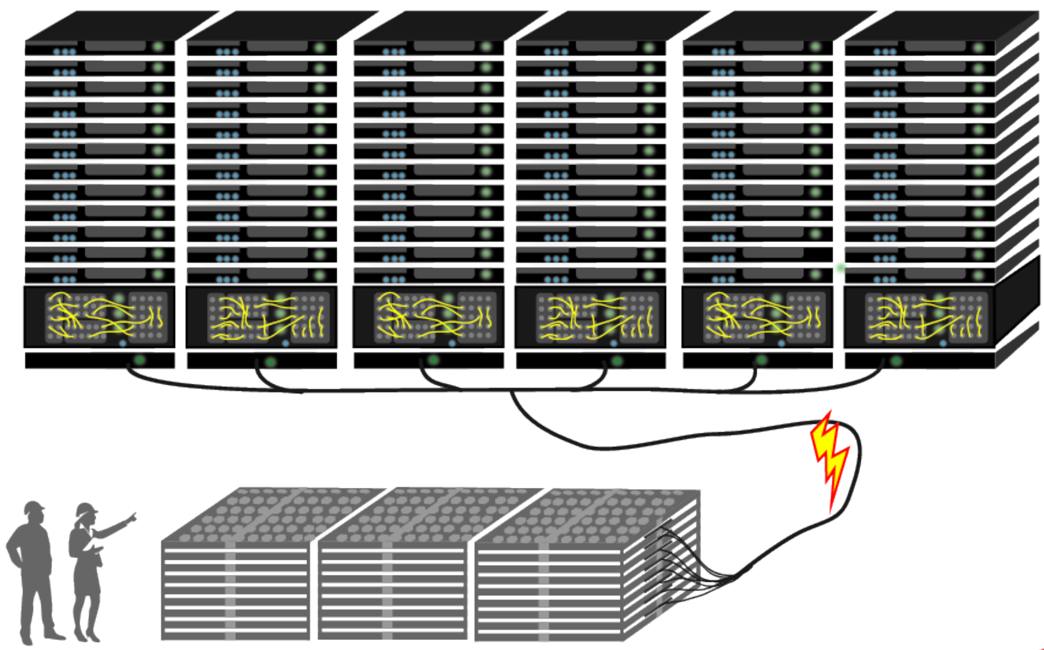
FUEL Cells for Server FARMS

How Fuel Cells Can Help Power America's Data Centers



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NEXTECH MATERIALS

THE OHIO STATE UNIVERSITY

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Paul Gruenbacher is a chemical engineering student at The Ohio State University. His writing interests include advances in the biotech and energy sectors. This paper was part of a scholarship contest sponsored by NexTech Materials.

Foreword

This paper was written as a comprehensive review for self-educational purposes. Fuel cells are a very interesting technology with much potential. Full-resolution files of the figures can be provided upon request. Included in the report are links to as many direct resources as available. Literature references are included in the appendix.

Addressing the Problem

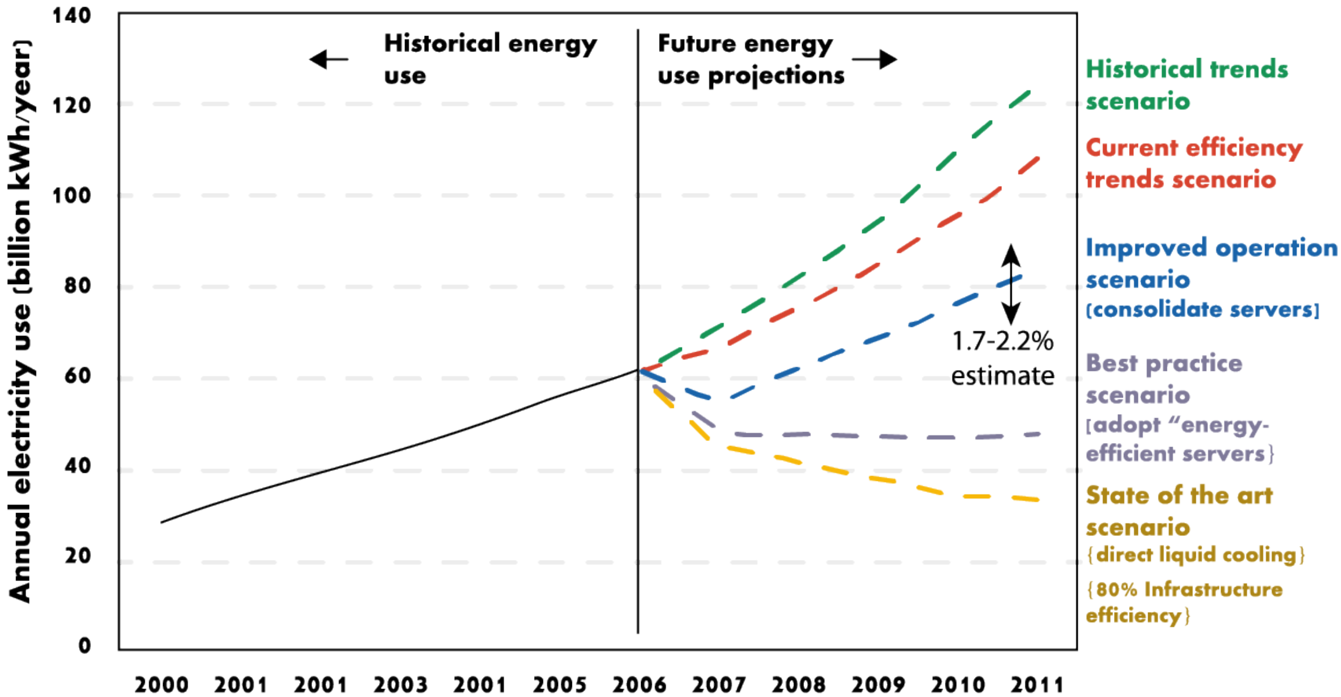
In less than two decades since its early adoption, the internet has expanded across the globe to around 2 billion people and reaching a magnitude of 10^{21} bytes of traffic. As companies wrestled with this flood of information, they began to resort to consolidating their servers into secure facilities in order to save on operating costs. The advent of cloud computing then saw a greater convergence towards larger shared data centers as businesses began reducing cost by outsourcing their computing needs to centralized services. The processing capacity of these large data centers is limited by the heat production of the servers, which necessitates an extensive cooling infrastructure. Together server power and cooling systems can lead to significant energy usage and often the greatest cost in operation of these data centers.

The most important document regarding the overall nation's data center power use is the EPA's Energy Star report to Congress in 2007 in response to public law 109-403. It estimated in the previous year of 2006 that national data centers consumed 61 billion kWh at a cost of $4.5 billion. Using the International Data Corporation (IDC) definition of data center classes, the report suggests that up to 33% of power consumption is attributed to the select few Enterprise data centers (telecommunications, cloud-services, major online retailers). It's five-year projection predicts a near-doubling in power consumption at $7.4 billion cost in 2011 if trends continue. Two years have passed since the report's most distant forecast, but it is difficult to assess where the nation stands currently due to most information being proprietary, so currently there is just speculation. However with current trends power consumption can only be expected to rise.

