Banking on Fuel Cells:
Increasing Efficiency and Availability with Fuel Cells

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ABSTRACT

Fuel cells are commercially viable and can compete on an economic basis with standard uninterruptible power generation systems. This paper analyzes an 800 kW phosphoric acid fuel cell installation that provides electrical power to a critical need credit card processing facility in Omaha, Nebraska. The installation provides electricity at over double the energy efficiency of current uninterruptible power generation systems. The fuel cell system achieves these efficiencies while producing 40% to 50% less greenhouse gases and at a calculated availability of 100 to 1000 times greater than traditional data center power systems. Life cycle analysis of the fuel cell system versus standard data center power conditioning systems proves the economic viability of the fuel cell system.

Fuel Cells Benefits
Background

In January 1998, First National Bank of Omaha commissioned the design of a "state of the art" credit card processing data center.

The data center is located in the heart of downtown Omaha, NE. The data center construction and design allows it to withstand prolonged utility outages, and terrorist threats. The data center's design incorporates these features while maintaining high levels of sustainability, availability and efficiency.

Efficiency, Emissions, Availability, and Economics

In order to meet the stringent design requirements set forth, a redundant electrical system consisting of four 200 kW fuel cell power plants (FCPP's) was installed. Use of FCPP's enables a 40-50% reduction in greenhouse gases, when compared to standard data center power conditioning and generation schemes. It also increases system availability by a factor of 100 to 10,000 times over current uninterruptible power supply systems.

Life Cycle cost analysis of the fuel cell power system shows that the system is economically viable, when compared to the standard data center electrical system designs.

Introduction
Infrastructure Requirements

In the early 1970's, computer operations relied primarily on batch processing for data entry and computations. Data entry consisted of batch processing hand punched paper cards manually fed into a punch card processor. If a computer system failed during this process, the cards were replaced and the batch was simply re-run.

In the early to mid-1980's, computer operations evolved into on-line data processing. Data entry was directly into the computer, via a computer keyboard or other electronic input, and immediately processed or batch processed later. If a computer system failed during this process, the data were re-entered/re-run with minimal economic impact. Processing at this time had not yet entered the uninterruptible era, and downtime was still manageable.

Starting in the late 1980's to early 1990's, batch processing and catching up during off-hours was no longer possible. The dawn of 7x24x365[1] processing had begun. Instant, online, immediate entry and processing of data was becoming a common occurrence. Downtime was no longer acceptable, except for several planned maintenance outages every year. A new marriage of uninterruptible power supplies (UPS) and diesel generators provided continuous, reliable and uninterrupted electricity to these data processing systems. These power systems provided a level of availability equal to or greater than the computer systems they were protecting.

Availability is the probability that a component or system will be operational during a given time period. Availability is a ratio of mean time between failures (MTBF) and mean time to repair (MTTR). The formula is shown in Equation 1.

$$\boxed{\text{AVAILABILITY} = 1 - \frac{\text{MTBF - MTTR}}{\text{MTTR}}}$$

Equation 1. Availability Calculations

Present day computer systems are packing more data and faster processing rates into smaller packages. This increased efficiency also requires a more demanding environmental infrastructure. Current server systems are operating at calculated availability levels of up to 99.99%, while high-end mainframe computing systems are operating at levels up to 99.999% (Cisco 2000). Standard UPS and diesel generator systems have a calculated availability of 99.9% to 99.99%, while higher-end systems have a maximum calculated availability of around 99.999%[2].

Business losses at the data center are calculated at over $6,000,000 per hour in the event of a computer system outage (Stargel 1998). The cost of lost business dictated that the availability of the electrical infrastructure meet or exceed the availability of the data center's computer system. The availability of the electrical infrastructure at the First National Bank of Omaha data center exceeds that of today's high-end mainframe computer systems.

