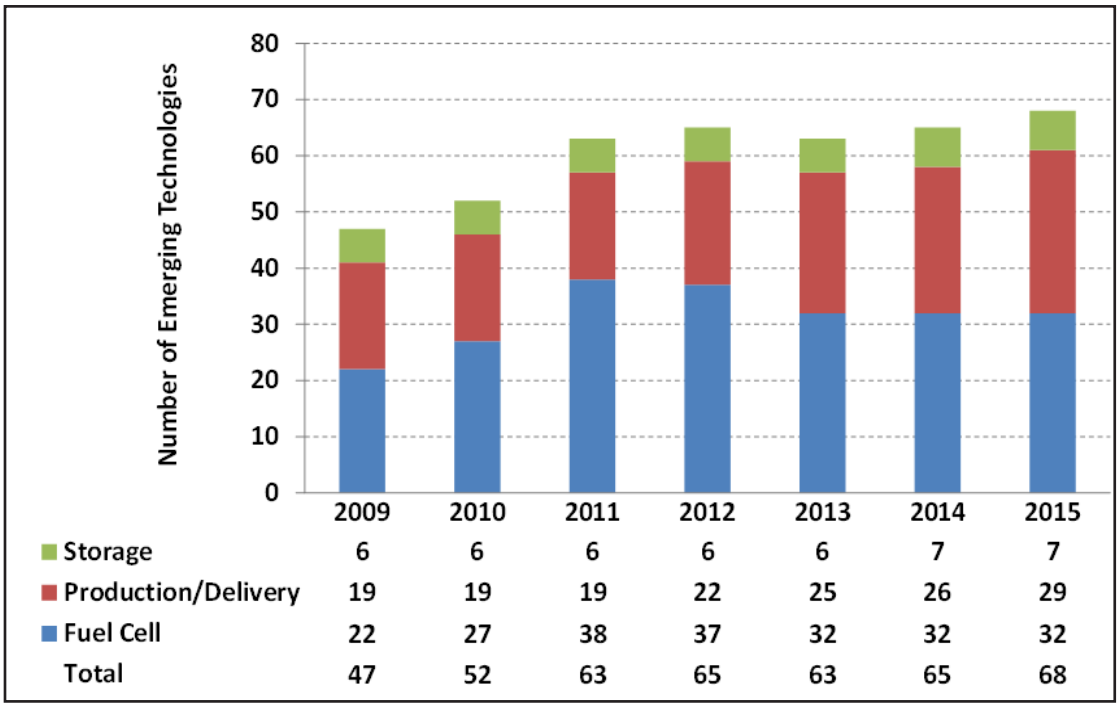

Figure 3.5. Number of Emerging FCTO Technologies

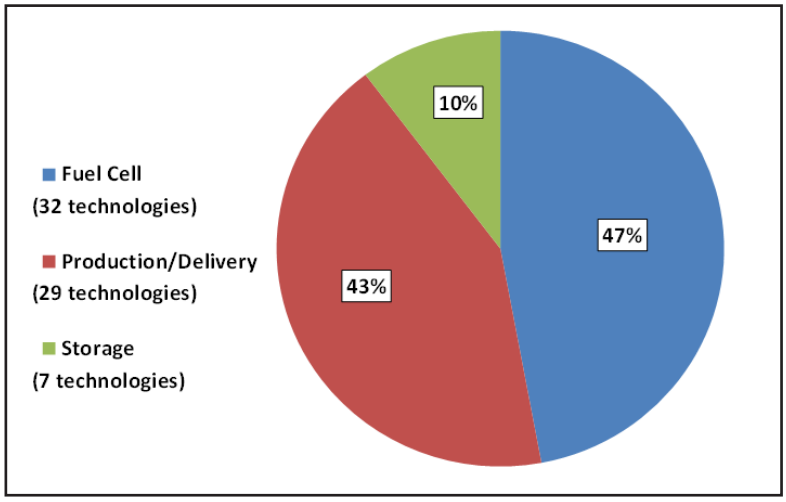

Figure 3.6. Distribution of Emerging FCTO Technologies in FY 2015

Table 3.7 briefly describes each of the 32 emerging fuel cell technologies and their benefits. The full descriptions of these technologies are provided in Appendix D.1. These technologies are quite diverse and include improved fuel cell components, such as membranes, plates, assemblies, cathodes and sensors, as well as entire systems for various uses.

Table 3.8 briefly describes each of the 29 emerging production/delivery technologies and their benefits. The full descriptions of these technologies are provided in Appendix D.2. These technologies include improved membranes, reformers, and compressors, as well as novel methods and fuels to produce hydrogen.

Table 3.9 briefly describes each of the 7 emerging storage technologies and their benefits. The full descriptions of these technologies are provided in Appendix D.3. These technologies include improved tanks or cylinders, as well as new approaches for storing hydrogen.

The 32 emerging fuel cell technologies in Table 3.7 are aligned with 6 of the 10 fuel cell tasks in the FCTO Program Plan, as Table 3.10 shows. Also, one topic in the manufacturing research area of the plan for PEM fuel cells is aligned with 4 emerging fuel cell technologies. Similarly, the 29 emerging production/delivery technologies in Table 3.8 are aligned with 8 of the 11 production and delivery items or challenges in the plan, as shown in Table 3.11. The 7 emerging storage technologies in Table 3.9 are aligned with 3 of the 4 challenges in the storage area, as shown in Table 3.12.

An alphabetized directory of the organizations that developed the commercial and emerging technologies described in Appendices C and D is provided in Appendix E.

3.3 Jobs Created or Retained as a Result of Commercially Available Technologies

Beginning in FY 2011, the PNNL team asked commercial technology POCs to estimate the number of jobs created or retained as a result of FCTO-funded technology development and commercialization. The types of jobs reported by the POCs include R&D, engineering, manufacturing, and marketing/sales jobs within their organizations. Figure 3.7 shows the number of jobs created or retained in FY 2011, FY 2012, FY 2013, FY 2014 and FY 2015 based on the responses from the POCs.[2] These numbers do not include estimates for indirect jobs. For example, the associated supply chain jobs (e.g., balance-of-plant components, stack materials, etc.) for a fuel cell system are excluded. Figure 3.8 shows the FY 2015 distribution of jobs created or retained in the three FCTO research areas.

[2] Some POCs declined to provide an estimate of the number of jobs created/retained due to business confidentiality.