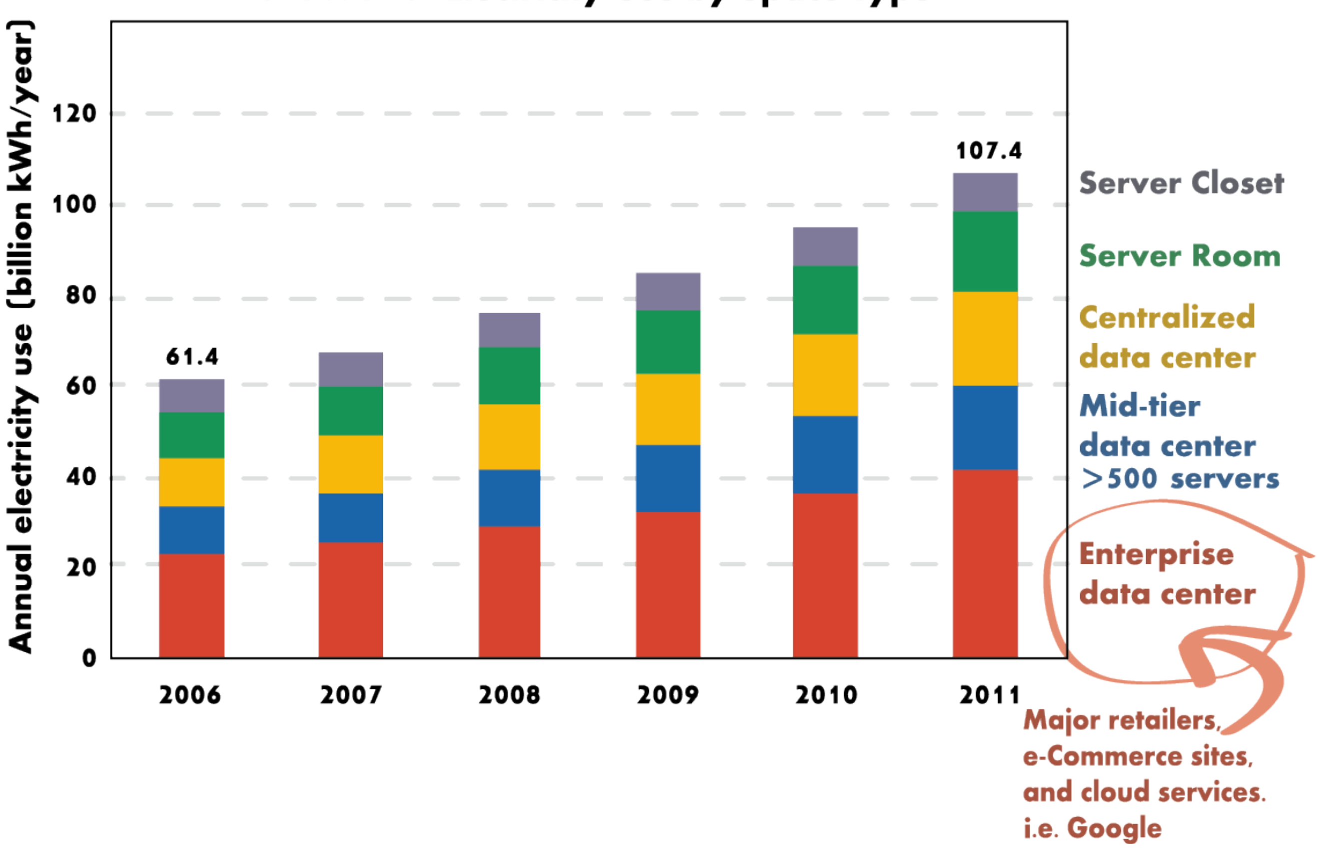
Using the 2007 EPA data and IDC forecasts, Dr. Jon Koomey popularized the statement that data centers probably accounted for 1.7-2.2% of total electrical consumption in the United States in 2010, represented in Figure 1. A significant driver of the demand originates from the installed base or number of servers, which show no sign of declining in quantity. A 2013 survey by Digital Reality reveal a vast majority (98%) of major companies expect to expand server base and to increase their power load in the upcoming years. While IT efficiency and smarter cooling systems will be a major factor in lowering the energy cost of data centers, they are also constitute a significant and expensive restructuring of the data center. Investing in an external power source can help keep up with demands while achieving energy regulations. Therefore data centers a focal points of high electrical demand present an economical opportunity for alternative energy sponsors including for those who develop fuel cells.

Fig. 1 Historical Estimates and Future Forecasts of National Data Center Use

*adapted from EPA 2007 Study



Forecast of Electricity Use by Space Type



Data Centers Begin Adopting Fuel Cells

Already facing an increasingly energy conscious public and government, many high profile companies have began to explore alternative means for their power sources. Apple built a 100-acre photovoltaic field near its data center in Maiden, NC, and Facebook pledged an entirely self sufficient 138-megawatt wind-powered data center in rural Iowa. Google, whose servers represent a major portion of internet traffic and storage in the US, is poised to offset its carbon footprint as well by global environmental projects. For other companies however, these large renewable sources projects are neither financially viable nor truly sustainable.

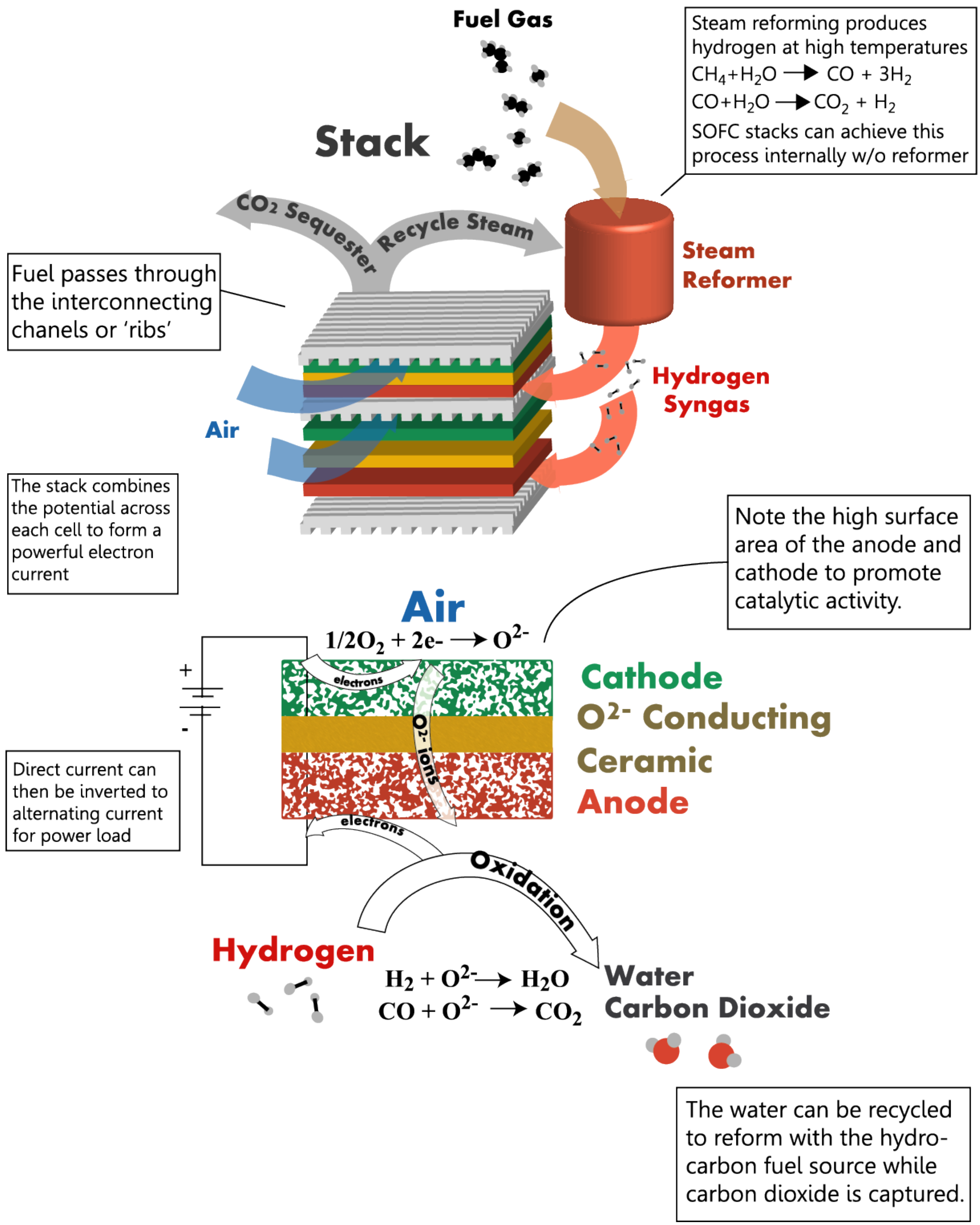
Renewable sources are intermittent in nature and geographically inconvenient, whereas data centers must rely on a dependable uninterrupted power supply and are constrained to where they can be located (secure locations near headquarters or within cities). For this reason companies must still negotiate with their local power utilities. Many IT departments find such a situation frustrating when faced with rising utility costs and monopoly entities that are resistant to change. An IDC study found that power and cooling expenses for IT departments are outstripping even the initial acquisition costs and reached around 10 billion dollars in global spending. An important challenge a chief technical officer may face then, is how to improve the power use effectiveness of their data centers while ensuring that power outages are avoided.

