Fuel Cells for Data Centers: Power Generation Inches From the Server

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ABSTRACT

Typically, improving data center availability requires designing in more infrastructure; the antithesis of reducing costs. Is there a way to cut infrastructure, cost and emissions while improving energy efficiency and server availability? We consider and evaluate the integration of fuel cells with IT hardware with various architectural designs, essentially collapsing the entire energy supply chain, from power plant to power supply unit, into the confines of a single server cabinet. In this paper, we propose a distributed power architecture for fuel cell powered data centers to achieve high reliability and efficiency. We experimentally validate the design and demonstrate the use of a 10kW Proton Exchange Membrane Fuel Cell (PEMFC) stack and system as the distributed power source to power a server rack, eliminating the power distribution system in the data center and the grid outside of the data center. The PEMFC is found to respond quickly and reproducibly to both AC and DC load changes directly from the rack. By utilizing the fuel cell DC output, 53% energy efficiency in a single server rack can be achieved. We also carry out cost analysis to quantify the cost savings that could be achieved with fuel cells placed in each rack. We evaluate and characterize the performance and the dynamic load following capability of the fuel cell. In addition, direct DC power from the fuel cell system eliminates the capital cost and operating conversion losses from systems that use energy storage and AC/DC conversion equipment. Reducing components in the energy supply chain not only cuts cost but reduces points of maintenance and failure improving availability.

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1. INTRODUCTION

In the last decade, we have witnessed dramatic advances in data center design due to the demand of offering uninterrupted cloud and online services at lower expense. For example, in many designs, aggressive air-side economization (using outside air directly to cool servers) has replaced computer room air conditioning (CRAC) systems; evaporative cooling has replaced chillers; and power over-subcription is used to better utilize power capacity. As a result, power utilization efficiency (PUE), defined by the ratio between overall facility power consumption and the power used by the servers, has improved from an industry average of 2 to the best practice of 1.11 in at least one news release [12]. However, the fundamental data center power infrastructure, consisting of transformers, power distribution units, UPS systems, and backup generators, has changed little. This power system is necessary to deal with the high-voltage AC power grid and its relatively low reliability at 99.9%.

In this paper, we explore a drastically different design point for data center infrastructure by leveraging the natural gas grid (or other locally available bio-gas or hydrogen source) and fuel cell technologies. Our analysis and experiments show that we can achieve low cost, low greenhouse gas emission, high reliability, and high efficiency by using mid-sized fuel cells (producing a few kilowatts) at the rack level, directly supplying DC power to the servers, and effectively replacing the power distribution system in a data center by a gas distribution network.

Fuel cells (FCs) convert energy from fuel (e.g., hydrogen, natural gas, ethanol, or bio-gas) into electricity [54] using an electrochemical process. FCs are not limited by the Carnot Cycle Efficiency [11] limit that conventional generators are. They are very clean, reliable and perfect for small form factor applications, as we will elaborate in section 2. Hydrogen fuel cells are widely used in forklifts today, since FCs are clean and power dense enough to operate indoors, but they have been also demonstrated in cars and buses. In recent years, natural gas and biogas FC systems have also been used as an alternative to the electrical grid [23, 25] as a greener alternative. In the U.S., the majority of fuel cell deployments was in California, supported by California's Self Generation Incentive Program (SGIP) [24].

There are several reasons that motivate us to consider fuel cells as data center power sources.

- High energy source reliability. The natural gas grid is known to be reliable. Its infrastructure is mainly buried and not subjected to severe weather. Distribution compressor stations themselves are typically power by a portion of the gas flowing through the stations. End user delivery contracts exhibit reliability greater than 99.999% [37], much higher than the 99.9% or less for the electric grid. On-site natural gas storage is also simple and cost effective to build.

- High end-to-end efficiency. Fuel cells are more efficient in extracting energy from natural gas than traditional combustion power plants of the same size. Placing fuel cells close to consumers also eliminates the energy lost in long distance power transmission.

- Low greenhouse gas emission. In addition to being more energy efficient, fuel cells are cleaner than traditional power generation – carbon dioxide emissions may be reduced by up to 49%, nitrogen oxide by 91%, carbon monoxide by 68%, and volatile organic compounds by 93% [60].

- Low operation costs. Electricity produced at typical fuel cell system efficiencies from natural gas is much cheaper than grid supplied electricity.

- Improved design reuse. Unlink grid electricity whose frequency and voltage are subject to variability around the world, from data center design. Natural gas is a fungible resource. The exact fuel cell data center design can be replicated around the world without modification. This greatly reduces the time to market for bringing new data centers online, and can lower system cost through mass production.

A simple way of incorporating fuel cells as data center energy sources is to treat them as grid replacements or backup generators. For example, eBay equipped its Utah data center with fuel cells from Bloom Energy [66]. Because of the relatively expensive fuel cells, this centralized design is not economical [1].

In contrast, we propose a direct generation method that places fuel cells at the rack level inches from servers. We call this a *Distributed Fuel Cell* (DFC) architecture. DFC limits the failure domain to a few dozen servers. Modern software technologies can tolerate such failures through replication and load balancing. Close proximity also allow us to directly use DC couples between fuel cells and servers without conversion. As a result, we can eliminate power distribution units, high voltage transformers, expensive switchgear, and AC-DC power supplies in servers from data centers. As we will compare in section 6, this design is up to 30% more economical than traditional designs to build and operate. With improving energy efficiency of small sized fuel cells, we also predict that DFCs are cheaper to operate than centralized fuel cells.

A main technical challenge for using fuel cells to power computing devices is to handle load following. It is well known that individual servers exhibit abrupt and large power consumption fluctuations due to variation in workload [59]. On the other hand, typical fuel cells are designed for relatively steady load. In this paper, we experimentally characterize the load following properties of a proton exchange membrane fuel cell (PEMFC) powered servers under both AC and DC power coupling. Our experiments show that we can achieve over 53% efficiency with direct DC powered servers. The PEMFC system is found to respond quickly to both AC and DC load changes to meet load fluctuations caused by server workload and reboots.

