RES | THE SCHOOL *for* RENEWABLE ENERGY SCIENCE

Hydrogen Fuel Cell Emergency Power System

Installation and Performance of Plug Power GenCore 5B48 Unit

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HYDROGEN FUEL CELL EMERGENCY POWER SYSTEM

Installation and Performance of Plug Power GenCore 5B48 Unit

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Stanisław Molitorys

A 30 credit units Master´s thesis

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A Master's thesis done at

RES │ the School for Renewable Energy Science

in affiliation with

University of Iceland &

the University of Akureyri

Akureyri, February 2009

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Printed in 14/05/2009
at Stell Printing in Akureyri, Iceland

ABSTRACT

Backup systems are crucial elements of modern electrical grids. They are used in places where an interruption in power supply can cause significant damage, e.g. in hospitals, banks or telecommunication towers. There are many solutions for how emergency power can be delivered. Hydrogen fuel cells are an emerging technology with great potential for the future. Fuel cells combine the advantages of batteries and diesel generators, and eliminate some of their significant disadvantages. They can work as long as they are supplied with fuel via a simple and efficient electrochemical reaction and at the same time they are quiet, produce no emissions and require minimum maintenance.

The aim of this thesis is to present the idea of hydrogen fuel cells as reliable backup power systems. The work consisted of two parts: one practical, the other theoretical. The first part includes the background of energy security, emergency power sources, fuel cell systems backup power market, as well as an introduction to fuel cell technology, principles of operation and hydrogen safety. The practical part of this project is focused on the Plug Power GenCore 5B48 fuel cell backup power unit, its description, installation, operation, safety precautions and performance characteristics.

The necessary hydrogen infrastructure was built according to safety codes and standards. The performance and reliability of the system was assessed. The system's behavior was stable except for several minor problems during start-up which required intervention. The measured efficiency of the fuel cell stack and the whole system at the maximum available load of 1.65kW was 42.5% and 35.8% respectively. It was noted that the auxiliary load of the system has great influence on the overall performance of the system, especially at low output power. Noted fuel consumption was 13slm at 1kW and fuel utilization efficiency was estimated at around 99%. A cold start-up analysis was conducted and described based on the output data. During the first few minutes of operation the system required additional power to warm the fuel cell stack. The transition analysis focused on the ability of the system to provide power in case of a sudden outage. It was working well with batteries, as the fuel cell needed approximately 15 seconds to be ready to completely take over the power demand. Reliability and availability were assessed to be 96.8% and 79.9% respectively. It has to be pointed out that it was not possible to completely determine the system's performance during some of the failure scenario and operation under different load because of the limitations of time and budget.

PREFACE

This thesis work was carried out at the Innovation Center Iceland in Reykjavik and supported by RES | The School for Renewable Energy Science in Akureyri, which we gratefully acknowledge.

Innovation Center is a leading institution in technological R&D in Iceland. Its departments specialize in everything from nanotechnology and environmental energy to concrete research and building technology. RES school is a new institution, established in the spring of 2006. Since February 2008, it offers a one-year M.Sc. Program in Renewable Energy Science in cooperation with the University of Iceland, the University of Akureyri, and a number of leading technical universities and institutions around the world.

We would like to take this opportunity to express our gratitude to everyone who contributed to the completion of this thesis. Dr. Thorsteinn Ingi Sigfusson, the Director General of Innovation Center Iceland, our teacher and Academic Advisor of Fuel Cell Systems & Hydrogen specialization in RES school, and the Supervisor of this project, for his work and guidance during this project and the whole academic year; Mr. Ingolfur Orn Thorbjornsson, the head of Department of Materials, Biotechnology and Energy in Innovation Center and our Project Advisor, for his support and help; the employees in Innovation Center for their interest and assistance; Mr. Jon Hanson from Framtak Company for his support and knowledge of hydrogen safety aspects and materials; Dr. Ebba Thora Hvannberg, Professor at the School of Engineering and Natural Science in University of Iceland for her valuable comments and corrections of this thesis report.

We are grateful to the whole RES school administration and faculty. Dr. Bjorn Gunnarsson, the Academic Director of the school and all employees for their hard work, patience, and commitment; Dr. David Dvorak, Professor at the University of Maine and Academic Advisor of Fuel Cell Systems & Hydrogen specialization in RES school; and all faculty members. We would also like to thank students of RES school (2008-2009) for their friendship.

Finally, we want to express gratitude to our families and friends for moral support and belief in us.

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LIST OF ACRONYMS

Symbol	Explanation	Common Unit
A	Area	cm^2
ASR	Area-specific resistance	$\Omega \cdot cm^2$
E	Electron charge	1.6×10^{-19}
E	Thermodynamically ideal voltage	V
F	Faraday constant	96.485 C/mol
G	Gibbs free energy	J/mol
H	Enthalpy of reaction	J
i	Current	A
j	Current density	A/cm^2
j_0	Exchange current density	A/cm^2
j_L	Limiting current density	A/cm^2
L	Thickness	cm
N	Avogadro's number	6.02×10^{-23} mol^{-1}
p	Pressure	bar, atm, Pa
P	Power	W
R_u	Ideal gas constant	8.314 J/mol·C
R	Resistance	Ω
S	Entropy	J/K
T	Temperature	K
U	Internal energy	J
V	Voltage	V
V	Volume	L, cm^3
W	Work	J
α	Transfer coefficiency	Dimensionless
ε	Efficiency	Dimensionless
η_{act}	Activation losses	V
η_{conc}	Concentration losses	V
η_{ohmic}	Ohmic losses	V
v	Fuel flow rate	Slpm
σ	Conductivity	S/cm

1 INTRODUCTION

As of November 2008, there are about 6,741,000,000 people living on Earth (U.S. Census Bureau 2008). These people need energy to survive, in the form of heat or electricity, which then is used to heat up the houses, supply power for electrical equipment or run vehicles such as cars or planes. An increase in the number of people, especially in developing countries, has led to an unavoidable increase in energy consumption.

The World's energy consumption shows that most of the energy comes from fossil fuels (about 87%) (Energy Information Administration 2006), and only about 7% comes from Renewables (NREL National Renewable Energy Laboratory 2006). The problem with fossil fuels is that, although they are relatively cheap, they release large amounts of carbon dioxide upon burning. CO_2 is considered to be the gas which is partly responsible for global warming, together with other human activities (IPCC Intergovernmental Panel on Climate Change 2007). One can also think – are the reserves of these carbon fuels such as coal, gas or oil enough for humans to develop further? It is very difficult to answer this question, but the solution for this problem can be to increase the share of Renewable Energy in the world's energy consumption.

Renewable Energy Sources produce a small amount of greenhouse gases, and there is plenty of energy coming from the sun, rivers or geothermal waters to cover human needs. There are, however, also some problems and limitations connected with these sources – the sun does not shine every day and its strength is different depending on location, wind does not blow with the same strength during the year and there is limited accessibility for hydro and geothermal power depending on the location. An energy carrier is needed to store the electricity during excess production so that it is ready to be used when the peak comes.

Hydrogen seems to be a good candidate for such a carrier. It has higher gravimetric energy density than oil (lower volumetric, that is why it has to be compressed, liquefied or stored in a metal as metal-hydride), it has no emissions and can be converted efficiently into electricity in a fuel cell. Although hydrogen is the most abundant element in the universe, it does not exist on Earth as a gas – it has to be obtained from hydrocarbons; for example by means of methane steam reforming, or water electrolysis, which uses electricity to split water into hydrogen and oxygen. However, only electrolysis makes it possible to produce hydrogen in a clean way, on the condition that the energy source is renewable, such as wind, sun or hydropower.

Having hydrogen is one thing, but it is also necessary to convert its chemical energy into a state that is more convenient to use. The most efficient and clean way is to use it in a fuel cell, which converts the energy from hydrogen into electricity in the presence of oxygen. This method is more efficient than burning the hydrogen in a combustion engine, because it is not limited by Carnot's Law (O'Hayre, Cha, et al. 2006). It is also more environment friendly than conventional combustion engines due to the fact that the only by-product of this process is water.

There are many applications in which hydrogen fuel cells can be used. They are scalable, so they can be used in mobile electronic devices such as cell phones or laptops as a power source, replacing batteries. At the same time there are types that can work as power plants providing power to the grid. Many car producers consider hydrogen fuel cells as a future power source for cars.

The big advantage of fuel cells is that they can work off-grid, in hard accessible places, for instance as a backup power for communication towers. Another, similar application is to use a fuel cell as the power source in an uninterruptible power supply (UPS) for use with digital equipment such as a personal computer (PC), or in hospitals in case of power failure to provide power for life-sustaining equipment (Gonzales and Tamizhmani 2006).

An ideal high-performance UPS system should provide a clean and regulated sinusoidal output voltage with low total harmonic distortion (THD) for both linear and non-linear loads, a fast transient response to sudden changes of the input voltage or load, on-line operation with zero switching time from normal to backup state and vice-versa, high power density, high reliability, high efficiency and low maintenance. The primary purpose of using a fuel cell instead of a battery as a power source is the fuel cell's high energy density, and therefore, the ability to operate the system for a very long period of time during utility grid failure (Zhan, et al. 2008).

The aim of this thesis is to present the idea of hydrogen fuel cells as reliable backup power systems. The work consisted of two parts: one practical, the other theoretical.

The practical part was to install and test a GenCore 5B48 hydrogen fuel cell backup power system manufactured by Plug Power. The testing site was Iceland Innovation Center in Reykjavik. A necessary hydrogen infrastructure was designed and created to deliver hydrogen to the fuel cell system. Safety precautions were made to insure that there were no leaks, and if any would occur, that hydrogen would be quickly and safely released outside the building. It was also necessary to set up testing equipment. Because of the fact that this system could only provide current at 48V, lights were used to simulate the load due to lack of other equipment which could support this voltage. The tests include behavior of the fuel cell system on different loads, characteristics of the fuel cell and the whole system, its response to the event of power shortage, influence of temperature and other conditions on its performance.

The theoretical part was to describe the process of installation and tests but also the background behind the backup power systems and fuel cells. The result of the work is this report, which was divided into several chapters.

In the "Background of the project" chapter, backup power and its importance is described in detail. This part contains the explanation of why there is a need for backup systems and examples of where and how they are used. The biggest blackouts and accidents are presented to illustrate the need for this kind of solution. Different projects all over the world involving fuel cells and backup power solutions are shown.

Fuel cells in general are described in the chapter "Fuel cell fundamentals", which tells the story behind the development of fuel cells, explains how they work and why they are considered as a future power source. Also, different types of fuel cells are shown together with their pros and cons.

In the chapter "Polymer Electrolyte Membrane Fuel Cells" a more detailed view on this kind of fuel cell is given. Cell components and details of the performance and operation of the fuel cell are described. The polarization curve and all the losses that influence it are depicted.

The whole GenCore Plug Power system tested in the practical part is explained in a separate chapter – "Plug Power GenCore 5B48 and electrical system Description". The role of a fuel cell stack, the whole balance of the plant, batteries and the control system are shown.

In chapter 7 the installation and operation of the system is presented. The Construction of the hydrogen infrastructure and the pre start-up procedures for the fuel cell system are explained. The startup procedure and basic operation are also illustrated.

General hydrogen safety issues, precautions and safety measures taken during installation are described in a separate chapter.

In the chapter “System tests and results” the methodology of test, results and conclusions are shown.

In the end, lifecycle assessment of the system will be presented and general conclusions will be depicted.

2 BACKGROUND OF THE PROJECT

2.1 Introduction

A reliable power supply is a major concern for many institutes, especially those where power generation and distribution systems are susceptible to interruptions and their effects can cause significant damages, like in hospitals, banks, data centers, telecommunication companies, computer departments, etc. In many backup power applications, even short power outages can be extremely costly. The tremendous growth of IT and telecommunication services has resulted in an increased demand for backup power. There is a need for power protection to cope with natural disasters and human mistakes. Utility deregulation, widespread overloading of transmission grids and reduced capital investment are all contributors to the declining quality of utility power. Consumers demand continuous up time and companies must provide extended run time backup power on the order of hours and days. Moreover, the backup power solutions must offer reliability, durability and flexibility at a reasonable cost.

There are a variety of backup electrical power systems that all strive to provide power when grid power is unavailable. For many years backup power has been provided primarily by battery systems and engine generator sets. More recently, ultra capacitors, flywheels and new battery technologies have been employed. Although each technology has some advantages, many defects of commercial backup systems are significant enough that service providers are searching for alternatives.

Hydrogen fuel cells offer a very promising solution for extended run time backup power. A wide understanding of emergency power supply systems results in this application diffusing more rapidly into the marketplace than others and becoming one of the first adopters of fuel cell technology.

This chapter covers the background of the project described in the thesis. It characterizes major issues related to energy security, a need for emergency power sources, main functions and features of backup power systems, describes the most common, traditional technologies, their advantages and disadvantages, and compares them to fuel cell solutions. The end of the chapter is intended to provide a short overview of the fuel cell based backup power market, provide examples of projects from around the world and finally explain the general objective and purpose of this work.

2.2 Energy security and need for backup energy source

This section covers a general overview of energy security, its importance and problems. This aspect applies to both global energy security concerns, such as dependence on unpredictable and unreliable suppliers of fossil fuels, ecological issues, and political or economical conflicts, as well as more local problems, such as grid power failures, power fluctuations, blackouts, brownouts, and dropouts, caused by natural disasters, equipment, or human mistakes. Each of these aspects has a different scale of consequences, but both are very important, whether from the point of view of the country, company, or regular customer, and both refer to the need of an emergency source of energy.

Energy security is always a very important element of policy for each country in the world. The fundamental objectives of national energy policies are to ensure that the economy of each nation has access to sufficient, affordable, and reliable energy supplies on terms and conditions that support that nation's economic growth and prosperity.