Clearly then, data centers represent a market opportunity for competitive alternative energy sources so long as they can fulfill the uninterruptable power requisite and operate within a constrained geography. Fuel cells are one such viable option for data centers. They are quiet, efficient, consistent with little outages, and are fueled by an uninterpretable natural gas source. This following report will explore the technology and implementation of fuel cells in relation to the data center market.

Fuel Cell Technology: What is it?

The fuel cell is an electrochemical device that converts a supply of chemical fuel directly into electricity and heat energy. Rather than using combustion like other electrical generators, the fuel cell produces electricity by an electrochemical reaction. Each fuel cell consists of an anode and cathode with an electrolyte “bridge” that channels the flow of ions. Much like a battery, the chemical reaction drives a current through the cell, leading to electricity generation. A typical solid oxide fuel cell is represented in Figure 2.

Figure 2. Representative Cell Fuel Stack



In a typical solid oxide fuel cell cell (the type we will be focusing on), a source of natural gas fuel is first brought through a steam reformer in which a hydrocarbon-rich mixture is endothermically treated by steam at a high temperature to form carbon monoxide and hydrogen gas otherwise known as “syngas”. The syngas then reaches the fuel cell, whereupon the hydrogen and carbon monoxide is oxidized at the anode by oxygen ions to form water and carbon dioxide. The electrons generated by the anodic reaction are conducted to the power supply as a direct current. Upon returning to the fuel cell, the electrons reduce oxygen from free air in a cathode reaction. The newly produced oxygen ions pass through the electrolytic medium that connects the cathode and anode and react with the hydrogen again, thus perpetuating the cycle. Because a single cell produces little power by itself, the fuel cells are formed into “stacks” in order to increase the reaction surface area and yield. A single fuel cell can generate up to 1-100 watts depending on scale, while an entire module of fuel cell stacks can produce hundreds of kilowatts.

The first advantage to recognize in a fuel cell is that its chemical process is more thermodynamically efficient than its combustion counterpart. Combustion of a fuel source is an exothermic process in which internal combustion engines use the heat to expand pistons for mechanical power. The engine's theoretical thermal efficiency can be described as a ratio of the heat produced and heat wasted or by the equation: $1-T_{out}/T_{in}$. The efficiency is also limited by the difference of the highest temperature achieved and the ambient temperature (Carnot Theorem). For instance, the recent polar vortex in January, 2014 cooled America's ambient temperature leading to record efficiencies at many nuclear steam turbines. A heat engine operating in the cold vacuum of space could achieve even higher efficiencies. However a typical steam turbine operating at 580 Celsius is limited by a maximum efficiency of 62%, so there is a limit to what engineers can achieve with the combustion system (with most achieving less than 40% with heat loss and friction).

The hydrogen fuel cell however, bypasses the combustion step and relies entirely on an electrochemical reaction. The ideal thermal efficiency of the fuel cell then, is simply a ratio of the free energy vs. enthalpy of the electrochemical reaction. If the change in free energy vs. enthalpy of $H_2 + O_2$ to H_2O is 228.61 and 241.818 kJ per mole respectively, then the reaction theoretical efficiency allows for up to 94% efficiency! This gives a higher upper limit than with typical turbine generators. The static fuel cell also bypasses other efficiency-loss mechanisms such as friction, but it also faces challenges such as ion resistance, reaction kinetics, and current loss. The true maximum efficiency then is more around ~85%, and this efficiency drops as the Gibbs free energy decreases with the increasing temperature of the fuel cell (important concept for SOFC at >950 Celsius). In a way, the fuel cell produces energy similar to the electrochemical processes of a biological cell. The early sulfuric acid fuel cells created a proton gradient much like the mitochondria in our body, which can be thought of as our own little internal “fuel cells”.

A second point to be made is the inherent design of a fuel cell. Little to no moving parts allows for a low noise emission of around 40-50 dB, quieter than a normal conversation. Low noise disturbance means broader commercial and residential applications. Fuel cells were also originally applied as the primary source of power for NASA's space flights, which hints at how portable and compact fuel cells were meant to be. They are now being considered for hydrogen-powered cars and unmanned aerial vehicles. Their overall weight can be less than that of a battery system of similar capacity because it takes advantage of the energy density of hydrocarbon fuel. A hybrid vehicle could juggle both much like they do now with batteries, using the engine only when greater power is needed but otherwise using the fuel cell for more efficient driving.

A third important concept of a fuel cell is that it separates the chemical streams. By keeping the air and the carbon fuel sources separate, the fuel cell is able to isolate the carbon dioxide for sequestering. It is much easier to capture the carbon dioxide right from the start than it is to separate the carbon emissions later from the gas exhaust (see air scrubber) at conventional power plants. In a way, it is much like the chemical looping system that is being proposed for coal power plants. A local researcher in Columbus, Ohio: Dr. Liang-Shih Fan, has demonstrated a process that utilizes a fluidized bed of iron oxide microparticles that will react with syngas produced from coal. It is a very similar operation to fuel cells but carried out on a much larger scale and is expected to have a major impact on clean coal for developing countries.

The fourth advantage to fuel cells is that they are considered to be more environmentally friendly. Unlike combustion, the electrochemical process does not produce toxic byproducts such as nitric or sulfur oxides. This is because the oxidation of the carbon fuel is controlled by the steam reforming, unlike the highly reactive and radical environment of an engine. A fuel cell module could therefore be installed near a commercial site without having to worry about noxious fumes or noise. Many companies that are considering fuel cell modules are pleasantly surprised to learn that they can simply look like a storage unit or a neighborhood power box.

Types of Fuel Cells

There are many different materials possible to achieve a working fuel cell. Most depend primarily on what sort of electrolyte they use. The original fuel cells in early 20th century used sulfuric or phosphoric acid as the electrolyte to transport protons. Later research would develop polymer membranes, high-temperature ceramics, and various other materials. There is no absolute advantage of one material over another, they each have tradeoffs in power density, lifetime durability, efficiency, and material cost. For instance platinum is an excellent catalyst for the cathode, but it is also very expensive as a rare earth metal with pricing at $1400/oz (until the day comes when we can mine asteroids). Polymer membranes can increase power density of a stack but are vulnerable to drying out. A summary of fuel cells characterized by their electrolyte or fuel type is provided in Table 1 and in Figure 3.

Table 1: Short Comparison of Fuel Cell Types

Electrolyte / Fuel Type	Company Sponsors	Comments
Alkaline (AFC)	Gaskatel (EloFlux), AFC Energy	Cheap, but poisoned by air, which necessitates a pure oxygen supply
Phosphoric Acid (PAFC)	ClearEdge Power, Fuji Power (200+ other systems global)	Mature tech, long lifetime (40,000 hours). Requires platinum catalyst. Costly.
Polymer Electrolyte Membrane (PEMFC)	Most automobile companies and other transport manufacturers.	Very thin/compact, poor CO tolerance, finicky with heat and water, degrades quickly.
PEMFC (integrated hydrogen/air supply)	BIC (Angstrom Power)	Smallest with its own air/hydrogen supply for phone/tablet battery replacement.
Direct Ethanol Fuel Cell (DEFC)	Early research stage	Alkaline electrolyte, need to develop catalyst in order to fully oxidize ethanol
Molten Carbonate (MCFC)	On-site applications: CFC Solutions , Ansaldo, Fuel Cell Energy, and others link	Molten carbonate at >600 Celsius. Actually consumes carbon dioxide at cathode. Cheaper but inferior power density to SOFC.
Solid Oxide (SOFC)*	Products available: Bloom, Ceramic Fuel Cells Ltd. Research: Rolls-Royce, Mitsubishi, others.	Oxygen-ion conducting ceramics that operate 800-1000 Celsius. Can internally reform fuel. Highly efficient. Need to lower temperature and degradation.