In summary, this paper makes the following key contributions:

- We propose a distributed power architecture for fuel cell powered data centers to achieve high reliability.

- We experimentally validate the design and characterize the end-to-end efficiency of PEMFC powered servers.

- We analyze the total cost of ownership (TCO)

[1] eBay claims that it may recover the capital expense in three years due to low natural gas price

of our design based on the experimental results and show that distributed fuel cell power data centers are less expensive to build and more efficient to operate than traditional data centers and centralized fuel cell alternatives.

The paper is organized as follows. In section 2, we give some background information about fuel cells and the technical challenges of using them to power data center servers. In section 3, we describe the distributed fuel cell power system design and the glue circuit between fuel cells and servers. In sections 4 and 5, we evaluate the electrical characteristics of fuel cell operation, and compute the end-to-end energy efficiency of traditional and DFC DC designs. We perform TCO analysis in section 6 based on experimental results. Discussion and conclusions are made in section 7 and section 8.

2. BACKGROUND AND RELATED WORK

2.1 Fuel Cells

Fuel cells offer an alternative to combustion that can more efficiently and with lower emissions convert fossil or renewable fuels into electricity. Combustion processes mix and burn fuel and oxidant with random, uncontrolled motion of electrons to produce heat that is subsequently converted to a useful form of energy (mechanical, electrical) through a heat engine. Conversely, fuel cells directly convert fuel chemical energy to electricity with a controlled flow of electrons through electrochemical reactions that keep fuel and oxidant separate [10]. Fuel cells produce power electrochemically by flowing fuel gas over an anode and air over a cathode, and utilizing an electrolyte in between to enable exchange of ions. Performance depends upon the chemical potential difference in contrast to the temperature difference required by heat engines which are thus limited by the Carnot efficiency, enabling the realization of high efficiency at almost any size power plant. There are five major types of fuel cells depending upon the type of electrolyte and charge transfer process used:

- Phosphoric acid fuel cell (PAFC)
- Alkaline fuel cell (AFC)
- Proton exchange membrane fuel cell (PEMFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

These fundamental differences lead to higher electrical efficiencies (greater than 50% in some simple-cycle cases and greater than 70% in some hybrid cycles [50]). In addition, fuel cells produce zero or near-zero amounts of criteria pollutants, while both the higher efficiency and renewable fuel use reduce carbon dioxide emissions per unit of power produced [10]. The technological progress of fuel cells has been astounding in recent decades. Modern fuel cell systems have been engineered with sufficiently low cost, and high enough power and energy density to meet increasingly stringent consumer demands [10].

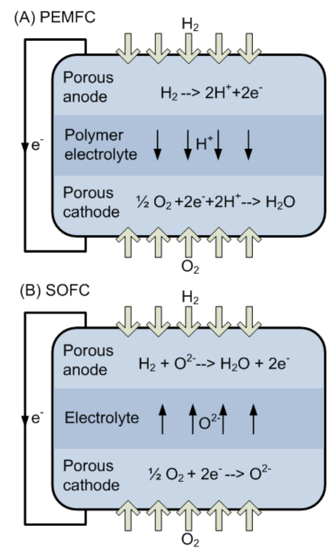

Figure 1: Schematics of (A) PEMFC and (B) SOFC.

	SOFC	PEMFC
Efficiency	50% - 60%	40% (incl. reformer)
Power range (kW)	10-100k	0.001-1k
Fuel	Natural gas or Hydrogen	Hydrogen
Internal reforming	Yes	No
CO tolerance	Fuel	Poison (<50ppm)
Balance of plant	Moderate	Low-moderate
Advantages	High efficiency	Load following, fast on/off

Table 1: PEMFC and SOFC charateristics.

Of the various fuel cell types, PEMFC and SOFC offer the best prospects to be the most promising options for powering data centers. Schematics of PEMFC and SOFC are presented in Figure 1, and their key characteristics are listed in Table 1 [55], PEMFC advantages include high power density, low operating temperature, and good start-stop cycling durability. Disadvantages include the requirement for expensive catalyst, poor poison tolerance and water management issues [55]. SOFC advantages include fuel flexibility, non-precious metal catalyst, completely solid-state cell components, and the production of high quality waste heat for co-generation applications. SOFC disadvantages include system complexity introduced by the high operating temperature, sealing difficulties under thermal cycling and relatively expensive cell components [55].

The use of fuel cells in data centers will also introduce a set of additional system components. A schematic of a fuel cell system design is presented in Figure 2. A typical fuel cell system includes fuel cell subsystem, thermal management subsystem, fuel delivery/processing subsystem and power electronics subsystem. The reliability, energy consumption, capital cost and footprint of the devices in these subsystems will also need to be carefully considered and evaluated.

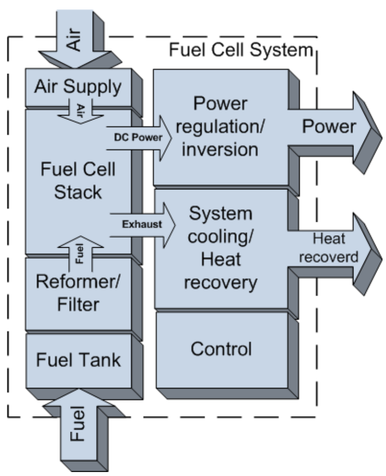

Figure 2: Schematic of a fuel cell system.

2.2 Related Work

Many groups have proposed methods to optimize traditional data center power infrastructure in various ways [21, 28, 40, 74, 73, 22, 9, 6]. Many of these optimizations reduce the power infrastructure cost by reducing peak capacity for which the infrastructure is provisioned, such as through server power scaling using DVFS [58, 16, 53, 77, 26, 41, 57, 75, 8, 42], use of inactive deep sleep states [45, 4, 47, 15, 1, 62, 46, 3], and power-aware workload scheduling techniques [49, 14]. Higher layer power optimizations such as consolidation, load migration, or load-distribution [13, 56, 72, 43, 2, 65] can also help reduce the cost of power infrastructure.