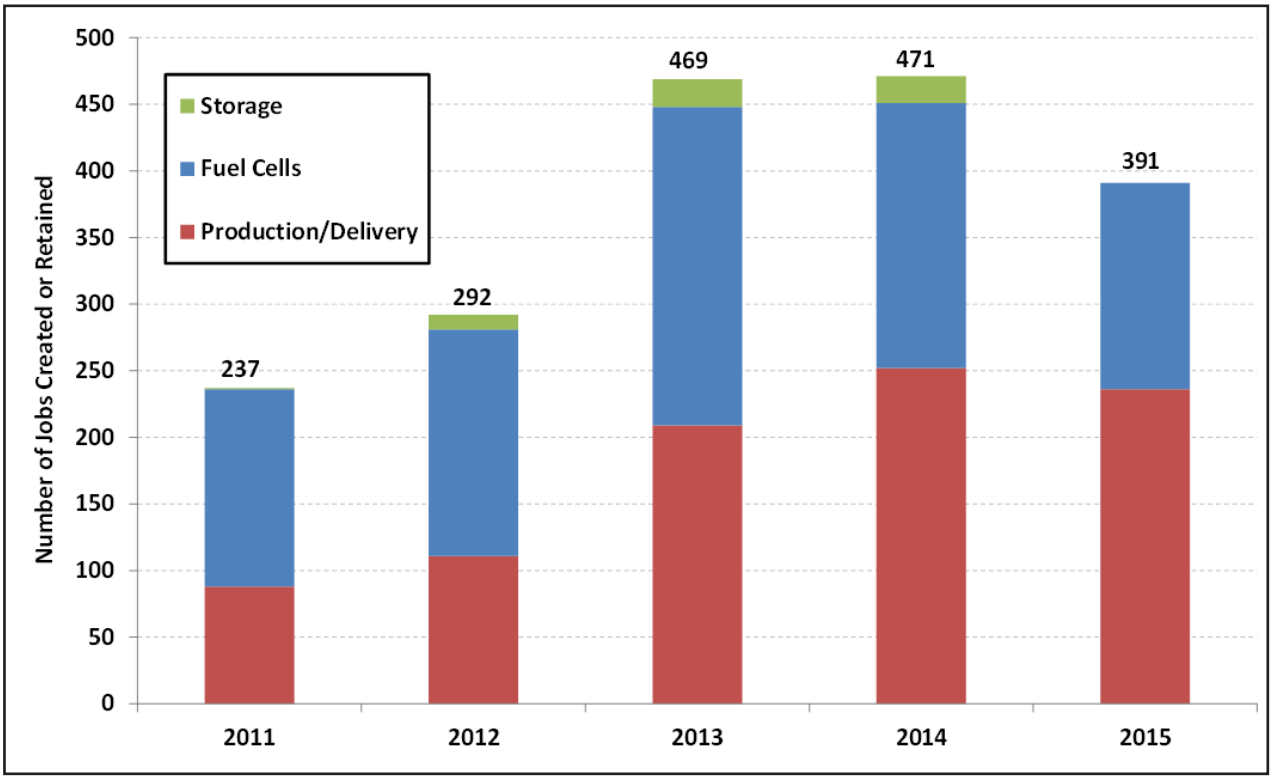

Figure 3.7. Jobs Created or Retained as a Direct Result of Commercially Available Technologies

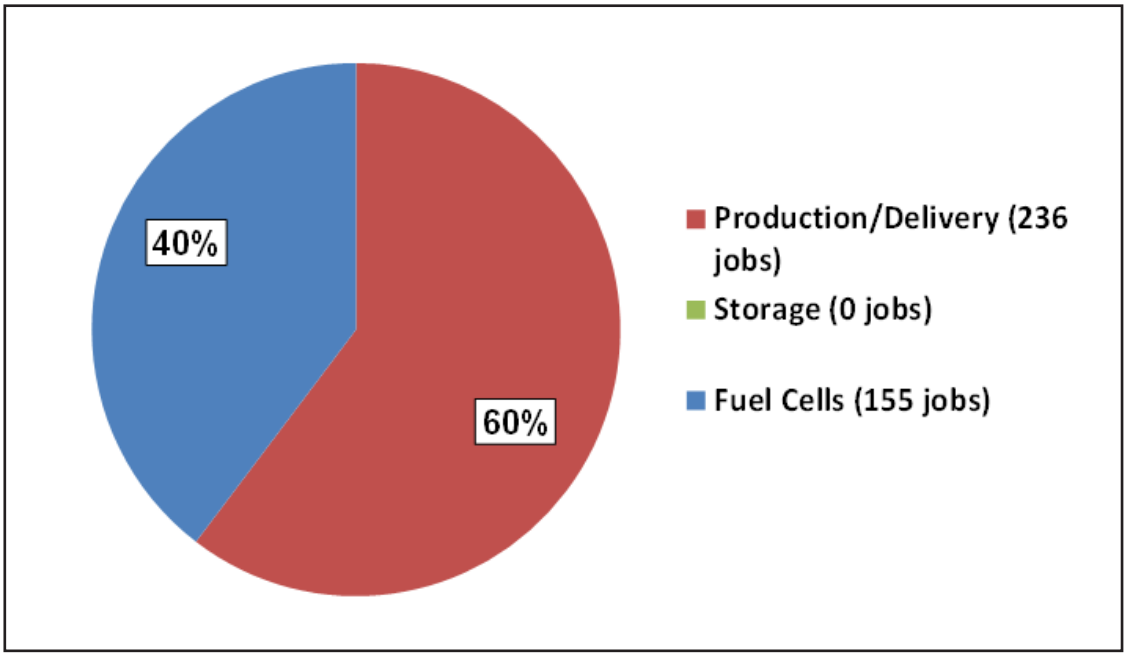

Figure 3.8. Distribution of Jobs Created or Retained in FY 2015

Table 3.1. Commercial Products Summary – Fuel Cells

Technology	Organization	Description	Benefits	Commercial Status
Bio-Fueled Solid Oxide Fuel Cells (SBIR Project)	TDA Research, Inc.	A novel catalyst and high-capacity sorbent were developed that allows biogas to be used in SOFCs.	This new technology allows SOFCs to operate on biogas as an alternative to natural gas.	Commercialized in 2011.
Cathode Catalysts and Supports for PEM Fuel Cells	3M Company	The membrane electode assembly (MEA) uses a carbon-free nanostructured thin-film catalyst and an ion-exchange membrane to achieve longer lifetimes using fewer precious metals.	The technology reduces costs because of lower precious metal loading and manufacturing costs, improved durability, and smaller fuel cell size. It can operate at higher temperatures and lower humidity.	Commercialized in 2007 and selling to select fuel cell developers.
Compact, Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.	The 1-kW modular, multi-fuel SOFC system is designed to produce electricity and heat for multiple mobile and onsite stationary applications.	The SOFC system is inherently flexible and sulfur tolerant and can operate on multiple renewable and conventional fuels, including biodiesel, vegetable oils, ethanol, diesel, kerosene, natural gas, and propane.	Commercialized in 2012 with demonstration units provided to several potential customers.
Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.	The complex coolant fluid consists of a base mixture and additives of non-ionic corrosion inhibitors and ion-suppressing nanoparticles, which maintain low electrical conductivity.	The technology eliminates de-ionizing filters, thereby reducing the overall cost and maintenance of the fuel cell while increasing the amount of time the cell can run continuously.	Commercialized in 2009.
Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.	The compound is a graphitized thermoset vinyl-ester, which is molded and used in producing bipolar plate (BPP) assemblies. (This technology was based on a technology licensed from Los Alamos National Laboratory.)	The compound allows thinner and less-expensive BPP assemblies to be produced; eliminates the need for expensive corrosion-resistant coatings; provides greater part flatness, creep resistance, and dimensional stability; and facilitates large-volume commercial production.	Commercialized in 2000.
Corrosion Test Cell for PEM Bipolar Plate Materials	Fuel Cell Technologies, Inc.	To screen materials that could be used in producing corrosion-resistant BPPs, the test cell simulates, as closely as possible, the conditions at the anode and cathode of a PEM fuel cell. (This technology was based on a technology licensed from Los Alamos National Laboratory.)	The test cell reduces the costs of traditional fuel cell corrosion tests, shortens the fuel cell development time, and allows for an intermediate level of BPP material screening between potentiostatic measurements and long-term fuel cell tests.	Commercialized in 2008.
Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc. *	The steam reforming module for producing hydrogen is designed to be cyclable (daily start/stop for 5 years) and runs at low pressure.	The system produces a low-cost supply of hydrogen (compared with bottles) and can minimize thermal cycling induced stress and exposure, thus increasing the lifetime of the module.	Commercialized in 2009 and being used to supply hydrogen for material-handling equipment.