At this point there are no clear winners or losers in the fuel cell technology field. Different types of fuel cells are required for different applications, and success depends on how well a company can tailor itself to a specific demand.

Figure 3: Types of Fuel Cells

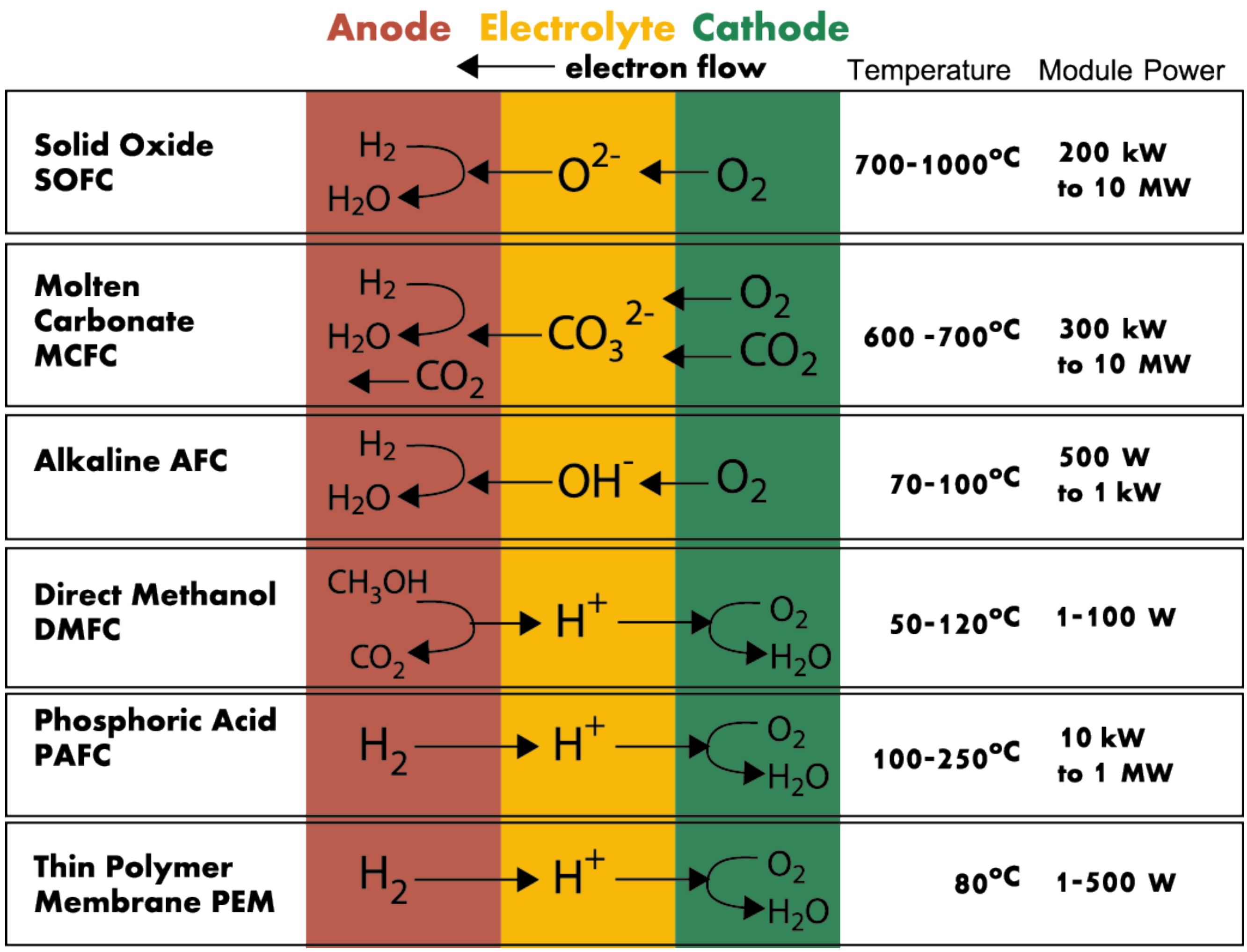


Figure 3 – The proton conducting electrolytes require a lower temperature because they can be in a liquid acid form. A drawback is that they are easily susceptible to contaminants in a fuel, which limits them to a pure hydrogen fuel source. The direct methanol fuel can also cross over into the electrolyte, thus resulting in loss of efficiency. The molten carbonate electrolyte actually recycles carbon dioxide as its ionic carrier of electrons. Therefore a MFCF could help sequester carbon emissions from another plant all while still producing electricity. While alkaline or acidic solutions can act as the electrolyte at low temperature, the MCFC and SOFC require ceramic electrolytes which can conduct oxide ions.

Solid Oxide Fuel Cells aka "Hot Boxes"

The solid oxide fuel cell type (SOFC) is the main focus of this paper because it is widely agreed upon as one of the most efficient cells and is already being implemented at many data centers. SOFCs are composed of a metallic ceramic that operates at very high temperatures of 800-1000 Celsius, which allows for ions to pass through the solid ceramic electrolyte. The high temperature also helps in combined heating and power (CHP)applications. The extreme environment of a SOFC stack has given it the colloquial name "Hot Boxes". While they can be constructed tubular to decrease likelihood of leaking, most SOFCs are designed to be planar due easier manufacturing and shorter current paths.

One advantage of solid oxide fuel cells is their efficiency and their ability to selectively transport only specific ions (oxygen, proton, carbonate) while preventing other contamination such as by carbon monoxide or sulfur. Because chemical poisoning of the ceramic is not an issue, SOFCs can tolerate a wide range of fuels directly (natural gas, coal, hydrogen sulfide, biofuel) so long as it is internally catalyzed or externally converted to syngas. By reforming the fuel source internally at the anode rather than needing a secondary steam reformer, the fuel cell can have a direct carbon fuel source fed to it. This cuts back on the need for other large equipment like a steam reformer. This is because the water product at the anode is directly recycled with the incoming fuel source at a very high temperature, reforming it again to hydrogen and carbon monoxide. Therefore the overall balance has the steam being internally recycled in the fuel cell which negates the need for water supply. Just hook it up to the gas utility and the electricity network, then power up. The steam reforming on the anode side does have the drawback of diluting the fuel however, and so some other alternatives are still being studied.

Research is being done on advanced catalytic materials for SOFCs in order to increase their durability, decrease activation temperature, and improve upon their reaction activity. Specific challenges that need to be overcome include sulfur poisoning, carbon deposition on the anodes, and oxidation corrosion on the cathode. One idea is that a SOFC ceramic could theoretically allow for both oxygen and proton conduction. Because proton conduction necessitates less activation energy, they can decrease the temperature needed for the ceramic. Other possible solutions include new composites with elements such as barium, chromium, and vanadium. Beyond new materials, there are also novel methods of deposition and production that can decrease cost and enable new designs of the fuel cell. Table 2 summarizes some of the latest in new materials.

Table 2: A short comparison of new materials for SOFC components.