The data center industry has experimented with centralized fuel cells through simulation and pilot installations. Such studies and demonstrations are mainly focused on: 1) installing high temperature fuel cells (several MW capacity) to power an entire data center [67, 68, 69], 2) advancing combined heat and power technology in the data center [30, 79] for better efficiency, and 3) performing economic and energy efficiency assessments [79, 31]. Manno [30] simulated a cogeneration system based on a natural gas membrane steam reformer producing a pure hydrogen flow for electric power generation in a polymer electrolyte membrane fuel cell. The study demonstrated that heat is recovered from both the reforming unit and the fuel cell in order to supply the needs of the data center. The possibility of further improving data centersâĂŹ energy efficiency adopting DC-powered data center equipment is also discussed. Qu [79] reported a comprehensive performance assessment for a combined cooling, heating and power (CCHP) system with fuel cell in a data center. Data analysis and simulation results demonstrated great advantages of CCHP systems over conventional systems in the data center with regard to energy, environment and economic performance. In the case study, if a single-effect absorption chiller is installed, the overall system efficiency could be improved from 53% to 67% and the primary energy consumption could be reduced by 6773 MWh. Hagstotz [31] described the use of a molten carbonate fuel cell for data centers and telecommunication installations supplying cooling and electricity. Few of these published studies pertain to utilizing a midsize PEMFC system within the server rack that directly uses DC power output, as is accomplished in this effort.

While prior methods have focused on reducing the cost of conventional power infrastructure or introducing fuel cells in conventional designs for energy efficiency and environmental friendliness, our design of FDC is the first to redesign and cost optimize the data center power infrastructure around distributed fuel cells being used as primary power source.

3. SYSTEM ARCHITECTURE

We consider the distributed fuel cell architecture of running natural gas pipes all the way to the racks and using fuel cells of a few kilowatts each to power one or a small number number of racks.

3.1 Distributed Fuel Cells

Figure 3 compares a traditional data center power infrastructure and a distributed fuel cell data center. In a traditional data center, power from the electrical grid needs to be converted multiple times and connected with various power backup systems and generators. In contrast, a DFC may only have a natural gas network and levels of valves to maintain gas pressure. PVC gas pipes are much cheaper to install while the fuel cells themselves can provide redundancy and backup power.

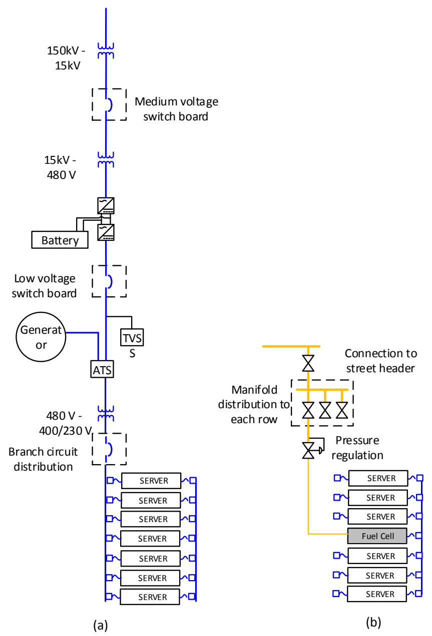

Figure 3: Architecture comparision between a traditional data center and a distributed fuel cell data center. (a) a traditional data center has tiers of power transformers and backup systems. (b) a DFC system distributes natural gas to the racks and eliminates much of the power infrastructure.

Note that using centralized FCs, much of the power distribution in Figure 3 (a) will remain to carry power through relatively long distances throughout the facility. Generators, transformers, converters, and much electrical equipment will be eliminated, but a centralized UPS (probably with reduced capacity) will likely still be required to handle possible FC failures.

In addition, eliminating electrical distribution in a data center can shrink its physical space. Over 40% of the interior square footage in a traditional data center is dedicated to electrical rooms including generator, UPS, transformer, switchgear, transfer switches, etc. While gas distribution replaces electrical distribution, the net result is still a much smaller footprint. From the street, large 6-inch gas pipes deliver large volumes of fuel to each computer room. Lateral pipes branch off down each row to each rack. At the rack level, pressure regulators bring the pressure to fuel cell operating conditions. Heat from the servers can be used to regulate valve and pipe temperature as the gas is decompressed.

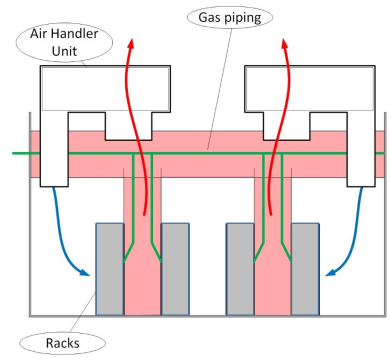

Figure 4: Gas piping can be placed in the hot aisle where air is exhausted out of the building.

To accommodate additional heat generated by the FCs and ensure gas safety, the air flow in DFC data centers needs to be designed carefully. Figure 4 shows a possible layout inside a data center room. The gas pipes run through the hot air compartment connected with the air handling units. Any leaking gas will be vented directly outside without creating a safety risk. Fuel cells themselves produce high temperature exhaust. However, they are not mixed with ambient air and can be emitted outside. Fuel cells are usually well insulated and can be cooled with exhaust of the servers, eliminating the need to supplementary cooling.