Building Requirements

First National Bank of Omaha's commitment to the revitalization of downtown Omaha required the data center to be located in the downtown area. Locating the data center in a downtown area required that the data center maintain as minimal an impact on the existing and sometimes strained downtown infrastructure. The building must maintain the

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1 Refers to 7 days per week, 24 hours per day, and 365 days per year for a completely uninterruptible system or process.

2 Availability calculations based on IEEE Gold Book standards.

highest efficiency and lowest emissions possible, to ensure the continued growth of downtown Omaha.

The data center houses credit card processing, cash management, check processing, and credit card embossing functions. The space design incorporates these functions, while maintaining the highest security and independence possible. The facility is designed to resist and maintain operations in case of natural and man-made disasters such as tornadoes, ice storms, terrorist attacks and flooding.

System Design

Integrating Fuel Cells and Building Design

Mechanical Systems

All occupied spaces of the data center are climate controlled. Variable volume systems with hot water reheat serve the more standard office areas throughout the building.

A downtown district heating and cooling plant, Energy Systems Company (ESC), provides the primary heating medium - high-pressure steam. The high-pressure steam reduced by a pressure reducing station, supplies medium pressure steam to separate heating systems within the building. The medium pressure steam is piped directly to integral face and bypass preheat coils serving the AHU's, and to heat exchangers serving hot water heating and humidification systems. The hot water heat exchanger serves a hot water heating loop used to provide perimeter heating, terminal unit heating and variable volume air terminal units reheat. The hot water distribution system provides a variable supply water temperature, which allows the resetting of the supply temperature to match the true heating load of the building. A clean steam generating heat exchanger provides building humidification at the discharge of the AHU's, to maintain space humidity requirements vital for paper handling and computer equipment areas. The humidity levels are controlled and adjustable at each unit to meet the needs of the computer or paper processing equipment served by the AHU's. The system provides approximately 33.6×10^9 British Thermal Units (BTU's) per year of heat to the building.

Excess heat from the fuel cells is removed through an integral heat exchanger on each fuel cell power plant. The captured waste heat, up to 700,000 BTUh per fuel cell, supplements the ESC steam heating system. The four fuel cell power plants generate approximately 2.7×10^6 BTU per hour for 2.4×10^{10} BTU of heat per year. Approximately 9.5×10^9 BTU per year of the recovered heat supplements steam purchases from ESC.

The excess heat is also used for snow melting applications. The snow melt system is used in the patio areas and the walkways on the perimeter of the building. The snow melt system eliminates the need for snow removal from the secured site.

Several other systems were proposed but not implemented. An absorption chiller was considered, but was found not to be a feasible investment. The smallest commercially available absorption chiller is a 120-ton lithium bromide unit, requiring approximately 2.2×10^6 BTU per hour of heat. This requirement is beyond the available heat output of 4 fuel cells (1.2×10^6 BTU per hour at 240 degree Fahrenheit). The relatively low temperature heat available from the fuel cells limits their use to a hot water driven absorption chiller.

The heat recovered from the fuel cells is not measured, so approximated design loads are used in the heat recovery comparisons in this report. The heating loads were modeled using an energy analysis program.

Electrical Systems

The electrical system incorporates a 2N or "system plus system" design. The system is divided into two boundaries, separate and distinct from each other, with each boundary capable of supporting the entire 320 KW critical load.

The electrical power generation system consists of four 200 kW fuel cell power plants (FCPP) that are the primary power source for the critical operating loads.

A fuel cell is an electrochemical device that converts hydrogen to DC electricity, with heat and water as by-products. A phosphoric acid electrolyte separates the anode and cathode terminals of a fuel cell. The electrolyte allows positive hydrogen ions to pass through, while blocking electron flow. The hydrogen ions combine with air at the cathode side in an exothermic reaction. The exothermic reaction produces heat and water. A load (inverter) is applied across the anode and cathode terminals to allow current flow to occur. The inverter changes the DC current to an alternating current, the standard form of power used in electrical distribution systems.

