No More Electrical Infrastructure: Towards Fuel Cell Powered Data Centers

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ABSTRACT

We consider the use of fuel cells for powering data centers, based on benefits in reliability, capital and operational costs, and reduced environmental emissions. Using fuel cells effectively in data centers introduces several challenges and we highlight key research questions for designing a fuel cell based data center power distribution system. We analyze a specific configuration in the design space to quantify the cost benefits for a large scale data center, for the most mature and commonly deployed fuel cell technology, achieving over 20% reduction in costs using conservative projections.

1. INTRODUCTION

We explore the use of fuel cells for powering data centers. Fuel cells (FCs) convert energy from fuel (e.g. hydrogen, natural gas, ethanol, or bio-gas) into electrical energy [19] using an electrochemical process. A common application of hydrogen fuel cells is in forklifts, since FCs are clean to operate indoors, but they have been also demonstrated in cars and buses. In the recent years, FCs have also been used as an alternative to the electrical grid [4]. The Japanese Large Scale Residential Fuel Cell Demonstration Project (ENE-FARM), for instance, has installed more than 20,000 FCs [6], aligned to the country's strategy of promoting distributed generation, as well as energy savings and carbon dioxide reduction. In the U.S., the majority of fuel cell deployments is in California, supported by the California's Self Generation Incentive Program (SGIP) [5].

The first reason to consider FCs as data center power systems is *reliability*. The gas grid infrastructure is mainly buried and not subjected to severe weather. Gas pumps themselves are typically power by a portion of the gas flowing through the stations. Gas grid reliability is known to be high, and the delivery contracts exhibit reliability greater than 99.999% [12], much higher than the 99.9% or less for the electric grid. As a result, FCs can eliminate diesel generators and batteries used for power backup. Local gas tanks are cheap to construct as backup energy storage. Reliability of the FCs themselves is high and because the data center will require multiple FCs anyway, adding a few redundant ones can easily account for FC failures. Also, most data center software is resilient to a small fraction of servers being unavailable due a single FC failure..

A second benefit is that gas distribution within a data center is much cheaper than high voltage switchgear, transformers, and copper cables. If the FCs are placed close to power consumption units, at the servers or racks, we can completely eliminate the power distribution system in the data center, including the power backup generation system. So, no data center wide electrical infrastructure is required. This is over 25% of the capital cost for state-of-the-art data centers. In addition, in many geographical regions, the energy-equivalent gas price is lower than electricity price, even after accounting for FC conversion efficiency. FCs do not have moving parts and can be easier to maintain than diesel generators.

Thirdly, fuel cells are environmental friendly. The cleanest FC fuel is hydrogen (produces only water as waste), but hydrogen is hard to store and distribute at scale. Even with natural gas as the most practical fuel option, FC emissions are cleaner than those from combustion - carbon dioxide emissions may be reduced by up to 49%, nitrogen oxide by 91%, carbon monoxide by 68%, and volatile organic compounds by 93% [21].

How to design a fuel cell powered data center (FCDC) to achieve minimum TCO is not obvious. There are sev-

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eral types of FC technologies, with different power outputs, efficiencies and load following capabilities. They can be placed at multiple levels in the power distribution hierarchy, leading to different end-to-end energy efficiency and operational costs. This paper presents the potentials and challenges in FCDCs, to achieve a cheaper, more reliable infrastructure, that is cleaner to operate than traditional data centers. After describing the basic principles, different types, and efficiencies of fuel cells in section 2, we discuss the key design dimensions in section 3. In section 4, we pick a particular design point and analyze the total cost of ownership, showing that a fuel cell data center can be at least 20% cheaper.

2. FUEL CELLS

A fuel cell (FC) is composed by an anode, a cathode and an electrolyte layer between them. For instance, in a hydrogen-fueled polymer electrolyte membrane fuel cell (PEMFC), hydrogen molecules split at the anode into protons and electrons, activated by a catalyst. The protons are able to run through the membrane while the electrons are not. This obliges them to travel across an external circuit, thus producing energy.

A single FC usually produces less than 1V and hence a *stack* of fuel cells is used. Aside from the stack, the FC also contains control systems to correctly manage the fuel flow rate, pressure, temperature, and humidity in the stack. Power electronics are also required to condition the output power depending on the application. For fuel cells that use hydrogen as fuel, a reformer is also required to convert natural gas to hydrogen.

Different types of FCs use different electrolytes and charge-transferring ions resulting in different efficiency, fuel used, and operating temperature. Some of the more studied varieties [19] are Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Direct Methanol Fuel Cell (DMFC), Solid Oxide Fuel Cell (SOFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC), and Direct Carbon Fuel Cell (DCFC).