3.2 Load Following Capabilities of Fuel Cells

A key concern of using fuel cells to power servers directly is the load following capability of fuel cells. Fuel cells themselves can usually respond sufficiently fast to changes in load due to their rapid electrochemical reaction rates [34]. Processes inside the fuel cell such as electrochemical reactions and charge transfer processes typically occur over time periods on the order of milliseconds [52]. The main issue in fuel cell system load following is the relatively slow response of the fuel processing and fuel/air delivery subsystems. Since the electrochemistry directly produces the electrical work output, a fuel cell system should be able to achieve rapid load following capability on the same order as that offered by the electrochemistry. Load following problems occur when the response of the fuel cell system cannot safely meet both the external system power demand and the balance of plant power demand. The limitations could result from conservative control techniques or from inherently slow response of subsystem components, such as flow or chemical reaction delays associated with fuel/air processing equipment [52]. In the case of slow subsystem response the fuel cell performance depends upon the performance of the subsystems.

Different types of fuel cell systems have distinctive features and subsystems. Therefore fuel cell systems exhibit different load following capabilities. The SOFC and PEMFC system response is fundamentally limited by the performance of the fuel preprocessor and the amount of hydrogen present in the anode compartment. During transients it is essential that sufficient hydrogen be maintained in the fuel cell to sustain the fuel cell voltage and avoid damage caused by hydrogen starvation. Fuel starvation in the anode compartment can occur if the fuel is consumed by the electrochemical reactions faster than it can be supplied by the fuel delivery system. Hydrogen is sustained in the anode compartment by controlling the fuel flow rate in proportion to consumed hydrogen and a desired utilization [5]. Studies have shown that SOFC systems with proper subsystem and control design should also be able to exhibit load following capabilities [5, 52, 51, 27]. Other operating conditions such as feed gas humidity, operation temperature, feed gas stoichiometry, air pressure, fuel cell size and gas flow patterns were also found to affect the dynamic response capabilities of PEMFC [38, 80].

To integrate fuel cell systems to data centers, transient analysis of the fuel cell system and components needs to be carried out combined with data center load changes. 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 events.

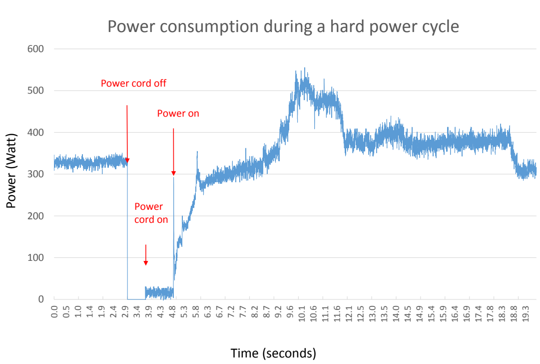

Figure 5: The Power trace from powering down and starting up a server under 48V DC.

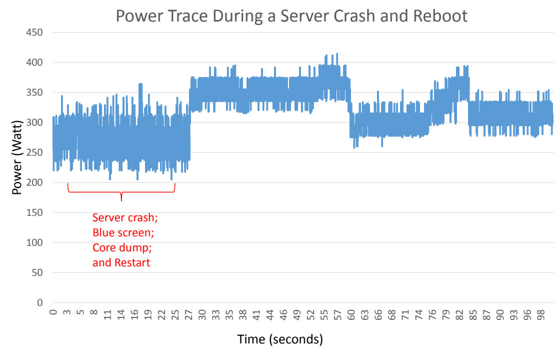

Figure 6: The Power trace from a server crash and reboot sequence under 48V DC.

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. Some of the power spikes can be absorbed by the server power supply with its internal capacitors. These spikes can cause fuel cell voltage fluctuation, but can be absorbed by the capacitors in the server power supply.

Short-Term Load Changes. It usually takes several seconds for a fuel cell to ramp power up or down as load changes depending upon the fuel cell type and system design. Figure 5 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 system must be able to follow sudden power consumption, which may require an external battery. Or, if load changes are predictable, the FC can increase its production ahead of time, which has efficiency implications that must be evaluated by further analysis and experiments.

Interestingly, unpredictable events, such as rebooting a server in software or server software crashes do not cause any significant power change, as shown in Figure 6. 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.

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 future 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. 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, in theory, the fuel cells do not need to aggressively over provisioned.

So the technical challenge for DFC is on handling short term load changes. A conservative design will use a UPS system to decouple of fuel cells and servers. The UPS may produce AC output so the servers can stay with their conventional design. Alternatively, one may rely on fuel cells' internal load management capabilities to directly power servers with DC power supplies. The efficiency and load following transients need to be studied carefully for the optimal design. If works, the latter option is attractive due to its lower cost. In the next section, we experimentally evaluate the short-term load following capability using a PEMFC and a rack of servers.

4. SYSTEM EVALUATION

To explore the feasibility and benefits of direct DC power distribution to the servers and the electrical properties of fuel cells, we demonstrated the use of a 10kW PEMFC stack and system as the distributed power source to power a server rack and eliminate the power distribution system in the data center. In this section, we evaluated and characterized the performance and the dynamic load following capabilities of the PEMFC system.

4.1 Experimental Setup

To analyze the transient response and efficiency of fuel cells, we designed, installed and tested a hybrid fuel cell-battery system. In this paper, we presented testing results of two system configurations, AC output and DC output configuration. The system and the schematic for the configurations tested are shown in Figure 7. In the hybrid system with the AC output configuration, the output of a 10 kW PEMFC was first converted to 192VDC and then connected to a 10 kVA, 208VAC L-L UPS system to supply AC power to the servers/load. The UPS system converts the fuel cell power to conditioned power for the connected server/load. This configuration was selected for initial investigation of the battery and the fuel cell dynamic response characteristics, but it does not represent any preferred or optimal design of the type of hybrid fuel cell battery system envisioned herein. In the system with DC output configuration, servers were directly connected to the PEMFC 48VDC output.