The fuel cell power plants are backed up by two 1250 kW diesel generators and 2 independent utility feeds from Omaha Public Power District, paralleled together at the Main Switchboard.

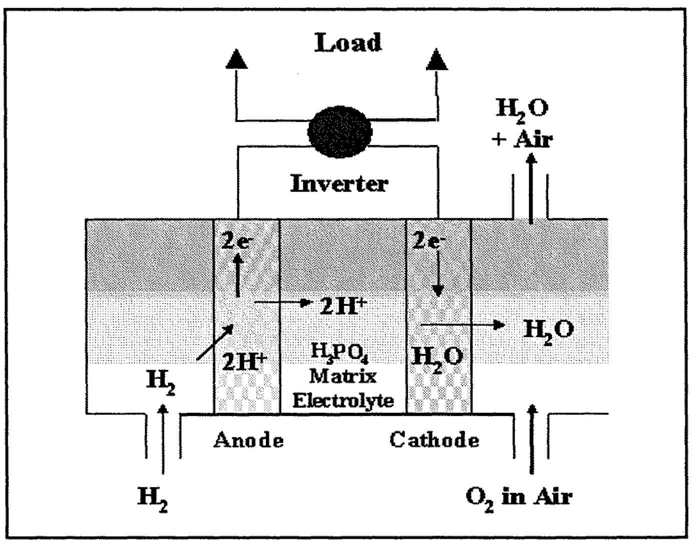

Figure 1. Fuel Cell Operation.

The electrical distribution system (Figure 2) consists of four rotary uninterruptible power supplies paralleled together at a double-ended distribution switchboard. Each rotary UPS unit receives input power from a fuel cell and a utility/generator feeder. In case of a power failure on the input to the rotary UPS, a flywheel activates and provides up to 40 seconds of backup power. This power is required while the generators start and assume load or the fuel cells reconfigure to a grid-independent mode of operation. The interconnection of the fuel cell, rotary UPS, and utility/generator allows excess power to parallel and export to the utility.

The fuel cell electrical system at the First National Technology consumed 47.73 million scf of natural gas, while producing 4950 MW of electricity, from May 10, 1999 to

May 10, 2000 (Higgins 2000). This data was collected from the building management system, which monitors the fuel cell gas intake and electricity production.

Due to a high concentration of nitrogen in the natural gas supply, the fuel cells were operated at 75% of capacity (600 kW). NH_3 in the fuel or oxidant gases reacts with H_3PO_4 to form a phosphate salt, which results in a decrease in the rate of o_2 reduction. A concentration of less than 0.2 mol% $(NH_4)H_2PO_4$ must be maintained to avoid unacceptable performance losses[3].

The current natural gas supply averages 8% nitrogen content, while ONSI specifies a 6% maximum nitrogen limit. A membrane is installed to reduce the nitrogen content of the natural gas supply by 2.5%. The membrane is currently operational and will be applied to the system in early June 2000, after significant testing has been completed.

System Performance

Utility

Efficiency

The utility feeds for the data center come from two separate substations fed from the Omaha Public Power District North Omaha Station. The North Omaha station is a five-generator 662,800-kilowatt coal fired plant, circa 1954, with the last generator added in 1968 (OPPD 2000).

Generator efficiency for the coal fired plant is approximately 32% (Annual Energy Outlook 2000, Table 37), with average transmission and distribution losses of 2 - 5% seen at the customer's facility. Total end use efficiency of fuel energy input to power output, seen at the data center is approximately 30% (McDermott 2000). OPPD consumes approximately 4.84×10^{10} BTU[4] of coal annually to equal the power output of the four fuel cells.

Emissions

The electricity emissions factor for Omaha Public Power is 1700 pounds of carbon dioxide (CO_2) and 4.45 pounds of nitrous oxides (NO_X) per megawatt hour (Benchmarking Air Emissions of Electric Utility Generators in the United States 1998). OPPD emits approximately 4,207 tons of CO_2 and 11 tons of NO_X annually in producing the same 4950 MW of power produced annually by the fuel cells.