Energy security is one of the major problem facing the global economy. Fossil fuels, particularly crude oil, are confined to a few regions of the world and the continuity of supply is governed by political, economical, and ecological factors. Excellent examples of energy security problems are provided by Europe and the USA. Europe has serious energy security concerns that are driven by soaring petroleum prices, persistent instability in the Middle East, Russia's energy policies for Europe, the fragmented European energy market and decreasing European energy production. Europe has increasingly become dependent upon a narrow band of suppliers. About 40% of the natural gas that is now consumed in Europe comes from Russia. The most recent example was present at the beginning of the year 2009. The energy conflict between Russia and Ukraine exhibited the clear dependence of almost all European countries on Russian natural gas. In addition, Europe imports 45% of their petroleum from the Middle East and the second largest exporter of this fuel is Russia. The USA has a similar problem. During the Arab oil embargo of the 1970s, 36% of US oil was imported. That figure rose to 56% by 2001 and will likely reach 64% over the next 15 years (Sheffield 2007). The problems described above are extremely important. However, the subject of this thesis focuses on a less global concern, which is the reliable supply of electricity to the end-user and a need for reliable backup power solutions.

Electric power transmission networks are complex systems. Due to economic factors, they are commonly run near their operational limits. Major cascading disturbances or blackouts of these transmission systems have serious consequences. Blackouts can be attributed to many causes, like natural peril, system malfunction or human behavior (Weron and Simonsen 2005). The history of power outages is very long. The largest and the most spectacular events are briefly described below.

On 9th of November, 1965, the power lines that connect Niagara Falls and New York City exceeded their maximum load, causing a transmission relay to fail. It started a chain of events that cut power to more than 25 million people in eight states and two provinces. On the 13th of July, 1977, in the middle of a midsummer heat wave, power was cut off to New York City, plunging 9 million people into darkness. Hundreds of shops were looted, buildings burnt to the ground, and damages amounted to over 300 million dollars. On the 19th of December, 1978, a blackout affected 80% of France. On the 27th of December, 1983, a storm destroyed equipment connecting the power lines in Enköping, Sweden, resulting in an almost total blackout that affected all of Sweden. The Great Storm of 1987 brought down power lines throughout southern England, causing extensive blackouts. On the 13th of March, 1989, sunspots caused Hydro-Quebec's power grid to switch off, cutting 6 million people off from electricity. In August 1996, a blackout in North-western America disconnected 30,390 MW of power to 7.5 million customers (Hoderski 2005).

The Disturbance Analysis Working Group (DAWG) database summarizes disturbances that have occurred in the electric systems in North America. The database is based on major electric utility system disturbances reported to the U.S. Department of Energy (DOE) and the North American Electrical Reliability Council (NERC). According to it, in the USA between 1984 and 2002, there were 646 documented blackouts yielding, on average, 34 blackouts per year. The average period of time between blackouts is 10.7 days, while the mean and the maximum restoration times are 16 hours and 15 days, respectively (Weron and Simonsen 2005).

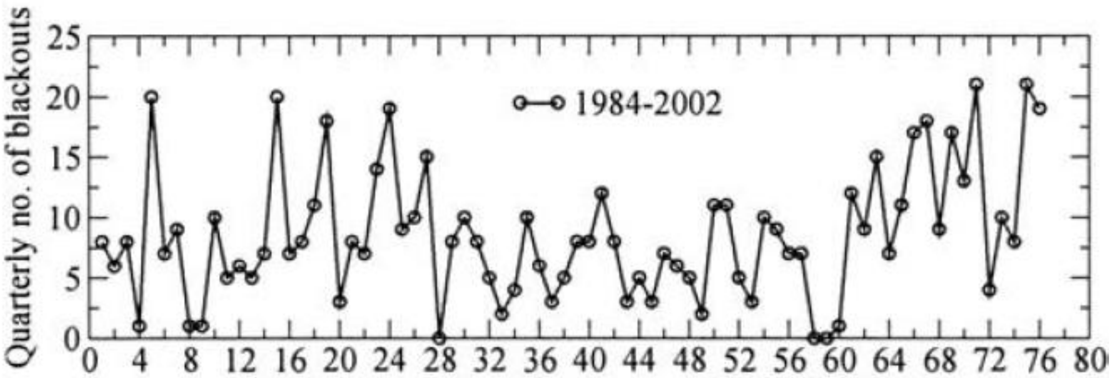

Figure 2.1 The quarterly number of blackout events from 1984 to 2002 for the North-American power grid (Weron and Simonsen 2005)

In August 2003, a spectacular blackout in north-eastern America disconnected 61,800 MW of power to 50 million people. Totally, in August and September 2003, six major power blackouts in the U.S., Britain, Italy, Denmark, and Sweden left 112 million people in darkness, illustrating the fragility of overloaded supply networks.

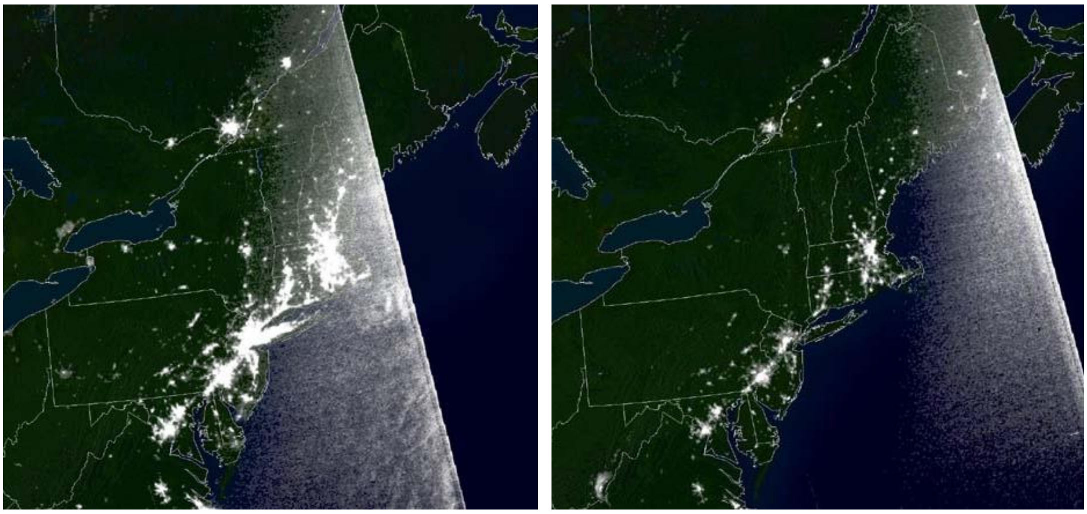

Figure 2.2 Satellite images taken before and after the historic blackout of the Northeastern United States in August 2003 (National Oceanic and Atmospheric Administration 2003)

On the 4th of September, 2004, five million people in Florida were without power at one point due to Hurricane Frances, one of the most widespread outages ever due to a hurricane. On the 18th of August, 2005, almost 100 million people on Java Island, the main island of Indonesia and the isle of Bali, lost power for 7 hours. In terms of population affected, the 2005 Java-Bali Blackout was the largest in history. On the night of the 4th of November, 2006, in parts of Germany, France, Italy, Belgium, Spain and Portugal over five million people were left without power after a big cascading breakdown. From the 8th to 12th of December, 2007, a series of ice events cut power to over 1 million homes and businesses across the Great Plains of the United States from Oklahoma to Nebraska (Wikipedia 2008). In December 2008 as many as one million people were left without power in the north-eastern US after one of the worst ice storms in a decade crippled the electricity grid (BBC 2008).

All of these examples demonstrate that the necessary operating practices, regulatory policies, and technological tools are not yet in place to assure an acceptable level of grid power reliability. Therefore, the supply of reliable emergency power in the case of similar events is a core element of energy security.

2.3 Functions and properties of backup power system

The risks of outages and the resulting need for emergency power supply systems are briefly described above. This section focuses on functions that should provide such systems and their most important features.

The main function of backup power systems is to provide security against the loss of power in a grid failure or grid fluctuations. In the case of power loss, the system should provide one of two functions – either enough power to safely shut all systems down once work has been saved or continuous power during the period in question to sustain machine operation until the power supply is back to normal (extended run-time backup power systems) (Chang, et al. 2006).

An emergency power system is characterized by certain properties, which may be less or more important depending on the application. The ideal system meets all the requirements for a given application. The main determining properties are:

- Range of power - systems must be able to supply the required power to the critical load. It is also important not to overload the system.
- System's capacity - it must be large enough so that it could provide adequate power for a long period of time.
- Efficiency - the more efficient the system is, the longer and more economical the operation time will be.
- The ability to immediately take over the full load in a power outage or out-of-tolerance situations - to avoid data loss, uncontrolled system shutdown or malfunctioning of the devices, some critical applications do not even allow power interruptions of only several tens of milliseconds, therefore, this property is essential for backup power systems which are employed as an uninterruptable power supply (UPS) unit and provide emergency power to a critical load, such as computers, medical/life support systems, communication systems, office equipment, hospital instruments, industrial controls and an integrated data centre (Choi, Howze and Enjeti 2005).
- Reliability (the ability of the system to perform and maintain its functions in all circumstances) - very important feature for all emergency power applications. Every system, regardless of its purpose, should be as reliable as possible in all conditions. The case of First National Bank of Omaha from 1997 shows how vital this property is. The old system of this bank consisted of batteries powering the computers until emergency engine generators could kick in. This system was considered to be 99.9% reliable. But when the Omaha Public Power District faltered one cold day in 1997, the bank hit that 0.1 percent moment: the batteries quit, too. Computers are not like light bulbs, which simply dim when there is a drop in current and return to normal when the power is restored. A computer deprived of power for even a fraction of a second could generally crash, often destroying data. On that day, the bank's check clearing, credit card processing, automatic teller machine support system, debit card system and other vital functions stopped. It was

estimated that such a failure costs the bank $6 million an hour. After that accident, Omaha Bank decided to install a fuel cell backup power system, which was quite expensive and large in those days (Wald 1999).

- Durability - directly related to reliability and an equally important property.
- Cost - in the case of a backup power unit can be very high. Companies seek to reduce money and time spent by increasing durability and thereby reducing maintenance activities.
- Flexibility and scalability - particularly significant in cases where space intended for the unit is limited, e.g. in buildings. It is related with size and weight of the system, as well as with its complexity.
- Ability to provide high-quality power to the external load, low maintenance, redundancy, monitoring and safety (Zhan, et al. 2008).

2.4 Incumbent backup power solutions

As with nearly all other applications for fuel cells, the backup power sector already has incumbent technologies with which it has to compete for market space. Conventional backup power units employ engine generators and/or batteries as their main power sources to provide electric power when the normal supply, e.g. utility power, is not available. These systems are reliable and well established. Unfortunately, they also have some significant issues, which encourage customers to seek alternatives. This part briefly describes major advantages and disadvantages of traditional backup power technologies.

2.4.1 Engine generators

Engine generators are a common source of emergency power. They are internal combustion-based units and may be powered by various fuels, like natural gas, gasoline, diesel or propane. The generator can provide power to the load as long as there is an adequate supply of fuel. If maintained properly, they offer high reliability. They are a mature, understood technology and can be bought at a low capital cost.

As with any engine, the moving parts in the units cause wear and tear and generators often require heavy maintenance. This can be a serious issue in remote places. Also, as with any combustion of fossil fuels, they are noisy and produce emissions that can cause problems in enclosed spaces. Another disadvantage is generator engine start-up time. During the power interruption there is a certain time of delay before the generator can power the load (Hoderski 2005; Adamson 2007).

2.4.2 Batteries

Battery systems as an emergency power source are one of the most common solutions. The principle of operation is very easy. When the battery charges, the metal plates inside act as receptors for the metal atoms from the electrolyte. When the battery discharges, these metals return to the solution in the electrolyte, releasing electrons and generating direct current at the battery poles. The various types of batteries are named for the type of plates or electrolyte used. Lead-acid battery packs are the most common and generally the most affordable option for backup power systems. However many other types, such as lithium-ion or nickel-cadmium, are also considered for this application.

Batteries have many advantages, like simplicity and reliability. As a backup power source, they are often used in enclosed spaces where the emissions from engine generators are unacceptable. The batteries are easily scaled by linking them together in a series, with the number depending on the amount of power required and the size of the batteries. They are able to provide backup power immediately after grid failure.

One of the key disadvantages of batteries is their sensitivity to temperature. This limitation is a major obstacle for some outdoor applications. Companies concerned with ensuring battery capacity and protecting their investment typically house systems within environmentally controlled spaces where air conditioning and heating aids in keeping the enclosure temperature between 15^{o}C and 35^{o}C. Maximum battery performance is supported at 25^{o}C. Another disadvantage of this technology is short lifetime. Most batteries must be replaced every 5 to 7 years. The replacement and disposal cost must be factored into the total energy cost. In addition, battery systems are heavy and can take a lot of space relative to the amount of power they can deliver and operation time. This causes a problem for applications which require extended run-time (Adamson 2007; Hoderski 2005; Egbert n.d.)**.**

2.4.3 Others

There are other technologies which are sufficient to use in backup power application, but they are not as popular. Those are flywheels and ultracapacitors systems. Both are simple, reliable and require very little maintenance; however, their energy storage is limited. These systems were mainly designed to supply energy over a fairly short period of time.

The characteristics of fuel cells make them an attractive solution for backup power supply systems. The next section of the chapter focuses on fuel cell technology as an emergency power source and compares it to incumbent technologies available on the market.

2.5 Fuel cell as a backup power source

Exactly what a fuel cell is and how it works is described and explained in the next two chapters. This section indicates the major benefits of fuel cell technology over incumbent systems, as well as its issues. Based on these advantages and disadvantages, it can be defined which emergency power application is the most suitable for a fuel cell backup power unit.

The characteristics of fuel cells make them very attractive for backup power supply systems. This technology displays most of the benefits of using batteries and engine generators, such as low maintenance and flexibility, without the disadvantages such as emissions, noise, footprint, or temperature issues. Fuel cell backup power systems have been proven to work properly over a wide range of outdoor conditions (-40°C to 50°C). They provide clean, efficient and reliable service.

The major difference between fuel cells and batteries is that fuel cells do not contain any reactants within the cells. The fuel is stored externally. The advantage of this configuration is that the structure within the fuel cell is fixed and, unlike a battery, the electrodes do not change as power is drawn from the device. The changes inside the battery during charge/discharge cycles eventually result in degraded energy output. Additionally, since all of the reactants are contained within a battery, it will continuously self-discharge to its lowest energy state. Therefore, batteries must be continuously charged, which can also accelerate decay and failure, as well as causing other adverse issues associated with overcharging. In addition, unlike batteries, fuel cells can continuously provide power as long as fuel is supplied. This feature is especially useful in situations where extended operation time is necessary. Therefore, they are perfect for long run-time applications, such as telecommunication tower sites or data centers.

