Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

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U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Stationary Fuel Cells

Chapter 4: Technology Assessments

Introduction to Technology/System

Opportunities

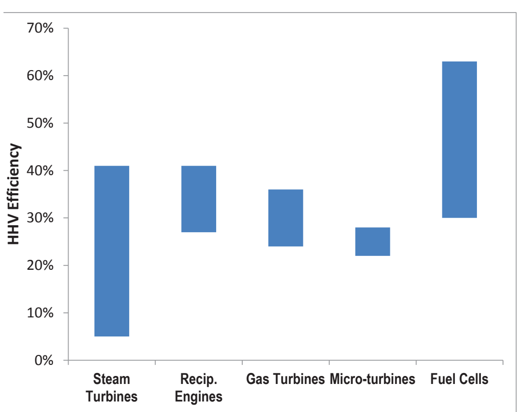
The commercial, residential, and industrial sectors emitted 3.5 billion tonnes (metric tons) of CO_2 in 2014, from using nearly 70 quads of electricity and other forms of energy per year, with large electricity losses during generation, transmission, and distribution.[1,2] Distributed generation (DG) is an attractive pathway to fuel cells deployment for primary power (e.g., power for data centers), backup power (including grid strengthening and backup for telecom sites), and combined heat and power (CHP) for commercial, institutional, municipal, and residential buildings.

DG technologies have the benefit of reducing peak electrical demand and congestion on the grid as well as providing a means for local production of CHP. If CHP displaced even a fraction of the conventional electricity and thermal energy supply system, it would reduce a substantial amount of carbon emissions.[3] Unlike DG systems based on fuel cells, DG systems employing engines or turbines as the prime mover require significant after-treatment to meet NO_x emission levels in many air basins and, even with after-treatment, are unlikely to reach the low NO_x and other emission levels of fuel cells.[4] Fuel cells are also less noisy, a valuable attribute in locations where noise is a concern.

Fuel cell technologies are well suited to stationary applications in view of their low emissions, inherently high efficiencies (Figure 4.Q.1) even at small scales, scalability (kW to multi-MW), high reliability, quiet operation, relatively low maintenance requirements, and ability to handle several types of fuels (natural gas, biogas[5] and higher hydrocarbons, and hydrogen). Unlike heat engines, which are limited by the Carnot efficiency and materials constraints, fuel cells can theoretically achieve electrical efficiency approaching 90%.[6] For example, current polymer electrolyte membrane fuel cell (PEMFC) technology can already exceed 60% electrical efficiency on hydrogen fuel, and research and development (R&D) are under way to reach 70% efficiency or higher.[7] Even when fuel cells use natural gas, the CO_2 reduction potential is high. Besides natural gas,

Figure 4.Q.1 Efficiency of Distributed Generation Technologies Using Natural Gas (Lower Heating Value Basis)[8]

Credit: National Renewable Energy Laboratory



Typical LHV range (on natural gas)	
SOFCs	50%-low 60%'s
MCFCs	45%-mid 50%'s
PAFCs	low 40%'s
PEMFCs	mid 30%'s

which is a relatively plentiful domestic resource, a limited supply of renewable hydrogen can be derived from biogas sources, such as wastewater treatment plants and landfills, and more may be available in the future (e.g., hydrogen from biomass, nuclear, and microbiological pathways) that would enable fuel cells to achieve even greater greenhouse gas (GHG) reductions.

Department of Energy (DOE)-funded analyses have shown that fuel cell CHP systems have the potential to achieve reductions in carbon emissions from 35% to more than 50% over conventional heat and power sources (with much greater reductions—possibly more than 80%—if biogas is used in the fuel cell).[9]

In 2000, Onsite Sycom assessed the technical (upper bound) potential for CHP in the commercial/institutional sector for the Energy Information Administration (EIA). They found that this potential was about 68 GWe for medium-scale CHP (up to 5 MWe) as summarized in the first three data columns of Table 4.Q.1. Onsite Sycom sized CHP systems based on average electrical demand for most building types. For office buildings, supermarkets, and restaurants, thermal loads are inadequate to support CHP systems sized to the average electric demand on the basis of current CHP technologies. Therefore, Onsite Sycom reduced MW capacities by the following factors: 0.6 for office buildings, 0.5 for restaurants, and 0.25 for supermarkets.

Table 4.Q.1 Technical (Upper Bound) Potential for CHP in the Commercial and Institutional Sector: 68 GWe for Up to 5 MW CHP Systems[10,11]

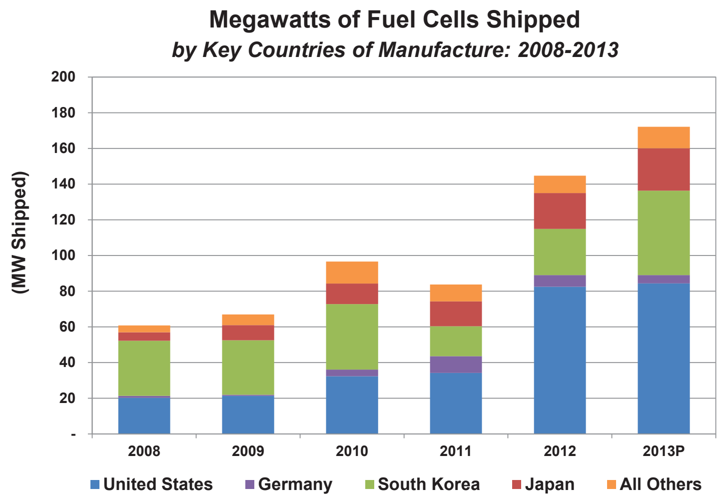
Applications	MW capacity (100–500kW)	MW capacity (500–1000kW)	MW capacity (1–5mW)	MW capacity (greater than 5mW)	MW capacity total
Hotels/motels	2,640	630	1,350	2,080	6,700
Nursing homes	1,010	2,840	3,920	220	7,990
Hospitals	650	900	5,270	2,060	8,880
Schools	7,120	6,770	970	0	14,860
Colleges/universities	220	410	1,700	1,930	4,260
Commercial laundries	180	280	20	0	480
Car washes	250	30	0	0	280
Health clubs/spas	660	2,840	50	0	3,550
Golf clubs	840	570	510	280	2,200
Museums	70	200	120	0	390
Correctional facilities	260	520	1,510	430	2,720
Waste treatment/sanitary	450	340	150	0	940
Extended services restaurants*	2,800	170	410	0	3,380
Supermarkets	900	200	80	0	1,180
Refrigerated warehouses**	130	450	180	30	790
Office buildings***	7,520	5,050	4,360	1,670	18,600
Total	**25,700**	**22,200**	**20,600**	**8,700**	**77,200**

* MW capacities were reduced by 50% because thermal loads do not match electrical demand.
** MW capacities were reduced by 75% because thermal loads do not match electric demand.
*** MW capacities were reduced by 40% because thermal loads do not match electric demand.