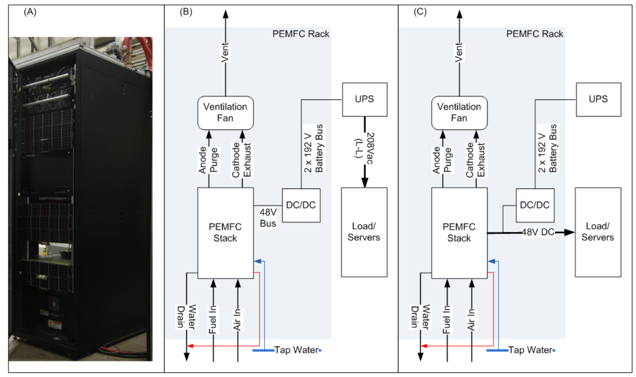

Figure 7: The experiment setup and schematics, (A) The testbed, (B) AC output configuration, and (C) DC output configuration.

4.2 Fuel Cell Performance

The performance of the PEMFC system tested in this study is presented in Figure 8. The current-voltage curve showed in the Figure represents a typical IV curve of the PEMFC, with relatively large activation losses at low current region. The average open circuit voltage (OCV) of the single cells in the stack was measured at 0.93V. With 60 cells in the stack, 55.8V was observed at open circuit. Maximum power of 10 kW was achieved, and no limiting current was observed for the fuel cell. It indicates that when the fuel cell is operating at 250A, diffusive mass transportation in the electrodes is sufficient and the reactant concentrations are sustained from depletion.

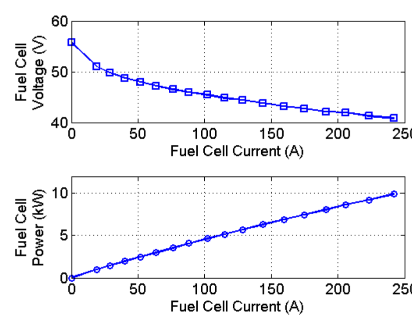

Figure 8: The polarization curve and power curve of the PEMFC system.

In Figure 9, PEMFC steady-state properties such as maximum disparity amongst cells, air flow rate and coolant temperature are presented. Single cell voltage and the maximum disparity amongst cells provide important information to the control and monitoring the system. Operating at high current, the voltages of some cells may fall and therefore lower than the average cell voltage because of membrane dehydration or fuel depletion [76]. As shown in Figure 9, the maximum cell voltage disparity increases with the fuel cell current and becomes relatively stable at 25mV. The air flow rate showed in Figure 9 indicates that the air flow rate is adjusted stoichiometrically with the power so that the reactant and the product ratio can be fixed. The coolant temperature remains below 60°C, suggest that low grade waste heat was rejected from the PEMFC system.

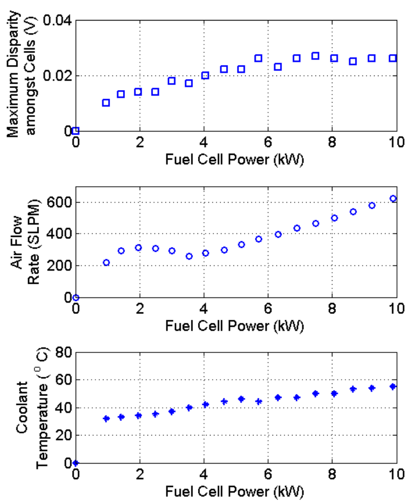

Figure 9: PEMFC system steady-state properties.

4.3 System Performance

Single Server Transient Characterization: Figure 10 shows the power consumption trace of a single 750W HP Proliant SE326M1 server with two quadcore CPUs and 98GB of memory, using various DC and AC sources. As shown in Figure 10, severer dynamics were observed during turning on for both AC and DC power traces.

Step Load Responses in AC Output Configuration: To understand the load following capabilities of the fuel cell and battery hybrid system, a step load power demand profile as shown in Figure 11 and Figure 12 (black line) was applied to the system. The system configuration is shown in Figure 7(B). The fuel cell power output and the

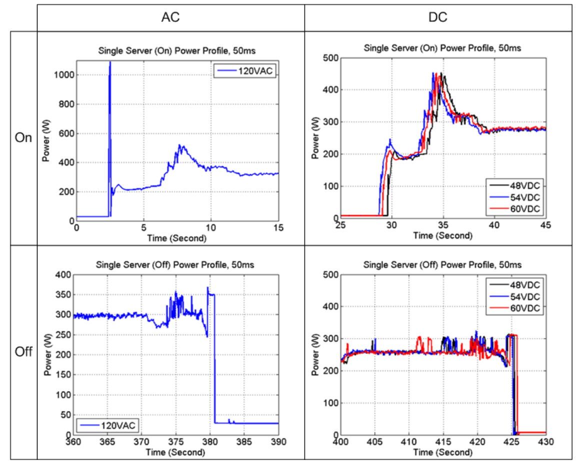

Figure 10: Single server power-on and power-off characterization.

DC/DC converter output were measured and are also shown in Figure 11 and Figure 12. Note that the system responds immediately to the power increase perturbation. Combined with the batteries in the UPS, the fuel cell system was able to meet the step load increases applied. The differences between the fuel cell output and the DC/DC converter output is the energy loss in the DC/DC converter. 10.2% of the fuel cell power is consumed in the 48V to 192V conversion process. The differences between the DC/DC converter output and the load is the sum of the energy losses in the UPS system inverter and the energy used to charge the batteries in the UPS system.

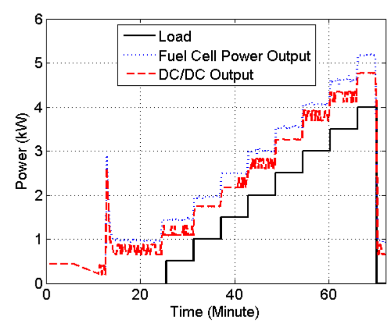

Figure 11: Fuel cell system responses to AC step load (0-4.5kW).

Server Load Responses in DC Configuration: To evaluate the dynamic response performance of the PEMFC, servers were also connected to the PEMFC 48VDC bus directly, as illustrated in Figure 7 (C). In this configuration, servers were only utilizing the fuel cell direct current (DC) output.