Fuel cells are simply fed fuel and air. Therefore, in a standby state they are truly off and undergo minimal degradation changes. This should result in excellent lifetime. Additionally, fuel cells are simpler than internal-combustion engines. An engine consists of a multitude of rapidly moving parts and a fuel cell stack has no moving parts. In addition, a fuel cell does not require an additional conversion device to generate electric power (Perry and Strayer 2006).

To date, the Polymer Electrolyte Membrane (PEM) fuel cell is used in over 99% of new emergency power units. They provide a high output power density at room temperature, easy and fast start-up and shut-down and they are compact and lightweight. The present lifetime capabilities of PEMFC are suitable for backup applications. Moreover, this type of fuel cell experiences significant benefits, in terms of research and development, from the other fuel cell applications, e.g. from the transportation sector (Adamson 2007; Choi, Howze and Enjeti 2005; Shank n.d.)**.**

Although fuel cell technology has many significant advantages, there is not a perfect solution. A few serious issues are related with application of this equipment as a backup power source. One of them is a concern associated with fuel – its safety during storage, distribution, and usage. Hydrogen, like all fuels, must be handled and stored appropriately to ensure safety. Another issue is start-up time. During start-up of the system or a sudden change of external load, hydrogen cannot be fed fast enough and the fuel cell stack may take a few seconds to reach the required output power. However, this problem can be easily overcome by employment of a rechargeable battery or supercapacitor to respond quickly to the external load and thereby protect the fuel cell from excessive use. Additionally, fuel cell systems need to be housed in an enclosure and require environmental protection (Gonzales and Tamizhmani 2006; Zhan, et al. 2008)**.**

In summary, fuel cells potentially combine the best features of engine-driven generators and batteries. Like a generator, they can operate for as long as fuel is available. And, like batteries, they produce electricity directly from this fuel via a very simple and efficient electrochemical process. Therefore, in backup power applications where hours of run time are required and traditional generators are considered unacceptable, fuel cells offer an attractive alternative.

2.6 Fuel cell based backup power systems – market overview

There are many fuel cell manufacturers at varying stages of development and commercialization of their products. Some of these manufacturers target the backup power markets (Table 2-1). This section briefly describes the largest producers who provide this type of equipment.

Table 2-1 Commercially available fuel cell backup power products (U.S. Fuel Cell Councill 2008)

Manufacturer	Product Name	Output Power	Web Page
Plug Power	GenCore (5B, 5T, 5U)	5 kW	www.plugpower.com
ReliOn	T-1000	600 – 1200 W	www.relion-inc.com
	T-2000	600 – 2000 W	
	I-2000	1 kW	
IdaTech	ElectraGen 3 (XTR, XTi)	3 kW	www.idatech.com
	ElectraGen 5 (XTR, XTi)	5 kW	
UTC Power	PureCell 5	5 kW	www.utcpower.com
Hydrogenics	HyPM XR	8 – 16 kW	www.hydrogenics.com

2.6.1 Plug Power

Plug Power is a designer, developer and manufacturer of on-site energy generation systems utilizing proton exchange membrane fuel cells for stationary applications. The company's headquarters are located in Latham, New York. Plug Power was founded in June 1997 as a joint venture between DTE Energy and Mechanical Technology. Plug Power units are distributed globally by a number of companies, as well as by Plug Power itself in North and South America, Europe, South Africa and East Asia.

The main product line for backup power systems is the GenCore, which is a direct hydrogen fuel cell system producing up to 5kW of DC power. This commercial fuel cell product provides backup power for telecommunications, utility and uninterruptible power supply applications. More about the company and GenCore unit is included in the chapter devoted to the description of this system (Stegemoeller 2005; Plug Power n.d.).

Figure 2.3 GenCore 5B system with fuel storage module

2.6.2 ReliOn

The company was incorporated in 1995 as Avista Laboratories, and since 2004 – ReliOn. It is based in Spokane, Washington State. ReliOn is focused on providing backup power solutions into applications requiring 300W–12kW of peak power load. Its systems are based on a unique modular design, where groups of MEAs are housed in a cartridge, which can be readily swapped without having to take the stack apart if there is a problem.

Figure 2.4 ReliOn backup power solution

The company's core product is the Independence 1000. This fuel cell system is designed to be used with communication systems. The unit supplies up to 1kW of power at 48V DC. For larger loads, multiple units can be connected in parallel to obtain the needed capacity. The I-1000 consists of six fuel cartridges connected in parallel, which increases the reliability of the system. This design also allows any of the six fuel cell cartridges to be replaced, even while the unit is operating (Fuel Cell Today n.d.; Myers and DeHaan n.d.; Sjoding and Hamernyik 2008).

2.6.3 IdaTech

IdaTech is a developer of fuel processors and integrated fuel cell systems for portable power, critical backup power and remote power applications in the telecommunications, utilities and military industries. IdaTech works with such companies as Tokyo Boeki, Dantherm and Rittal, a global supplier of enclosure systems for industrial, electronic, telecommunication, and data communication equipment.

IdaTech's portfolio of reliable fuel cell solutions includes the ElectraGen family of backup power systems in the 3 to 5kW range. The company offers this product with a liquid fuel reformer or without it as hydrogen fueled system (Fuel Cell Today n.d.)**.**

Figure 2.5 ElectraGen backup power system

2.6.4 UTC Power

UTC Power began as a division of Pratt & Whitney in 1958. The company supplied NASA with complete fuel-cell systems for both the Apollo and Space Shuttle programs. In the early 1990s, UTC Power was the first company to manufacture and commercialize a large, stationary fuel cell application for use as a co-generation power plant. UTC Power, formerly known as UTC Fuel Cells or International Fuel Cells was established as a unit of United Technologies Corporation. The company has expanded into the broader fuel cell industry over the last 10 years, developing fuel cells for automobiles, buses, mobile applications, and also stationary applications, including backup power systems. The company's headquarters are located in South Windsor, Connecticut.

UTC Power offers PureCell 5, a backup power system for critical load applications. One system is capable of delivering 5kW of power with about 43% efficiency from the hydrogen fuel to electricity supplied. The fuel type is compressed hydrogen. One bottle provides enough fuel for a constant output of 5kW for approximately 1.2 hours. The run time is scalable with the number of bottles that are sited with the system and the fuel can be replenished on an emergency basis to temporarily extend the capacity if needed. This complete backup power solution consists of three system modules: the Fuel-Cell System, the Power Conditioning System, and the Energy-Storage System (ESS). The modular approach allows for the same system components to be applicable for multiple power outputs and various energy-storage options (Perry and Strayer 2006).

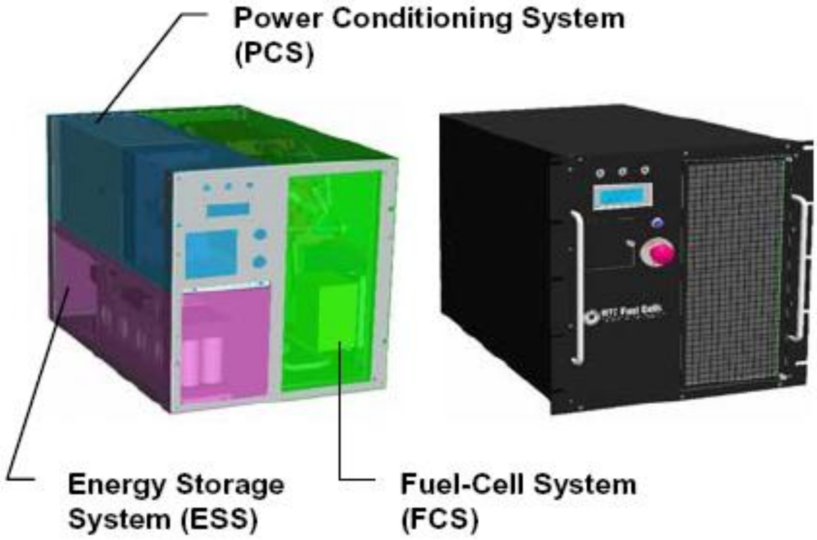

Figure 2.6 The PureCell 5 backup power product

2.6.5 Hydrogenics

Hydrogenics Corporation is a global developer and provider of hydrogen and fuel cell products and services, serving the industrial and clean energy markets. Its headquarters and R&D facility are located in Mississauga, Ontario, Canada. The Company's segments include OnSite Generation, Power Systems and Test Systems. OnSite Generation group sells hydrogen generation products to industrial, transportation, and renewable energy customers. Power Systems group sells fuel cell products to original equipment manufacturers (OEMs), systems integrators and end users for stationary applications, such as backup power and light mobility applications. Test Systems group provides testing services to third parties to validate their fuel cell development efforts

Working with American Power Conversion (APC), a supplier of UPS solutions for critical network infrastructure, Hydrogenics offers an Uninterruptible Power Supply (UPS) fuel cell product for extended run customers (Fuel Cell Today n.d.; Hydrogenics n.d.).

Figure 2.7 HyPM backup power system

2.7 Examples of fuel cell backup power projects

Different regions of the world have varying levels of interest in emergency power systems. In regions where the electricity grid is very stable, like in Japan, interest is higher in systems that take some of the primary load off the grid, e.g. residential systems, rather than providing power in the case of grid failure. In Europe and North America, where the grid is wide spread but not as stable, interest in backup power applications is intense. The third level of interest comes from those regions where either there is simply no grid electricity or it is very unreliable, e.g. in South Africa (Adamson 2007).

Recently, many of the fuel cell backup power manufacturers have tested their products in many different field applications. Several government facilities and individual companies employed fuel cells as backup power for communications and other systems in order to increase data safety and service reliability. This part covers the short example descriptions of the fuel cell backup power system applications and projects in various locations around the world.

2.7.1 Elk Neck State Park, Maryland State, USA

In April 2003, Avista Labs (now ReliOn) and havePOWER entered into a distribution agreement covering government wireless communications applications. HavePOWER is a leading integrator of fuel cell power solutions specializing in state, county and municipal government wireless communications equipment which is used in both everyday and emergency communications. The Elk Neck site consists of a single-channel microwave repeater radio tower that has to be operational and powered at all times. This site was selected as a fuel cell backup power application because of the overall site logistics. Its location is near the end of a single line utility feed, which could present a higher risk of primary power loss. In addition, the remote nature of the site means that, in the event of a primary power outage, it is more difficult to deploy maintenance personnel to the site. Because of these issues, it is critical that the backup power equipment installed at the site is highly durable, reliable, and has the capability for extended backup runtime.

The Elk Neck site comprises one 60m tower and four microwave radios which are configured to operate at 48V DC power normally provided through the primary grid. The total peak power load for this equipment configuration ranges from 200 to 450W. The purpose of the backup power solution is to have no microwave radio downtime, which requires an absolutely seamless transition to and from backup power in the event of a loss of primary grid power. The Elk Neck site utilizes primary power from the grid for its main power supply, and is configured to have a backup propane generator in the event of primary grid loss. The ReliOn Independence 1000 (I-1000) was added to provide an additional level of backup power. This system was installed inside the radio shelter and connected in parallel to the existing DC power bus. Since the fuel cell system requires a short time interval to produce peak power loads, a battery was needed for the time during fuel cell start-up. The hydrogen fuel source was located outside the shelter, and includes six cylinders of standard industrial-grade hydrogen. These six cylinders provide a total capacity of 48kWh, or approximately 120 hours of backup runtime at the estimated full site load. This duration is much longer than the runtimes which would be possible using the battery banks originally provided at the site. Installation went according to plan, and was completed with assistance from havePOWER and ReliOn personnel.

On the 18th of September, 2003, Hurricane Isabel struck a wide area of the east coast of the United States and had a massive impact on the following states: Washington, Maryland, North Carolina, New Jersey, Pennsylvania, Delaware, West Virginia, and Virginia. Reports indicated that 40 people died as a result of the storm, and damage across the region was estimated at nearly $1 billion. The governors of Pennsylvania, West Virginia, Maryland, New Jersey and Delaware declared state emergencies. Maryland had 1.25 million people without power. The Elk Neck site, along with much of Maryland, lost power and its propane generator started to provide backup power to the site. In the midst of Isabel's fury, it was necessary to remove the propane generator from service. When this occurred, the fuel cell system detected the loss of power and the I 1000 unit was activated. The fuel cell system enabled critical emergency radio communications for State Police and EMS services during the hurricane, until primary grid power was restored (Saathoff 2004).

2.7.2 Pole Hill Power Plant, Colorado, USA

The Bureau of Reclamation (BOR) operates 58 hydroelectric power plants and has multiple backup power systems deployed at these plants to provide emergency power to systems such as plant protection, controls, security, communications, and lighting. In 2003, the Hydroelectric Research and Technical Services Group within the BOR investigated backup power sources for use at BOR plants. The BOR evaluated backup power options and determined that fuel cell technology was the best choice for the Pole Hill Power Plant near Loveland, Colorado. They decided to replace an existing battery bank of 48V DC at this communication site and install a fuel cell system manufactured by ReliOn. This site is fairly easy to reach, making evaluation throughout the year possible. It experiences extreme temperature swings throughout the year (-25^{o}C to +40^{o}C) which could demonstrate the ability of the fuel cell to operate in harsh environments.

Figure 2.8 Pole Hill Power Plant

The site required low-power (about 350W) of 48V DC for microwave communications equipment. The unit was installed in October 2003. The system included a modular, hot swappable cartridge-based fuel cell, controls and an outdoor enclosure. The system was fuelled by industrial grade hydrogen gas. The system was configured as a backup power supply and was powered down and idle the majority of the time. When primary power is interrupted the bridge battery supplies power while the fuel cell is started. Once up to full power, the fuel cell delivers power to the equipment and recharges the battery until the primary power is restored. The backup run time at this site, given six full hydrogen cylinders, exceeds 72 hours of continuous operation.