Maturity

Many of the first applications of distributed fuel cells have been in niche markets that require high reliability, such as data centers, telecommunication towers, emergency response and life support systems, and national defense and homeland security applications.[12] Installed capacity of backup power and CHP fuel cell systems in the United States was approximately 200 MWe in 2014.[13]

Figure 4.Q.2 Key Countries Producing Fuel Cells (Navigant Research).[15] Figure 2 includes stationary and transportation fuel cells (in terms of MW, stationary fuel cells dominate).[16]



In 2013, U.S. fuel cell manufacturers produced approximately twice the MW produced in 2011 (Figure 4.Q.2). R&D success for low-carbon production pathways would enable increased use of fuel cells and related technologies (e.g., electrolyzers) for grid stabilization applications while reducing carbon emissions.[14]

The Role of Government and Public/Private Activities

The federal investment tax credit of up to 30% of capital costs (or $3,000 per kW) and state incentives such as California's Self-Generation Incentive Program have helped drive deployment. Although U.S. expertise and exports related to medium-scale (roughly in the 0.2 to ~5 MWe range) fuel cells lead the world,[17] cost sharing of high-risk R&D is needed if industry is to advance at the pace necessary for a domestic supply chain to develop and be available in the future. Public funding needs to focus mainly on innovative concepts instead of the typical low risk incremental improvements to already commercialized products that industry normally self-funds. It is also appropriate for the government to provide testing and diagnostic capabilities at sites (e.g., national laboratories) for use by industry. Other appropriate government-funded activities include safety, codes and standards, market transformation, and technology validation (discussed in subsequent sections).

A potential arrangement that could accelerate DG deployment involves utilities financing and owning distributed fuel cell systems installed at customer sites. Those utilities would get the benefit of electricity (and heat) sales and could potentially coordinate maintenance on an integrated system (multiple DG sites), reducing the need for maintaining excess backup capacity (e.g., through coordinating maintenance schedules for utilities' DG facilities with the objective of minimizing the required backup capacity at power plants). Compared to private building owners, utilities generally have broader access to more favorable financing costs, tax incentives, and other market support measures, such as renewable energy credits.

Technology Assessment and Potential

The major types of fuel cells are PEMFCs, phosphoric acid (PAFC), molten carbonate (MCFC), and solid oxide (SOFC). PEMFCs operate at 50°C–100°C, PAFCs at 150°C–200°C, MCFCs at 600°C–700°C, and SOFCs at 500°C–1000°C.[18] The high temperatures at which these last two types operate enable them to internally reform hydrocarbons, such as natural gas, to generate hydrogen within the fuel cell. At these elevated temperatures, carbon monoxide (CO) poisoning is not an issue. The excess heat generated can also be used for CHP. However, the higher temperature fuel cells are less suitable for load-following operation[19] because rapid heating and cooling may result in damage to cells and stacks, such as cracking.

As discussed on a previous page, fuel cells (particularly higher temperature ones) inherently have high electrical efficiencies. Through combining a high-temperature fuel cell with a traditional heat engine such as a gas turbine (hybridization), high-temperature fuel cells may achieve even greater electrical efficiency, to more than 70% for multi-MW systems. Hybrid configurations have an inherent low level of pollutant emission and are likely to make up a major percentage of the next-generation advanced power generation systems for a wide range of applications.[20] Other combinations may be investigated (e.g., a SOFC/battery hybrid using the battery for ramp rate control and load-following functions or a SOFC/PEMFC hybrid using the PEMFC for the same purpose). Table 4.Q.2 summarizes the characteristics and R&D needs.

Table 4.Q.2 Characteristics and R&D Needs of Fuel Cell Platforms[21,22,23]

Fuel cell type	Temp (°C)	Electrical efficiency	Unit capacity for DG	Life time (hours)	Salient characteristics and R&D needs
Polymer Electrolyte Membrane (PEMFC)	50–100	35% e-	<1 MW	20,000–40,000	Useful for residential & light commercial CHP; good for load following. Very high cost for contaminant removal from fuel streams. Catalyst performance needs to improve; need non-carbon catalyst support for the oxygen reduction reaction and oxygen evolution reaction; bipolar plates—coatings for corrosion resistance with cheaper base plate materials; membranes need to be thinner and stronger, etc.; durability needs to increase; efficiency needs to increase (ideally to MCFC and SOFC levels).
Phosphoric Acid (PAFC)	150–200	40% e-	0.4 MW	80,000	Load following between 50%–100% of rated capacity. Low power densities; cost for contaminant removal from fuel streams; high cost of balance-of-plant. Efficiency needs to increase (ideally to MCFC and SOFC levels); phosphate anion adsorption on PAFC catalysts must be decreased to improve performance and reduce cost.
Molten Carbonate (MCFC)	500–700 (most appl. at 600 or higher)	>45% e-	0.3–2.8 MW	40,000	NH_3 and CO tolerant. High system costs owing to low-power densities; cost for contaminant removal from fuel streams; high cost of balance-of-plant; long start-up (less suitable for load following). Need improved electrolyte matrix materials with stable microstructure; address effects of sulfur on Ni anodes.
Solid Oxide (SOFC)	600–1000	50%–60% e-	<1 MW	20,000	NH_3 and CO tolerant, but significant cost for removal of other contaminants from fuel streams; limited ability to thermal cycle; long start-up (less suitable for load following). Need to address effects of sulfur on Ni anodes and performance stability (e.g., seals, interconnects, active materials); improve stability of electrode microstructure; improve thermal cycling capability and decrease start-up time; develop electrolytes and electrode materials with high performance at reduced temperature.

Figure 4.Q.3 Electrical Efficiency (LHV) of SOFC Systems as a Function of Power Output[24,25]

Credit: National Energy Technology Laboratory

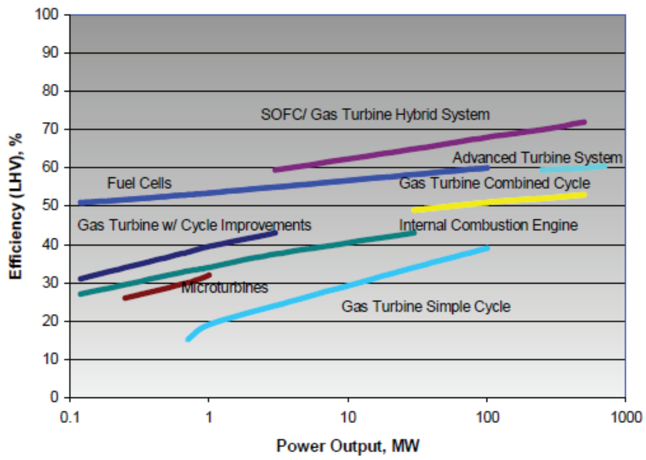


Figure 4.Q.3 summarizes efficiency trends as a function of power output for SOFC systems, including hybrid systems. At over 70% lower heating value (LHV) efficiency, the hybrid system would be more efficient than the combined cycle natural gas power plants powering the grid. Besides efficiency, there are other attributes that need to be considered (e.g., suitability for a desired operating strategy such as load following [see Table 4.Q.2]).

Technology Potential

In 2010, a panel of independent experts evaluated the technology potential for small scale PEMFCs and SOFCs. The panel concluded that production costs could be reduced by up to 50%–55% between 2012 and 2020 for PEMFCs and SOFCs.[26] Since then more than 100,000 fuel cells have been deployed, primarily in Japan for residential power, space heating, and hot water. While most have been PEMFCs, more work is under way on SOFCs.[27] Employing a learning curve methodology, the National Energy Technology Laboratory (NETL) analysis estimated that after 25 MW of installed capacity, SOFC power systems (at least 1 MWe) have the potential to be cost competitive with incumbent DG technologies.[28] A recent market report projects a worldwide $14 billion market in 2020 for stationary fuel cells compared to $1.2 billion today.[29] Technology potential for the remaining major fuel cell types may be assessed in the future.