Availability

The reported availability of the utility lines and substations feeding the data center is 94.6% with a calculated mean time between failures (MTBF) of 471 hours and a calculated mean time to repair (MTTR) of 25.2 hours (Nicholls 1998). OPPD's current system availability is 99.97%, with an average outage time of 1.97 hours (Nicholls 2000).

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[3] Information from Fuel Cell Handbook 4th Edition, p. 3-18

4 Comparisons are to fuel cells producing 4950 MW of power per year.

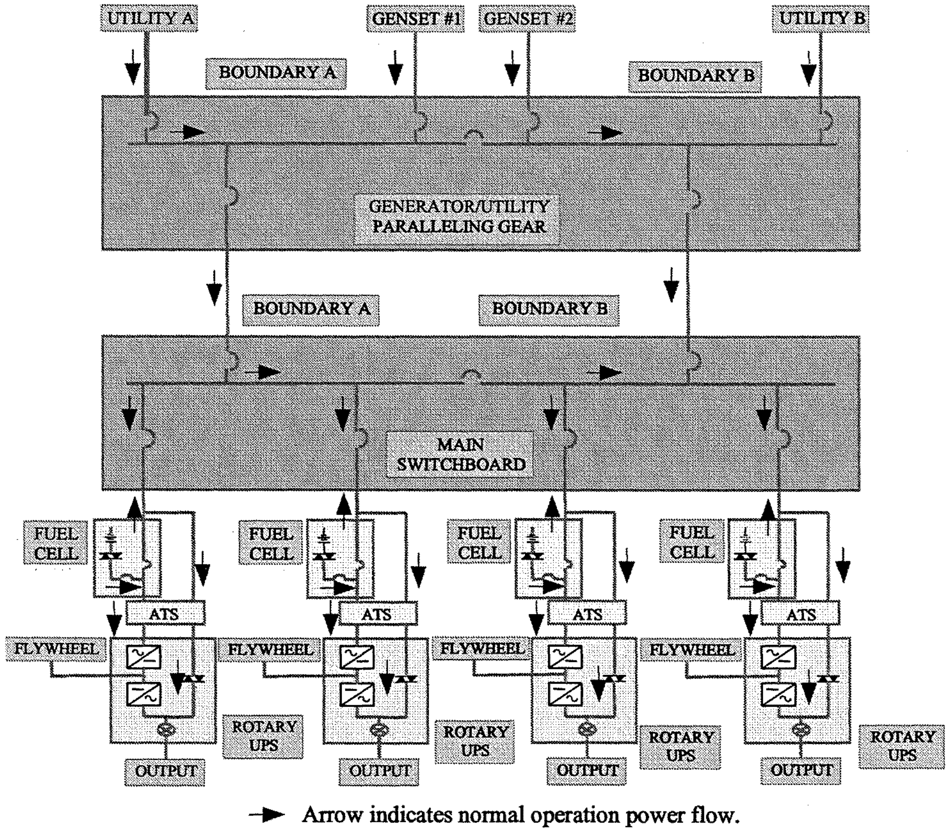

Figure 2. Power System Diagram

Life Cycle Costs

Electricity rates at First National Bank of Omaha are some of the lowest in the country, at \$0.04/kWH. Monthly demand charges equal \$11.00 per kW, for a total demand charge of \$79,200.00 per year for a 600kW demand. ESC steam costs for $9.5x10^9$ BTU is \$98,956. The 20-year life cycle cost of 600 kW of utility power and $9.5x10^9$ BTU of steam from ESC is \$4.9 million.