The unit was subjected to extensive testing, including: power quality, behavior during low or loss of voltage, cold start, etc. It has been cycled about 50 times, for a total run time of about 25 hours with only minor issues needing to be addressed. These tests were critical in determining the true capabilities of the fuel cell. In addition, the BOR engineers completed an economic analysis based on their experience and test data, which exhibited an economic savings associated with using fuel cell technology over batteries alone.

The BOR considered the fuel cell a viable backup power solution for systems requiring long backup times at low power consumption. However, the BOR concluded that presently it would not recommend the use of fuel cells for primary or vital systems (Myers and DeHaan n.d.; U.S. Department of Energy n.d.)**.**

2.7.3 Elgin, Scotland, UK

A Plug Power GenCore unit provides backup power to the remote cell tower in Elgin, Scotland in collaboration with Orange, a mobile communication company; FDT Associates, the provider of design and construction services for telecommunication sites throughout the UK and Northern Ireland; and BOC Group, one of the largest hydrogen gas suppliers in the world. The system was installed in January 2004 and has provided more than 550 hours of backup power to the site. The fuel cell unit site is situated in a forest, 450 meters above sea level at the Huntly Nordic Ski Center training site, and provides telecommunication coverage between Rhynie and Elgin. The site's primary power is supplied by an LPG generator provided by Harrington Generators. Plug Power's GenCore system, which is fueled by hydrogen, provides backup power to the remote location (Business Wire 2004)**.**

2.7.4 McChord Air Force Base

On January 14, 2003, a 3kW system (consisting of six smaller ReliOn Independence 500W modular fuel cells) was installed at McChord Air Force Base in Tacoma, Washington. This 1-year demonstration project was sponsored by Construction Engineering Research Lab (CERL), a division of the U.S. Army Engineer Research and Development Center (ERDC). In this demonstration, the fuel cell system responded to a loss in power and supplied backup power to a load bank located at a radio transmit receiver (RTR) equipment site owned and operated by the U.S. Federal Aviation Administration (FAA). The purpose of the demonstration was to provide reliability data to both the FAA and ERDC to support commercial purchases and installations of the ReliOn Independence fuel cell systems.

The project was divided into two phases. During the first phase the fuel cell responded to a 20 minute loss of AC power three times each day for seven days a week. The second phase added a 2 hour grid power failure every Sunday to the daily tests. During the simulated grid failure, the fuel cell system carried the entire RTR load while maintaining charge voltage to the facility battery system for the 2 hour period. Over the demonstration period, the system was monitored over 8800 hours, and accumulated over 1100 successful starts, for a total system run time of 418.9 hours. Total reliability was 99.4% and total availability was 97.4%. Availability and reliability of less than 100% was attributed to issues associated with the subcomponents, like: overly sensitive hydrogen sensors causing system shutdown, inappropriate gas connections that led to loss of fuel supply and shorting of pad heaters which resulted in the system failing to start. This installation and demonstration illustrated the viability of utilizing hydrogen fuel cell systems to supplement and/or replace large battery systems (ReliOn 2004; U.S. Department of Energy n.d.).

2.7.5 Caracas, Venezuela

Telefonica Moviles, one of the largest wireless providers in Latin America, deploys Plug Power's GenCore backup power systems in Venezuela. Nine backup fuel cell systems were purchased through Plug Power's Venezuelan distributor Corpo Teletecnical. The systems were placed at tower locations with critical backup needs in the greater Caracas area. Telefonica Moviles identified these sites as those where there is insufficient space for additional batteries or a generator, or where generators are prohibited due to noise or pollution issues or weight restrictions. The new deployment followed the completion of a successful 8-month trial at an active Telefonica Moviles wireless location outside of Caracas. The GenCore system responded effectively to several grid outages during the trial period, including one that lasted approximately 12 hours, providing power and maintaining tower operation when the AC grid failed due to overloading and weather-related factors.

Plug Power was also participating in GenCore trials with Telefonica Moviles in other key markets including Mexico, Brazil and Spain (Fuel Cell Works 2006)**.**

2.7.6 Telecom Italia, telecommunication sites, Italy

During 2005, Telecom Italia contracted the SGS - Italian distributor agent of fuel cell manufacturer ReliOn for a number of its Independence 1000 units to test reliability as a backup power for telecommunication sites. Telecom Italia chose the test sites. Considering the requested power in each site, four ReliOn systems were installed in the center of

Mattarello and two units in Vezzano and Calvino. The main pieces of hardware at the sites were the fuel cell and the small battery array, which were housed in indoor enclosures with external venting of the heat produced. The hydrogen was stored externally in high-pressure storage vessels.

The goal of the project was the testing of the fuel cell system and its integration into telecommunication stations for backup power solutions. The study was set up to go through four test phases, each looking at critical metrics such as start-up time, time to full load and overall reliability. The results of the tests and project outcomes are:

- The best conclusion from the study was that under all conditions tested, the fuel cell operated with full reliability;
- The measured electric efficiency of the units was between 38.4% and 39.1%;
- The fuel cell required, as predicted, minimal maintenance;
- The units were stated to be an economically viable choice.

The short-term outcome of the project was that Telecom Italia expanded the project to include 20 more sites (Tomais, et al. 2006).

2.7.7 ISR University of Coimbra, Portugal

The Institute of Systems and Robotics (ISR) is a research institute associated with the University of Coimbra. It promotes the penetration of advanced energy-efficient technologies through innovative projects, demonstration, education, training, dissemination, energy monitoring, energy audits, and design of energy policies, in collaboration with the utilities, local and regional authorities, industry, building operators, and gas and electricity utilities.

A 5kW Plug Power GenCore fuel cell unit was installed in the Institute of Systems and Robotics – University of Coimbra facilities. The objectives of this project were to provide high quality power supply to critical loads including the network servers and conduct some experiments and research for dynamic modeling of the PEMFC in different operation modes. The installation included the grid connection inverter to provide interaction with the power grid and a supercapacitor bank allowing changing the dynamic system characteristics. The fuel cell system was located in an indoor testing laboratory, and the hydrogen fuel storage was situated outdoors, close to the lab. AMM was the company that was engaged to install the house to store the hydrogen cylinders. Hydrogen was supplied by the company Air Liquide. The monitoring of the power generation and transient processes could be surveyed by a dedicated personnel computer. Three operational modes for the fuel cell based system were considered: an island mode of fuel cell operation, a power grid interconnection mode and an energy storage–inverter-fuel cell mode. The second task was devoted to the dynamic modeling of the PEMFC based system: transient response, load following capabilities, and start up, step changes and shut down characteristics (Institute of Systems and Robotics University of Coimbra n.d.).

2.7.8 Keflavik International Airport, Iceland

The Keflavik Airport fuel cell backup power system demonstration project was conducted in 2006 as a joint technological initiative between Icelandic and US stakeholders: the United States Army Corps of Engineers, the Construction Engineering Research

Laboratory (CERL), the US Naval Air Station Keflavik, LOGANEnergy, the Ministry for Foreign Affairs & Ministry of Industry and Commerce in Iceland, Icelandic New Energy, the Leifur Eiríksson Air Terminal, Plug Power, AGA and EXTON. The Keflavik Airport is a major stopping point between North America and Europe as well as a vacation destination in its own right.

Figure 2.9 Plug power GenCore unit in Keflavik Airport (LOGANEnergy 2007)

The project was designed to provide DC electricity to a simulated DC bus, which consisted of two DC lighting circuits. They were configured to illuminate the fuel cell during the airport's peak evening traffic periods and the board containing information on fuel cells. The main objective behind that project was to investigate the reliability of GenCore backup power unit. The project also served to educate airport visitors by demonstrating current fuel cell technology (LOGANEnergy 2007).

2.8 About this work

The project was prepared in Innovation Center in Reykjavik, Iceland. The study case system is a Plug Power GenCore 5B48 backup power unit, which was previously used at the Keflavik International Airport in Iceland as a one-year reliability demonstration project conducted in 2006.

2.8.1 Project objectives

The main objective of this work was to determine if a fuel cell could be installed and used as a reliable indoor backup power source, how well the system would perform, establish its dynamic response, installation and safety issues. An analysis of lifecycle costs was also performed to establish if and at what point there may be an economic case for fuel cell systems over incumbent backup power technologies. This information is critical to anyone who may consider employing fuel cell systems in place of battery banks or engine generators in emergency power applications. All results and conclusions are specified and explained in the later chapters.

2.8.2 Why Iceland

Iceland is a leading country in the sustainable use of natural resources, including energy. Almost all electricity and space heating are derived from renewable sources, constituting 72% of all energy consumption in Iceland. The remaining 28% is based on fossil fuel. The Icelandic government aims at increasing the share of renewable energy within the Icelandic economic profile.

Figure 2.10 Shell Hydrogen station in Iceland

Hydrogen, as an energy carrier made from water and renewable energy, would reduce Iceland's dependency on fossil fuel. In 1998, the Icelandic Government declared its intention to introduce the world's first Hydrogen Economy and it has offered Iceland as a platform for hydrogen research and demonstration (Arnason and Sigfusson 2000; Sigfusson 2003).

2.8.3 About Innovation Center Iceland

Innovation Center Iceland was established on the 1st of August, 2007 with the merger of the Technological Institute of Iceland and the Icelandic Building Research Institute. It operates under the Ministry of Industry and receives revenue from both the public and private sectors. The center is a leading institution in technological R&D in Iceland. Its departments specialize in everything from nanotechnology and environmental energy to concrete research and building technology. Projects include applied research and testing, research in many areas, consultation and technology transfer (Innovation Center Iceland n.d.).

Figure 2.11 Innovation Center Iceland – research facility

3 FUEL CELL FUNDAMENTALS

3.1 Introduction

In order to fully understand the content of the thesis, it is good to gain some basic knowledge of fuel cell technology. This and the next chapter will contain a discussion on fuel cell technology. They describe what a fuel cell is, how it works, cover simple characteristics, advantages and disadvantages, types and applications, fuel cell based systems, and their impact on the environment.

3.2 What is a fuel cell?

Fuel cells are future energy systems with a high potential for efficient, environmentally-friendly energy conversion that can be used in stationary, mobile and portable applications. A fuel cell is defined as an "electrochemical cell which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy by a process involving an essentially invariant electrode-electrolyte system" (Kordesh and Simader 1996)**.** In other words, a fuel cell is like a small "factory" that takes fuel and produces electricity and heat (Figure 3.1). There are similarities between fuel cells and primary batteries. Both systems have two electrodes separated by an electrolyte, and electrical energy can be withdrawn from the cell reaction. Unlike batteries, in a fuel cell the reactants are supplied from an external source and it operates as long as it is supplied with fuel and oxidant. Viewed this way, a fuel cell is similar to a combustion engine, which also takes the chemical energy stored in the fuel and transforms it into useful mechanical or electrical energy. The difference is that in a fuel cell there is no combustion as an intermediate step, so it is not limited by thermodynamic limitations of heat engines such as the Carnot efficiency. These are the key benefits of a fuel cell over a battery and conventional combustion engine (O'Hayre, Cha, et al. 2006; EG&G 2004)**.** More about advantages and also disadvantages of fuel cell technology will be pointed out further on in this chapter.

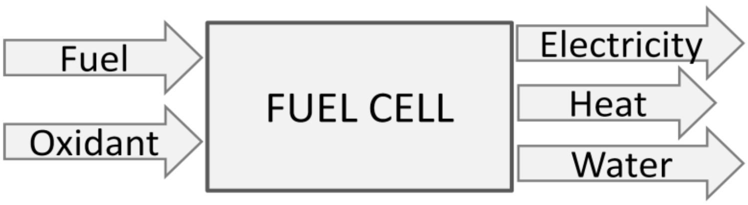

Figure 3.1 Basic concept of fuel cell

3.3 Fuel cell history

The history of fuel cells starts in 19th century, and the invention of this device is widely attributed to Sir William Robert Grove, a Welsh judge and amateur scientist, born in Swansea in 1796. In 1839, he discovered that mixing hydrogen and oxygen in the presence of an electrolyte produced electricity and water. The term "fuel cell" for Grove's invention was first used in 1889 by Ludwig Mond and Charles Langer, who attempted to develop a fuel cell that uses industrial coal gas and air as a source. The main step they made was replacing the liquid electrolyte with soaked up asbestos, the predecessor to the solid electrolyte.

In 1932 an engineer at Cambridge University, Francis T. Bacon built a fuel cell which was based on a less corrosive alkaline electrolyte and made it possible to use inexpensive nickel as the catalyst. In 1959, Bacon demonstrated a stack of forty cells, which was able to produce 5kW of electric power and was comparable to modern fuel cells. In 1959, the first fuel cell vehicle, a tractor, was made by Allis-Chalmers farm equipment firm in Milwaukee, Wisconsin. The first Proton Exchange Membrane Fuel Cell (PEMFC) was made in 1954 in USA by a chemist William Thomas Grubb from General Electric.

When the USA and USSR, the two superpowers of 20th century, started the race for space, fuel cells became a matter of great interest as the need grew for compact energy conversion devices onboard spacecraft. In the 1950's, NASA decided to use fuel cells to supply power during space flight for their manned space missions. NASA funded over 200 research projects on fuel cell technology and consequently, fuel cells have provided on-board electricity and water to the Gemini, Apollo and Space Shuttle missions.

In 1983 a team headed by Geoffrey Ballard from Canada received a Canadian government's request to develop a PEM fuel cell. Ballard is currently a leading company in the fuel cell business and provides fuel cell stacks and components to many system manufacturers.

The development of other types of fuel cells started in the late 1930s with the work of Emil Bauer and H. Preis in Switzerland on solid oxide electrolytes in the fuel cells and O. Davtyan of Russia in 1945 on mixing carbonate and oxides with a sand separator (T. I. Sigfusson 2008).