Energy Storage and Grid Integration

With R&D success, another potential application of fuel cell (primarily low-temperature fuel cells) and hydrogen technologies is the energy storage for electric power systems, particularly given the growth of intermittent renewable generation. For example, low-temperature fuel cells can ramp up in producing electricity to augment the grid as needed and ramp down when no longer needed (high-temperature fuel cells can do so in a more limited fashion). Also, solar or wind electricity can power electrolyzers that split water into hydrogen and oxygen. Hydrogen (and/or oxygen) can be stored and converted back to electricity by using fuel cells.[30] These functions can be performed by discrete systems (a fuel cell and a separate electrolyzer) or by a unitized system, known as a reversible fuel cell, that can operate in either fuel cell mode or electrolyzer mode (regenerative systems consisting of fuel cell stacks and electrolyzer stacks that are integrated into a single system are another option). Further R&D on reversible fuel cells is needed to increase round-trip efficiency and make them cost competitive. As this market grows, cost reduction could result from the synergy between electrolyzers and fuel cells and the opportunity to drive material volumes with more commonalities between the two technologies.

Success in developing cost-competitive fuel cells, electrolyzers, and reversible fuel cells can contribute to the use of hydrogen to integrate multiple energy sectors, including electric, transport, heating fuel, and even industrial processes, and open entirely new ways to integrate renewable electricity into the energy system while preventing a potential decrease in system flexibility associated with a reduction in the use of fossil fuels. The Quadrennial Technology Review main report Chapter 3 on the modernization of electric power systems and the corresponding technology assessment discusses these opportunities in more detail.

Near-term opportunities for electrolyzers include regions with low-cost electricity and situations where electrolysis can play a role in additional value streams (e.g., use with stationary fuel cells to provide grid stability and use of electricity that would otherwise be curtailed to produce hydrogen for fuel cell electric vehicles or other higher-value applications). According to Navigant Research, there were 363 MW of energy storage projects announced worldwide in 2013–2014, with roughly one-third in each major region (North America, Asia Pacific, and Western Europe). Navigant Research projected that energy storage would grow from 538 MW ($675 M in revenue) in 2014 to 21 GW ($15.6 billion in revenue) in 2024.[31] Electrolyzers and other hydrogen production technologies are discussed further in QTR Chapter 7 and its technology assessments and supplements.

Program Considerations to Support R&D

R&D Needs

R&D goals directed at enabling large-scale penetration of stationary fuel cells, along with current status, are shown in Table 4.Q.3.

Table 4.Q.3 Technical Targets versus Current Status for Medium-Scale (0.2–5 MW) Fuel Cells.[32,33]

	2020 Targets	Current (2013) Status[34]
Installed costs	$1,500/kW (natural gas) $2,100/kW (biogas)	$2,400-5,500/kW(natural gas) $4,900-8,000/kW (biogas)[35]
Electrical efficiency (LHV)	>50%	42%–47%
CHP energy efficiency (LHV)	90%	70%–90%
Durability	80,000 hours	40,000–80,000 hours (depending on fuel cell types)

Breakthroughs in fundamental science—in particular, advances in materials, innovative catalysts and membranes/electrolytes, analytical and characterization tools and techniques, and innovative synthetic techniques—may be useful in the development of all fuel cell systems as well as technologies for hydrogen fuel production (e.g., electrolyzers) and infrastructure. For example, advances in membranes and catalysts can be useful both for improving individual fuel cell stack components and improving technologies for producing hydrogen. Although fundamental breakthroughs in science may not be necessary for successful and large-scale commercialization of fuel cells, any such advances are likely to hasten the pace of progress and ultimately expand the scope of successful commercialization.[36]

Manufacturing cost reductions can benefit all aspects of fuel cell systems, hydrogen production and storage systems, and hydrogen infrastructure.[37] Until now, fuel cells and related technologies have been built at very low volumes—market demand has not yet been sufficient to enable investment in advanced manufacturing. While a large portion of the necessary cost-reductions will come from improvements in the technologies themselves and from industry achieving economies of scale, it is likely that advanced manufacturing techniques and processes will be required to enable manufacturing at competitive costs. Costs may be reduced through advances in areas such as improved membrane fabrication and catalyst application; online automated measurement tools for characterization, sampling, and testing; advanced bonding processes for membrane electrode assemblies; and analysis to assess the manufacturability and potential areas for cost-reduction in new technologies.[38]

Demonstrating and analyzing the performance of new and improved technologies are also needed. Validation in demonstrations under real-world conditions is an essential extension of R&D. These demonstrations are needed to provide critical data, to identify new technical issues and challenges, and to assess the status of the technologies. To gain the greatest benefits, the performance and durability of all the technologies will need to be demonstrated in complete, integrated systems, involving all necessary advanced technologies, from the fuel cell applications to the technologies for fuel production, delivery, and storage (particularly applicable to fuel cells using hydrogen).[39]

For the various fuel cell types, successful development requires R&D on materials, nanoengineering, stack components, balance-of-plant subsystems, and integrated fuel cell systems,[40] with an emphasis on science and engineering at the cell level, and from a systems perspective, on integration and component interactions. Examples of activities needed to realize necessary advances include the following:

- Developing improved catalysts for PEMFCs that enable higher performance with lower precious metal loading
- Developing improved membranes for PEMFCs at lower cost and enhanced durability (including development of membranes with higher strength, lower swelling, and lower gas permeability to enable thinner membranes)
- Identifying PEMFC degradation mechanisms and approaches for mitigating the effects
- Characterizing and optimizing transport phenomena to improve cell and stack performance in PEMFCs
- Developing electrolyte matrix materials for MCFCs with improved stable microstructure, which could increase performance and efficiency while also improving durability
- Identifying strategies to reduce the performance and efficiency losses caused by phosphate anion adsorption on PAFC catalysts
- Addressing effects of impurities on fuel cell performance, including effects of sulfur on Ni anodes for SOFCs and MCFCs
- Developing fuel cell systems capable of handling contaminants from biogas sources
- Characterizing the ability of high-temperature fuel cells to ramp up/down and the effect on degradation
- Developing improved SOFC components, such as seals and interconnects, that are mechanically and chemically stable throughout the life of the system
- Improving the ability of SOFCs to tolerate thermal cycling and transient operation
- Developing SOFC electrolytes and electrode materials with high performance at reduced temperature (less than 600°C)
- Developing improved catalyst supports (non-carbon) for PEMFC oxygen reduction reaction and oxygen evolution reaction
- Developing cheaper materials for bipolar plates and coatings with improved corrosion resistance
- Conducting reversibility assessments, aiming at developing reversible fuel cells that are superior to current combinations of fuel cells and electrolyzers
- Developing low-cost, durable balance-of-plant components
- Developing manufacturing and diagnostics technology

The application of high performance computing, high-throughput combinatorial approaches, and advanced modeling are necessary approaches (such as those resulting from the federal Materials Genome Initiative). R&D is also needed on system balance-of-plant components (e.g., for air management) that can lead to lower cost and lower parasitic losses as well as on component integration in systems for stationary power applications.