* Note: acquired by Hyster-Yale

Table 3.1. Commercial Products Summary – Fuel Cells (Cont'd)

Technology	Organization	Description	Benefits	Commercial Status
FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates (SBIR Project)	Faraday Technology, Inc.	The new manufacturing process, FARADAYIC ElectroEtching, is based on electrochemical through-mask etching and is producing stainless steel BPPs with flow channel designs that cannot be manufactured cost-effectively using more conventional machining techniques.	The new manufacturing process reduces the overall manufacturing cost of BPPs through use of a high-volume batch process with low capital equipment and tooling costs.	Commercialized in 2012 and a patent awarded in December 2012.
GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory	The GCtool allows designers to model, analyze, and manipulate different configurations of fuel cell propulsion systems without building a functional prototype in order to address issues such as thermal and water management, design-point and part-load operations, and fuel economies.	The model saves users time and money while exploring various fuel cell system configurations. It provides developers with a library of models for subcomponents and allows them to incorporate their own models.	Began licensing in 1999.
GenDrive™ Fuel Cell Power System (American Recovery and Reinvestmet Act [ARRA] Project)	Plug Power Inc.	A fuel-cell-based power source for electric forklift fleets that increases fleet productivity and improves forklift performance compared to conventional lead-acid batteries.	The system can be refueled with hydrogen in less than 3 minutes (compared to 10 minutes or more for a battery change), allowing operators to spend more time moving product out on the floor. Constant voltage is provided throughout the entire shift, eliminating the performance degradation experienced with batteries.	More than 2,500 units are currently in use.
Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods (SBIR Project)	NuVant Systems Inc.	The MEA testing equipment is composed of two devices, an array potentiostat (Arraystat™) and a parallel array flow-field fuel cell, which allow rapid, accurate testing under realistic operating conditions.	The equipment allows for the preparation and testing of various MEAs in a single test stand with high throughput under realistic catalyst loadings and reactant flow rates. This eliminates random error introduced by multiple test stands and reduces the costs associated with testing MEAs.	The Arraystat was commercialized in 2006 and the parallel array fuel cell in 2007. To date seven Arraystats and seven parallel array fuel cell test units have been sold.
Low-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.	A low-cost fabrication process produces durable, low-contact resistance metallic BPPs for use in PEM fuel cells for automotive, stationary and portable power applications.	The new process reduces costs by using commercially available, stainless steel, low-cost carbon steel or aluminum as substrate materials and by reducing or eliminating the use of more expensive electrically conductive materials.	Commercialized in 2011.
Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership	The seals, used in fuel cell assemblies, use a custom elastomer and carrier material that provide an interfacial design that exhibits improved chemical and mechanical properties compared with conventional silicons.	The seals increase durability, which reduces fuel cell operation and maintenance costs, and eliminates catalyst poisoning concerns in the fuel cell. The system can be mass-produced and leads to shorter fuel cell assembly time.	Commercialized in 2009.

Table 3.1. Commercial Products Summary – Fuel Cells (Cont'd)

Technology	Organization	Description	Benefits	Commercial Status
Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions	3M Company	The MEAs use a low equivalent weight, perfluorinated sulfonic acid-based membrane with improved chemical and mechanical stability, and proton conductivity.	The new MEA has improved durability and performance with increased lifetimes while operating under hot (up to 120°C), dry conditions.	Commercialized in 2006 with sales to a wide variety of fuel cell customers for stationary and automotive applications.
Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation	The one-step molding process creates the structure necessary to seal the stack and five-layer MEAs. Two portable power system product lines for military customers are now using it.	The process lowers costs because fewer components with lower tolerances are used. It reduces part count and manufacturing time and improves stack fabrication reliability.	Delivered over 30 M250-CX and M300-CX systems through 2011.
Orion™: Fuel Cell Technology for Hybrid Power Applications	Nuvera Fuel Cells, Inc. *	A fuel cell stack design that improves fuel cell performance under subfreezing conditions. The ORION™ uses higher current density operation (1.3 A/cm^2) to increase the power density of the stack (300 W per cell) and reduce its thermal mass, enhancing freeze starting ability.	The new fuel cell improves startup performance in applications involving subfreezing conditions, such as automobiles, forklifts, and auxiliary power units. The stack achieves 50% of rated power in 28 seconds from a startup temperature of -20°C.	Commercialized in 2013.
Portable Reformed Methanol Fuel Cells	UltraCell Corporation	The XX25 fuel cell, using methanol as a fuel source, is a self-contained, 25-W output power system that can be used by individual soldiers for portable power. Fuel cartridges can be hot swapped for continuous operation, and the fuel cell can be hybridized with external batteries for high power peaks or with a 5-gallon fuel tank for long run time.	The fuel cell features a rugged, lightweight (1.24 kg), reliable power system that uses a contained fuel with no toxic byproducts during use. It contains no moving parts that can fail.	Commercialized in 2007.
Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC	The new gas diffusion layer (GDL) manufacturing process produces continuous rolls of GDL material and reduces GDL fabrication costs by 60%. Cost-saving measures used in the process include replacing batch processes with continuous ones, implementing on-line control systems, and reducing the number of process steps.	The new process reduces GDL costs through high-volume manufacturing and improves GDL quality and uniformity by using real-time process monitoring.	New process now being used to manufacture GDLs at Ballard.

* Note: acquired by Hyster-Yale

Table 3.2. Commercial Products Summary – Production/Delivery

Technology	Organization	Description	Benefits	Commercial Status
California Hydrogen Refuling Stations	Air Products and Chemicals, Inc.	Stationary and mobile refueling stations with differing hydrogen supply methods that were developed to demonstrate hydrogen delivery infrastructure and improve hydrogen fueling station technologies through consumer feedback.	The stations demonstrate the ability to deliver hydrogen using a variety of methods (over-the-road, pipeline, and a connection to a nearby source of anaerobic digester gas). The mobile delivery trailer can provide liquid hydrogen and high-pressure gaseous hydrogen.	Commercial production and delivery of hydrogen under contract began in 2013.
H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	Atlas Copco	The integrated, onsite hydrogen generation, purification, compression, storage, and dispensing system deploys quickly and produces 20 to 200 kg of hydrogen per day by reforming natural gas, propane, E-85, biodiesel, or other liquids. Alternatively, it can use electrolysis for hydrogen production. The dispenser can be purchased individually or as part of the system.	The system can produce hydrogen from various sources, achieves full-cycle energy savings compared with trucked-in hydrogen, and is delivered as a pre-assembled system, thereby minimizing costs and setup time.	Commercialized in 2007, with one fuel station in use at the University of Texas in Austin.
High Performance Palladium-Based Membrane	Pall Corporation	The palladium-based membrane works as a selective barrier to let only H_2 pass through by using sophisticated high-temperature analysis and inorganic membrane development/manufacturing techniques.	The membrane can be economically integrated into the overall H_2 production process and is easily scalable to industrial applications.	Commercialized the AccuSep® Pd membrane module in 2011.
HRS-100™ Hydrogen Recycling System (SBIR Project)	Sustainable Innovations, LLC	An electrochemical hydrogen recovery system that separates hydrogen from a mixed gas stream (e.g., furnace exhaust), purifies it, and pumps it back into the feed stream of an industrial process. The system can recycle up to 100 kg-H_2/day (1,600scfh) and recovers up to 90% of the hydrogen present in the exhaust stream.	The system reduces hydrogen feedstock costs for industrial processes by recovering previously wasted hydrogen at a lower cost than would be required for a new supply.	Commercialized in 2014.
Hydrogen Generation from PEM Electrolysis	Proton OnSite	The HOGEN® electrolysis-based hydrogen generator incorporates a PEM and produces 99.999% pure hydrogen at 90 to 275 grams per hour at pressures up to 400 psi without requiring additional compression.	The system is very compact, can be installed in less than a day, is very reliable, and produces high-purity hydrogen.	Commercialized the HOGEN S series in 1999, selling 187 units in the U.S. and 228 internationally through 2011. Commercialized the HOGEN H series in 2004, selling 88 units in the U.S. and 90 internationally through 2011. Commercialized the HOFEN C series in 2011, selling 2 units in the U.S. and 3 internationally.