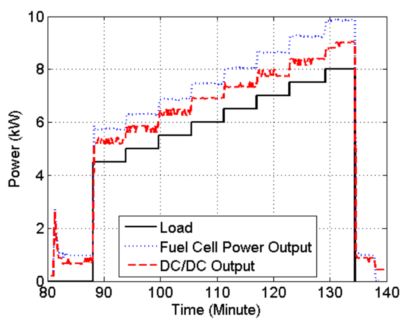

Figure 12: Fuel cell system responses to AC step load (5-10kW).

Dynamic operation of servers were performed and the response of the fuel cell voltage and current (sampling period=10s) are presented in Figure 13. Five major transient load changes were applied, without any batteries in the system the PEMFC was able to meet the server load dynamics. During load up event A (with 3 servers turned on), event B (with 3 more servers turned on) and event D (with 9 servers turned on), the maximum ramp rate of the PEMFC system are 52W/s, 60W/s, and 192W/s, respectively.

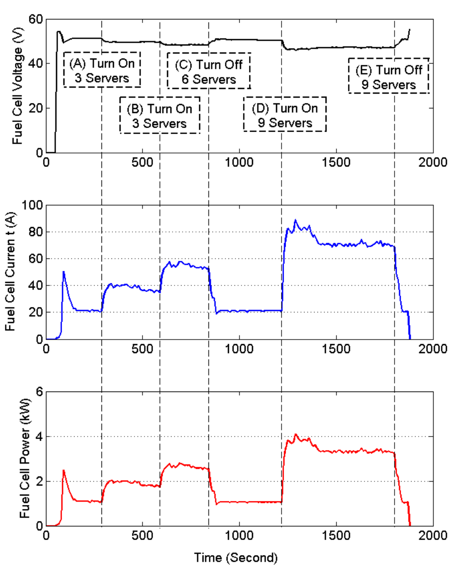

Figure 13: Fuel cell system responses to servers dynamic operation.

Higher resolution (sampling period=50ms) voltage response of the fuel cell were also obtained and presented in Figure 14 to further characterize the dynamic response performance of the PEMFC. As shown in the figure, fuel cell voltage undershoot behavior were observed after load stepped up. As can be seen in Figure 14, with 3 servers turned on, two voltage undershoots of 500mV and 800mV occurred. When the load stepped up to 9 servers, one voltage undershoot of 900mV was observed. In both cases, the fuel cell voltage recovered to the new steady-state voltage within 12 seconds. The dynamic response of the PEMFC can be improved by increasing the air flow rate in the cathode. Higher air stoicihiometry could result in lower voltage undershoot and faster transient response under dynamic load [78, 80].

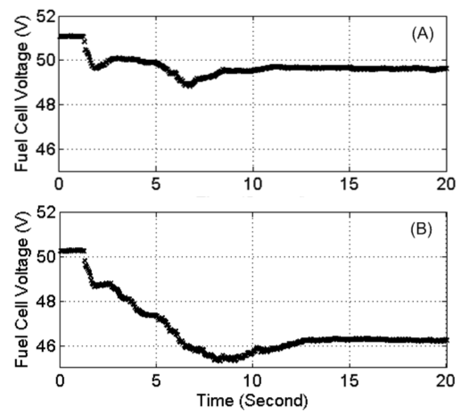

Figure 14: Fuel cell voltage transient response to (A) 3 servers turn on and (B) 9 servers turn on.

System Efficiency with DC Configuration: System efficiency was evaluated at steady state with 9 servers operating when fuel flow rate and coolant inlet/outlet temperatures were at equilibrium. As shown in Figure 15, when the fuel cell power output is 3.3kW, the system electrical efficiency reaches 58.3% (using the lower heating value of hydrogen). 5.1% of the electric power generated was consumed in the fuel cell balance of plant. 13.4% of the electric power was consumed in charging the UPS, while 39.8% of the power delivered to the server PSU (power supply unit).

As the servers were connected directly to the fuel cell 48VDC bus, there was no DC/DC conversion losses in the system therefore higher efficiency was achieved. It is noted that in our current DC system configuration, UPS system is charged by the fuel cell system. With optimized system design, the UPS system could be disconnected from the system. As a result, 53% of the power generated by the PEMFC could delivered to the server PSUs under the operating condition, as shown in Figure 16.

5. DATA CENTER EFFICIENCY

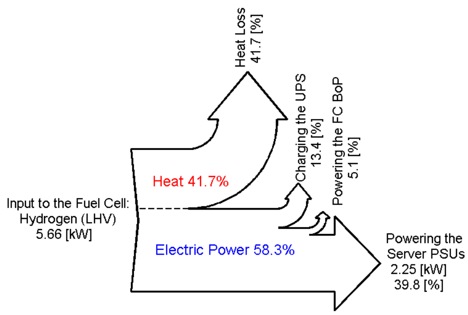

Figure 15: Efficiency sankey diagram of DC configuration (with charging the UPS).

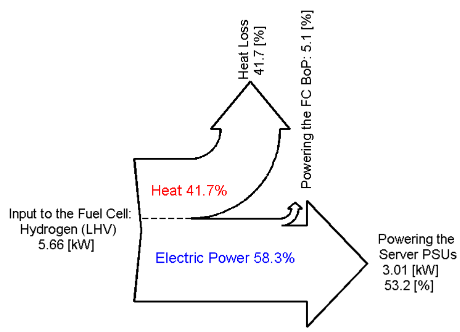

Figure 16: Efficiency sankey diagram of DC configuration (without charging the UPS).