Figure 4.Q.4 R&D Targets for Fuel Cells "Levelized" Cost of Energy (LCOE) Reduction[41,42,43,44]

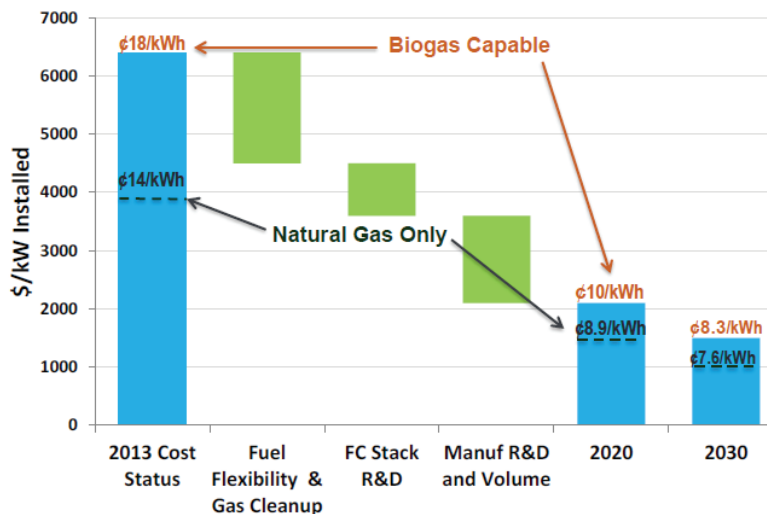


Figure 4.Q.4 shows the R&D waterfalls chart for CHP fuel cells on natural gas and biogas.

Large-Scale Fuel Cells for Central Generation (SOFCs)

Fuel flexible SOFCs can be eventually deployed in power plants to make more efficient use of natural gas or the synthesis gas from coal. For large SOFCs, targets for industrial-scale DG and utility-scale generation include high-volume production at $900/kW and durability >50,000 hours.[45]

R&D Aimed at Grid Integration Applications

For reversible PEMFCs that operate at less than 100°C, R&D is needed to develop catalysts and other cell components with sufficient activity and durability in both fuel cell and electrolyzer modes.[46] In addition, R&D is also needed to reduce costs in view of the need for more robust stack materials for reversible operation and different balance-of-plant requirements for fuel cell versus electrolyzer modes. The existence of different design requirements for a fuel cell and for an electrolyzer makes it difficult to combine both these functions into a single device without making significant design compromises. Significant R&D would be required to develop a reversible fuel cell with performance and durability approaching either that of a discrete fuel cell or a discrete electrolyzer. For high-temperature reversible fuel cells, such as reversible MCFCs or SOFCs, the challenges are somewhat reduced because of the more favorable oxygen reaction kinetics at high temperatures, which enables use of a single catalyst for both oxygen reduction and oxygen evolution with fewer design compromises. Still, R&D is needed to improve electrode durability and optimize electrode performance while reducing costs in view of the wide operating voltage range that reversible cells must tolerate and the existence of different degradation modes in fuel cell and electrolyzer modes.[47]

It is also necessary to develop controls and associated system architectures needed to manage a diverse set of resources and grid assets, including fuel cell technologies and electrolyzers, across the distribution system; to investigate how fuel cells in combination with electrolyzers can help mitigate variable generation and enable energy from the system to be more easily dispatched over the course of a given day; and to integrate fuel cells and electrolyzers with other grid service components through a distributed management system. It is also helpful to design, simulate, and demonstrate a transactional energy ecosystem as the basis for accomplishing grid integration. From the systems perspective this should include integration with the grid as well as the building/built environment in which the fuel cell system is to be installed, through characterizing the system's capabilities for the grid and understanding trade-offs associated with fuel cell sizing and operation.

Collaboration and Coordination

To maximize returns on R&D, collaboration and information exchange with other offices and agencies (e.g., other offices in DOE's Office of Energy Efficiency and Renewable Energy, DOE's Office of Science, Advanced Research Projects Agency-Energy [ARPA-E],[48] the National Science Foundation, the Department of Defense) are needed. The Office of Science funds research on materials chemistry, physical behaviors of materials, chemical physics, and catalysis science, among other topics. Fuel cell R&D in DOE needs to be coordinated with the Office of Science's relevant R&D as appropriate. R&D planning also needs to include consideration of stakeholder (industry, academia, R&D firms, etc.) input through requests for information, workshops, and other venues.

International Coordination and Collaboration

International coordination and collaboration are needed because progress is being made also outside of the U.S. International R&D activities are needed, primarily through the International Energy Agency's Hydrogen Implementing Agreement (IEA-HIA[49]) and Advanced Fuel Cells Implementing Agreement.[50] Additionally, DOE and U.S. Department of Transportation, in coordination through the U.S. State Department, founded the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE[51]) to organize and implement effective, efficient, and focused international research, development, demonstration, and commercial utilization activities related to hydrogen and fuel cell technologies. Participation in these organizations' activities can facilitate the regular exchange of information and diffusion of knowledge across national borders.[52] International collaboration is needed in areas that complement fuel cell technologies, such as hydrogen safety, codes, and standards, hydrogen-based energy storage, renewable hydrogen production, consistent data collection from various countries' R&D projects, and hydrogen for grid integration support.

Safety, Codes, and Standards

To complement R&D and facilitate deployment, it is necessary to focus on codes and standards and real-world demonstrations, along with data collection and analysis, of pre-commercial technologies. Demonstration and validation ensure that pre-commercial technologies are ready for the deployment phase and provide critical feedback to R&D efforts, revealing issues that come to light when technologies are operated in complete systems under real-world conditions. Efforts in safety (including risk management measures), codes, and standards enable development of codes and standards that are necessary for commercial deployments and help reduce permitting times. In addition to activities supporting codes and standards development, it is necessary to conduct safety activities focused on development of information resources and best practices to ensure safety in the operation, handling, and use of hydrogen and fuel cell technologies in all funded projects.

Market Transformation

Early market deployment activities need to focus on key markets for commercial-ready technologies, where a modest number of new orders will have a significant impact on long-term commercialization by reducing costs through economies of scale and catalyzing growth of domestic manufacturing. With increased deployment, the development of more robust networks for maintenance activities will also contribute to operating cost reduction.

Other Interactions and Activities

For advanced technologies in the initial deployment phase, public-private partnerships are important enablers. Examples of key partnerships include the following:

- The Fuel Cell and Hydrogen Energy Association whose membership represents a broad range of stakeholders, including manufacturers of fuel cell components, systems, and materials; hydrogen producers and fuel distributors; universities; government laboratories; and others.
- The California Stationary Fuel Cell Collaborative, a public-private partnership working to advance the commercialization of stationary fuel cells for DG throughout the state of California.

While the main thrust of R&D needs to be on technical issues, nontechnical barriers need to be analyzed to find ways to overcome them. For instance, some utility companies impose high standby rates[53] on customers deploying CHP technology. An Environmental Protection Agency (EPA) analysis[54] concluded that standby rates should be designed to give customers a strong incentive to use electric service most efficiently, to minimize the costs they impose on the system, and to avoid charges when service is not taken. This means that they reward customers for maintaining and operating their on-site generation. Another example of a barrier is some utilities' restrictive policy regarding net metering (i.e., they pay distributed generators less per kWh of electricity that these generators feed to the grid than consumers pay the utilities when buying from the utilities).[55]

Impacts and Metrics

Figure 4.Q.5 shows the cost of electricity from fuel cell CHP at target relative to competing DG technologies (the commercial photovoltaics [PV] cost from the Sunshot Program serves as a point of reference).