Table 3.2. Commercial Products Summary – Production/Delivery (Cont'd)

Technology	Organization	Description	Benefits	Commercial Status
Hydrogen Safety Sensor for Energy Applications	NexTech Materials, Ltd.	A chemi-resistive three-phase ceramic sensor exhibits a highly sensitive (500 ppm to 1%), selective (no interference from CO, CH_4, or VOC), and rapid response to the presence of hydrogen in ambient air, even with varying humidities and background combustible gases.	Because of its low materials and fabrication cost, minimal power consumption, and wide detection range, the sensor lends itself to wide-scale implementation in any application requiring the safe use or handling of hydrogen gas. It is durable and reliable, with fast response and recovery times.	Commercialized in 2010.
Intellipigment™: Visible Hydrogen Gas Leak Detection Material	HySense Technology, LLC	A palladium oxide pigment that changes color in the presence of hydrogen and can be used to identify hydrogen gas leaks in industrial settings. The pigment is used in a tape form that can easily be wrapped around pipes, flanges, valves, and other leak-prone locations.	The Intellipigment™ tape identifies hydrogen leaks quickly (response times of 20 seconds with 100% H_2 gas and less than 3 minutes with 1% H_2 gas) at the exact leak location. The fast, accurate leak detection improves workplace safety and reduces the time/costs associated with leak detection and lost hydrogen gas.	Commercialized in 2013.
ME100 Methanol Reforming Hydrogen Generator (SBIR Project)	REB Research & Consulting	The generator is constructed with palladium-coated membranes within the reactor zone and can produce 99.99995% pure hydrogen independent of back-pressure changes or variable loads at a variable rate of up to 10 kg/day at pressures up to 40 psig.	The generator produces very high purity independent of back pressure changes caused by varying fuel cell demand. It produces hydrogen at costs far lower than bottled gas from a readily available feedstock (methanol). The system is compact, reliable, and ideal for remote and mobile applications.	Commercialized in 2002.
Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.	The water gas shift catalysts are based on ceria-supported precious metals that can be tailored to specific reactions/ conditions (i.e., steam reforming and/or the partial oxidation of various hydrocarbons) and can be used for small reactors and/or reactors with multiple startup-shutdown cycles.	The catalysts are available in multiple forms and allow applications to perform efficiently over a wide range of temperatures.	Commercialized in 2005.
Novel Catalytic Fuel Reforming	InnovaTek, Inc.	The hydrogen generator reforms multiple fuel types (natural gas, gasoline, and diesel) to produce pure hydrogen by integrating microreactor and microchannel heat exchanger technology with sulfur-tolerant catalysts and membranes.	The generator system can produce 30 to 150 grams of hydrogen per hour that can be used to fuel a 1- to 5-kW polymer electrolyte membrane fuel cell or other auxiliary power unit.	Commercialized in 2015.
PEM Electrolyzer Incorporating a Low-Cost Membrane	Giner Electrochemical Systems, LLC (GES)	An electrolysis system that produces 0.5 kg-H_2/hr at 350 psig and uses a dimensionally stable membrane with improved durability under high-pressure conditions.	The electrolyzer stack capital cost has been reduced to <$500/kW by using low-cost materials, lower catalyst loading, and a reduced part count per cell. The system can make use of renewable electricity sources such as wind and solar.	Commercialized in 2011. GES has delivered 6 stacks and has taken orders for several more.

Table 3.2. Commercial Products Summary – Production/Delivery (Cont'd)

Technology	Organization	Description	Benefits	Commercial Status
Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.	During hydrogen production via steam reforming, a drop-in replacement for the loose ceramic media eliminates the periodic replacement required in conventional ceramic packed beds.	The drop-in replacements lower costs, increase performance, and minimize maintenance costs and inconveniences.	Commercialized in 2012 with one international sale and one domestic unit being installed
TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Hexagon Lincoln*	The large composite tank for storing and transporting compressed hydrogen gas over road, rail, or water has an internal volume of 8,500 liters and contains 150 kg of hydrogen at 3,600 psi. Four of these tanks are mounted in a frame for transport and a system for loading, unloading, and pressure relief has been designed and implemented.	The tank and frame system reduces costs by improving volumetric hydrogen storage capacity compared to conventional tube trailers, while meeting strength, environmental, and durability targets.	Commercialized in 2011.

* Note: Formerly Lincoln Composites, Inc.

Table 3.3. Commercial Products Summary – Storage

Technology	Organization	Description	Benefits	Commercial Status
Hydrogen Composite Tanks	Quantum Technologies, Inc.	For storage applications at 5,000 and 10,000 psig, the hydrogen tank uses a seamless, one-piece, ultra-high-molecular-weight polymer liner wrapped in layers of a carbon fiber/epoxy laminate and a proprietary external protective layer for impact resistance.	The 10,000-psig tank offers a high-capacity, lightweight, safe hydrogen storage system that exceeds regulatory safety requirements and may increase a hydrogen-powered vehicle's driving range by >55% compared with equivalent-sized 5,000-psig tanks.	Commercialized in 2001.

Table 3.4. Fuel Cell Tasks and Related Commercial Technologies

Tasks*	Technology Title	Organization
Catalysts/Electrodes	Cathode Catalysts and Supports for PEM Fuel Cells	3M Company
	Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems Inc.
Electrolytes	Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions	3M Company
Fuel Cell Systems	Bio-Fueled Solid Oxide Fuel Cells	TDA Research, Inc.
	Compact, Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.
	Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc. **
	GenDrive™ Fuel Cell Power System	Plug Power Inc.
	Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation
	Portable Reformed Methanol Fuel Cells	UltraCell Corporation
Membrane Electrode Assemblies, Gas Diffusion Media, and Cells	Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC
Seals, Bipolar Plates, and Interconnects	Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.
	Corrosion Test Cell for PEM Bipolar Plate Materials	Fuel Cell Technologies, Inc.
	FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates	Faraday Technology, Inc.
	Low-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.
	Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
Systems BOP Components	Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.
	Orion™: Fuel Cell Technology for Hybrid Power Applications	Nuvera Fuel Cells, Inc. **
Testing and Technical Assessment	GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory

* Note: The fuel cell tasks are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf.

** Note: acquired by Hyster-Yale

Table 3.5. Production/Technology Pathway Items and Delivery Challenges and Related Commercial Technologies

Technology Pathway Items or Challenges*	Technology Title	Organization
Containment	TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Hexagon Lincoln
Distributed reforming of renewable liquid feedstocks	H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	Atlas Copco
	ME100 Methanol Reforming Hydrogen Generator	REB Research & Consulting
	Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.
	Novel Catalytic Fuel Reforming	InnovaTek, Inc.
	Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.
Electrolysis	California Hydrogen Refueling Stations	Air Products and Chemicals, Inc.
	Hydrogen Generation from PEM Electrolysis	Proton OnSite
	PEM Electrolyzer Incorporating a Low-Cost Membrane	Giner Electrochemical Systems, LLC
Separation and purification systems	High Performance Palladium-Based Membrane	Pall Corporation
	HRS-100™ Hydrogen Recycling System	Sustainable Innovations, LLC
	Hydrogen Safety Sensor for Energy Applications	NexTech Materials, Ltd.
	Intellipigment™: Visible Hydrogen Gas Leak Detection Material	HySense Technology, LLC

* Note: These production technology pathway items are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf and for delivery challenges at http://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf

Table 3.6. Storage Challenges and Related Commercial Technologies

Challenges*	Technology Title	Organization
Physical Storage	Hydrogen Composite Tanks	Quantum Technologies, Inc.