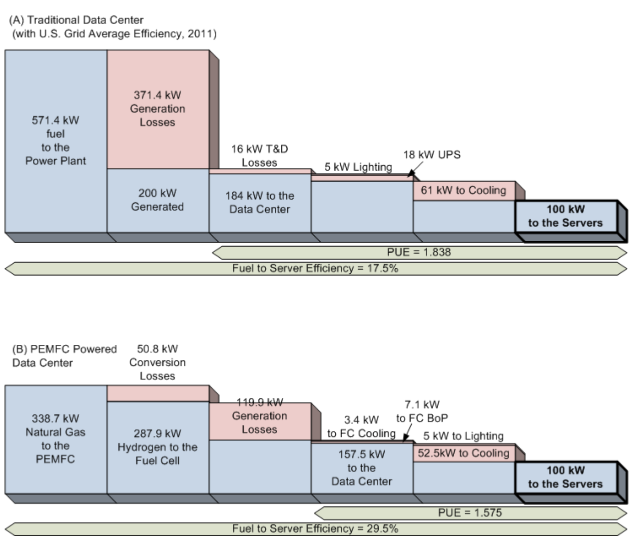

Figure 17: (A) Traditional data center system losses, and (B) Fuel cell powered data center system losses.

In a traditional data center connected to the electric grid, less than 35% of the energy that is supplied to a power plant is delivered to the data center due to generation losses [20] (based on U.S. 2011 average generation efficiency of 35%), transmission and distribution losses (8%). With energy consumptions associated to the cooling, lighting and energy storage [36], only 17.5% of the energy supplied to the power plant is ultimately delivered to the servers. Based on our system design and the performance evaluated in the previous section, system losses from a traditional data center and a PEMFC powered data center is compared in Figure 17. In the comparison, we assume that the cooling load is proportional to the electric load for both traditional and fuel cell powered data centers. As shown in the figure, fuel to server efficiency of PEMFC powered data center reaches 29.5% and significantly higher than 17.5% of traditional data center. We also assume that no heat is recovered from the fuel cell exhausts. However, with combined cooling, heat and power (CCHP) technology, the waste heat of a high temperature fuel cell system (such as MCFC and SOFC) could potentially be recovered and provide enough cooling for data centers. In this case, the power delivered to the servers will be significantly increased. To further understand the effect of the fuel cell system on the PUE, we also carried out a sensitivity analysis. In the two base cases we discussed in Figure 17, we assume that for every 1kW electric load, 0.5kW power is consumed for cooling (cooling ratio=0.5)[36]. With advanced cooling system design, less cooling power consumption will be required. We present the effect of more efficient cooling system on PUE for both data centers in Figure 18. PEMFC powered data center has better PUE under all cases, reaches 1.15 when the cooling ratio is 0.1.

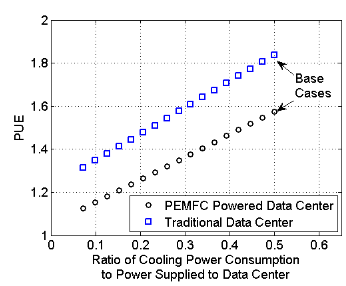

Figure 18: PUEs of data centers with various cooling energy consumption ratios.

6. TOTAL COST OF OWNERSHIP (TCO) ANALYSIS

We analyze data center TCO savings based on the FC characteristics and the efficiency at which they can supply a server. In the power subsystem architecture, FCs can be placed at multiple levels. At one extreme, one could place them at the data center level (*At DC*), in a central bank that supplies all of the data center. The eBay data center in Utah [66] is an instance of this design. Or, they could be placed closer to the servers at the rack level (*At Rack*), eliminating much of the existing power distribution infrastructure inside the data center (high voltage switchgear, safety measures to prevent arc-flashes, voltage transformers, AC to DC power supply in the server, etc.), replacing it with much cheaper gas lines and gas leak sensors. We analyze both options. We break the total cost analysis into capital cost (cap-ex), i.e., the cost of the equipment, and operational expense (op-ex), the cost of the fuel used on an ongoing basis.

6.1 Capital Cost

Capital cost depends on the price of the FC, its service life, and extra components added to and eliminated from the data center due to fuel cells.

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 that accounts for 34% of the FC stack cost [61]. Another estimate [64] projects the price at $1.5-5/W by 2020. Yet another estimate based on cost reduction with economies of scale for products using similar materials points to a 20% reduction in price with doubling of volume [63, 29]. Starting with current US production volume [29], and targeting just 1% of projected US data center energy consumption of 200TWh in 2016 [48], this leads to $1.12/W. Since these estimates are only extrapolations, we conservatively use a range of $3-5/W for the FC price.

The FC stack, the component with the shortest life, has a service life of 9-10 years [70] but manufacturers guarantee it for only 5 years and we conservatively take 5 years as the service life; and let rest of the system last 10 years.

DC level FCs eliminate the diesel generator and backup batteries because gas grid reliability is already as high as a DG backed up utility power [37]. Rack level FCs additionally eliminate the internal data center power distribution equipment. On the other hand, rack level FCs do add the cost of gas pipes to each rack. Using typical gas line installation costs [18], we estimate this at $1.2/rack/month. Rack level FCs also generate heat inside the DC. The FC is well insulated and its waste heat leaves with the exhaust gas ventilation, already accounted for in the FC cost. However, to be conservative, we assume that extra fans are added beyond what is in the FC for faster cooling (no chillers are needed since FCs operate well above the outside air temperature). At FC efficiency η, the waste heat is $(1/\eta - 1)$ W per Watt of IT power, and we scale the fan subsystem cost of cooling by this factor. We use $\eta = 60\%$ as state of the art FC efficiency for both types of FCs, based on [17]. We also show the calulation for the measured efficiency $\eta = 0.44$ (Figure 16, with reformer losses) for the FC testbed we used in our experiments.

Another additional component added due to FCs is some battery capacity for load following transients. While this battery is much smaller than the backup battery, we conservatively assume the cost of as much battery capacity as the backup.