Fuel Cell
Efficiency

The electrical efficiency of the FCPP is 40% on a lower heating value basis and 36% on a higher heating value basis using natural gas (ONSI PC25 Product Description Manual, 2-3). This efficiency remains the same for all loads between one-half and full load of the FCPP, with little deviation for loads between one-quarter and one-half of full load. The FCPP consumes 1900 scf/hr of natural gas at full load, to produce 200 kWh output. Using actual operating values and fuel cell power plant performance, the efficiency is calculated to be 35.4%. The efficiency is calculated using the higher heating value of 1000 BTU/scf for natural gas

BTU of Fuel Consumed Annually = 47.73×10^6 scf * 1000 BTU/scf = 47.73×10^9 BTU
Heat Rate = 47.73×10^9 BTU / 3412 BTU/kW[1] = 13,988,863 kW = 13,989 MW
Efficiency = Q_{OUT} / Q_{IN} = 4950 MW / 13,989 MW = 35.4%

[1]Heat Rate Conversion: 3412 BTU = 1 kW

Equation 2. Verification of Fuel Cell Efficiency

ONSI states that the PC25C fleet has a 96% availability (Wheat 1998), while the PC25C units at First National Bank of Omaha have an availability of over 98% (Higgins 2000).

Recovering 100% of the excess heat via the heat exchanger can increase efficiency to approximately 75%. The FCPP system produces approximately 2.4×10^{10} BTU of heat annually, with approximately 9.5×10^9 BTU[5] of the heat recovered and the remainder vented to the atmosphere via packaged dry-cooler units. This heat recovery increases the fuel cell efficiency to 54.1%.

<u>FCPP – Electrical Efficiency</u>

BTUh of Fuel Consumed Annually = 47.73×10^6 BTU* 1000 BTU/scf = 47.73×10^9 BTU
Rotary UPS Efficiency = 97.55 through synchronous motor path (normal operation)[1]
Total BTUh consumed to produce 600kW = 47.73×10^9 BTUh / 0.9755 = 48.93×10^9 BTU
Heat Rate = 48.93×10^9 BTU / 3412 BTU/kW[2] = 14,340,198 kW = 14,340 MW

<u>FCPP – Thermal Benefits</u>

Heat Rate of Recovered Heat = 9.515×10^9 BTU / 3412 BTU/kW[1] = 2,789 MW

<u>Total System</u>

Efficiency = Q_{OUT} / Q_{IN} = (Electricity Produced + Heat reclaimed) / Fuel Consumed =
(4950 MWh + 2789 MW) / 14,340 MW = 54.0%

[1]Value confirmed during system commissioning.
[2]Heat Rate Conversion: 3412 BTU = 1 kW

Equation 3. Fuel Cell System Efficiency Calculations

Emissions

Each FCPP emits approximately 230 pounds of CO_2 per hour at full load. NO_X, SOx and hydrocarbon emissions are negligible[6]. The four FCPP set produces approximately 3868 tons of CO_2 per year, when run at full load. At a 75% load (150 kW per cell), the emission totals approximately 2901 tons of CO_2 per year.

[5] Value calculated with computer model.
[6] ONSI Product Description Manual, p.2-5

The heat recovered from the FCPP system displaces the purchase of $9.5x10^9$ BTU of steam from ESC annually. ESC has a reported efficiency rate of 83% (Woods 1998). ESC produces approximately 576 tons of CO_2 to produce this steam.

<u>ESC – Emissions</u>
Natural Gas Consumed = 9515×10^6 BTU / 1000 BTU/scf = 9515×10^3 scf
CO_2 produced = 121 pounds of CO_2/1000 scf * 9515×10^3 scf * 1 ton/2000 pounds = 576 tons

Equation 4. ESC Emission Calculations

Availability

Independent analysis of the FCPP system indicates a calculated availability of 99.999995%[7]. A simplified system model and associated failure/repair rates are shown in Figure 3. Data was obtained from field conditions, manufacturer reports and the IEEE Gold Book.