Achieving performance and cost targets for this DG technology can help the nation substantially in reducing GHG emissions relative to grid electricity (Figure 4.Q.6). Similar to other CHP technologies, fuel cells can provide more than 50% reduction in CO_2 emissions when compared with the national grid.

In Figure 4.Q.6, generator emissions refer to emissions from the power plant or the CHP system and feedstock emissions refer to the emissions associated with upstream operations, which include the extraction, processing, storage, and transportation of fuels. The ANL analysis for PEMFCs also shows GHG reduction with fuel cells.[57]

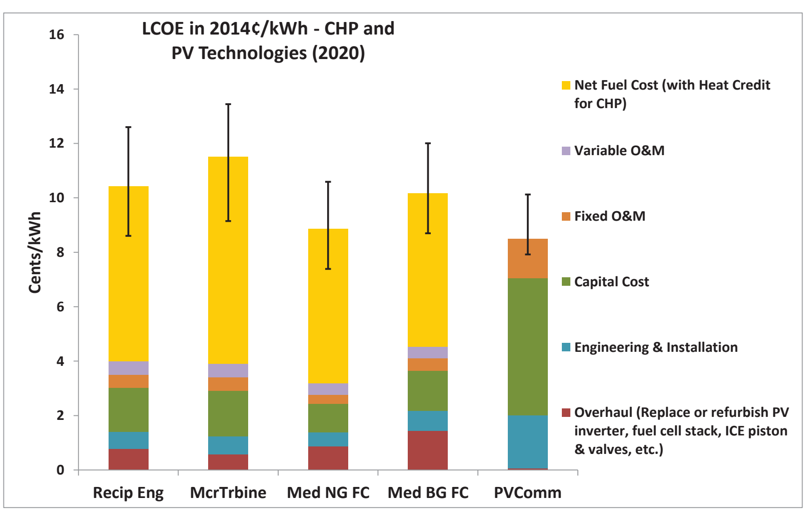
With respect to criteria pollutants, fuel cells emit about 75%–90% less NO_x and about 75%–80% less particulate matter than other CHP technologies on a life-cycle basis (Figure 4.Q.7).

Promise and Challenges

Fuel cells inherently can offer high efficiencies and low emissions because they are based on direct chemical-to-electrical conversion (there is no combustion involved). They are modular and scalable from small (watts) to large sizes (multi-megawatts). The primary challenge is cost. However, there is a need to increase efficiency and durability further. Durability is a key issue for high-temperature fuel cells. Fuel cleanup is a challenge if fuel cells use biogases (e.g., landfill gas). With further R&D, fuel cells and related technologies (such as electrolyzers) can play a major role in the DG and grid integration areas.

Beyond the need to improve performance and economics, integrating education and public outreach in the transition from hydrogen and fuel cell R&D to demonstration and deployment (or from limited deployment to more broad-based deployment) is key to transforming the marketplace, ultimately leading to a long-term market adoption and acceptance.

Figure 4.Q.5 Levelized Cost of Electricity for 2020 Technologies: Internal Combustion Engine Generator (Future Status), Microturbine (Future Status), Commercial PV (Sunshot), and Medium-Scale Fuel Cell for Combined Heat and Power FCCHP (Fuel Cell Technologies Office target).[56]



Key: **NG** = natural gas; **BG** = biogas; **OM** = operations and maintenance. Energy storage costs not included for PV.

Technology Description Supplement

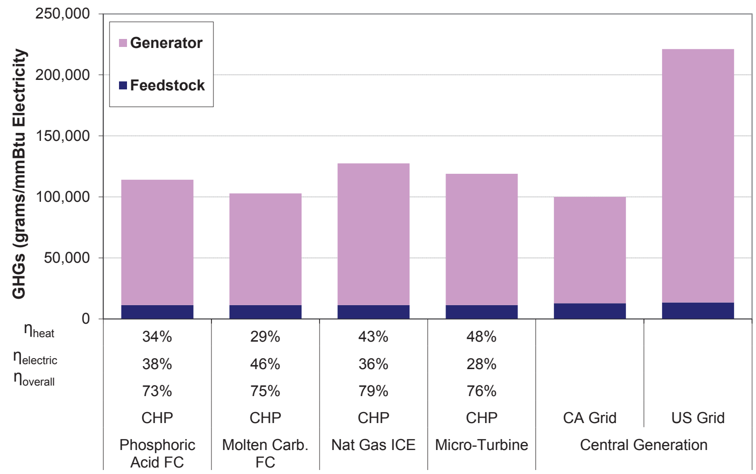
Table 4.Q.4 lists the electrolytes and applications of the four fuel cell types.

Additional information for the four fuel cell types is provided below:[60,61,62]

- **PEMFC**: Compared to the larger facilities that are suitable for the use of PAFC and MCFC systems, the facilities that are more suitable for PEMFC systems are smaller (e.g., residential and light commercial applications) because PEMFCs produce lower temperature heat at about 60°C. Current R&D is aimed at increasing the durability and the operating temperature of PEMFCs, while reducing costs. PEMFCs operating on hydrogen can start up very rapidly and can handle rapid transients from intermittent loads (such as when an appliance starts and stops) better than other fuel cell platforms.[63] Their ability to produce power quickly also allows them to serve as grid support (Ballard Power and First Energy have demonstrated

Figure 4.Q.6 Comparison of GHG Emissions from Load-Following Fuel Cells, Internal Combustion Engine, Micro-Turbine, and Grid Electricity (Thermal, electric, and combined CHP efficiencies are listed for each CHP technology.)[58]

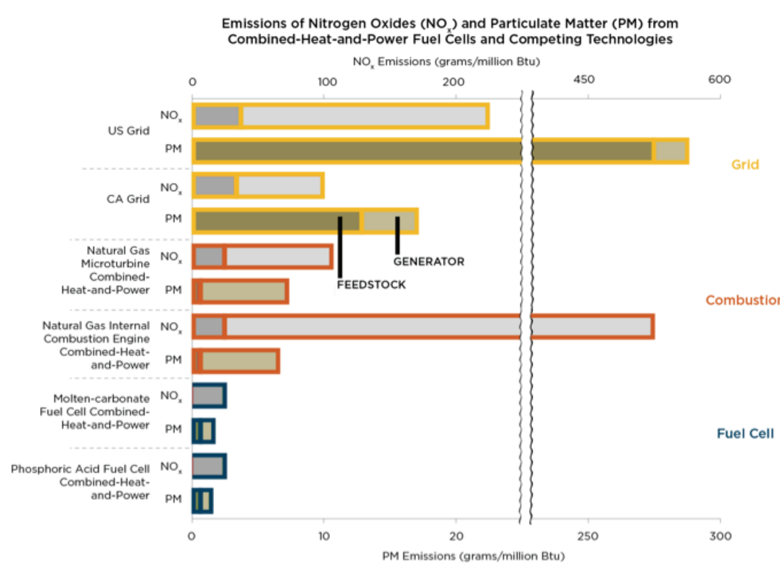
Credit: Argonne National Laboratory



Note: Analysis by Argonne National Laboratory (ANL) by using current fuel cell technology assumptions. The ANL study did not include SOFCs. However, SOFC GHG emissions would be comparable to those from MCFCs.