PEMFC and SOFC are believed to be the most promising options. Table 1, based on [18, 19], lists their key characteristics. PEMFC is the most well developed, primarily due to its potential use in FC vehicles [5], due to compact size and lower operating temperature. It uses hydrogen as fuel, requiring a reformer that increases the data center cost. SOFC is notable for high efficiency, larger capacity, and suitability for continuous power generation [19]. SOFCs use natural gas (methane) directly. However, they run at a higher temperature and are hence less responsive to variable load [11].

Table 1: PEMFC and SOFC characteristics

	SOFC	PEMFC
Size range	up to 200kW	up to 10kW
Typical app.	Commercial buildings	Vehicles, residential, small business
Fuel	Natural gas or H_2	H_2
Efficiency	50% - 60%	40% (incl. reformer)
Advantages	High efficiency	Load following, fast on/off

3. DESIGN CONSIDERATIONS

Although various experimental fuel cell powered data centers, mainly using Bloom Box [**?**]and server containers in dense urban areas, have been demonstrated, adopting FCs as the main, or only, power source for mainstream stationary data centers to achieve minimum TCO requires fundamental rethink and redesign of data center infrastructure. Using fuel cells has the potential to greatly reduce the complexity and cost of the electrical infrastructure. However the electrical properties of FCs must be carefully examined.

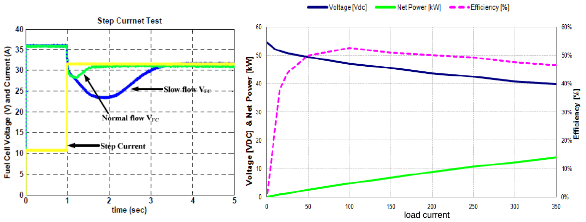
3.1 Fuel Cell Placement

Architecture wise, there are several possible ways to incorporate fuel cells in data center power systems.

At the utility power level. A group of FCs can be used to replace the utility power input, with the data center disconnected from the electric grid. Existing deployment are typically of this type with a few mega-Watt SOFCs. Larger FCs tend to have better efficiencies but the FC failure domain is large. This design requires a power distribution system like traditional data centers. At least in the near future, FC cost may be too high to make this option economical.

At the rack level. FCs can be brought closer to the servers. In this case, a FC of several killo-Watts can be used to power one or a few nearby racks. This design eliminates the entire power distribution system in the data center and replaces it with a fuel distribution network. As we will show in the next section, the infrastructure cost can be significantly reduced. Power failures due to FC malfunctions are limited to a couple of racks, which modern data center software can tolerate. Having FCs close to the servers makes direct DC power distribution possible. This can also eliminate the AC power supply unit in servers, currently used to convert AC input to internal DC power.

At the server level. With small FCs that only produce a few hundred Watts of power, it is possible to integrate them into servers. This option eliminates even the short distance power cabling from the rack level FC to servers, minimizing DC transmission losses. The reliability is also maximized because FC failures only affect a single server. However, smaller FCs may not be as energy



(a) (b)

Figure 1: transient behavior and efficiency of a 10kW PEMFC. (a) voltage response with sudden current increase. (b) efficiency as a function of power output.

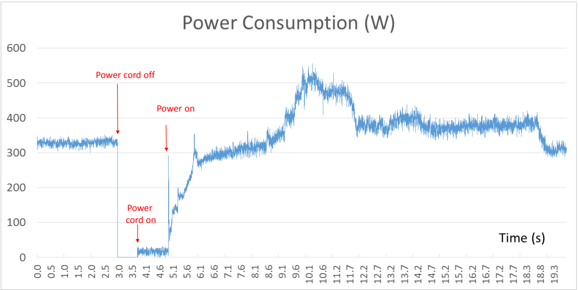


Figure 2: The power trace from powering down and starting up a server under 48V DC.

efficient and cost effective as their larger counter parts. We will also see in the electrical property analysis that the slow load following characteristics of FC may not be suitable for the high variation of server power consumption. At the server level, one cannot take advantage of statistical multiplexing across multiple servers to smooth the load.

Although the overall reliability of natural gas grid is high, integrating FC into a data center brings additional equipment such as reformers, battery systems, start-up systems, and auxiliary circuits. From an end-to-end service reliability point of view, we need to understand the dependency and failure domains of different FCDC architectures. Much further research is needed.