Table 2 shows the cap-ex, using the TCO calculation methodology followed in [32, 39], that amortizes all costs to a monthly basis. Baseline (utility powered DC) costs are from [39]. FC based designs are cheaper than the utility based baseline. Fuel cells at the rack level are more cost effective than a central bank of FCs.

Additional calculations show that the FC based cap-ex stays below the baseline cap-ex for FC costs up to $10/W in the most expensive configuration (At DC).

6.2 Operational Cost

The op-ex depends on the cost of the fuel (natural gas), and for the rack level design also the energy overhead of extra cooling. Natural gas has traditionally been 70% cheaper than electricity at equivalent energy [19]. Even accounting for the reformer losses and fuel cell efficiency, the output power turns out to be cheaper than utility power.

We have assumed extra cooling requirements for the rack level FCs in our conservative analysis. We scale up fan energy by $(1/\eta) - 1$, where fan energy is about 26% of the cooling energy [35].

Table 3 shows the results. Again, all FC designs are better than the baseline.

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

Item	Baseline	At Rack ($\eta = 60\%$)	At Rack ($\eta = 44\%$)	At DC
IT	186.16	92.62	126.30	92.62
Cooling	37.35	43.82	49.70	37.35
TOTAL	**223.51**	**136.44**	**176.00**	**129.97**

6.3 TCO

Since we amortized both cap-ex and op-ex over the same duration (per month), the TCO is simply

Table 2: Cap-ex (USD per rack per month). Baseline represents the current electric infrastructure.

Item	Baseline	At Rack \$3-5/W ($\eta = 60\%$)	At Rack, Measured ($\eta = 44\%$)	At DC \$3-5/W ($\eta = 60\%$)
Facility space	50.99	33.99	33.9	33.99
UPS/battery	2.00	0.00	0.00	0.00
Power infrastructure	89.08	0.00	0.00	42.75
Fuel cell system	0.00	18.95-31.58	18.95-31.58	18.95-31.58
Gas Pipes	0.00	1.20	1.20	0
Load following battery	0.00	2.00	2.00	2.00
Cooling infrastructure	36.84	45.02	52.46	36.84
Labor, network, etc.	134.52	134.52	134.52	134.52
TOTAL	**313.43**	**235.68-248.31**	**243.12-255.75**	**269.05-281.68**

the sum of the two (Fig 19). The rack level placement is clearly the lowest cost for up to 30% lower than conventional designs. This placement has additional advantages in terms of a smaller failure domain for servers, and is hence more reliable from the application standpoint. It also eliminates more of the internal data center power distribution infrastructure and will likely have lower maintenance cost (not accounted in our analysis).

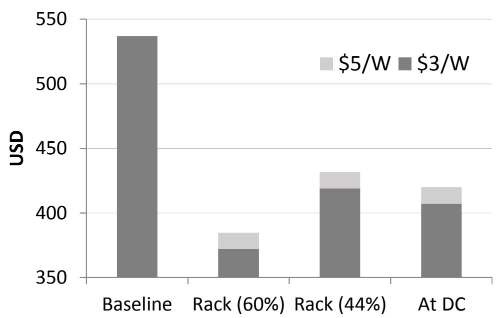

Figure 19: Total Cost of Ownership (per month per rack)

7. DISCUSSIONS

In these preliminary experiments, we focused on the load following capabilities and end-to-end efficiency. To make DFCs practical, a few engineering concerns must also be addressed.

7.1 Renewable Energy and Backup Energy Storage

Our design of using PEMFC is friendly to renewable energy sources such as solar and wind, which are known to be unpredictable. When energy is available, an electrolyzer can produces hydrogen from water, which can be stored to form a constant supply to fuel cells. Hydrogen energy storage has been considered less favorable due to its low round trip efficiency and relatively high cost [71]. However, for integration with large-scale wind energy, large energy capacity and low self-discharge become more important than round trip efficiency [7], therefore hydrogen energy systems with electrolyzers and fuel cells become more attractive as the amount of energy storage required increases [44]. Hydrogen energy storage has been demonstrated by NREL and Xcel Energy with the Wind-to-Hydrogen demonstration project in Boulder, Colorado. In the most recent demonstration, low temperature electrolysis is applied using a proton exchange membrane (PEM) electrolyzer to split water into hydrogen. The PEM electrolyzer achieved a system efficiency of 57% [33].

7.2 Battery and Protection Circuit

Our design of directly coupling fuel cells with servers shows the best energy efficiency, but may need further engineering improvement for production. For example a small amount of local energy storage, load banks, and supporting circuitry may be required to cover large step loads, open circuit conditions, and brief electrical overloads. This can be accomplished without any “in series” conversions or switching, so efficiency losses due to this added power management will be negligible. Local energy storage is also necessary to “ignite” a fell cell from a completely off state. How to optimize this local energy storage and protection circuit requires further study.

7.3 Safety

Safety remains a top priority with gas distribution but we believe fire hazards can be engineered out. For example, much of the ignition sources are eliminated by the fact that this type of datacenter has so little electrical equipment. Our design of the high volume of air movement within the datacenter that keeps servers cool will quickly dilute any leaks. In addition, natural gas contains a very potent odorant to alert personnel of even the smallest leaks. Inexpensive gas leak sensors are commercially available.

8. CONCLUSIONS

In this paper, we propose a distributed power architecture for fuel cell powered data centers to achieve high reliability and efficiency. We describe the distributed fuel cell power system design and the system components such as glue circuit and air cooling system. We experimentally validate the design and demonstrate the use of a 10kW PEMFC stack and system as the distributed power source to directly supply DC power to the servers. We evaluate and characterize the performance and the dynamic response of the PEMFC, and the PEMFC system is found to respond quickly to both AC and DC load changes. We compute the end-to-end energy efficiency of the DFC DC design, 53% of efficiency can be achieved. We also analyze the total cost of ownership of our design based on the experimental results and show that distributed fuel cell power data centers are less expensive to build and more efficient to operate than traditional data centers and centralized fuel cell alternatives.

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