3.4 Structure and principle of operation

The physical structure of all fuel cells consists of an electrolyte layer sandwiched between an anode and cathode electrodes. This configuration is called the Membrane Electrode Assembly (MEA). The electrolyte allows the passage of ionic charge between the electrodes, blocks the passage of electrons, and provides a physical barrier to prevent the direct mixing of the fuel and the oxidant. The specific type of material depends of the type of fuel cell. The main types are briefly described in a later part of this chapter. A porous electrode is used to deliver a fuel or oxidant, and to maximize the three-phase interface between the catalyst, electrolyte and the fuel (gas or liquid) (Larminie and Dicks 2003; Adamson 2007)**.** The picture below (Figure 3.2) exhibits the basic structure and operation of a simple hydrogen-oxygen fuel cell. Fuel is fed continuously to the anode (negative electrode) and an oxidant (often oxygen from air) is fed continuously to the cathode (positive electrode). The electrochemical reactions take place at the electrodes. Hydrogen molecules are split on the anode into protons and electrons. The electrons move from high-energy reactant bonds, through an external circuit, to low-energy product bonds. This creates electric current that performs work on the load. The protons travel through the electrolyte membrane to the cathode, where oxygen, protons, and electrons combine to form water. Heat, as a by-product, is also created (EG&G 2004; O'Hayre, Cha, et al. 2006)**.**

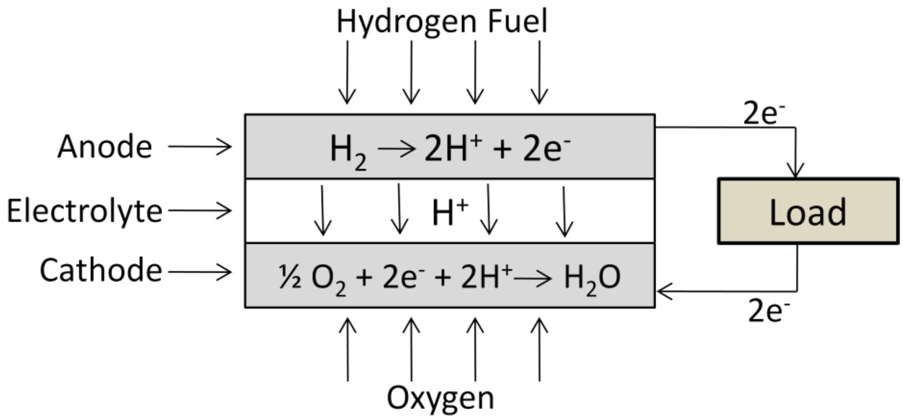

Figure 3.2 Simple cathode-electrolyte-anode construction of hydrogen-oxygen fuel cell

The next chapter describes and explains hydrogen fuel cell performance, its construction, characteristics, and limitations in more detail. It is dedicated to the Polymer Electrolyte Membrane Fuel Cell (PEMFC), a fuel cell type that is used in most of the backup power systems based on this technology.

3.5 Advantages and disadvantages

The main fuel cell advantages are:

- production of electricity as long as they are supplied with fuel;
- production of electricity directly from chemical energy;
- potential for very high efficiency – especially as a CHP unit;
- high energy density and ability for quick recharging by refueling;
- simple, no moving parts, silent;
- potential for high reliability and long-lasting systems;
- environmentally friendly - undesirable products such as NOx, SOx, and particulate emissions are virtually zero;
- flexible – allow easy independent scaling between power and capacity.

Fuel cell technology develops very fast. Many studies and researches are conducted all over the world. Despite that, it still possesses several very serious disadvantages. The most significant are:

- high cost – the main barrier to fuel cell implementation;
- limitations in power density;
- fuel availability and storage – hydrogen fuel has a low volumetric energy density and is difficult to store, alternative fuels are difficult to use directly and usually require reforming;
- temperature compatibility;
- susceptibility to environmental poisons – some materials used, especially in low temperature fuel cells, are quite vulnerable to reactant contaminations;
- durability issues (O'Hayre, Cha, et al. 2006)**.**

3.6 Types of fuel cells and applications

Fuel cells are customarily classified according to the electrolyte employed. The five most common fuel cell types are:

- Polymer Electrolyte Membrane Fuel Cells (PEMFC);
- Alkaline Fuel Cells (AFC);
- Phosphoric Acid Fuel Cells (PAFC);
- Molten Carbonate Fuel Cells (MCFC);
- Solid Oxide Fuel Cells (SOFC).

There are also other ways to divide fuel cells into types. One of them is the distinction between the movements of ions through the electrolyte. On one hand there are fuel cells in which protons move to the cathode, producing water and heat (PEMFC and PAFC). On the other hand, there are fuel cells in which negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons (AFC, MCFC, SOFC). Another way to classify fuel cell types is according to the fuels they utilize: direct fuel cells, in which hydrogen is fed directly to the anode; indirect fuel cells, in which external reformers are used; and finally the regenerative type, in which the fuel cell product is reconverted into reactants and recycled. The types of fuel cells could also be divided into stationary, mobile or portable. It all depends on their application (T. I. Sigfusson 2008).

This part of the chapter covers a general description of each of the fuel cells listed above. For detailed characteristics of different fuel cell types it is recommended to read, for example, Fuel Cell Handbook, 7th ed. (EG&G 2004) or Fuel Cell Systems Explained, 2nd ed. (Larminie and Dicks 2003).

3.6.1 Polymer Electrolyte Membrane Fuel Cell (PEMFC)

The PEMFC operates at 50-100°C. The electrolyte is a solid ion exchange membrane used to conduct protons. Hardware corrosion and gas crossover are minimized as a result of the solid electrolyte and very high current densities, and fast start times have been realized for this cell. However due to the low temperature operation, catalysts (mostly platinum) are needed to increase the rate of reaction. In addition heat and water management issues are not easily overcome in a practical system, and tolerance for CO is low (Holland, Zhu and Jamet 2007). PEMFCs use hydrogen (or hydrogen-rich) gas as the fuel and oxygen as the oxidant. Oxygen may be supplied pure or as air, depending on the application.

PEMFCs are an attractive option for a wide range of applications, including transportation, stationary power source, and even portable systems. At this moment, the automotive industry is the largest investor in PEMFC development. PEMFC systems fuelled by hydrogen, methanol, and gasoline have been integrated into vehicles by at least twelve different automakers. Before releasing these types of vehicles into market, many improvements are still required, including: reduction of fuel cell system volume and weight, life and reliability improvement, systems must be made more robust in order to be operable under the entire range of environmental conditions expected of vehicles, additional technological development is required to achieve the necessary cost reductions, and finally, hydrogen infrastructure and the accompanying safety codes and standards must be developed (EG&G 2004). Stationary power generation applications include both large-scale utility plants and smaller scale systems for distributed electricity and heat generation in buildings and individual homes. Fuel cells are already an alternative for power generation in areas where there is no existing power grid or the power supply is often unreliable. PEMFC technology is used in over 99% of new fuel cell based backup power systems (Adamson 2007) and it is also used in the GenCore system, which is a case study of this thesis. Therefore, a more detailed description of PEMFC is given in the next chapter.

Specially optimized PEMFCs can be fed with methanol, creating a so-called Direct Methanol Fuel Cell (DMFC). Conceptually, this could lead to a very simple system with a fuel that has a relatively high energy density and is a liquid under ambient conditions. Despite significant progress in development, DMFC has also many issues like: cross-over of neutral methanol from the anode to the cathode site, which causes high overpotential, the platinum requirement is much higher than in direct hydrogen PEMFC, high kinetic losses, and problems with water transport. Despite these challenges, there is significant interest in DMFCs for portable power applications in the 1W to 1kW capacity range (EG&G 2004).

3.6.2 Alkaline Fuel Cell (AFC)

The AFC operates between 50-250°C. The electrolyte is KOH, and can be either mobile or retained in a matrix material. Many catalysts can be used in this fuel cell, an attribute that provides development flexibility. The ACF has excellent performance with hydrogen and oxygen compared to other candidate fuel cells. The major disadvantage of this fuel cell is that it is very susceptible to CO2 and CO poisoning, hence its use with reformed fuels and air is limited (Holland, Zhu and Jamet 2007).

The AFC is not economically viable for most terrestrial power applications. However, because of its high efficiencies and power densities, this type of the fuel cell is used in the aerospace industry (O'Hayre, Cha, et al. 2006). Some developers pursue AFC for mobile and closed-system (reversible fuel cell) applications (EG&G 2004).

3.6.3 Phosphoric Acid Fuel Cell (PAFC)

The PAFC operates at 200°C with phosphoric acid (H3PO4) used for the electrolyte. The matrix universally used to retain the acid is silicon carbide (SiC), and the catalyst is platinum. The use of concentrated acid minimizes the water vapor pressure so water management in the cell is not difficult. The cell is tolerant to CO2 and the higher temperature operation is beneficial for co-generation applications. The main limitation of the PAFC is the lower efficiency realized in comparison with other fuel cells (Holland, Zhu and Jamet 2007).

PAFCs are mostly developed for stationary applications. Both in the U.S. and Japan, hundreds of PAFC systems were produced, sold, and used in field tests and demonstrations. Development of this type of fuel cell has slowed down in the past few years, in favor of PEMFCs that were thought to have better cost potential. However, PAFC development continues (EG&G 2004).

3.6.4 Molten Carbonate Fuel Cell (MCFC)

The MCFC operates at 600°C. The electrolyte is usually a combination of alkali carbonates retained in a ceramic matrix. At a high temperature of operation the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. The high reaction rates remove the need for noble metal catalysts, and gases such as natural gas can be internally reformed without the need for a separate unit. In addition the cell can be made of commonly available sheet metals for less costly fabrication. One feature of the MCFC is the requirement of CO2 at the cathode for efficient operation. The main disadvantage of the MCFC is the very corrosive electrolyte that is formed, which impacts on the fuel cell life, as does the high temperature operation (Holland, Zhu and Jamet 2007).

The MCFC is best suited for stationary, continuous power applications. In Combined Heat and Power (CHP) applications efficiency of the system could reach close to 90% (O'Hayre, Cha, et al. 2006).

3.6.5 Solid Oxide Fuel Cell (SOFC)

The SOFC operates between 500-1000°C. The electrolyte is a solid, nonporous metal oxide and the charge carriers are oxygen ions. The electrolyte always remains in a solid state, adding to the inherent simplicity of the fuel cell. The solid ceramic construction of the cell can minimize hardware corrosion, allows for flexible design shapes, and is impervious to gas crossover from one electrode to the other. Due to its high temperature operation, high reaction rates are achieved without the need for expensive catalysts, and gases such as natural gas can be internally reformed without the need for fuel reforming. Unfortunately the high operating temperature limits the materials selection and a difficult fabrication processes results. In addition the ceramic materials used for the electrolyte exhibit a relatively low conductivity, which lowers the performance of the fuel cell (Holland, Zhu and Jamet 2007).

SOFCs are now considered for a wide range of applications, including stationary power generation, mobile power, auxiliary power for vehicles, and specialty applications (EG&G 2004).

3.7 Fuel cell system

In order to provide the required amount of power, a fuel cell system generally includes a set of fuel cells, which is called a fuel cell stack; but a typical fuel cell system includes not just the fuel cells but also other equipment like compressors, ejectors, fans, blowers, pumps, heaters, and many more devices. They create specific subsystems, like thermal management, fuel processing and delivery, or power conditioning, in order to provide proper system performance. The technology for such equipment is very mature, having already been developed for other applications. Chapter 5 provides a detailed description of such a system and each of its components.

3.8 Impact on the environment

The environmental impact of fuel cell use depends upon the source of the hydrogen fuel. Fuel cells that use processed fossil fuels have emissions of CO_2 and SO_2, but these emissions are lower than those from traditional thermal power plants or engines due to the higher efficiency of fuel cell power plants. Potential higher efficiencies result in less fuel being consumed to produce a given amount of electricity. This corresponds to lower emissions. Fuel cell power plants also have longer life expectancies and lower maintenance costs than their alternatives.

By using pure hydrogen, fuel cell systems have no emissions except water. Many people predict the growth of hydrogen production from renewable energy sources in the future. Photovoltaic cells convert sunlight into electricity. This electricity would be used to split water, by electrolysis, into hydrogen and oxygen. The same scenario is real for wind or hydro energy. In such a configuration, fuel cell systems would have virtually no emissions of greenhouse or acid gases, or any other pollutants.

4 POLYMER ELECTROLYTE MEMBRANE FUEL CELLS

4.1 Introduction

PEMFC (Polymer Electrolyte Membrane Fuel Cells) were briefly explained in the previous chapter, now it is time to take a closer look at them. In this chapter the components of this kind of fuel cell are described together with the basic principles of the operation and performance.

4.2 Cell components

A Polymer Electrolyte Fuel Cell is built in a very similar way to other fuel cells. There are two electrodes (anode and cathode), which are on opposite sides of an electrolyte and bipolar plates, which are used to connect cells in series and to properly distribute gas around the fuel cell. However, there are some significant differences in the materials used in a PEMFC.

4.2.1 Membrane Electrode Assembly

In PEMFC, a catalyst porous electrode is bonded onto each side of the electrolyte, which is an ion conduction polymer. The anode – electrolyte – cathode assembly is thus one item, and is very thin. These 'membrane electrode assemblies' (or MEAs) are connected in series, usually using bipolar plates.

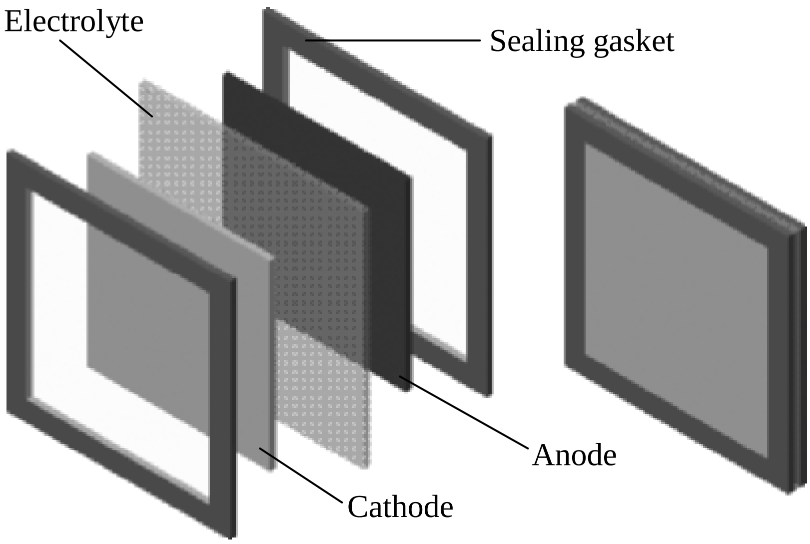

Figure 4.1 Membrane Electrode Assembly with a gasket sealing the edges. (Larminie and Dicks 2003)

The different companies producing polymer electrolyte membranes have their own ways to manufacture them, mostly proprietary. However, a common theme is the use of sulphonated fluoropolymers, usually fluoroethylene. The most well known and well established is Nafion, developed by DuPont. This material is in a sense an 'industry standard' and other polymer electrolytes function in a similar way. The main features of Nafion and other chemical compounds of this kind are their high chemical resistivity and mechanical strength, which results in the creation of very thin films, down to 50μm. They can absorb large quantities of water, and if they are well hydrated, the H^+ ions can move quite freely within the material. They are also very good proton conductors.