Ceramic Anodes	**Comments**	**Example Preparation**
Nickel-based cermet anode	Conventional for catalyzing fuel to hydrogen. Poor tolerance to carbon deposition and sulfides. Susceptible to re-oxidation corrosion.	Coated-by electro-deposition
Ca and Cerium-doped $LaCrO_3$	Poor performance with CH_4.	Sol-gel method
Vanadium-oxide	Can store hydrogen and charge for power generation without fuel. Harvard Team (2012)	Normal deposition / sputtering technique
Electrolytes		
Yttria-doped Zirconia (YSZ)	Zirconia lattice changes with high temperature changes (1000 Celsius).The yttria dopant stabilizes the Zirconia much like a pore would.	Dry pressing, doctor blade. Most conventional methods including sintering.
Strontium and Manganese-doped $LaGaO_3$	Good sulfure tolerance	Glycine Nitrate Combustion (GNC) or Solid State Reaction
Samaria-doped Ceria	Can operate at lower temperatures, sensitive	
Barium zirconium cerium yttria oxide composite	Proton-conduction at low temperature of 400-700. Uses nickel anode.	Solid-state reaction method. (SSR)
Gadolinium-doped Cerium Oxide (CGO)	“Ceres Cell”, 500-600 ºC operation. Allows for stainless steel substrate.	
Cathode		
Lanthanum strontium manganite (LSM)	Common cathodes all with good activity and durability. Selections are made out of finite differences. They are prone to oxidation. LSM and LSCF are the most popular. Mixed ionic and electronic conductors (MIEs) are being researched as well as thin coating techniques for improved duration.	Conventional techniques involving printing, spray coating, and chemical vapor deposition. Some scaffolding techniques of the electrolyte before deposition of the cathode are being discussed.
Lanthanum strontium ferrite (LSF)		
Lanthanum strontium cobaltite (LSC)		
Lanthanum strontium cobaltite ferrite (LSCF)		

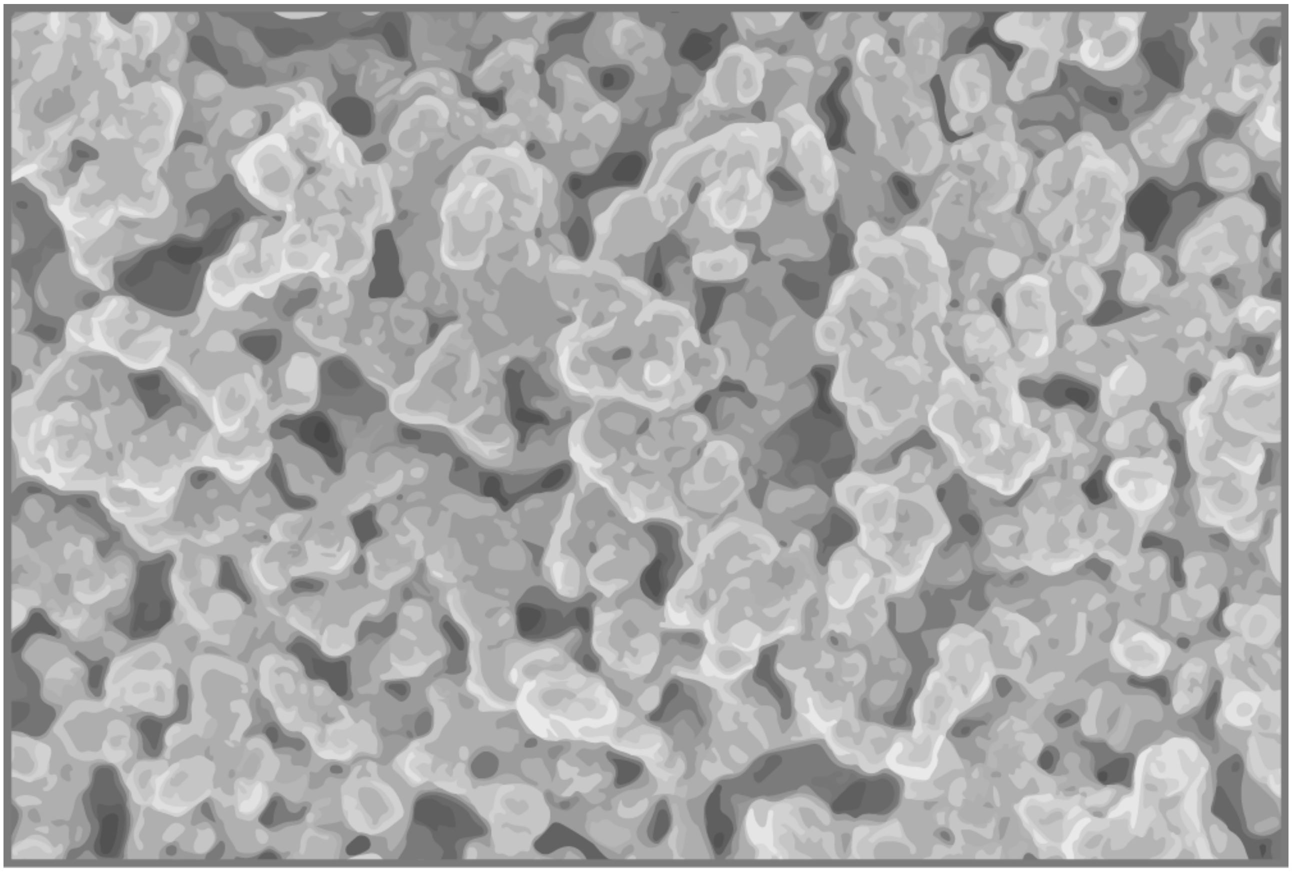


Figure 4- A scanning electron image of a nickel anode impregnated with gadolinium-doped ceria (GDC) particles. Nickel by itself is an effective anode catalyst for hydrogen oxidation, but it is limited by the high temperature sintering process which stunts its grain growth. A nanoparticle solution of DGC was deposited on the nickel anodes and fired to form a porous cerium oxide phase. Note the high porosity of the image for increased surface area. The impregnation of GDC reduced overall electrochemical impedance across the anode and improved performance. The image was adopted from an ECS letter (Jiang et al. 2004). Gadolinium-doped ceria nickel anodes are now a common component considered to improve the performance of an YSZ-electrolyte fuel cell. Other possible solid state catalysts to look out for include samarium and bismuth oxides.

The SOFC Industry: Will 2014 be the year the break a profit?

Fuel cell technology is not a new concept, but it has been a difficult business to be profitable in due to cost and alternative energy sponsors competing for limited public subsidies. The earlier commercial market for advanced fuel cells was in automobiles. However this field was especially fraught with failed sales attempts. Elon Musk, founder of the all-electric Tesla Motors, when discussing the potential for future hydrogen fuel cells for vehicles puts it plainly: bull&%I!. It's a harsh comment, but his point is sound, there is no justification for hydrogen-powered vehicles unless there's a way to efficiently produce and distribute the hydrogen. A modern rechargeable lithium ion battery could provide just as much power density. However an SOFC unit that could operate off of the fuel source could allow the engine to turn off while leaving the power on for an extended time, resulting in greater efficiency while adapting to the current energy infrastructure. As one will see too, SOFCs represent a potentially profitable solution for energy market demands by meeting on-site demands.

Markets in large on-site SOFC power supplies had been explored, but little commercial success was seen due to initial costs. It is hard to come up with a flexible product that can compete with the public power utilities. Imagine to everyone's surprise then when in 2010 a young start-up in California announces a commercially available 100-kW SOFC product that has already been sold to various companies such as Coca-Cola and Adobe. Bloom Energy and its "Bloom Box" was going to reinvigorate excitement for the SOFC industry across the country.

Bloom Energy: You pay for the juice, not the box.

Bloom Energy is a California-based company founded on technology developed in the NASA Ames Research Center to originally convert electricity to oxygen on Mars. The company under Dr. KR Sidhrar reversed the process and built its first modular 100-kW unit in 2008. Their success so far can be largely attributed to the $1.1 billion in private funding and from the tariff subsidies they have received from the state of California. Their benefits have included subsidization from the self-generation incentive program, the federal renewable energy 30% tax credit, and the 20% credit by the California public utilities commission. Combining this with California subsidies for using natural gas and for bio-gas derived from waste treatment, Bloom was to quickly grow as a start-up and begin selling its products for high profile companies.