* Note: The storage challenges are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf

Table 3.7. Emerging Products Summary – Fuel Cells

Technology	Organization	Description	Benefits
Alternative and Durable High-Performance Cathode Supports for PEM Fuel Cells	Pacific Northwest National Laboratory	A support structure for cathodes used in PEM fuel cells. The technology takes advantage of the stable interface between platinum, a conductive metal oxide, and a honeycombed carbon support.	The support structures increase cathode performance and durability, and are synthesized using a method that can be easily scaled up for high-volume manufacturing.
Dimensionally-Stable High-Performance Membrane (SBIR Project)	Giner Electrochemical Systems, LLC	The robust PEM material uses a high-performance plastic support structure, which allows lower-equivalent-weight ionomers to be used without forfeiting mechanical durability.	Because of its mechanical properties, the new membrane prevents stress-induced failure and improves performance at low humidity and high temperature.
Direct Methanol Fuel Cell (DMFC) Anode Catalysts	National Renewable Energy Laboratory	An improved anode catalyst for direct methanol fuel cells. The catalyst is manufactured using ion implantation and magnetron sputtering of platinum-ruthenium (PtRu) on high-surface-area carbon support materials.	The new PtRu catalyst materials have shown up to 30% improvement in methanol oxidation reaction activity and increase the durability of membrane electrode assemblies.
Direct Methanol Fuel Cell for Handheld Electronics Applications (ARRA Project)	MeOH Power	The Mobion® DMFC uses passive means for water and air management to simplify the conventional DMFC process, resulting in a smaller and simpler fuel cell for handheld applications. Received ARRA funding to facilitate commercialization.	The device uses methanol fuel instead of hydrogen, avoiding hydrogen-handling issues. Using micro fuel cells for handheld electronics may extend device operating times between charges and enhance device versatility.
Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors (SBIR Project)	InnoSense, LLC	The hydrogen sensor was developed using high-output, inkjet printing manufacturing techniques and detects hydrogen at concentrations from 1% to 75%.	The high-volume fabrication process produces safe, all-optical sensors and eliminates the individual calibration of sensors by making many identical sensors in one batch.
Durable Catalysts for Fuel Cell Protection During Transient Conditions	3M Company	The new catalyst materials alleviate the damaging effects of transient conditions (e.g., startup, shutdown, and fuel starvation) on fuel cells. The materials are being developed by modifying the catalyst's behavior so that oxidation of water instead of carbon corrosion is the preferred reaction during transient conditions.	Fuel cell durability is improved by controlling catalyst reaction behavior during transient conditions. Low platinum-group-metal loading reduces material costs.
Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells	OneD Material LLC	A nanowire-supported platinum-cobalt (PtCo) catalyst for PEM fuel cells increases catalyst mass activity relative to commercially available platinum-carbon (Pt/C) catalysts while using reduced amount of precious metal catalyst.	The new catalyst support structure ensures a high catalyst utilization, enables a higher power density using low catalyst loading, and ensures an improved durability compared with conventional carbon-supported catalysts.
Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes	National Renewable Energy Laboratory	The nanostructured platinum (Pt) catalysts have extended surface areas and show improved specific activity and durability compared to traditional Pt catalysts supported on carbon (Pt/C). The catalysts are synthesized from metal nanowire templates using the spontaneous galvanic displacement process.	The new catalysts achieve increased performance (specific activity) and durability compared to traditional Pt/C catalysts and reduce material costs by using less Pt.

Table 3.7. Emerging Products Summary – Fuel Cells (Cont'd)

Technology	Organization	Description	Benefits
Fuel Cell Membrane Measurement System for Manufacturing (SBIR Project)	Scribner Associates, Inc.	The Rapid Membrane Measurement System uses a proprietary electrode design for robust long-term operation, custom measurement and control hardware and software, and state-of-the-art electrochemical measurement methods.	The system rapidly (a few minutes per test) and accurately measures the through-thickness ionic resistance of fuel cell membranes under controlled temperatures and humidity and may allow for more consistent results, higher productivity, and lower manufacturing costs because of waste reduction.
Fuel-Cell-Based Mobile Lighting	Sandia National Laboratories	The fuel cell mobile lighting system uses a 5-kW, hydrogen-fueled PEM fuel cell stack to power high-efficiency plasma lighting. The system is an energy-efficient, environmentally-friendly alternative to the diesel-fueled generators currently used to power most portable lighting equipment.	The system produces zero emissions at the point of use, reduces noise compared to diesel generators, and can be used in indoor or outdoor applications. The use of a fuel cell power source and plasma lighting maximizes the unit's overall energy efficiency.
Ground Support Equipment Demonstration	Plug Power Inc.	A hydrogen-fuel-cell-based alternative to internal-combustion-engine-powered baggage tow tractors at airports.	The fuel-cell-powered tow tractors will reduce carbon emissions compared to existing diesel-fueled vehicles.
High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System	Intelligent Energy Inc.	The combined heat and power (CHP) system is composed of two main parts: a fuel processor that uses hydrocarbon feedstock in a steam-methane reforming reaction and water-gas shift reaction to produce hydrogen, and a PEM fuel cell that uses the hydrogen for electricity production. Heat is recovered from the fuel cell and the fuel processor and can be used for a variety of applications.	The system achieves 35% electrical efficiency with greater than 70% combined efficiency possible, depending on the application. The modular and scalable design allows for easy installation and the unit can be configured to provide emergency backup power in the event of a grid failure.
High Performance, Durable, Low Cost MEAs for Transportation Applications	3M Company	A fuel cell membrane electrode assembly (MEA) with increased durability for use in vehicles. The MEA is based on 3M's nanostructured thin-film (NSTF) catalyst technology.	The new MEA improves fuel cell cold-start performance through changes to the anode gas diffusion layer structure and composition. The design decreases MEA costs by reducing the platinum group metal content of the NSTF catalyst.
High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders	Applying an approach to formulate and test low-Pt cathodes has led to six Pt-alloy compositions that demonstrate an improvement in performance compared with pure Pt electrocatalysts.	Reducing Pt in cathodes reduces costs (Pt is very expensive), and in some cases, improves performance and durability. The new formulation and testing approach allow rapid synthesis and testing of electrocatalysts, thus reducing research costs.
High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.	The composite fuel cell membrane has enhanced ionic conductivity and mechanical properties, allowing the fuel cell to retain water and maintain proton conductivity and mechanical integrity at low humidities and elevated temperatures.	The membrane improves fuel cell durability, reduces system costs, and improves performance over extreme and fluctuating humidity and temperature conditions.
Low-Cost 3-10 kW Tubular SOFC Power System	Acumentrics Corporation	The system is a natural-gas-based SOFC that is being developed for use as a micro-CHP unit to provide electricity and hot water in residential applications. The system has demonstrated an electrical efficiency of 35%–40% and a CHP energy efficiency of 85%.	The system handles readily available fuels such as natural gas and propane, without requiring an external reformer to produce hydrogen. Onsite simultaneous generation of heat and power will increase efficiency and lower energy costs to consumers.

Table 3.7. Emerging Products Summary – Fuel Cells (Cont'd)

Technology	Organization	Description	Benefits
Low-Cost Hydrogen Sensor for Transportation Safety	Makel Engineering, Inc.	The micro electromechanical systems hydrogen sensor system incorporates a highly sensitive Schottky diode made of a palladium alloy on a silicon substrate for measurements in the low concentration range (50 ppm to a few percent). It can provide low-cost hydrogen leak monitoring in fuel cell vehicles, stationary fuel cells, or other areas where hydrogen leaks might occur.	The sensor is low-cost and compact, has low power consumption, can be mass-produced, and operates in suboptimal environmental conditions.
Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells (SBIR Project)	Nanotek Instruments, Inc.	A new system is being developed to produce low-cost/high-performance BPPs for fuel cells using sheet molding compound manufacturing techniques. Use of the new roll-to-roll system for producing multiple layer bipolar plates will allow large-scale manufacturing.	The new system optimizes the composition and forming process, improving the performance of the BPPs while reducing the manufacturing cost.
Low Platinum Loading Fuel Cell Electrocatalysts	Brookhaven National Laboratory	The patented anode electrocatalysts have low platinum (Pt) loading that resists CO poisoning.	The electrocatalysts are cost effective to fabricate because of the extensive use of noble metals (rather than Pt) and are more durable, thereby promising an improved fuel cell lifetime.
Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers	W.L. Gore and Associates, Inc.	A system that uses the product water from a hydrogen fuel cell's reaction to humidify the incoming reactant gases on the cell's anode and cathode sides. The system contains an inexpensive and durable composite membrane consisting of an ionomer layer sandwiched between micro porous polymer layers. The membrane is capable of high water transport rates and prevents gas crossover from occurring.	The system improves the performance and longevity of fuel cell electrolyte membranes by controlling reactant gas humidity, which is essential for maintaining proper membrane hydration.
Nitrided Metallic Bipolar Plates for PEM Fuel Cells	Oak Ridge National Laboratory	The technique deposits a thin Cr-nitride coating on stainless steel bipolar plates to form an electrically conductive, defect-free, corrosion-resistant surface layer, even on complex surface geometries.	This technique allows for low-cost, high-volume production techniques that will reduce the net cost of fuel cells and improve their longevity and durability.
Platinum and Fluoropolymer Recovery from PEM Fuel Cells	Ion Power, Inc.	The process dissolves the used PEMs into a slurry, which is then processed to separate the Pt and Nafion® for re-use.	The process eliminates hydrofluoric acid emissions typical of other recycling methods in use today. It reduces PEM fuel cell replacement costs by recovering valuable materials from used cells.
Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC	The technology recovers >98% of the platinum from various MEAs, independent of MEA aging history, membrane construction, or electrocatalyst composition.	The technique eliminates the need for hydrofluoric acid remediation, and batching multiple fuel cell types eliminates manual separation labor in the recycling process.
Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports	Brookhaven National Laboratory	The high-surface-area electrocatalysts have a platinum (Pt) monolayer that is deposited on top of transition metal nanostructures. These catalysts, which are used in the fuel cell's oxygen reduction reaction, have a higher activity per mass of Pt than pure Pt nanoparticles.	The new catalysts achieve high activity for the oxygen reduction reaction, resist Pt dissolution under cycling conditions, and reduce costs by reducing Pt loading.