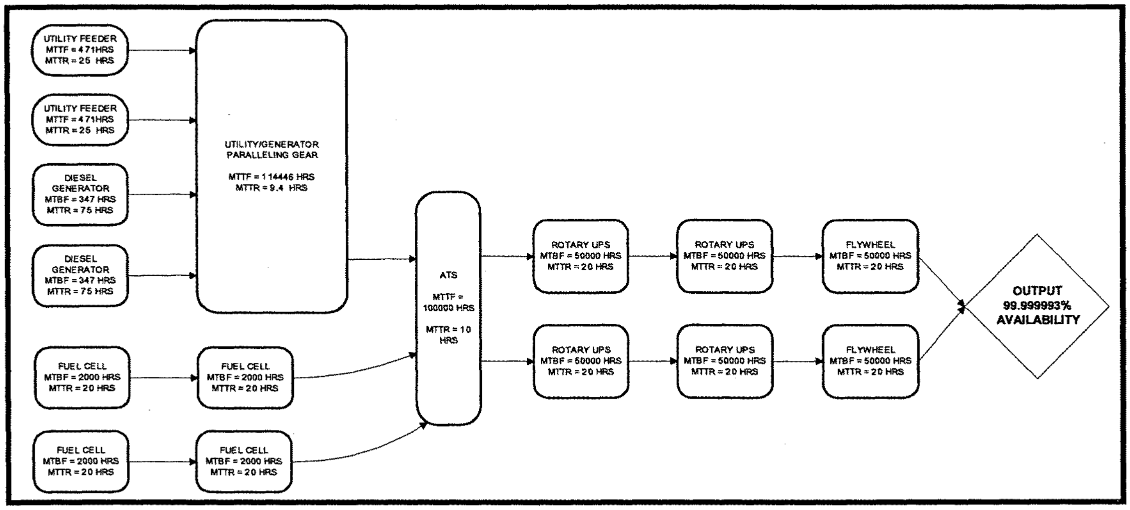

Figure 3. Availability Model of the FCPP system.

Life Cycle Costs

The fuel cell system required an initial investment of $3.8 million, annual maintenance costs of $120,000, and cell stack replacements every 7 years ($175,000 per cell). This results in a 20-year life cycle cost of $8.1 million.

[7] Information from the report "Long-term Availability of the Sure Power System Installation at the First National Technology Center".

Standard Data Center Electrical System

The standard data center design, for comparison and as shown in Figure 4, consists of two independent utility feeders, four 400kW static UPS modules, 15 minutes of battery backup at full load, and two 1250 kW diesel generators.