Much of Bloom's success can be attributed to its technical achievements. Their early patents from 2003 can offer much information on their improved designs. Their first notable patent claimed a SOFC composed of a samaria-doped ceria supported by yttria-stabilized zirconia (SOFC patent). Most likely their cathode is an LSM or other common material and their anode is a nickel-based YSZ cermet (non-noble catalyst patent). Their more recent submissions indicate a double-inverter arrangement to help power data centers with their fuel cells in conjunction with the electrical grid (data center patent) as well as a Mn-Co spinel coating (MCO-coating) that helps protect the chromium inter-connectors from degradation and poisoning (coating patent). Because the company laser prints its anode and cathode, it is possibly able to achieve a higher surface area at lower thickness, allowing for increased power density. Their patents also boast a steam reformer for flexible fuel use (hybrid reformer patent). Their future improvements will likely be in the realm of combined heat and power for achieving greater efficiency.

After an exclusive 60-Minutes piece in 2010, the company was thrust into the public spotlight as a major commercial developer in green fuel. Since then, the company has successfully been installing its “Bloom Boxes” at many commercial facilities including the massive eBay data center in Salt Lake City, Utah. Their “mission-critical” product line has been marketed directly to data centers for the ability of the fuel cells to operate on a consistent basis with little risk of outages or surges. Because they are on-site they can serve as both conventional power source but also as the back-up. However, the cost of the fuel cells can still range up to $700k to manufacture (*as of 2011), making it $7-8 / watt. Because of this major capital cost, many companies are reluctant to adopt a technology that they are not technically adept enough to maintain. For this reason Bloom launched it's Bloom Electron Services which offers a 10-year contract to install, own, and maintain the on-site fuel cells while the customer pays a flat electrical use rate. This helps lower the risk of investment for a wary company. Future Bloom customers that have submitted petitions to their local governments include Home Depot and WalMart for locations in Delaware and Connecticut. In the near future one should expect an IPO launch by Bloom, perhaps after a new quarterly announcement of positive revenue.

Competing researchers and SOFC developers should not be envious. The success of Bloom will help bring SOFC technology into the public eye as a viable possibility for green energy. It will also help build confidence in the performance of fuel cells for data center customers. Bloom's current customers represent as small portion of a much more massive potential data center market that all SOFC developers can take advantage of. A short summary of other SOFC companies is presented in Table 3.

Table 3: Comparison of select SOFC companies.

Company	Location	Comments
Bloom	Sunnyvale, California	$1.1 billion in funding, major installations.
Fuel Cell Energy (1969 research institute) (1990 first product)	Danbury, Conneticut	Focuses on carbonate electrolytes. High revenue. Is licensing its technology to a steel manufacturer in South Korea. Recently built 11 MW fuel cell park in South Korea.
Fuel Cell Ceramics	Noble Park, Australia	Focus on micro-CHP products including BlueGEN 13-kW residential unit and the modular Gennex fuel cell.
Topsoe (1972)	Lyngby, Denmark	Focus on micro-CHP 20 kW units. Operating landfill, working on making compatible with ethanol. 14,000 hours demonstrated for stack.
Ceres Power (2001)	Horham, United Kingdom	Novel CGO anode allows low temperature and steel supports. Announced >50% energy conversion and improved redox resistance.
NexTech Materials	Columbus, OH	Planar SOFC, small ~35 employees. Focus on technological advances in materials and methods.
Global ThermoElectric	Calgary, Canada	Produces cells at equivalent of about 5 MW / year.
Redox Power Systems (2014)	Melbourne, Florida	Claim $1/watt cost for 25 kW unit of 32 stacks at around 650 Celsius (rubix cube module design)

NexTech Materials

Along with the major commercial product developers, there is a slew of smaller suppliers and researchers that offer services to the developer market. NexTech Materials is a company in Columbus, Ohio that for the past twenty years has been researching cell components, developing sensors, and supplying oxide materials for fuel cell developers. Across the highway from the American Ceramic Society and supported by the Federal SBIR program, Ohio's Third Frontier Program, and the NETL Solid State Energy Conversion Alliance, NexTech is a company focusing on an advanced materials approach for improving the fuel cell industry.

NexTech hosts the capability of manufacturing its own planar fuel cells. The FlexCell planar SOFC is a planar cell consisting of a sulfur-tolerant Ni/Ceria anode and YSZ electrode, which has been shown to scale up to an area of 800 cm^2 and achieve 14,000 hours of continued operation without degradation. A single stack of 24 cells is expected to generate 1-2 kW in power and they are achieving manufacturing costs of around $50/kW. The company intends to further explore the 1-2 kW stack platform along with its existing 5-10 kW platform, as well as test sulfide-containing fuels for military application.

In order to fulfill other specific market needs, the company also began developing a sensor line for detection trace amounts of gas in the air. This is an essential safety feature for fuel cell manufacturing and testing when hydrogen and hydrogen sulfide have a low flammability limit and because odorants are not necessarily an option due to sulfur-removal and reforming steps. The hydrogen sensor is the newest of their line in sensors that include detection of nitric oxide and hydrogen sulfide.

In 2010 NexTech received a license for a MCO coating developed by Ceramic Fuel Cells ltd (CFCL). The deal would expand CFCL royalties into North America while NexTech would also seek optimized coating techniques. After optimizing an automated aerosol spray deposition technique, the company was able to show in 2012 continued operation of SOFC interconnects after a year of accelerated testing. The initial estimate of the coating lifetime was up to 40k hours or 4.5 years. Since then they have been attempting to modify the particle composition of the MCO powder to improve the coating quality. MCO coating is essential in improving the durability of fuel cells, and NexTech's research will be vital to its success.

Future work at NexTech includes expanding its product lines, developing new manufacturing techniques, and testing non-destructive evaluative methods. They also look to meet the needs of other SOFC developers. The company's commercial supply store can be found at nextechmaterials.