Table 3.7. Emerging Products Summary – Fuel Cells (Cont'd)

Technology	Organization	Description	Benefits
Portable PEMFC System Using Buckypaper	Bing Energy Inc.	A proton exchange membrane fuel cell that uses a catalyst made of highly conductive buckypaper (a thin sheet of carbon nanotubes) coated with platinum catalyst nanoparticles.	The technology reduces fuel cell manufacturing costs by optimizing electrode assembly and reducing platinum content.
PowerEdge™ Fuel Cell System (ARRA Project)	Nuvera Fuel Cells, Inc. *	A fuel-cell-based power source for electric forklift fleets that increases fleet productivity and improves forklift performance compared to conventional lead-acid batteries.	The system can be refueled with hydrogen in less than 2 minutes (compared to 10 minutes or more for a battery change), allowing operators to spend more time moving product out on the floor. Constant voltage is provided throughout the entire shift, eliminating the performance degradation experienced with batteries.
Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd.	The BPP uses expanded graphite in conjunction with a high-temperature resin system that is designed for high-volume production.	The system results in improved gas impermeability, low contact resistance, high thermal/electrical conductivity, and improved mechanical strength. The plates continuously operate at temperatures up to 120°C.
Roots Air Management System with Integrated Expander	Eaton Corporation	To enable the use of PEM fuel cells in vehicles a new air management system was developed and tested that will improve costs and reliability.	The air management system improves system performance, operates at a lower speed, reduces the number of parts and uses a plastic expander thus reducing overall cost.
Sensors for Automotive Fuel Cell Systems	NexTech Materials, Ltd.	The H_2S sensor operates by a reversible change in resistance caused by adsorption and desorption of H_2S in a film of H_2S-sensitive material. It can detect H_2S from 25 ppb to 10 ppm, with response times of less than one minute.	The sensor will detect H_2S in the hydrogen stream, alerting operators so they can protect the cell stack from damage. This will increase membrane life, allow fuel cells to remain online longer, and extend the life of guard beds used to remove sulfur from hydrocarbon fuels before they are processed into hydrogen.
Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.	The solid acid fuel cell stack generates electricity using hydrogen from a variety of commercial fuel reformate sources, including diesel fuels commonly used in the trucking industry. The technology offers near silent operation, quick startup time, and the ability to handle start-stop cycling.	The technology can operate reliably on a variety of gas and liquid fuel reformates and reduces emissions by providing a more fuel-efficient alternative to auxiliary power generated from combustion engines. The stacks can be manufactured by low-cost, high-volume methods because of the solid nature of the electrolyte and the use of metal and polymer components.
Ultra-Low Platinum Alloy Cathode Catalysts for PEM Fuel Cells	University of South Carolina	A new catalyst synthesis process reduces the precious metal content in the cathode of PEM fuel cells while maintaining or exceeding current fuel cell durability and performance specifications.	The new catalyst process reduces fuel system costs by reducing precious metal content and is scalable from the laboratory to high-volume production.
Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture	Rensselaer Polytechnic Institute	To aid in cost-effective, high-volume manufacturing of PEM fuel cell MEAs, diagnostic methods and ultrasonic bonding processes are being developed.	The new methods and processes will reduce manufacturing costs by reducing cycle time and energy consumption and improving product yield.

* Note: acquired by Hyster-Yale

Table 3.8. Emerging Products Summary – Production/Delivery

Technology	Organization	Description	Benefits
Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC	A new, high-efficiency hydrogen liquefier that uses active magnetic regenerative liquefaction (AMRL) to produce ~25 kg of liquid hydrogen per day with a thermodynamic cycle efficiency (figure of merit) of ~0.5.	The technology improves the efficiency and reduces the cost of hydrogen liquefaction.
Catalysts/Electrodes for Hydrogen Production by Water Electrolysis	Proton OnSite	Catalyst structures that reduce the amount of platinum group metals used in electrolyzer stack electrodes.	The less expensive catalyst materials reduce the cost of hydrogen production via electrolysis.
Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC	A centrifugal compressor system for pipeline transport of hydrogen gas achieves higher compression efficiency than conventional reciprocating compression equipment and delivers hydrogen at a rate of 240,000 kg/day at a discharge pressure of 1,285 psig.	The compressor system can be used to support existing hydrogen pipeline infrastructure in the industrial sector and for future pipeline transport of high-pressure hydrogen gas from production sites to vehicle fueling stations at reduced capital costs.
Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas (ITM Syngas)	Air Products and Chemicals, Inc.	The ion transport membrane (ITM) system uses ceramic membranes to generate syngas and hydrogen in a more compact, lower-cost, and higher-efficiency process than competing technologies. ITM syngas membranes combine air separation and methane partial oxidation into a single unit operation.	The system has very high flux and selectivity that help reduce both capital and operating costs. The ITM syngas process is also readily configured for carbon capture from the high-pressure syngas product.
Composite Membrane for High Temperature Hydrogen Separation	Bettergy Corporation	A robust, high temperature hydrogen separation membrane has high hydrogen selectivity and permeability, excellent hydrothermal and chemical stability, and durability in harsh operating conditions.	The membrane system has low energy consumption, the possibility of continuous operation, ease of operation and is cost effective.
Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory	Extensive testing of fiber-reinforced polymer pipelines is underway to determine their use for safe delivery of hydrogen over long distances.	Composite pipelines can reduce the cost of installation and increase the corrosion resistance of the pipes
Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.	The new compressor is more efficient than existing mechanical compressors, contains no moving parts, and has a modular architecture, which allows the capacity to be increased by simply adding more fuel cells.	The compressor can produce up to 4 lb of hydrogen per day at pressures up to 12,000 psi at a hydrogen recovery efficiency of 95%.
Flexhose: Cryogenically Flexible, Low Permeability Thoraeus Rubber Hydrogen Dispenser Hose	NanoSonic, Inc.	This new hose is cryogenically flexible, has low permeability, and delivers high pressure hydrogen at hydrogen fueling stations.	The hose reduces hydrogen losses to evaporation during fueling and maintains hose integrity even when bent to 180° with no hydrogen embrittlement.
High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis	Giner, Inc.	New catalysts are being developed for water electrolysis that use less costly materials and improve the efficiency and lifetime of proton exchange membranes. These new catalysts are undergoing extended durability testing in harsh conditions to optimize their performance.	The new catalysts will increase electrolyzer system efficiency using nanotechnology by enhancing performance and durability while using less costly materials.
High-Pressure PEM Electrolyzer and Composite Tube Hydrogen Storage	Proton OnSite	A packaged system that includes hydrogen production, storage, and dispensing equipment in an intermodal transport International Organization for Standardization (ISO) container.	The system provides a modular, manufactured hydrogen-fueling infrastructure that is scalable and can be deployed quickly.