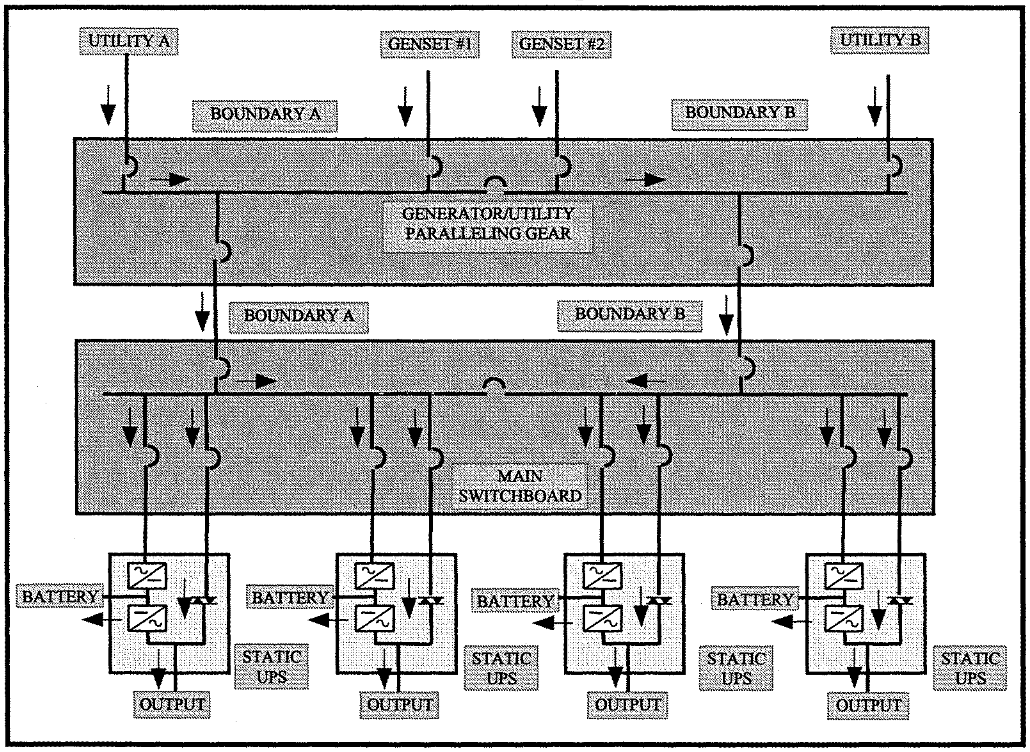

Figure 4. Standard Data Center Diagram

Efficiency

The electrical efficiency of the static UPS system is 91.5% if an input isolation transformer is used (Liebert Product Manual 1999). The static UPS system consumes approximately 5410 MW of utility generated electricity to equal the same 4950 MW output of the FCPP system. Another 460 MW of utility electricity is consumed to provide space cooling for the static UPS and batteries. The total power consumed by the static UPS system is 5870 MW (5410 MW + 460 MW), to produce the same 4950 MW produced by the FCPP system annually. This consumption rate equates to an overall efficiency of 25.3% for the static UPS system.

Static UPS – Electrical Efficiency

Power consumed by static UPS system = $\frac{4950\ \text{MW}}{91.5\%\ \text{Eff}} = 5410\ \text{MW}$

Equiv. Power produced by OPPD = $\frac{5410\ \text{MW} + 460\ \text{MW}}{30\%\ \text{Eff}} = 19{,}567\ \text{MW}$

Efficiency = $\text{Power}_{out} / \text{Power}_{in}$ = 4950 MW / 19,567 MW = 25.3%

Equation 5 - Static UPS Efficiency Calculations

Emissions

Emissions generated by the utility power consumed by the UPS system are approximately 4,599 tons of CO_2 and 12 tons of NOx.

Static UPS – Emissions

CO_2 emissions = 1700 pounds/MW * 5,410 MW * 1 ton/2000pounds = 4,599 tons

NO_X emissions = 4.45 pounds/MW * 5,410 MW * 1 ton/2000pounds = 12 tons

Equation 6 - Static UPS Emissions Calculations

Availability

The standard data center power system ranges in availability from 99.9% to 99.999%. The system used in this study has an availability of 99.99%. The system model and associated failure and repair rates are shown in Figure 5. Data was obtained from actual field conditions, manufacturer reports and IEEE Gold Book values.