Opportunity in the Energy Sector: A future of diversity

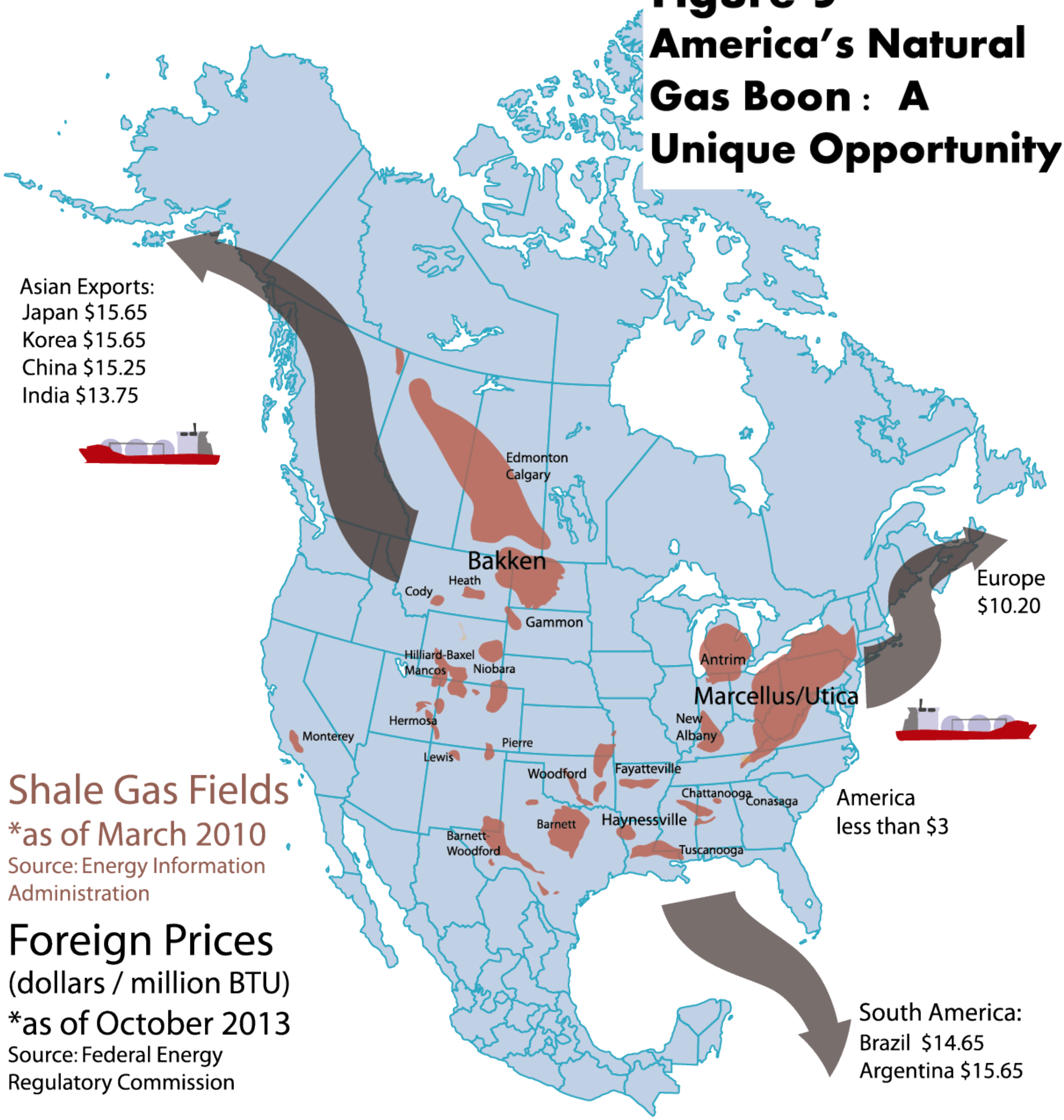
The Natural Gas Boon

A major benefit with solid oxide fuel cells is that they can operate with a direct line from a natural gas utility. With gas prices now bordering the price of electricity, it can be cheaper to generate electricity from natural gas than to pay the current electrical rate. The future will likely see a continuation of this trend, and so the fuel cell industry will do well to hinge its bets on the growth of natural gas energy sources.

If the 20th century was the century of oil, then the 21st will be that of gas. With new developments of shale horizontal drilling and pressurized fracturing of the gas-containing shale or “fracking”, the US has been able to take considerable advantage of shale gas fields that had been lying latent for years. According to the EIA the gross withdrawal of natural gas in 2012 was 29 trillion cubic feet and there has been an increase of 110 trillion cubic feet (600% increase) in proven shale reserves alone over the past five years. The Bakken shale and oil fields of North Dakoa and the Utica Basin in Western Pennsylvania both have made millionaires of its rural residents and revitalized depressed economies. Despite past allegations to the contrary, there is no sign of our domestic reservoirs running dry or of us being dependent on foreign oil in the far future.

It can be argued that natural gas is a national strategic resource, one that should be effectively utilized to help drive the US economy. As a portable fuel it can be condensed to liquid natural gas (LNG) to work in large ships, buses, and other vehicles. Today, the natural gas industry is waiting for a competitive market beyond cooking and heating. Many entities are applying for LNG export authorizations beyond that of the North American Free Trade Agreement to Asian importers Japan and Korea. They must hurry though, as many other countries are quickly developing large LNG export capabilities including Qatar, Malaysia and Australia. Australia will outpace the others soon as it develops its North West Shelf and completes construction of its first-of-a-kind supremely massive "Prelude" floating-LNG ship for remote condensing in the Browse Basin. The US will eventually develop LNG export facilities along its Northeastern Shore and in the Chesapeake Bay area (see figure 4)**,** but in the meantime domestic gas prices are expected to remain low. There is potential in domestic and foreign applications of natural gas that fuel cells can fulfill.

Figure 5 America's Natural Gas Boon : A Unique Opportunity



Japan and Korea as a Foreign market

Japan and Korea are two major importers of natural gas (due to scarce natural resources) that are also encouraging the development of fuel cell parks in their residential and commercial areas. In 1990 Japan launched it's Ene-Farm subsidization scheme after four years of trials and in response to the Fukishima Incident. They initially offered a $14k reimbursement for every residential fuel cell unit, with the subsidies to ultimately expire before 2015. The PEM fuel cells have been selling out as fast as they are made, and 2013 was expected to sell around 50,000 units. Korea is also entering into agreements with Fuel Cell Energy for manufacturing of large-scale manufacturing plants as well recently signing a memorandum of understanding with the UK's fuel cell researchers. Both Japan and Korea have high-tech sectors (with amazing internet speeds) that involve large data centers including recent facilities KDDI and Digital Reality. Japan and Korea then are viable data center markets for early adoption of solid oxide fuel cells.

Can SOFC displace conventional coal and gas?

Coal represents the *de facto* energy source in the world. Coal was originally a product of condensed peat from the carboniferous age when plants first developed lignin (bark) and would no longer rot (they simply were buried). It took fungi hundreds of millions of years to eventually develop an enzyme (ligninase) that would end this dominance by plants. Ironically, the burial of coal led to a time of reduced atmospheric carbon, only to trouble us 358 million years later in our atmosphere today. Coal today is perhaps the most dirty but cheapest form of energy and is the most plentiful in most countries. Without the consideration of environmental cost, coal would still be the dominant form of electricity. However current EPA regulations in the US and international agreements will set carbon emission standards that most coal plants will be unable to meet without excessive refurbishing of its processes.

Perhaps the greatest competitor against natural gas powered fuel cells are the conventional gas turbines that populate the electrical grid. The combined cycle gas turbine (CCGT) system is a response to the periodic spikes in demand within the electricity grid. When natural gas prices are lower than coal or when power demands peak, a CCGT plant can turn on within minutes to supplement electrical production. The GE FlexEfficiency 50 combined cycle can produce 510 MW at an efficiency of more than 61% while operating down to 87% of its full load. One could argue that these turbines serve the same function as the fuel cells in producing electricity from natural gas sources. However CCGTs are very large and remote. Their efficiency is difficult to maintain when scaling down and there is also a loss in efficiency from transmission over power lines. Fuel cells on the other hand scale well for on-site generation but likewise should not be expected to enter into the 100 MW scale of the CGGT system. Therefore SOFCs and CGGTs can coexist in their own niches.

Energy Burden of Renewable Sources vs. SOFC

This decade may see a contraction in the public push for renewable energy as the costs of intermittent renewable energy begins to coalesce. Last year Spain announced its renewable energies met 49% of demand, with wind energy the top energy source link. Their electricity tariff deficit however has leaped to over 30 billion euros, which is forcing the government to raise prices on an already beleaguered nation in recession link. Germany, which is displacing its nuclear energy with wind, is considering subsidy cuts after facing the second-highest electrical costs in the European Union at 35 cents/kWh (the current slumping trend should be attributed to lowered economic demand). The intermittent nature of the renewable has much to do with significant cost in infrastructure and inefficient market supply. However it is somewhat unfair to point to the cost of green energy subsidies when the fossil fuel industry has benefited from billions of dollars in energy subsidies as well (which are targeted towards stabilizing consumer markets in foreign countries). In any case, renewable energy sources such as wind and solar aren't an end-all argument for energy.

Large manufactured renewable energy sources aren't emission free. Think of the energy cost of smelting the steel and aluminum for a wind turbine's blades and nacelle, or the pyrolyzing of silane for a solar array. A 125 ton Vesta wind turbine would require at least 11 million kWh to manufacture, and more than 7 years to break even before it can start offsetting its energy cost to manufacture. This is all while only having a 20-year service lifetime. For solar cells a publication by a PhotoVoltaic Environmental Research Center reviews an energy payback time of 2-6 years with a 20-year service life. This depends on the solar insolation of the region, which is limited for many Western countries. This should in no way detract the reader from pursuing green energy. Researchers and companies acknowledge the energy cost of manufacturing and efficiency is improving everyday such as the Siemens process for solar photovoltaics. Renewable sources are still better than the alternative. The Chinese smog emergencies can attest to the problems of coal-based power.