Figure 4.Q.7 Criteria Pollutant Emissions from Generating Heat and Power[59]

Credit: Argonne National Laboratory



Note: Analysis by Argonne National Laboratory (ANL), using current fuel cell technology assumptions. The ANL study did not include SOFCs. However, SOFC emissions would be quite low, comparable to those from MCFCs or PAFCs.

Table 4.Q.4 Electrolytes and Applications.

Type	Electrolyte	Applications
PEMFC	Hydrated polymer	Commercial & Institutional, Residential, Transportation, Portable Power
PAFC	Liquid acid in a solid matrix	Commercial & Institutional, Electric Utility
MCFC	Liquid metal carbonate in a solid matrix	Commercial & Institutional, Electric Utility
SOFC	Ceramic	Commercial & Institutional, Electric Utility, Residential, Transportation,* Portable Power

* As auxiliary power units on heavy-duty vehicles or main power unit on locomotives or other vehicles that are not subject to frequent start-ups/shutdowns.

a 1 MW grid support unit). For stationary PEMFCs, a growing market for PEMFC-based material handling equipment and fuel cell vehicles would synergistically accelerate the rate of manufacturing cost reduction for stationary fuel cells. PEMFCs could also enable multiuse vehicle fueling stations that provide peak power, hydrogen, and fast charging for electric vehicles.

- **PAFC**: PAFC systems have demonstrated the greatest durability for commercial systems with stack lifetimes in excess of 80,000 hours on the 400 kW units that are being deployed in telecommunication centers and other commercial buildings, including supermarkets, hotels, etc. The net electrical efficiency of this product line is about 41% (LHV) when operating on natural gas. The major challenge for PAFCs is the high cost of materials such as those for the bipolar plates.

There are fuel cell systems that are a cross between PEMFCs and PAFCs (i.e., with similar operation to PAFCs but with a polymer-phosphoric acid electrolyte, such as gel-type polybenzimidazole). These would allow for enhanced performance and higher tolerance (HT) to CO impurities in the fuel when operating in the 130°C–180°C range, a higher operating temperature range than that of PEMFCs. ClearEdge Power (now Doosan Fuel Cell America), the main PAFC developer and producer in the United States, developed such cross-type 5 kW units operating on hydrogen from natural gas and designed to be connected to natural gas lines in buildings. Since the Doosan conglomerate acquired ClearEdge in 2014, the company has been focusing on PAFCs.

- **MCFC**: They are being sold in sizes up to 3.4 MW for commercial buildings and certain industrial applications such as food and beverage processing plants. The baseline 1.4-MW power plant offered by FuelCell Energy has achieved stack lifetimes of 40,000 hours with availability as high as 97%. The baseline product operating on natural gas in non-CHP applications produces 52% less carbon dioxide (CO_2) per MW-hour of power generated than a fossil-fueled steam-electric power plant, 35% less than a single-cycle natural gas turbine, and 30% less than the combined average CO_2 emissions of all US generation. The net electrical efficiency of this product line is about 47% (LHV) when operating on natural gas.[64] The major challenges to MCFC systems are stack life and system costs. As a higher-temperature class of fuel cells, their ability to handle contaminants in fuel streams is high, although thermal cycling effects need to be addressed.
- **SOFC**: SOFCs can have a higher electrical efficiency than any of the other fuel cell types. In SOFCs, power is generated by the migration of oxygen anions from the cathode to the anode to oxidize the fuel gas, which is typically a mixture of hydrogen and CO. The electrons generated at the anode move via an external circuit back to the cathode, where they reduce the incoming oxygen, thereby completing the cycle.

As for MCFCs, high operating temperatures result in fuel cells with greater resistance to poisoning by CO, which is readily oxidized to CO_2 (no need of external reforming to extract hydrogen from fuel when using natural gas directly). SOFCs exhibit the highest tolerance to sulfur among the fuel cell types (however, ppm levels of sulfur can still impact performance). While they have higher power density, thermal cycling is a concern and the construction materials needed to withstand high temperatures can cost more. R&D is needed to achieve higher durability and lower stack and system costs.

The systems offered by companies such as Ceres Power (UK) and Bloom Energy have electrical efficiencies in the 50%–60% range (LHV). Depending on the use of a fossil or renewable fuel for the SOFC, a significant reduction in the carbon footprint (compared with the U.S. grid) could be achieved. While long lifetimes have not yet been demonstrated for SOFC systems in real world applications, SOFCs are highly scalable and suitable for large-scale applications. They consume relatively little water and are amenable to carbon capture and sequestration.

Fuel Cell Systems' Operating Strategies

Fuel cell sizing is generally based on a desired operating strategy. For example, systems intended for baseload operation are sized to meet the minimum electrical load of a building, and load-following systems are sized to meet peak demand.[65]

Grid Support Capabilities

Fuel cells and electrolyzers have the potential to enhance grid operation and reduce emissions from the power sector. For example, recent analysis by the National Renewable Energy Laboratory (NREL) shows that electrolyzers can perform well enough to participate in electricity markets, particularly when operating as demand response devices, and that the sales of hydrogen as a fuel for transportation markets can enhance the economic viability of fuel cells.[66]

Endnotes

1 U.S. Energy Information Administration. "Annual Energy Outlook 2014. Table 2, Energy Consumption by Sector and Source." Accessed April 8, 2015: http://www.eia.gov/forecasts/archive/aeo14.

2 U.S. Energy Information Administration. "Annual Energy Outlook 2014. Table 18. Energy Related Carbon Dioxide Emissions by Sector and Source." Accessed April 8, 2015: http://www.eia.gov/forecasts/archive/aeo14.

3 U.S. Department of Energy. "Combined Heat and Power: Effective Solutions for a Sustainable Future." December 1, 2008. Accessed April 8, 2015: http://info.ornl.gov/sites/publications/files/Pub13655.pdf. Oak Ridge National Laboratory estimated a reduction of CO_2 emissions by over 800 million tonnes per year if CHP capacity displaces 20% of U.S. electric generation capacity.

4 U.S. Environmental Protection Agency. "Catalog of CHP Technologies." March 2015. Accessed April 8, 2015: http://www.epa.gov/chp/documents/catalog_chptech_full.pdf.

5 U.S. Department of Energy. "Request for Information (RFI): Gas Cleanup for Fuel Cell Applications Workshop Report, DE-FOA-0001331/Modification 000001." June 12, 2015. Accessed June 18, 2015: https://eere-exchange.energy.gov/#FoaIdcaf72f36-34d0-4012-96c9-cc37e3cd3f86. Biogas clean-up is needed for any distributed energy technology. DOE issued a request for information on this topic in 2015 because gas clean-up is still relatively costly for all fuel cell types.

6 Fuelcell.co. "Successful Fuel Strategies for the Future – Theoretical Maximum Efficiency." Accessed April 8, 2015: http://www.fuelcell.co.uk/theoretical-maximum-efficiency. Higher temperature fuel cells are generally associated with higher efficiency.