Table 3.8. Emerging Products Summary – Production/Delivery (Cont'd)

Technology	Organization	Description	Benefits
Hydrogen by Wire — Home Fueling System (SBIR Project)	Proton OnSite	A new PEM electrolysis system produces 2 kg/day of hydrogen at 350 bar for refueling hydrogen-powered vehicles or for stationary/portable power devices.	The new onsite system enables widespread adoption of hydrogen-powered transportation without a well-developed hydrogen supply infrastructure.
Hydrogen Gas Sensing System	Intelligent Optical Systems, Inc.	The quick-response sensor system accurately detects hydrogen leaks in a broad range of operating environments including fuel cell vehicle garages, production facilities, and refueling stations. The sensor detects hydrogen at concentrations from 100 ppm to 10% hydrogen-in-air with a response time of less than 5 seconds.	The system operates over a wide range of conditions, including temperatures of 10–55°C and 0–90% relative humidity. The system identifies the points at which hydrogen is leaking thus alerting users before safety is compromised.
Hydrogen Production for Refineries (SBIR Project)	TDA Research, Inc.	The hydrogen generation process uses a fluidized bed reactor to produce hydrogen from heavy feedstocks at refineries.	The process saves energy and costs by operating at lower temperatures compared with conventional methods (methane steam reforming or petcoke gasifiers).
Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.	A chemically stable carbon molecular sieve separates hydrogen from caustic streams that contain CO, CO_2, H_2S, and heavy hydrocarbons at stream temperatures above 250°C and pressures up to 1,500 psi.	The membrane offers a low-cost, mechanically durable option for hydrogen separation under harsh conditions and functions as a membrane reactor for water gas shift reactions.
Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.	The hydrogen transport membrane features uniform small pores on the surface that enable a thin membrane layer to span the pores, while larger pores in the bulk of the substrate provide strength to the membrane and do not restrict hydrogen flow.	The membranes help increase hydrogen yield, purity, and system energy efficiency and reduce capital costs. They are applicable to small, onsite hydrogen generators, such those located at fueling stations.
Integrated Hydrogen Energy Station	Air Products and Chemicals, Inc.	A fuel-cell-based powerplant that co-produces electricity and hydrogen using a high-temperature fuel cell that internally reforms methane.	The co-production of hydrogen and electricity improves the economics of a standalone hydrogen fueling facility. The system can use methane from renewable sources like digester gas or landfill gas.
Integrated Short Contact Time Hydrogen Generator	GE Global Research Center	The technology integrates short contact time catalytic partial oxidation, steam reforming, and water gas shift catalysis into a single process (staged catalytic partial oxidation) in a compact reactor that can produce 60 kg of hydrogen per day.	The technology has relatively low operation temperatures that allow lower-cost stainless steel to be used, is relatively compact, is amenable to mass production, and provides efficiency gains and lower capital costs by staging and integrating three catalysts.
Leak Detection and Hydrogen Sensor Development	Los Alamos National Laboratory	A robust zirconia-based, electrochemical sensor for vehicular and stationary applications. The low-cost sensor measures hydrogen in air from 0.04–4% with an accuracy of ± 1%.	The safety sensor is low-cost and durable with good response time, stability, and resistance to aging and degradation from thermal cycling.
Low-Cost Hydrogen Generation from Renewable Energy	Proton OnSite	New fuel cell materials, components, and manufacturing methods to reduce the cost and improve electrical efficiency for fuel cells integrated with renewable energy sources.	The new system is compatible with high-volume manufacturing by consolidating fuel components and simplifying assembly.
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage (SBIR Project)	Proton OnSite	A new electrolysis system using improved catalyst and membrane materials to reduce efficiency losses arising from oxygen evolution over-potential and membrane ionic resistance.	The new catalysts and membranes reduce MEA cost by using less expensive materials while improving long-term stability and scale up.

Table 3.8. Emerging Products Summary – Production/Delivery (Cont'd)

Technology	Organization	Description	Benefits
Materials Solutions for Hydrogen Delivery in Pipelines	Secat, Inc.	Methods are being developed to identify steel compositions and associated welding filler wires and processes that would enable safe transmission of hydrogen at high pressures (800–3,000 psi).	The methods would reduce pipeline infrastructure costs by identifying suitable existing pipelines, thus avoiding replacement costs while ensuring safety.
Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	UC Berkeley	The technique involves genetically engineering the length of the chlorophyll "antenna" of a strain of algae to prevent over-absorption at the surface, allowing sunlight to penetrate deeper into the culture, thereby decreasing the heat dissipation and increasing the light utilization efficiency of hydrogen production from 3% to 15%.	The technology generates carbon-neutral hydrogen from algae and sunlight without requiring fossil fuels.
MEMS Hydrogen Sensor for Leak Detection	Oak Ridge National Laboratory	Microelectromechanical system (MEMS) hydrogen sensor uses a nanostructured palladium/argon alloy to improve sensitivity and response. The sensor can be used for hazardous condition detection in hydrogen fuel-powered applications.	The sensor has sufficient response, sensitivity, and accuracy for safety applications at low cost.
Nanotube Array Photocatalysts (SBIR Project)	Synkera Technologies, Inc.	The photoelectrochemical hydrogen production system uses high-density arrays of nanotubes with coaxial architecture to enhance light harvesting through a large absorption cross section and a high surface area to promote catalytic chemistry.	The photocatalysts increase efficiency through broadband light absorption and a vertically graded bandgap. The system is scalable to large size and high volumes and lowers costs compared to traditional technologies.
Oil Free Hydrogen Compressor (SBIR Project)	Mohawk Innovative Technology, Inc.	The oil-free, high-speed centrifugal compressor uses compliant surface foil gas bearings and seals, engineered coatings in conjunction with high-speed drives, and centrifugal compressors.	The technology reduces capital, maintenance, and operating costs of compressors; improves compressor reliability and efficiency; and eliminates the potential for hydrogen contamination for sensitive hydrogen-consuming devices such as fuel cells.
Rapid High-Pressure Liquid Hydrogen Refueling for Maximum Range and Dormancy	Lawrence Livermore National Laboratory	This liquid refueling system uses a low pressure vapor return system and reduces hydrogen boil-off losses at a high hydrogen flow rate.	This high pressure system quickly refuels vehicles from high pressure cryogenic storage tanks.
Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory	The approach reduces the impact of the inherent variability of renewable energy production by storing excess energy in the form of hydrogen. Varying renewable sources are being matched to the direct current (DC) requirements of multiple alkaline and PEM electrolyzer stacks.	Coupling hydrogen production to renewable energy production allows for greater renewable energy infrastructure penetration and pollution-free production of energy.
Reversible Liquid Carriers	Air Products and Chemicals, Inc.	This technology deploys a fully reversible liquid carrier that can be readily hydrogenated, transported to a distribution center, and then catalytically dehydrogenated to provide hydrogen gas to an end use such as fuel cells.	The technology increases catalyst efficiency and allows thermodynamically favorable liquid carriers to be deployed.
Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi	Giner, Inc.	The technology is a 5,000 psi PEM-based water electrolyzer system that produces hydrogen for residential refueling of hydrogen vehicles.	The refueling system reduces overall cost by eliminating the need for hydrogen storage and compression at the user end site.