The energy burden of solid oxide fuel cells is then brought to question. A household 1-kW planar SOFC micro-CHP system link by Fuell Cells Scotland could offset its initial CO_2 emission cost of construction after a year of operation when competing against a coal-powered grid. The total manufacturing energy cost of the system can total up to 8-15 thousand kWh when one considers the additional stacks (3.8) for replacement over a 10 year basis. It would take around two years for the SOFC to displace that same amount of energy from the grid. It's important then that the SOFCs extend their lifetime over two years so that their displacement of carbon emissions and energy is more strongly felt. SOFCs can also work with renewable bio-gas sources and thus displace their carbon footprint even quicker. It can be expected that biogas will serve as a powerful energy source in the future as new techniques in anaerobic digestion emerge by engineered organisms such as Craig Venter's synthetic genomics for hydrocarbon-producing algae.

Fuel Cell Adopters in the Data Center Market

An important question a CTO will face for his data center is whether the energy savings can best be saved by upgrading his servers, installing a new coolant system, or agreeing to a fuel cell service lease. The two former options pose the greatest cost but are also necessary to match IT demands. Fuel cell installation is a simple process of delivering and hooking up to the conventional electrical supply. A 10-year service agreement that is offered by Bloom and other developers will negate most of the risk a CTO will have to undertake in capital cost and maintenance. Finally, CTOs should act soon, most state and federal subsidies for energy sources are only temporary. A list of State subsidies can be found on the DSIRE website with specific fuel cell programs in California, New Jersey, New York, South Carolina, North Dakota (almost all states offer efficiency subsidies as well).

Finally, one of the greatest arguments for a data center to adopt: is that when a single hour of downtime can result in millions of dollars lost, and when power lines are problematic, on-site generation of power is the most reliable method. The natural gas pipelines are buried and are not subject to intense weather. The modular design of SOFCs also sets failure rate at extremely low levels. They are simply put the most consistent means of electrical generation with miniscule risk of outage. A list of current data centers that have adopted fuel cells is listed in Table 4.

Table 4. Compilation of data centers using fuel cells.

Company	Location	Maker	Produce	Comments	Ref
FNBO	Omaha, NE	UTC Power (Clear Edge	Four 200-kW PureCell (matches 100% demand)	Oldest usage at 14 years and without a single outage	link
Fujitsu	Sunnyvale, CA	UTC Power (Clear Edge)	One 200-kW PureCell (meets 50% of power)	Powers chiller-plant for HVAC system on campus.	link
AT&T	11 sites, CA	Bloom	7.5-MW by Bloom Energy Servers	Bloom's largest non-utility customer yet	link
Verizon	San Jose, CA NJ, NY,	Bloom, Clear Edge	Bloom Energy Server, 200-PureCell	Part of $100 million green implementation	link
Microsoft	Cheyenne, WY	Fuel Cell Energy	200-kW Direct FuelCell	First-carbon neutral data center. Near bio-gas waste plant	link
eBay	Salt Lake City, UT	Bloom	6-MW by 30 Bloom Energy Servers	Partially powers more than $175-billion in ecommerce activity	link
Equinix	Frankfurt, Germany	N2telligence	~159-kW QuattroGeneration fuel cell	Exploring fire-suppression ability to produce low-oxygen environment	link
JP Morgan Chase	Newark, DE	Bloom	500-kW by Bloom Energy Servers	Produced by Bloom's new manufacturing site in Newark	link
Savvis	Irvine, CA	Bloom	500-kW by Bloom Energy Servers	Savvis is a cloud-service provider	link
Apple	Maiden, NC	Bloom	5-10 MW by Bloom Energy Servers	Bio-gas powered from waste plant	link

Other Fuel Cell Adopters

Hospitals are another large consumer of energy that could benefit from fuel cells. Because lives may be at stake, hospitals are required to house back-up generators. They also exist in the public eye and so would benefit from a green energy initiative. A large acute care hospital of about 70,000 square meters would need about 3300 kW peaking during the summer, running up to about $1-3 million annually. Kaiser Permamente, the largest HMO in the country, has agreed to install 4 MW of Bloom Boxes at seven of its hospitals. American universities are another large entity that are quick to adopt early energy technologies as they are more likely to favor the touted scientific achievements of a particular technology over the cost.

Overcoming Challenges:

The greatest challenge facing SOFC is the high heat of activation required to enable the ceramics to conduct ions. At temperatures over 900 Celsius, the fuel cell sees electrochemical efficiency loss, heat stress, corrosion of interconnects, slow start-up times, and leaks by structure contractions. Advances in materials will help lower this activation temperature by finding electrolytes that are more conducive to ion conduction and discovering more durable anodes with high catalytic activity. Most discoveries have been empirical so far, so a highly thorough research method may quickly turnover new high-performance materials.

Some miscellaneous future technical advances may include:

- Plasma for formation of syngas. Essentially a plasma arc in conjuction with a catalyst forms syngas out of a variety of heavy hydrocarbons. Bioleux (Poland) has several smaller steam reformers using cold plasma technique. Solena Fuels has a similar process.
- New SOFC materials by Cerces and Redox.
- Improved analytical techniques (focused ion beams, TGA, x-ray diffraction,)
- Predictive computations (density functional theroy, continuum) to find better materials.
- Reversible fuel cells (unitized) that can use electrolysis to form hydrogen can be more flexible and can feed into a hydrogen supply infrastructure.
- Velocys formerly known as Oxford Catalysts may have even more interesting technology with its Fischer-Tropsch catalysts and microchannel reactors.

Carbon Capture System

The US emissions of CO2 in 2012 was 5 billion tonnes, surpassed only by China. Clean fuel cell technology is touted for its low carbon emission, but there currently is no actual application to capture the carbon emitted from fuel cells. This still leaves the challenge of how to sequester the carbon dioxide. The most popular current method is geological injection. The pressurized CO2 would need to be transported via infrastructure and injected in underseas formations such as the Juan De Fuca plate at the West Coast or depleted oil and gas reservoirs. The largest carbon capture project presently is Weyburn-Midale, Canada, where 40 million tonnes is anticipated to be sequestered in the oil field. There are many other scientific ventures exploring this process, but no self-sufficient profitable commercial project exists or can be expected soon. For instance the Weyburn-Midale project cost $80 million in international funding and is part of $1.4 billion funding carbon capture project by Alberta, Canada. Just recently (Sept. 213) there is a $2 billion by Chevron to build a CO2 injection site at its even larger liquid natural gas facility in Gorgon, Australia. These are extremely expensive projects of a massive undertaking that are impossible to implement commercially. They may have the greatest impact overall, but smaller-scale low-cost carbon sequestering is also important, if simply to have the “carbon-captured” label for a company.

One chemical process for carbon sequestering is to treat the carbon dioxide by metal oxides to form carbonates. The molten carbonate fuel cell takes advantage of the last process and can perform further separation of carbon oxides from a power plant's exhaust, actually capturing more carbon than originally in the fuel. It also may be possible and even necessary to integrate the carbon capture with the fuel cells system in order to be economically viable and useful. One start up firm in the United Kingdom, Carbon Capture Cambridge, suggests a system of introducing mineral silicates to an alkaline fuel cell to extract carbonate minerals and silica. The carbonated products could then be sold to offset the additional cost of the process, such as silica powder and calcium carbonate for mineral fillers and for cement manufacturing. This is a material-intensive process however and the logistics would be difficult to implement other than at already existing industrial parks. There is a small field currently of carbonate producers including: Skyonic's Skymine in Texas, Carbon8 in the UK, Calera in California, SABIC's carbon capture and utilisation plant in Saudi Arabia (largest at 1500 tonnes daily), Solvay's CDRmax plant in India, and Alcoa's Kiwinana Plant in Australia.

To end short, solid oxide fuel cells represent a viable option for on-site power generation for data centers. There are many challenges to overcome but the potential benefits that can be achieved are a clear-cut choice for further development of the technology.

Final Important Points to Take

- Adoption by high-profile companies is useful for market penetration, but large-scale adoption will ultimately depend on improved performance and lowered costs.
- Much of the improvements in SOFC efficiency will depend on either integrating a combined heating and power process to the system or making the activation temperature lower.
- Integrated carbon capture processes can appeal to green energy marketing.
- Pursue data centers in states that offer subsidies (California, New Jersey, New York)
- Other potential early technology adopters include: hospitals and college campuses.
- Establish relations with Japanese and Korean data centers.

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