The basic structure of the electrode in different designs of PEMFC is similar, though of course details vary. However, the anodes and cathodes are essentially the same. The best catalyst for both the anode and the cathode is platinum. It is formed into very small particles on the surface of somewhat larger particles of finely divided carbon powders. The platinum is spread out so that a very high proportion of the surface area will be in contact with the reactants. Carbon paper or cloth is used to provide the basic mechanical structure for the electrode. In addition it also diffuses the gas onto the catalyst, so it is often called the gas diffusion layer. The carbon-supported catalyst particles are joined to the electrolyte on one side, and the gas diffusion layer on the other.

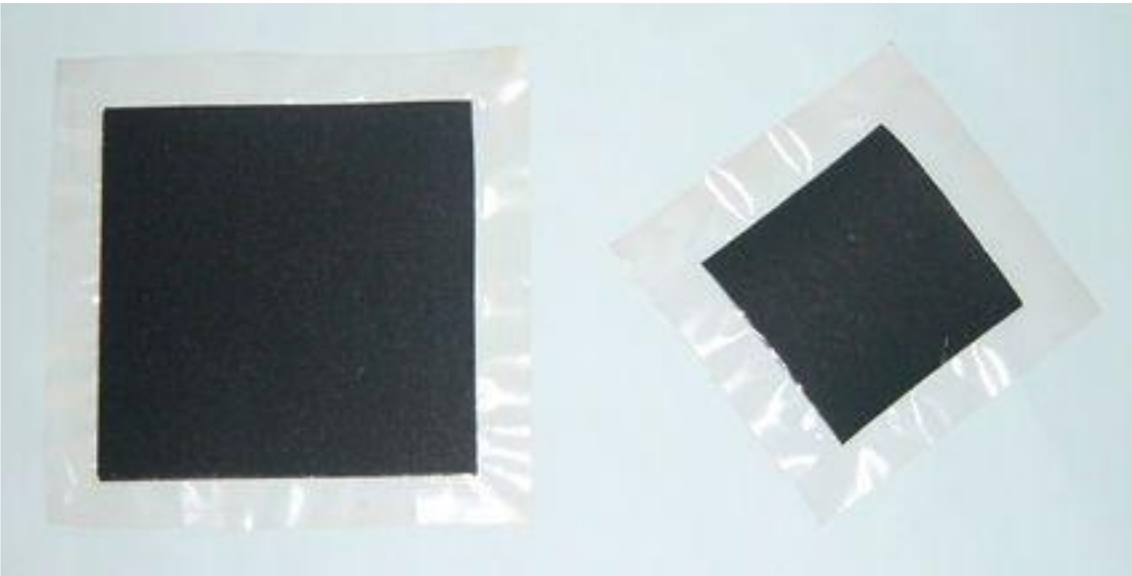

Figure 4.2 Example of a complete MEA (Fuel Cell Store n.d.)

4.2.2 Bipolar plates

The voltage of a fuel cell is quite small, about 0.7V when drawing a current. This means that to produce a useful voltage many cells have to be connected in series. Bipolar plates are used for cell interconnection. This creates connections all over the surface of one cathode and the anode of the next cell. At the same time, the bipolar plate serves as a means of feeding oxygen to the cathode and fuel gas to the anode. Although a good electrical connection must be made between the two electrodes, the two gas supplies must be strictly separated. The grooved plates are made of a good conductor such as graphite, or sometimes metals. The plates also have channels cut in them so that the gases can flow over the face of the electrodes. At the same time, they are made in such a way that they make a good electrical contact with the surface of each alternate electrode.

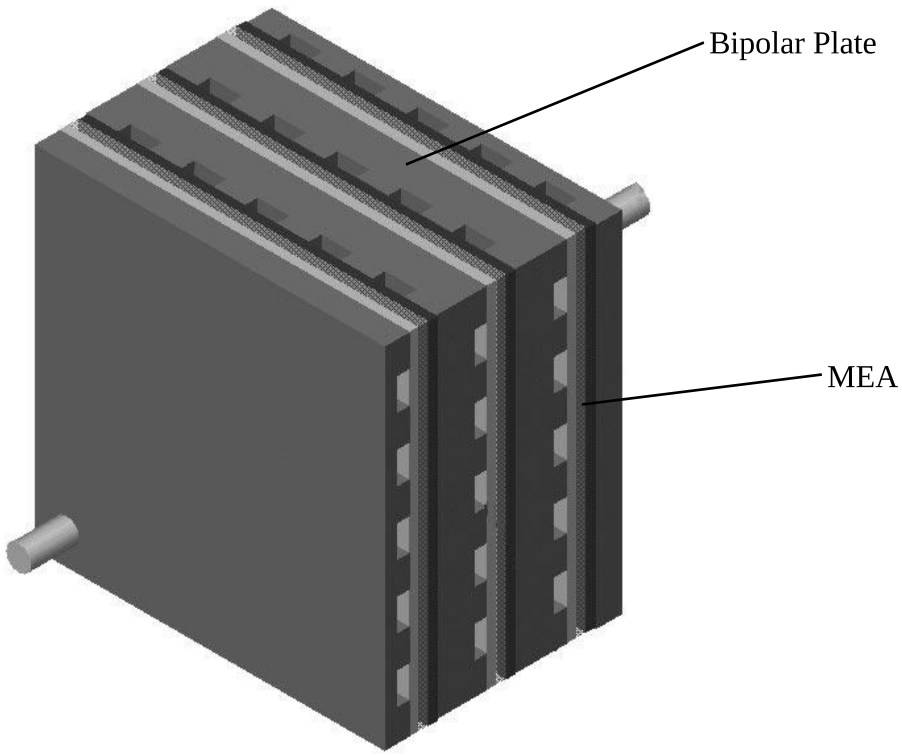

Figure 4.3 Example of the connection of 3 MEA's with bipolar plates (Larminie and Dicks 2003)

Most PEM fuel cells are constructed along the general lines of multiple cells connected in series with bipolar. However, there are many variations in the way the bipolar plate is constructed and the materials they are made of. This is a very important topic, because the MEAs for PEM fuel cells are very thin, so the bipolar plates actually comprise almost all the volume of the fuel cell stack, and typically about 80% of the mass (Larminie and Dicks 2003). Also, the platinum usage has been drastically reduced and the result is that the bipolar plates are usually also a high proportion of the cost of a PEM fuel cell stack.

The bipolar plates used in PEMFC are usually made of graphite. The reason for this is that they are electrically conductive and reasonably easy to machine. They also have low density – less than that for any metal that might be considered suitable. Fuel cell stacks made in this way have achieved a competitive power density. However there are some disadvantages of using graphite as a material for bipolar plates – it is very fragile, thus it requires careful handling and it is difficult to assemble. Although machining of the graphite can be done automatically, cutting still requires a lot of time and expensive equipment. Graphite is also quite porous, so the plates have to be a few millimeters thick to keep reactant gases apart, which results in higher weight.

Besides graphite, metals are sometimes used, although they are good conductors and they are not as porous as graphite (which makes it possible to manufacture thinner plates) and they have higher densities. They are also prone to corrosion in the highly corrosive atmosphere of the fuel cell. In order to avoid it, one of the advantages of metals has to be sacrificed. For example stainless steel can be used, but it is quite an expensive material and difficult to work with. Alternatively, a special coating can be applied, but the time and complexity of this operation negates the short manufacturing process. Some important developers prefer metal, such as Siemens (Ise, Schmidt and Waidhas 2001) and Intelligent Energy, but the majority, including Ballard Power Systems, use graphite-based materials.

Not only are the material and the technique of production of the bipolar plate important, but also the shape of the pattern of the gas channels made in the plate. There are almost limitless possibilities of how such a conduit can look and there is no clear consensus as to which way is the best. In Figure 4.4 there are two examples of how the pattern can look.

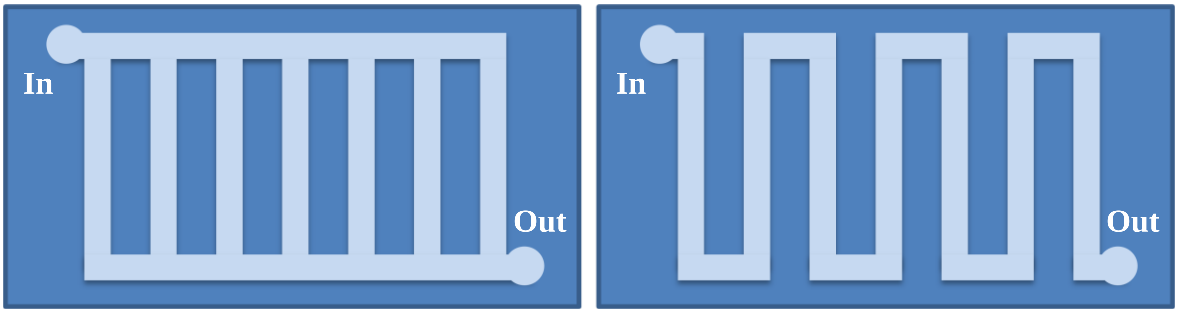

Figure 4.4 Parallel system (on the left) and serpentine system (on the right) of the gas channels in a bipolar plate

The supposed problem of the parallel systems (left, Figure 4.4) is that it is possible for water, or some reactant impurity such as nitrogen, to build up in one of the channels. The reactant gas will then move along the other channels and the problem will not be shifted, leaving a region of the electrode unsupplied with reactants. The serpentine system (right, Figure 4.4) can guarantee that if the reactants are moving, they are moving everywhere – a blockage will be cleared. The problem with the serpentine system is that the path length and the large number of turns mean that excessive work has to be done in pushing the gases through (Larminie and Dicks 2003).

4.3 Fuel cell performance

The performance of the fuel cell depends on several factors. It can be summarized with a graph of its current-voltage characteristics. This graph shows the output voltage of the fuel cell for a given current output. An ideal fuel cell would provide any amount of current, while maintaining constant voltage, determined by thermodynamics; but because of the limitations, its real voltage output is lower than ideal voltage. The typical look of the PEM fuel cell's i-V curve together with power density curve can be seen in Figure 4.5.

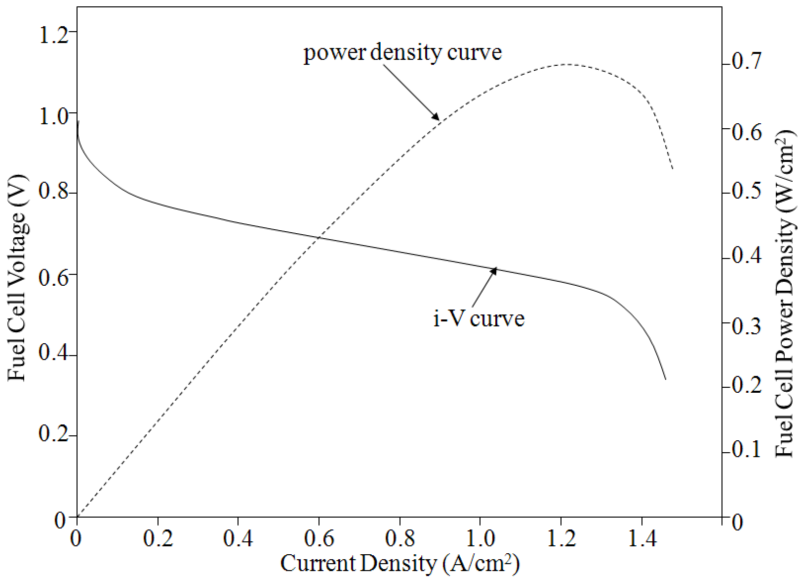

Figure 4.5 Schematic of the fuel cell i-V curve together with power density curve (O'Hayre, Lecture 2: Intro to Fuel Cells 2008)

The power density curve is constructed by multiplying the fuel cell's output voltage by a corresponding current density point:

$$P = iV$$

As can be seen on the graph, power density rises to one point, but because of the voltage drop caused by the losses, it goes down at the end of the curve. The higher the current drawn from the fuel cell, the lower the voltage it can supply, so the power that can be delivered is lower than expected. Fuel Cells are designed to work at or under the power density maximum, because at current densities below the power maximum voltage efficiency improves, whereas above the power maximum both voltage efficiency and power density fails (O'Hayre, Cha, et al. 2006).

Because of this fact, the current provided by the fuel cell is directly proportional to the amount of fuel consumed (in this way, for each mole of fuel – in this case hydrogen – a constant number of electrons is produced), and when voltage decreases, the electric power of the unit also decreases. Therefore maintaining high voltage is a "must" in successfully implementing this technology.

Although having high voltage under current load would be the ideal solution, it is impossible to achieve. The voltage output of the real fuel cell is less than the thermodynamically calculated voltage output due to irreversible losses. The more current is drawn from the cell, the bigger the losses. When calculating the real voltage of the fuel cell, one has to take into consideration three kinds of losses:

- Activation losses, caused by electrochemical reaction;
- Ohmic losses, due to ionic and electronic conduit;
- Concentration losses, which have a foundation in mass transport.