7 U.S. Department of Energy fuel cell program's discussion with fuel cell experts in 2015.

8 U.S. Environmental Protection Agency. "Catalog of CHP Technologies." March 2015. Accessed April 8, 2015: http://www.epa.gov/chp/documents/catalog_chptech_full.pdf.

9 U.S. Department of Energy. "The Department of Energy Hydrogen and Fuel Cells Program Plan." September 2011. Accessed April 8, 2015: http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf.

10 Onsite Sycom Energy Corporation. "The Market and Technical Potential for Combined Heat and Power in the Commercial/Institutional Sector." January 2000 (Revision 1.) Accessed April 8, 2015: http://energy.gov/sites/prod/files/2013/11/f4/chp_comm_market_potential.pdf.

[11] For CHP, although there are no recent technical potential studies with this level of details, EIA-reported prices for electricity and natural gas have not changed much from 1998 to 2013 after adjusting for inflation. The spread between the price of electricity and that of natural gas is an important factor for the penetration of natural gas-based CHP technologies, aside from CHP costs. Therefore the 2000 assessment is largely applicable today.

[12] Raymond Corporation. "Fuel Cell Material Handling: Pioneering Productivity with Fuel Cell Technology." Accessed April 8, 2015: http://www.raymondcorp.com/fuel-cell. Fuel cells are attractive for powering material handling equipment (e.g., forklifts) because they increase worker efficiency through faster refueling and improved performance.

[13] Ganji, J. "Fuel Cell Installed Capacity." June 2015. Unpublished analysis prepared for the Fuel Cell and Hydrogen Energy Association.

[14] Electrolyzers can help reduce carbon emissions through certain grid support services, such as energy storage for renewable electricity with intermittency issues in the absence of plentiful low-carbon hydrogen.

[15] Navigant Research. Market charts deliverable to Department of Energy (Fuel Cell Technologies Office) in 2014.

[16] Approximately 9% deployed for backup power, 56% for power without heat recovery, and 35% for CHP, based on information provided by Fuel Cell and Hydrogen Energy Association in June 2015.

[17] Fuel Cell Energy. "FuelCell Energy Enters Into Partnership Agreement With Abengoa to Develop Localized Fuel Cell Power Plants for Europe and Latin America." December 12, 2011. Accessed April 8, 2015: http://fcel.client.shareholder.com/releasedetail.cfm?ReleaseID=632474.

[18] Bourzac, K. "Cooling Down Solid-Oxide Fuel Cells." MIT Technology Review. April 20, 2011. Accessed April 8, 2015: http://www.technologyreview.com/news/423788/cooling-down-solid-oxide-fuel-cells. Current commercial SOFC technology operates at greater than 700°C but lower temperature operation has been demonstrated in the lab and R&D is underway to move lower temperature SOFC technology to the marketplace.

[19] The fuel cell power output is set to self-adjust as electricity demand fluctuates.

[20] Williams, M. and Samuelsen, S. "Stationary Fuel Cells: The Next Generation of Electrical Power." March 2011. Accessed April 8, 2015: https://www.asme.org/engineering-topics/articles/energy-efficiency/stationary-fuel-cells-the-next-generation-of-electrical-power.

[21] University of California at Irvine. National Fuel Cell Research Center. Energy Tutorial, http://www.nfcrc.uci.edu/3/TUTORIALS/EnergyTutorial.

[22] EG&G Technical Services, "Fuel Cell Handbook (Seventh Edition)." November 2004. Accessed April 8, 2015: http://www.netl.doe.gov/File%20Library/research/coal/energy%20systems/fuel%20cells/FCHandbook7.pdf

[23] Salemme, L., Menna, L., and Simeone, M. "Energy Efficiency of Fuel Processor – PEM Fuel Cell Systems." Accessed April 8, 2015: http://cdn.intechweb.org/pdfs/11469.pdf. 35% electrical efficiency is typical for PEMFCs running on reformed natural gas.

[24] EG&G Technical Services, "Fuel Cell Handbook (Seventh Edition)." November 2004. Accessed April 8, 2015: http://www.netl.doe.gov/File%20Library/research/coal/energy%20systems/fuel%20cells/FCHandbook7.pdf

[25] Patel, P. and Farooque, M., "DFC Technology Status". Accessed April 8, 2015: http://energy.gov/sites/prod/files/2014/03/f12/mcfc_pafc_workshop_patel.pdf. MCFC/gas turbine hybrid systems can also achieve high electrical efficiency, up to 65% LHV.

[26] National Renewable Energy Laboratory. "1-10 kW Stationary Combined Heat and Power Systems Status and Technical Potential - Independent Review." NREL/BK-6A10-48265. November 2010. Accessed April 8, 2015: http://www.hydrogen.energy.gov/pdfs/48265.pdf.

[27] The News. "FCO Develops Solid Oxide Fuel Cell Cell Stack for Residential Systems." March 10, 2015. Accessed April 8, 2015: http://www.achrnews.com/articles/129085-march-10-2015-fco-develops-solid-oxide-fuel-cell-stack-for-residential-systems. In Japan, SOFCs are targeted for commercialization in 2020.

[28] Krulla, K., Iyengar, A., Keiarns, and Newby, D. "Assessment of the Distribution Market Potential for Solid Oxide Fuel Cells." September 29, 2013, DOE/NETL-342/093013.

[29] Globe Newswire. "Stationary Fuel Cells Market Will Grow to $14.3 Billion in 2020: Radian Insights." November 26, 2014. Accessed April 8, 2015: http://globenewswire.com/news-release/2014/11/26/686526/10110097/en/Stationary-Fuel-Cells-Market-Revenue-Will-Grow-to-14-3-Billion-In-2020-Radiant-Insights.html.

[30] International Electrochemical Commission. "Electrical Energy Storage." 2011. Accessed April 8, 2015: http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf. R&D is needed to improve the round-tripefficiency that is necessary to achieve significant market penetration.

[31] Renewable Energy World. "Energy Storage Market Outlook 2015." February 11, 2015. Accessed April 8, 2015: http://www.renewableenergyworld.com/articles/2015/02/energy-storage-market-outlook-2015.html.

[32] U.S. Department of Energy. Hydrogen and Fuel Cells Program Record #11014. "Medium-scale CHP Fuel Cell System Targets." September 30, 2011. Accessed April 8, 2015: http://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf.

[33] Excludes SOFCs. Current SOFC costs are at least as high as those of the other fuel cell types.

[34] U.S. Department of Energy. Hydrogen and Fuel Cells Program Record #11014. "Medium-scale CHP Fuel Cell System Targets." September 30, 2011. Accessed April 8, 2015: http://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf.

[35] Based on $2,500/kW higher cost for operation on biogas versus natural gas.

- Globe Newswire. "Stationary Fuel Cells Market Will Grow to $14.3 Billion in 2020: Radian Insights." November 26, 2014. Accessed April 8, 2015: http://globenewswire.com/news-release/2014/11/26/686526/10110097/en/Stationary-Fuel-Cells-Market-Revenue-Will-Grow-to-14-3-Billion-In-2020-Radiant-Insights.html.

[36] U.S. Department of Energy. "Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan." 2012 (Updated November 2014). Accessed April 8, 2015: http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf.

[37] Some fuel cells use natural gas and biogas instead of hydrogen, and these depend much less on a mature hydrogen supply infrastructure.