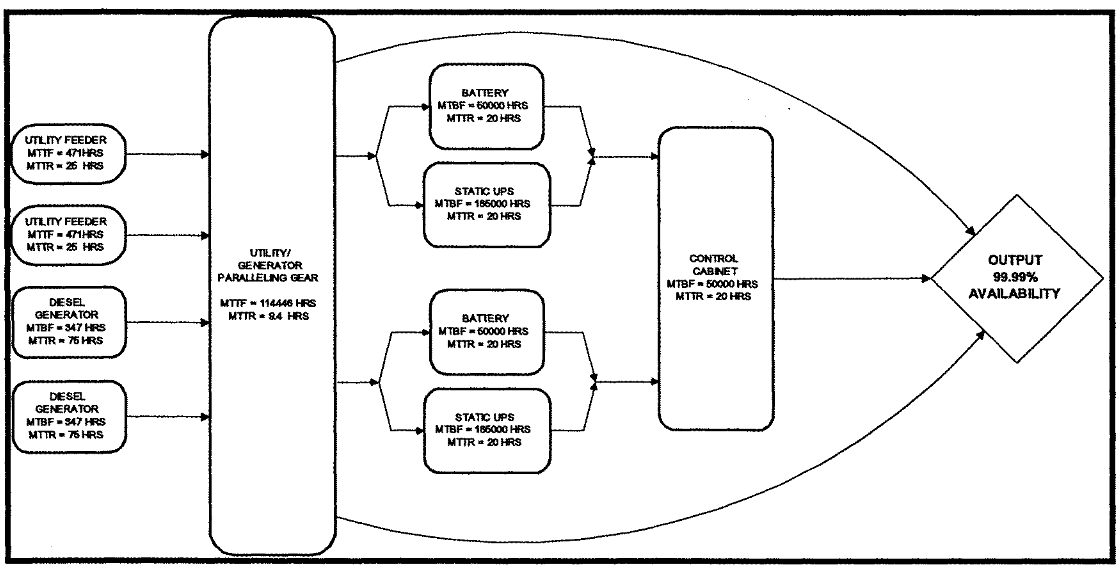

Figure 5. Availability Model of the UPS system

Life Cycle Costs

Initial installation cost of a high quality UPS system is approximately $1.6 million, with annual maintenance costs of $50,000 and wet cell battery replacement every 7 years at a cost of $215,000. This results in a 20-year life cycle cost of $8.6 million.

System Comparisons

A comparison of the above systems is shown in Table 1. This comparison proves the efficiency, environmental, and economic performance of the fuel cell system exceeds the standard data center power generation systems. The fuel cell system produces these benefits, while providing an availability 100 times premium data center power generation systems design.

Table 1 – Summary of Systems for Omaha, NE

System	Efficiency	Emissions		Availability	20-year Life Cycle Cost
		CO2	NOX		
Utility	30%	4,207 Tons*	11 Tons	94.60%	$4.9 Million
UPS	25%	4,599 Tons*	12 Tons	99.999%	$8.6 Million
Fuel Cell	54%	2901 tons	Negligible	99.999995%	$8.1 Million

* Includes ESC steam production.

Future Uses

Data Centers

Data centers represent a niche market, due to their requirements for critical power. Fuel cells can be utilized in existing data centers, and can replace existing diesel generators. Replacing the diesel generators with fuel cells can improve reliability and emissions. The fuel cells are always operational, so there is no reliance on being called to start during an emergency. Generators fail to start approximately 1 in 1000 times (IEEE Gold Book). If they were constantly running these failures would be evident and not a surprise.

Plastics Industry

Hydrogen is a byproduct of the plastic production process; the hydrogen generated is usually sufficient to produce enough power for the entire plant. The plants require some portion of high availability power to minimize downtime and product loss. The downside is that most plastic processing plants are located in areas with low electricity and gas costs, making life cycle costs between the utility and the fuel cell a tough comparison. With future reductions in fuel cell costs, or increases in utility rates, this industry will be a prime avenue for generating fuel cell power.

Conclusions

Utilizing fuel cells as a primary energy source in a building increases the sustainability of the facility. Efficiency and availability are increased, while emissions and life cycle costs are reduced.

Due to their cost, data centers and high availability applications are currently the application of choice since these applications already have alternative power conditioning devices. The use of fuel cells versus standard utility power produces higher availability, efficiency, and lower emissions; but at a price considerably higher than the utility supplied energy.

There are some sites where fuel cells can compete with the local electric utility, where; 1) there is free fuel (hydrogen, methane, etc.), 2) utility line extensions are costly, 3) emission penalties are imposed, 4) gas rates are low and / or electricity rates are high, 5) where rebates and grants are available to promote alternative energy use.

These applications will continue to increase as fuel cell prices decrease and utility rates increase.

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