Therefore, the real voltage output is the difference between ideal, thermodynamical voltage and a sum of these losses and can be written as:

$$V = E_{thermo} - \eta_{act} - \eta_{ohmic} - \eta_{conc}$$

Where:

Table 4-1 Explanation of the symbols

Symbol	Explanation	Common Unit
V	Real output voltage of the cell	V
E_{thermo}	Thermodynamically predicted output voltage	V
η_{act}	Activation losses	V
η_{ohmic}	Ohmic losses	V
η_{conc}	Concentration losses	V

These three major losses contribute to the shape of the i-V curve. The activation losses influence the first part of the graph, the ohmic losses influence the middle section and mass transport (concentration) losses are most present in the last part of the curve. Throughout this chapter, all of the components of the equation above will be briefly explained.

4.4 Thermodynamic fuel cell voltage

Thermodynamics is the study of the conversion of one form of energy into different forms of energy (in particular, mechanical, chemical, and electrical energy) and its relation to macroscopic variables such as temperature, pressure, and volume. In essence, thermodynamics studies the movement of energy and how energy instills movement. Historically, thermodynamics developed out of the need to increase the efficiency of early steam engines (Wikipedia 2009). In fuel cells, thermodynamics is the key to understanding the principles of the conversion of chemical energy into electrical energy. It also sets the upper limit of what the fuel cell can do. In practice, fuel cells can never achieve thermodynamical voltage (also called open circuit or reversible voltage) – which for PEM fuel cells is 1.22V, and they are always operating below it, at about 0.7V depending on the current drawn from the cell.

The goal of the fuel cell is to extract the internal energy from a fuel and convert it into a more useful form of energy (electrical). Therefore it is necessary to know how much energy can be extracted from hydrogen. It all depends on the form in which we want to have this energy, either heat or work.

4.4.1 Enthalpy of reaction

The maximum heat energy that can be extracted from a fuel is given by the fuel's heat of combustion or, more generally, the enthalpy of reaction. Under constant pressure, the formula for enthalpy looks like this:

$$dH = TdS = dU + dW$$

Where:

Table 4-2 Explanation of the symbols

Symbol	Explanation	Common Unit
dH	Enthalpy of reaction	J
T	Temperature	K
dS	Entropy	J/K
dU	Internal energy	J
dW	Work	J

From the equation above, it can be seen that after accounting for the energy that goes to work, the rest of the internal energy difference is transformed into heat during the reaction. The internal energy change is mostly due to reconfiguration of chemical bonding, similar to that which takes place during the burning of hydrogen, when molecular bonding changes. This enthalpy change is called heat of combustion.

4.4.2 Work potential

The work potential of the fuel, the amount of "usable" energy that can be recovered from it at constant pressure and temperature, is represented by Gibbs free energy.

$$G = H - TS$$

The equation above describes Gibbs free energy as enthalpy minus the energy connected with the entropy (O'Hayre, Cha, et al. 2006). In a fuel cell Gibbs free energy involves moving electrons round an external circuit. If there are no losses, or if the process is 'reversible', then all the Gibbs free energy is converted into electrical energy (in practice, some is also released as heat.) It is then used to find the Open Circuit Voltage of the fuel cell.

In PEMFC two electrons pass round the external circuit for each water molecule produced and each molecule of hydrogen used. So, for one *mole* of hydrogen used, *2N* electrons pass round the external circuit – where *N* is Avogadro's number. If $-e$ is the charge on one electron, then the charge that flows is:

$$-Ne = -2F$$

F being the Faraday constant, or the charge of one mole of electrons.

If *E* is the voltage of the fuel cell, then the electrical work done moving this charge round the circuit is:

$$Electrical\ work\ done = charge \times voltage = -2FE$$

If the system is reversible (or has no losses), then the electrical work that is done will be equal to the Gibbs free energy released $\Delta\bar{g}_f$(molar Gibbs free energy). So:

$$\Delta\bar{g}_f = -2F \cdot E$$

Therefore:

$$E = -\frac{\Delta \bar{g}_f}{2F}$$

This fundamental equation gives the electromotive force (EMF) or reversible open circuit voltage of the hydrogen fuel cell (Larminie and Dicks 2003).

To account for reactant and product activity, a Nernst equation is used, which also includes pressure effects on reversible cell voltage, but does not involve temperature effects:

$$E = E^0 - \frac{RT}{2F}\ln\frac{\prod a_{products}^{\nu_i}}{\prod a_{reactants}^{\nu_i}}$$

E^0 in this equation is open circuit voltage and R is an ideal gas constant (8.314 J/mol·K). a represents the amount of products or reactants. For example, if pure oxygen is used the amount of this reactant will be 1. However, if we use air instead of pure oxygen, the amount will be 0.21, because there is 21% oxygen in the air. v is the amount of moles of products/reactants used in the process – for instance if the reaction for PEM fuel cell looks like this:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

v for H_2 would be 1, for O_2 – 0.5 and for water 1.

There is one more thing that needs to be explained in this chapter – fuel cell efficiency. The ideal efficiency is the amount of useful energy that can be obtained to the total amount of energy available. In the fuel cell that will be the amount of energy available to perform work (Gibbs free energy) to the heat of combustion of the fuel (enthalpy of the formation). Therefore the ideal, thermodynamic efficiency of the fuel cell is:

$$\varepsilon = \frac{\Delta \bar{g}}{\Delta \bar{h}}$$

At room pressure and temperature, the H_2-O_2 fuel cell has Δg = -237.3 kJ/mol and Δh = -286 kJ/mol, so the ideal efficiency of the fuel cell is 83%.

However, to calculate real efficiency one has to be aware of voltage and fuel utilization losses. Voltage efficiency of the fuel cell can be obtained from the ratio between the real operating voltage of the fuel cell V and open circuit voltage E. The fuel utilization efficiency accounts for the fuel that is not used to obtain electric power. It is the ratio of the amount of fuel used to generate current i/nF to the total amount of fuel delivered to the cell v_{fuel}.

$$\varepsilon_{real} = \left(\frac{\Delta \bar{g}}{\Delta \bar{h}}\right)\left(\frac{V}{E}\right)\left(\frac{i/nF}{v_{fuel}}\right)$$

4.5 Activation losses

Electrochemical reactions in the fuel cell occur on the surfaces and the involve transfer of electrons, therefore the rate of the reaction (generated current) is proportional to the reaction surface area. To normalize and compare systems, current density (current per area unit - j) is used, instead of just current. To increase the speed of reaction, so the rate at which reactants are converted into products, a part of the fuel cell voltage is sacrificed to lower the activation barrier. This voltage is known as the activation overvoltage η_{act}. The activation overvoltage can be calculated from this equation:

$$\eta_{act} = -\frac{RT}{\alpha 2F}\ln j_0 + \frac{RT}{\alpha 2F}\ln j$$

Where α is a transfer coefficient (always between 0 and 1, usually 0.2 – 0.5), and j_0 being exchange current density, which measures the equilibrium rate at which reactants and products are exchanged in the absence of activation overvoltage. Increasing j_0 minimizes activation overvoltage losses.

Simplified version of this equation is called Tafel equation:

$$\eta_{act} = a + b\log j$$

4.6 Ohmic losses

In fuel cells, the voltage gradient is mainly responsible for the charge transport. It represents the loss of fuel cell performance, and it is called ohmic overvoltage. It generally obeys the Ohm's law of conduction:

$$V = iR$$

R, the fuel cell's resistance, is composed of the resistance of electrodes, electrolyte, interconnections etc., however the electrolyte resistance is the most significant one. To calculate the fuel cell's resistance, we have to take into consideration the area of conductor *A*, its thickness L and conductivity σ. Therefore, the equation for *R* looks like this:

$$R = \frac{L}{\sigma A}$$

To be able to compare different size fuel cells, area-specific fuel cell resistance *ASR* is calculated, which uses the fact that resistance scales with area. This leads to the equation for fuel cell's ohmic overvoltage:

$$\eta_{ohmic} = jASR$$

One of the ways to decrease the effects of ohmic overvoltage is making the electrolytes in fuel cells as thin as possible. It is also critical to develop high-conductive electrodes and electrolyte material. In PEMFC, conductivity in Nafion is dominated by water content. A high amount of water leads to high conductivity.

4.7 Concentration losses

To effectively generate current in the fuel cell, proper supply and removal of reactants and products is necessary. Mass transport governs the distribution of these compounds. If there are problems, such as reactant depletion or clogging of products, the fuel cell's performance is affected. Limitations in mass transport, especially in electrodes, lead to generation of a limiting current density j_L, which corresponds to the situation where the reactants concentration drops to zero in the catalyst layer of the fuel cell. A drop in the amount of reactants affects the overall cell voltage and is called "concentration loss". The voltage represented by these losses can be calculated with this equation:

$$\eta_{conc} = c\left(\frac{j_L}{j_L - j}\right)$$

Where c is a constant that depends on the geometry and mass transport of the fuel cell.

Concentration losses can be minimized by the careful design of a fuel cell's flow channels in bipolar plates. Parallel or serpentine designs (Figure 4.4) are preferred, because they provide a compromise between pressure drop, which is required to drive gas through the channels, and water removal capability, which is a big issue in a PEMFC.

4.8 Simple fuel cell model

Up until now, all of the "pieces" of the equation for the real voltage have been gathered. It is now possible to construct a simple model of a fuel cell. From the information gathered in previous chapters, a j-V graph can be drawn using the equation shown below, and some typical parameters for a low-temperature PEMFC from Table 4-3:

$$V = \left(E^0 - \frac{RT}{2F}\ln\frac{\prod a_{products}^{\nu_i}}{\prod a_{reactants}^{\nu_i}}\right) - \left(-\frac{RT}{\alpha_A 2F}\ln j_{0_A} + \frac{RT}{\alpha_A 2F}\ln j\right) -$$

$$-\left(-\frac{RT}{\alpha_C 2F}\ln j_{0_C} + \frac{RT}{\alpha_C 2F}\ln j\right) - (jASR) - \left(c\ln\frac{j_L}{j_L - j}\right)$$

Table 4-3 List of typical parameters of a low-temperature PEM fuel cell.

Parameter	Typical Value	Unit
Temperature (*T*)	350	K
E^0	1.229	V
j_{0A}	0.10	A/cm^2
j_{0C}	10^{-4}	A/cm^2
α_A	0.5	-
α_C	0.3	-
ASR	0.01	Ω·cm^2
j_{leak}	10^{-2}	A/cm^2
j_L	2	A/cm^2
c	0.10	V

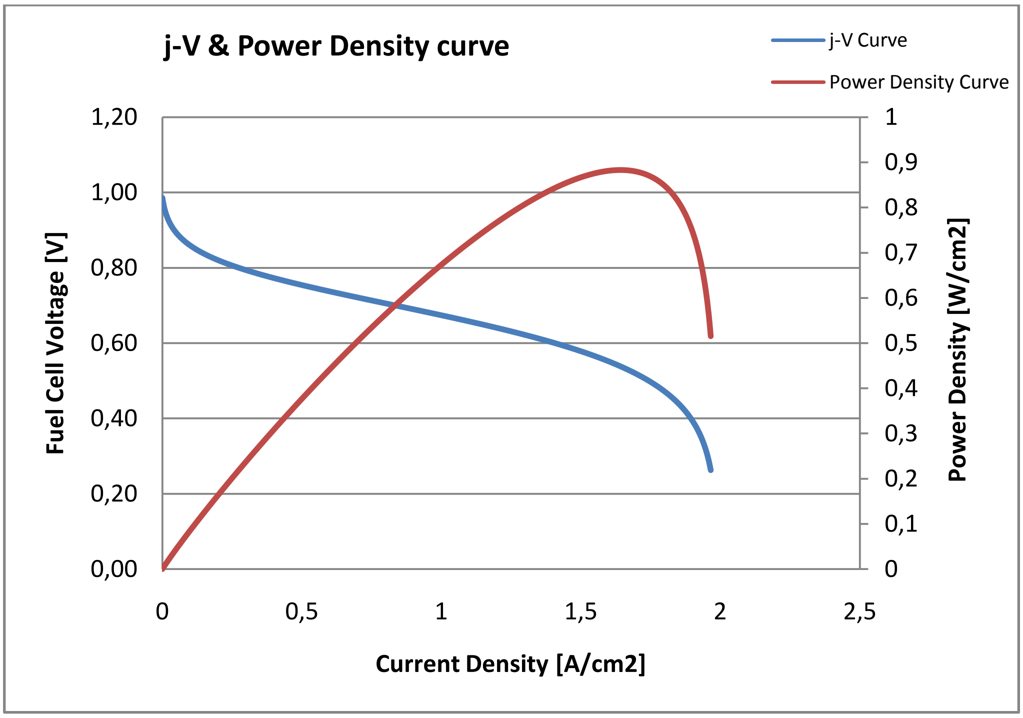

Figure 4.6 j-V and Power Density curve constructed using data from Table 4-3

As it can be seen on the graph, three voltage loss areas are clearly recognizable. The steep slope at the beginning is the loss caused by the activation overvoltage. Ohmic losses are represented by the semi-straight line in the middle, and concentration losses can be distinguished at the end.

Of course the model presented here is very simplified and it can be different than the real results obtained from the fuel cell with the same parameters, but it can also give a good overview and understanding on the rules of a fuel cell's operation.

5 PLUG POWER GENCORE 5B48 AND ELECTRICAL SYSTEM DESCRIPTION

5.1 Introduction

In this chapter the system will be described. It will include system parameters and present all the components that are part of the backup power system as well as the equipment which was necessary to run it, such as the Chemical Storage Module and custom DC Bus.

The fuel cell system that was used in the project was a Plug Power GenCore 5B48 backup-power system. It is a direct hydrogen fueled PEM fuel cell system, designed to provide backup-power to Telecommunication Cable Broadband and UPS applications (Plug Power 2004).

5.2 Keflavik Airport Project

This particular unit, together with a Chemical Energy Storage Module (CESM), was used as a demonstration project in Keflavik in 2006. It was placed at the Keflavik International Airport and provided power for lights and reflectors which illuminated a board with information about hydrogen and fuel cells. Because GenCore 5B48 provides power at +48V DC, it was necessary to install additional equipment to simulate a DC bus. It included a power supply, a 100 amp contactor and electronic timer with a set of relays. It was also needed to adjust the height of the storage module, as the European standard hydrogen bottles could not fit in an American design case. Plug Power was able to provide adapters that allowed connection of the European style valve fittings to the existing hydrogen manifold. After the installation an acceptance test had to be performed. During the test, it occurred that there is a problem with the operating software. It had to be changed to properly initiate the internal heater after each run cycle.