3.2 Load following capabilities

Fuel cells are typically suitable for constant power generation. They perform the best when the fuel and oxygen supplies are steady, and the load is constant. Due to high inertia in internal thermodynamics and chemical processes, ramping up or down power production is slow. For completeness, we show a plot from [14] on the dynamic response of a 48V 1kW PEMFC under load variation in Figure 1(a). With a controller that regulates fuel supply to follow the load, when the current jumps from 10A to 30A, the output voltage dips by up to 8V and it takes half a second for the controller to catch up with 500W additional power production. Research has report very slow response time for SOFC (e.g. 200W/min) [1]. In (b), we show the overall energy efficiency under different load. We can see that the too much, but especially too little load cause the FC to operate inefficiently.

It has been widely studied and reported that data center power consumption has both short and long term variations due to workload fluctuation and server on/off.

Instantaneous Load Changes. The load of the server can change almost instantaneously reacting to workload. A change in CPU utilization from 0% to 100% can happen within milliseconds, causing tens of Watts of spikes in power consumption. Some of the spikes can be absorbed by the server power supply with its internal capacitors. But large changes like flash crowd and hardware failures must be handled by an external energy storage (batteries or super-caps) or load banks [20].

Short-Term Load Changes. From Figure 1, we see that it takes several seconds for FC to ramp up or down its power production when load changes. Figure 2 shows the power consumption trace of a single 750W HP Proliant SE326M1 server with two quadcore CPUs and 98GB of memory. In situations when the server has to be cold rebooted, the fuel cell power production will lag behind where there are sudden power consumption changes. The gap must be filled by external battery. Or, if load changes are predictable, the FC can increase its production ahead of time. This gap further reduces the end-to-end efficiency of energy usage, which must be evaluated by further analysis and experiments.

Long-Term Load Changes. Data center workload also exhibits long term changes over days and weeks. However these changes are typically slower than the FCs ramping up or down rates. So, as long as the long term trends are predictable, fuel cells can be provisioned accordingly.

Under load fluctuations, a key research question is how much we need to over provision fuel cell power source. From our experiments with real servers, the only time that the server can cause large load change is in the startup and shutdown process. Interestingly, unpredictable events, such as rebooting a server in software or server software crashes do not cause any significant power change. This is because the electrical components are still powered in the reboot process. So, as long as single server spikes are handled internally, large load changing events are known to the management system. If we stagger server power on and off events over time, a single server sized battery can be shared by multiple servers in a rack. Thus the fuel cells do not need to aggressively over provisioned.

4. COST STUDY: RACK LEVEL FC

To understand the potential cost savings quantitatively, we analyze an FCDC configuration where FCs are placed at each rack, as one of the promising placing options.

Capital Costs (cap-ex): The amortized cap-ex depends on the price of the fuel cell, its expected service life, data center space saving, and extra components added to the data center for using fuel cells.

FC Cost: Current FC prices are high due to limited volumes, at about 25,000 units/year globally. FCDC adoption can greatly change the landscape and scale up the demand. To estimate FC costs at scale, one approach is to consider the cost of bottleneck components and materials used. The U.S. Department of Energy estimates the FC price at \$1.2/W by 2015, and \$1/W by 2020, based on the price of platinum (catalyst in FC), that accounts for 34% of the FC stack cost [22]. Another estimate [24] projects the price at \$3,000-5,000 for a 1-2kW system by 2020, or \$1.5-5/W. We can consider the cost reduction due to economies of scale for products based on similar systems. For fuel cells, this boils down to a 20% reduction in price with doubling of production volume [23, 8]. Based on the current US volumes [8], and the target of reaching only 1% of projected US data center energy consumption of 200TWh in 2016 [15], leads to a price of \$1.12/W. In this analysis, we use a conservative range of \$3-5/W.

Service Life: The fuel cell component with the shortest lifetime is the stack [25]. Manufacturers currently offer 5 year warranties on the stack but have measured lifetimes around 9-10 years. Reliability may improve with maturing manufacturing processes [17]. We conservatively assume that the stack, which is 20% of the cost [24], lasts 5 years, and the entire system, 10 years.

Supporting Components: Since the gas grid reliability is already as high as a DG backed up utility power [12], we no longer need DGs and uninterrupted power supplies (UPS) systems. Thus, FCs at the rack level eliminate the power distribution infrastructure including the transformers, high voltage switchgear, and cabling. Distributing gas to each rack with gas pipes (and gas leak sensors) is much cheaper. Using typical gas line installation costs [2], we estimate \$1.2/rack. Eliminating back up power and distribution infrastructure also reduces data center space. We estimate 30% space reduction based on typical data center real estate use.