[38] Transition to new processes is capital intensive, a potential barrier for most firms.

[39] More conservative consumers generally want to see an objective verification of the performance of new technologies.

[40] Integration and component interactions are needed at the stack level as well.

[41] At high production rates (e.g., >200 MW per year)

[42] LCOE methodology discussed at http://www.hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf.

[43] Krulla, K., Iyengar, A., Keiarns, and Newby, D., "Assessment of the Distribution Market Potential for Solid Oxide Fuel Cells." September 29, 2013, DOE/NETL-342/093013. Accessed April 8, 2015: http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/FINAL_DG_SOFC.pdf. For SOFCs (not shown in the graph), this study shows approximately 12 cents/kWh for natural gas at $6.5/mmBtu after cumulative installed capacity of DG SOFCs reaches 50 MWe (range: 11–14 cents for natural gas at $4.0–$9.3/mmBtu). After 110 MWe has been installed, the range would be 9–12 cents.

[44] Farrell, J. "the Economics of Distributed Generation." Institute for Local Self-Reliance. June 30, 2011. Accessed April 8, 2015: http://www.ilsr.org/economics-distributed-generation. The cost of electricity from fuel cells is approximately 15 cents/kWh. As a check, this agrees with the cost of electricity from natural gas shown in the figure.

[45] Vora, S. Office of Fossil Energy's Solid Oxide Fuel Cells Program Overview. 15th Annual SECA Workshop. July 22-23, 2014. Accessed April 8, 2015: http://www.netl.doe.gov/File%20Library/Events/2014/2014%20SECA%20workshop/Shailesh-Vora.pdf.

- SOFC power systems have the potential to achieve greater than 60% efficiency and more than 97% carbon capture, for a target cost-of-electricity at approximately 40% below presently available integrated gasification combined cycle (IGCC) systems with carbon capture.

[46] As more R&D results become available in the future, analysis should be conducted to identify when reversible fuel cells are preferred to regenerative systems that are not unitized, on the basis of efficiency and cost.

[47] Remick, R. J. and Wheeler, D. "Reversible Fuel Cells Workshop Summary Report, July 2011." Accessed April 8, 2015: http://energy.gov/eere/fuelcells/reversible-fuel-cells-workshop.

[48] For example, while DOE Office of Energy Efficiency and Renewable Energy (EERE) is not sponsoring R&D on intermediate-temperature fuel cells for distributed generation, it is worthwhile to keep track of ARPA-E projects in this area and exploit any potential synergy.

[49] International Energy Agency. "Hydrogen Implementing Agreement (HIA)." Accessed April 8, 2015: http://ieahia.org.

[50] International Energy Agency. "Advanced Fuel Cells Implementing Agreement." Accessed April 8, 2015: http://www.ieafuelcell.com/.

[51] International Partnership for Hydrogen and Fuel Cells in the Economy. "An International Vision for Fuel Cells." Accessed April 8, 2015: http://www.iphe.net/.

[52] Manufacturing overseas could also be a threat to domestic employment, and one should have adequate intellectual property and other applicable safeguards.

[53] Standby rates are fees imposed by utilities to cover costs for providing continuing electric service when the fuel cell is off line (e.g., for maintenance). The charges are used to recover the capital costs of the capacity necessary to meet customers' peak loads.

[54] U.S. Environmental Protection Agency. "Standby Rates for Customer-Sited Resources." December 2009. Accessed April 8, 2015: http://www.epa.gov/chp/documents/standby_rates.pdf.

[55] Kowalski, K. "Ohio Utilities Take Net Metering Fight to State Supreme Court." Midwest Energy News, August 4, 2014. Accessed April 8, 2015: http://midwestenergynews.com/2014/08/04/ohio-utilities-fight-net-metering-rules.

[56] U.S. Department of Energy. "Levelized Costs of Energy from CHP and PV." March 14, 2014. Accessed April 8, 2015: http://www.hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf.

- Assuming fuel prices at 9.5 cents/mmBtu (low: 8 cents, high: 11 cents). The costs and efficiencies of commercial PV are from DOE's SunShot Program, and the costs and efficiencies of reciprocating engines and micro-turbines are from Table 1.3 of the EPA "Catalog of CHP Technologies" (see endnote 4).

[57] Elgowainy, A., Wang, M. "Fuel Cycle Comparison of Distributed Power Generation Technologies." Argonne National Laboratory. November 2008. Accessed April 8, 2015: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fuel_cycle_comparison_report.pdf.

[58] Wang, M.Q.; Elgowainy, A.; Han, J. "Life-Cycle Analysis of Criteria Pollutant Emissions from Stationary Fuel Cell Systems." 2010 Annual Merit Review Proceedings, U.S. Department of Energy. 2010. Accessed April 8, 2015: www.hydrogen.energy.gov/annual_review10_proceedings.html.

[59] Ibid.

[60] University of California at Irvine. National Fuel Cell Research Center. Energy Tutorial accessible at: http://www.nfcrc.uci.edu/3/TUTORIALS/EnergyTutorial.

[61] EG&G Technical Services. "Fuel Cell Handbook (Seventh Edition)." November 2004. Accessed April 8, 2015: http://www.netl.doe.gov/File%20Library/research/coal/energy%20systems/fuel%20cells/FCHandbook7.pdf.

[62] U.S. Department of Energy. First Quadrennial Technology Review (QTR 2011). November 2011. Accessed April 8, 2015: http://energy.gov/downloads/first-quadrennial-technology-review-qtr-2011).

[63] This quality of PEMFCs has enabled applications beyond those previously described (i.e., backup power and material handling [lift trucks, etc.] deployment).

[64] Remick, R., Wheeler, D., and Singh, P. "MCFC and PAFC R&D Workshop Summary Report." January 13, 2010. Accessed April 8, 2015: http://energy.gov/sites/prod/files/2014/03/f12/mcfc_pafc_workshop_summary.pdf.

[65] Ainscough, C., Wipke, K., McLarty, D., Sullivan, R., and Brouwer, J. "Modeling and Optimization of Commercial Buildings and Stationary Fuel Cell Systems." October 23, 2013. Accessed April 8, 2015: http://www.nrel.gov/docs/fy14osti/60904.pdf.

[66] Eichman, J. "Electricity Market Valuation for Hydrogen Technologies." June 17, 2014. Accessed April 8, 2015: http://www.hydrogen.energy.gov/pdfs/review14/an049_eichman_2014_o.pdf.

Glossary and Acronyms

BG	Biogas, i.e., landfill gas and other methane-containing gases produced by the fermentation of organic matter
CHP	Combined heat and power, i.e., the simultaneous production of electricity and heat from a single fuel source, such as: natural gas, biomass, biogas, coal, waste heat, or oil
DG	Distributed generation, i.e., generation by units that are smaller than central generating plants and that are on customer sites or within local distribution utilities
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse gases
HT-PEM	High temperature polymer electrolyte membrane (fuel cell)
LHV	Lower heating value, i.e., the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered
MCFC	Molten carbonate fuel cell
NG	Natural gas
OM	Operations and maintenance
PAFC	Phosphoric acid fuel cell
PEMFC	Polymer electrolyte membrane fuel cell
PV	Photovoltaic, i.e., relating to the production of electric current at the junction of two substances exposed to light
SOFC	Solid oxide fuel cell