Table 3.9. Emerging Products Summary – Storage

Technology	Organization	Description	Benefits
Electrochemical Reversible Formation of Alane	Savannah River National Laboratory	The process uses direct hydrogeneration and electrochemical synthesis to produce alane, a low-cost rechargeable hydrogen storage material for portable or stationary fuel cell applications.	The process increases alane production by using more efficient, less costly electrochemical reactions and avoids hazardous material handling problems by surface passivation.
Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks	Pacific Northwest National Laboratory	The onboard vehicle tank is formed with polyvinyl ester resins that are less costly and reduce tank mass. The tank is undergoing evaluation and testing.	The tank can be used at cryogenic temperatures to increase hydrogen storage capacity while also reducing costs by using lower cost resins.
Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory	The cryo-compressed hydrogen storage tank maintains high energy density without evaporative losses, requires fewer carbon fiber construction materials, and can store either compressed or liquid hydrogen.	The storage tank has a 500-mile range, can be dormant for extended periods without losing fuel from the tank, and has demonstrated an improved thermal endurance compared with low-pressure vessels.
Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers, LLC	A metal hydride solid-state-based hydrogen fuel system to power PEM fuel cell forklifts has the advantage of reduced charging/fueling time, consistent power delivery, longer lift span, added ballast, and the ability to be used with renewable energy source.	The new system offers safer operation, increased tank storage capacity, lower capital cost, reduced fleet size, and the capability to fill directly from an electrolyzer or other low-pressure source.
Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Oak Ridge National Laboratory	This lower cost carbon fiber precursor, polyacrylonitrile with methyl acrylate (PAN-MA), will be used to improve the strength-to-weight ratio of carbon fiber composite materials for hydrogen storage tanks.	The carbon fiber can be manufactured using existing high-textile production processes rather than highly specialized processes and materials thus reducing fiber costs by 25%.
Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.	The fabrication technique can create high-pressure storage tanks in less than 20 minutes to allow a production rate approaching vehicle production.	The automated system will reduce production time, lower costs, improve fabrication reliability and volumes, and provide safer failure modes compared with filament winding tanks.
Ultralightweight High Pressure Fuel Tanks Reinforced with Carbon Nanotubes	Applied Nanotech, Inc.	Methods for reducing the amount of carbon fiber used in the construction of carbon-fiber-reinforced polymer (CFRP) tanks used for hydrogen storage. Carbon nanotubes are used to improve the mechanical properties of the tanks.	The hydrogen storage tanks produced using these methods weigh less and cost less than conventional CFRP tanks.

Table 3.10. Fuel Cell Tasks and Related Emerging Technologies

Tasks*	Technology Title	Organization
Catalysts/Electrodes	Alternative and Durable High-Performance Cathode Supports for PEM Fuel Cells	Pacific Northwest National Laboratory
	Durable Catalysts for Fuel Cell Protection During Transient Conditions	3M Company
	Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes	National Renewable Energy Laboratory
	High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders
	Low Platinum Loading Fuel Cell Electrocatalysts	Brookhaven National Laboratory
	Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports	Brookhaven National Laboratory
	Ultra-Low Platinum Alloy Cathode Catalysts for PEM Fuel Cells	University of South Carolina
Electrolytes	Dimensionally-Stable High-Performance Membrane	Giner Electrochemical Systems, LLC
	High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.
Fuel Cell MEA Manufacturing R&D	Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors	InnoSense, LLC
	Fuel Cell Membrane Measurement System for Manufacturing	Scribner Associates, Inc.
	Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells	Nanotek Instruments, Inc.
	Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture	Rensselaer Polytechnic Institute
Fuel Cell Systems	Direct Methanol Fuel Cell (DMFC) Anode Catalysts	National Renewable Energy Laboratory
	Direct Methanol Fuel Cell for Handheld Electronics Applications	MeOH Power
	Fuel-Cell-Based Mobile Lighting	Sandia National Laboratories
	Ground Support Equipment Demonstration	Plug Power Inc.
	High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System	Intelligent Energy Inc.
	Low-Cost 3-10 kW Tubular SOFC Power System	Acumentrics Corporation
	Portable PEMFC System Using Buckypaper	Bing Energy Inc.
	PowerEdge™ Fuel Cell System	Nuvera Fuel Cells, Inc. **
	Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.

* Note: The fuel cell tasks are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf and manufacturing topics at http://energy.gov/sites/prod/files/2015/06/f22/fcto_myrdd_manufacturing.pdf.

** Note: acquired by Hyster-Yale

Table 3.10. Fuel Cell Tasks and Related Emerging Technologies (Cont'd)

Tasks*	Technology Title	Organization
Membranes Electrode, Assemblies, Gas Diffusion Media, and Cells	Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells	OneD Material LLC
	High Performance, Durable, Low Cost MEAs for Transportation Applications	3M Company
	Platinum and Fluoropolymer Recovery from PEM Fuel Cells	Ion Power, Inc.
	Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC
Seals, Bipolar Plates, and Interconnects	Nitrided Metallic Bipolar Plates for PEM Fuel Cells	Oak Ridge National Laboratory
	Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd.
Systems BOP Components	Low-Cost Hydrogen Sensor for Transportation Safety	Makel Engineering, Inc.
	Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers	W.L. Gore and Associates, Inc.
	Roots Air Management System with Integrated Expander	Eaton Corporation
	Sensors for Automotive Fuel Cell Systems	NexTech Materials, Ltd.

* Note: The fuel cell tasks are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf and manufacturing topics at http://energy.gov/sites/prod/files/2015/06/f22/fcto_myrdd_manufacturing.pdf.

Table 3.11. Production Technology Pathway Items and Delivery Challenges and Related Emerging Technologies

Technology Pathway Items or Challenges*	Technology Title	Organization
Auxiliary	Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC
	Reversible Liquid Carriers	Air Products and Chemicals, Inc.
Biological	Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	UC Berkeley
Containment	Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory
	Materials Solutions for Hydrogen Delivery in Pipelines	Secat, Inc.
Dispensing	Flexhose: Cryogenically Flexible, Low Permeability Thoraeus Rubber Hydrogen Dispenser Hose	NanoSonic, Inc.
	Rapid High-Pressure Liquid Hydrogen Refueling for Maximum Range and Dormancy	Lawrence Livermore National Laboratory
Electrolysis	Catalysts/Electrodes for Hydrogen Production by Waste Electrolysis	Proton OnSite
	High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis	Giner, Inc.
	High-Pressure PEM Electrolyzer and Composite Tank Hydrogen Storage	Applied Nanotech, Inc.
	Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory
	Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi	Giner, Inc.
Photoelectrochemical (PEC)	Nanotube Array Photocatalysts	Synkera Technologies, Inc.
Pressurization	Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC
	Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.
	Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.

* Note: These production technology pathway items are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf and for delivery challenges at http://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf.

Table 3.11. Production Technology Pathway Items and Delivery Challenges and Related Emerging Technologies (Cont'd)

Technology Pathway Items or Challenges*	Technology Title	Organization
Reforming of renewable, bio-derived feedstocks	Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas (ITM Syngas)	Air Products and Chemicals, Inc.
	Hydrogen by Wire – Home Fueling System	Proton OnSite
	Hydrogen Production for Refineries	TDA Research, Inc.
	Integrated Hydrogen Energy Station	Air Products and Chemicals, Inc.
	Integrated Short Contact Time Hydrogen Generator	GE Global Research Center
	Low-Cost Hydrogen Generation from Renewable Energy	Proton OnSite
	Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage	Proton OnSite
Separation and purification systems	Composite Membrane for High Temperature Hydrogen Separation	Bettergy Corporation
	Hydrogen Gas Sensing System	Intelligent Optical Systems, Inc.
	Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.
	Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.
	Leak Detection and Hydrogen Sensor Development	Los Alamos National Laboratory
	MEMS Hydrogen Sensor for Leak Detection	Oak Ridge National Laboratory

* Note: These production technology pathway items are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf and for delivery challenges at http://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf.

Table 3.12. Storage Challenges and Related Emerging Technologies

Challenges*	Technology Title	Organization
Materials Storage	Electrochemical Reversible Formation of Alane	Savannah River National Laboratory
	Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers, LLC
Physical Storage	Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks	Pacific Northwest National Laboratory
	Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory
	Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Oak Ridge National Laboratory
	Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.
	Ultralightweight High Pressure Fuel Tanks Reinforced with Carbon Nanotubes	Applied Nanotech, Inc.

* Note: The storage challenges are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf.

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