FCs at the rack generate additional heat within the data center. Since FC efficiency, η, is not 100%, every 1W of IT power will result in $1/\eta$ of total energy being dissipated as heat within the data center. In effect, $(1/\eta) - 1$ of extra heat must be removed from the data center. FCs operate much warmer than the outside air. Hence, no chillers or compressors are required to cool them, and outside air can be used directly. In the cost calculation, we leave the chiller capacity untouched and increase fan capacity by $(1/\eta) - 1$. The fan and vent cost are approximately a third of the cooling cap-ex, and we increase that by $(1/\eta) - 1$.

FCs are slow to respond to changes in load. Fluctuations in server power may have to be smoothed out using batteries [7]. While the battery capacity required for this is typically lower than that for backup, we conservatively assume that the entire backup battery is used for load smoothing. Of course, this battery would be placed at the rack level (as already done at Microsoft and Facebook [16, **?**]), since we eliminated the power distribution from a centralized battery location.

Operational Costs (op-ex): The op-ex depends on the cost of the fuel (natural gas) and the energy overhead for the extra cooling. Natural gas has traditionally been 70% cheaper than electricity at equivalent energy [3]. Of course, not all the energy in natural gas can be used since the fuel cell efficiency, η, is below 100%. We account for the fuel cell efficiency of 25-35% for PEMFC and 50-60% for SOFC in our fuel cost calculations. Extra energy is incurred to run additional fans. Fan energy accounts for approximately 26% of the cooling energy [10]. We increase fan capacity, and energy use, by $(1/\eta) - 1$. We ignore the maintenance cost of FCs because they have no moving parts and hence their maintenance cost will be lower than that of DGs and other components that FCDC eliminates.

Results: Using the total cost of ownership (TCO) calculation methodology followed in [9, 13], that amortizes all costs to a monthly basis, we present the quantitative results in Tables 2 and 3 for cap-ex and op-ex respectively. The numbers for the electrically powered data center (baseline) are taken from [13]. We see 16-20% savings in cap-ex and 4% savings on op-ex on PEMFC. Savings would be greater for SOFC due to higher efficiency. The savings can be more significant also depending on the electricity prices of each State.

The key observation from the table is that fuel cells have the potential to reduce costs compared to the traditional electrical power distribution. Recall that fuel cells offer additional advantages: higher reliability of the gas grid, reduced power distribution complexity and maintenance, and increased environmental friendliness, available gas supply capacity in regions where the electric grid is not accepting new loads, and ability to operate on bio-gas from waste re-cycling plants. This makes fuel cells a promising option to be considered for data center architectures.

5. CONCLUSIONS

We presented the benefits and challenges of using fuel cells to power data centers. Much of the discussions in the paper use data and information reported from fuel

Table 2: Cap-ex (per rack per month)

Item	Baseline	Fuel cell $3/W	Fuel cell $5/W
Facility space	50.99	33.99	33.99
UPS/battery	2.00	0.00	0.00
Power infrastructure	89.08	0.00	0.00
Fuel cell system	0.00	18.95	31.58
Gas Pipes	0.00	1.20	1.20
Load following battery	0.00	2.00	2.00
Cooling infrastructure	36.84	59.41	59.41
Labor, security, networking, other	134.52	134.52	134.52
TOTAL	**313.43**	**250.07**	**262.71**

Table 3: Op-ex (per rack per month)

Item	Electricity	PEMFC (35% eff.)
IT	186.16	158.78
Cooling	37.35	55.28
TOTAL	**223.51**	**214.06**

cell research community. We plan to install a fuel cell with servers to get first hand measurements. This is a new domain that leads to many interesting research problems such as (i) best fuel cell types; (ii) placement of the fuel cell in the power hierarchy; (iii) managing load fluctuations to match fuel cell capabilities (iv) new computer and cloud service architectures that take advantages of fuel cell powers; and (v) the best cooling strategy among water or air based cooling. We expect interesting future research problems to be addressed along these lines to verify if the fuel cell is a useful power source for data centers.

6. REFERENCES

[1] P. Acharya, P. Enjeti, and I. Pitel. An advanced fuel cell simulator. In *Applied Power Electronics Conference and Exposition, 2004. APEC '04. Nineteenth Annual IEEE*, volume 3, pages 1554–1558 Vol.3, 2004.

[2] B. Eckert. How much does gas line piping cost? `http://www.costowl.com/home-improvement/hvac-gas-line-piping-cost.html`.

[3] EIA - U.S. Energy Information Administration. Short-term energy outlook. `http://www.eia.gov/forecasts/steo/report/natgas.cfm`, July 2013.

[4] Fuel Cells 2000. Fuel cells 2000 - fuel cells in america 2012. `http://www.fuelcells.org/uploads/StateoftheStates2012.pdf`, September 2012.

[5] FuelCellToday. The fuel cell industry review 2012. `http://www.fuelcelltoday.com/media/1713685/fct_review_2012.pdf`, July 2012.

[6] FuelCellToday. Fuel cell residential micro-chp developments in japan. `http://www.fuelcelltoday.com/analysis/analyst-views/2012/12-02-29-ene-farm-update`, February 2012.

[7] S. Govindan, D. Wang, A. Sivasubramaniam, and B. Urgaonkar. Leveraging stored energy for handling power emergencies in aggressively provisioned datacenters. In *Proceedings of the international conference on Architectural Support for Programming Languages and Operating Systems*, 2012.

[8] D. L. Greene, K. G. Duleep, and G. Upreti. Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities. 2011.

[9] J. Hamilton. Overall data center costs. `http://perspectives.mvdirona.com/2010/09/18/OverallDataCenterCosts.aspx`, 2010.

[10] Intel. Reducing data center cost with an air economizer. `http://www.intel.com/content/www/us/en/data-center-efficiency/data-center\-efficiency-xeon-reducing-data-center-cost\-with-air-economizer-brief.html`, August 2008.

[11] International Energy Agency. Iea energy technology essentials. `http://www.iea.org/techno/essentials.htm`, April 2007.

[12] N. Judson. Interdependence of the Electricity Generation System and the Natural Gas System and Implications for Energy Security. Technical report, Massachusetts Institute of Technology, Lincoln Laboratory, 05 2013.

[13] V. Kontorinis, L. E. Zhang, B. Aksanli, J. Sampson, H. Homayoun, E. Pettis, D. M. Tullsen, and T. Simunic Rosing. Managing distributed ups energy for effective power capping in data centers. In *Computer Architecture (ISCA), 2012 39th Annual International Symposium on*, pages 488–499. IEEE, 2012.

[14] J. M. Lee and B. H. Cho. A Dynamic Model of a PEM Fuel Cell System. In *Applied Power Electronics Conference and Exposition Annual IEEE Conference*, pages 720–724, 2009.

[15] Microsoft Corporation. Future datacenter sustainability. `http://www.microsoft.com/en-us/download/details.aspx?id=1177`, 2011.

[16] Microsoft Reveals its Specialty Servers, Racks. `http://www.datacenterknowledge.com/archives/2011/04/25/microsoft-reveals-its-specialty-servers-racks/`.

[17] National Renewable Energy Laboratory. National renewable energy laboratory (nrel) reports increase in durability and reliability for current generation fuel cell buses. `http://www.nrel.gov/hydrogen/pdfs/48869.pdf`.

[18] National Renewable Energy Laboratory. Gas-fired distributed energy resource technology characterizations. `http://www.nrel.gov/analysis/pdfs/2003/2003_gas-fired_der.pdf`, November 2003.

[19] H. Nehrir and C. Wang. *Modeling and Control of Fuel Cells: Distributed Generation Applications*. IEEE Press Series on Power Engineering. Wiley, 2009.

[20] C. Ramos-Paja, C. Bordons, A. Romero, R. Giral, and L. Martinez-Salamero. Minimum fuel consumption strategy for pem fuel cells. *Industrial Electronics, IEEE Transactions on*, 56(3):685–696, 2009.

[21] Research co-Ordination, Assessment, Deployment and Support to HyCOM. Case study: Power plant/commercial chp, 2008.

[22] S. Satyapal. U.S. Department of Energy - Fuel Cell R&D Progress. `http://www.iphe.net/docs/Events/China_9-10/1-2_sunita%20satyapal.pdf`, September 2010.

[23] I. Staffell and R. Green. Estimating future prices for stationary fuel cells with empirically derived experience curves. *International Journal of Hydrogen Energy*, 34(14):5617 – 5628, 2009.

[24] I. Staffell and R. Green. The cost of domestic fuel cell micro-chp systems. `https://spiral.imperial.ac.uk/bitstream/10044/1/9844/6/Green%202012-08.pdfm`, July 2012.

[25] M. Tanrioven and M. Alam. Reliability modeling and analysis of stand-alone {PEM} fuel cell power plants. *Renewable Energy*, 31(7):915 – 933, 2006.