During the test cycles, which were performed twice a day, a timer simulated a bus failure by disabling the output from the power supply. It also closed the load relay, which allowed current to flow to the lights and turn them on. Once the backup system detected a drop in the voltage, the fuel cell started and ran the load for the specific time.

Throughout the 12 month demonstration, the backup system achieved a reliability of 96.8% and an availability of 79.9%. There were several hardware issues concerning power supply and control relay, probably due to hard weather conditions. The cell stack was replaced with an improved version and an upgrade to the CESM ventilation system was made (LOGANEnergy 2007).

5.3 System parameters

GenCore 5B48 Hydrogen Fuel Cell Backup Power System is designed to work with +48V DC bus voltage. It can produce up to 5kW of power at 48V. It uses dry, 99.95% gaseous hydrogen as a fuel, which has to be supplied to the system at pressure of 5.5 bars. It can operate from -40°C to 46°C. It produces a maximum 2 liters of water per hour and emits less than 1ppm of CO, CO_2, NO_x and SO_x. It can communicate with a personal computer or laptop through a RS-232C serial cable or optional modem connection.

Table 5-1 Summary of system's parameters

Attribute	**Specification**
Power Output	0 - 5000W
Operating Voltage Range	+42V to +60V DC
Operating Current Range	0 – 109 Amps
Fuel Supply Purity	Hydrogen @ 99.95%
Fuel Supply Pressure	5.5 bars
Ambient Operating Temperature	-40°C to 46°C
Emissions – Water	2 liters / hour
Emissions - CO, CO_2, NO_x and SO_x	< 1 ppm
Communication	RS-232C or modem

Figure 5.1 Plug Power GenCore 5B48 Hydrogen Fuel Cell Backup Power System on site in Innovation Center

The system described is a complicated device with many sub-systems designed to maintain operating temperature, supply hydrogen and air at a desired pressure and temperature in desired amounts. A special control card governs the whole system and allows controlling and monitoring it from a personal computer. The power distribution module provides output and also supplies system components with necessary electricity. The battery module helps the system at start-up, when the fuel cell stack is not ready to provide the amount of power needed. There are also several safety components such as a hydrogen detector, flooding control, a sensor which detects if the enclosure is opened and solenoid valves which can immediately cut out the fuel in case of emergency.

5.4 Fuel cell stack

The fuel cell stack consists of 63 cells. Their function is to convert air and hydrogen into DC power by means of electro-chemical reactions. Each cell generates from 0.5V to 1.0V DC. Cell voltages are monitored all the time by the control system to optimize the electro-chemical processes. Four scanner cards are used to sense the voltage of particular cells. The data is then sent to the GenCore Control Card (GCC) via RS-422 communication protocol.

During electricity production, heat and water are created as by-products. Excess heat is removed from the stack by circulating coolant and dissipated through the radiator. The water drainage subsystem collects and drains all excess water, including condensation from the anode, cathode and humidifier drain. All water is directed to a drain header and removed from the system through a drain hose at the bottom of the enclosure.

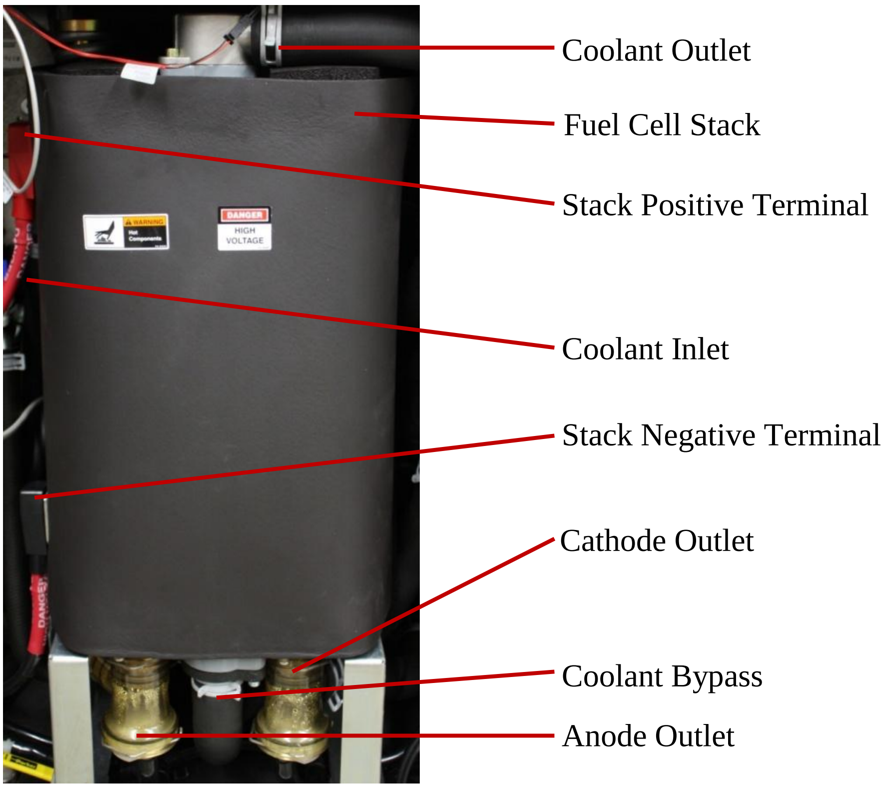

Figure 5.2 Fuel Cell Stack as seen inside the system. The black coating around it is a thermal isolation material

5.5 Balance of Plant

The Balance of Plant is the sum of all equipment for safe operation as well as the technical coordination of all concerned parts of an energy system. It consists of the remaining systems, components, and structures that are not included in the prime energy generation unit (fuel cell stack in this case).

In the fuel cell system, Balance of Plant has to do three things:

- Manage the air flow into the stack;
- Manage the hydrogen flow into the stack;
- Manage the flow of water and coolant out and into the stack. (Gearhart 2008)

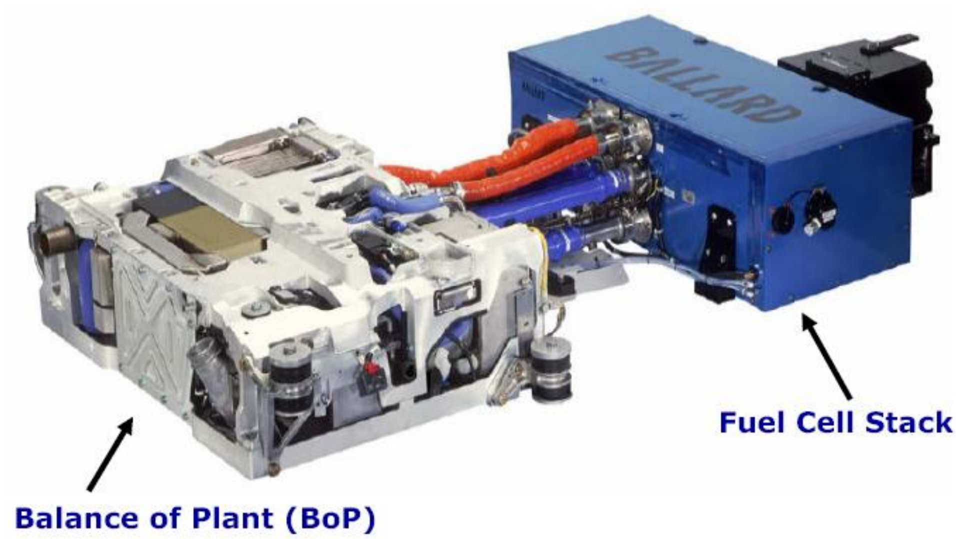

Figure 5.3 Example of Balance of Plant and a Fuel Cell Stack used in cars

5.5.1 Air delivery system

The aim of the air delivery system is to provide filtered, conditioned air to the stack's cathode side. The major components of the system are the cathode air filter, cathode air blower and humidifier.

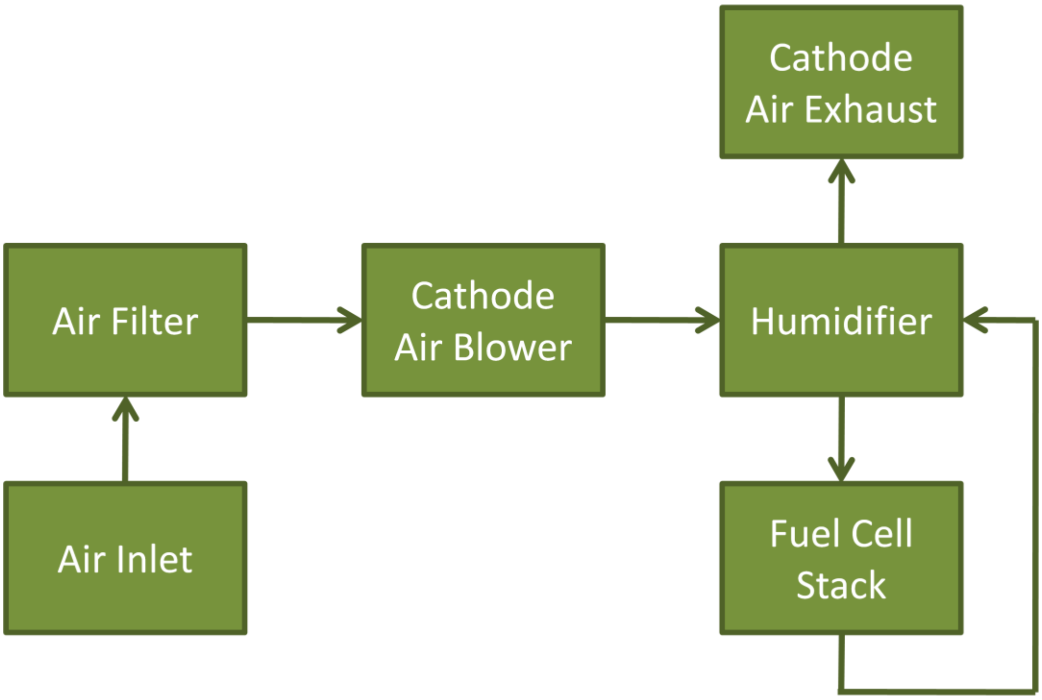

Figure 5.4 Diagram showing air circulation in the system

The cathode air filter removes particulate from the air stream using mechanical filtration. The chemical contaminants are removed by chemical absorption with the help of activated carbon media.

The cathode air blower (Figure 5.5) is a variable speed blower that controls the air flow to the stack. It has a motor managed by a separate controller, which processes the output signal from the control card, and delivers power to the cathode air blower. The speed of the blower's motor depends on the power required by the load connected to the system.

The air delivered to this system is not compressed, although that would probably increase the power of the fuel cell by reducing the activation losses. The compressor also needs some power that would have to be generated by the fuel cell stack, therefore reducing its net power output. Installing the compressor also makes the system more complicated and increases its size and weight.

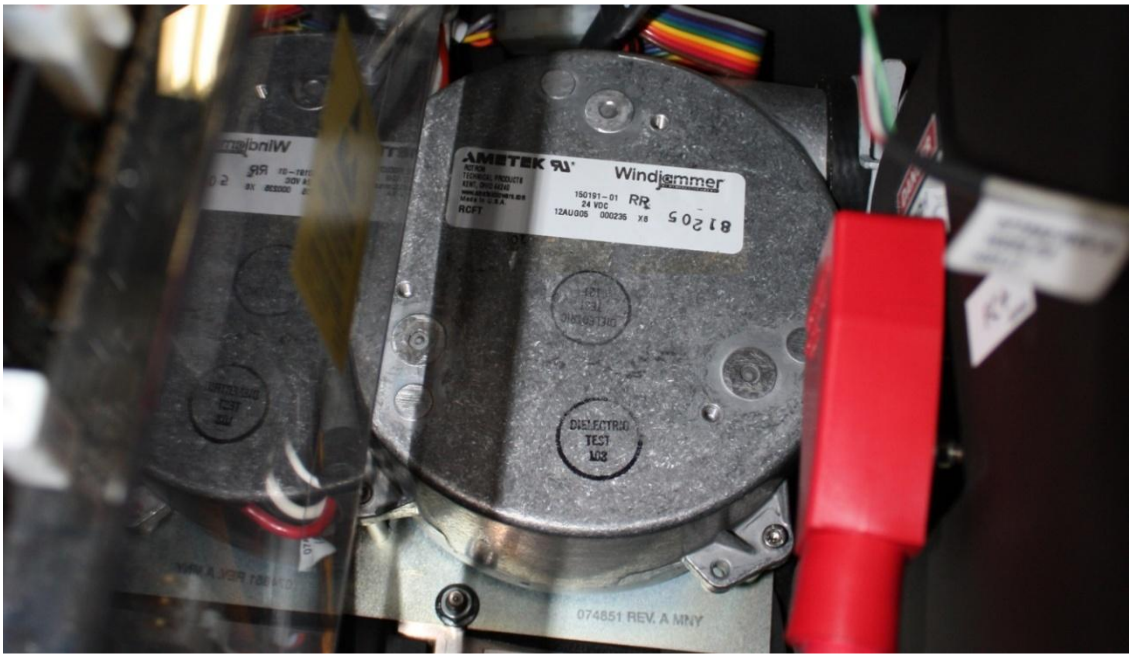

Figure 5.5 Cathode air blower

The humidifier (Figure 5.6) transfers heat and moisture from the stack exhaust air to the inlet air. It has no moving parts and uses a membrane material to exchange heat and humidity between the incoming and outgoing air streams. The humidifier is connected to four air connections: the inlet from the cathode air blower, the stack inlet and outlet, and the system exhaust. There is also a port to drain water from the bottom of the humidifier.

Figure 5.6 Air humidifier

5.5.2 Fuel delivery system

The fuel delivery system maintains the amount of hydrogen let in the system and into the fuel cell stack. The gas circulates through the stack to supply the fuel and to remove excess water and non-fuel gas. The hydrogen is admitted only if there is no E-STOP emergency alarm and the ventilation fan is working. Otherwise the inlet solenoid valves are closed and hydrogen is not delivered to the fuel cell stack.

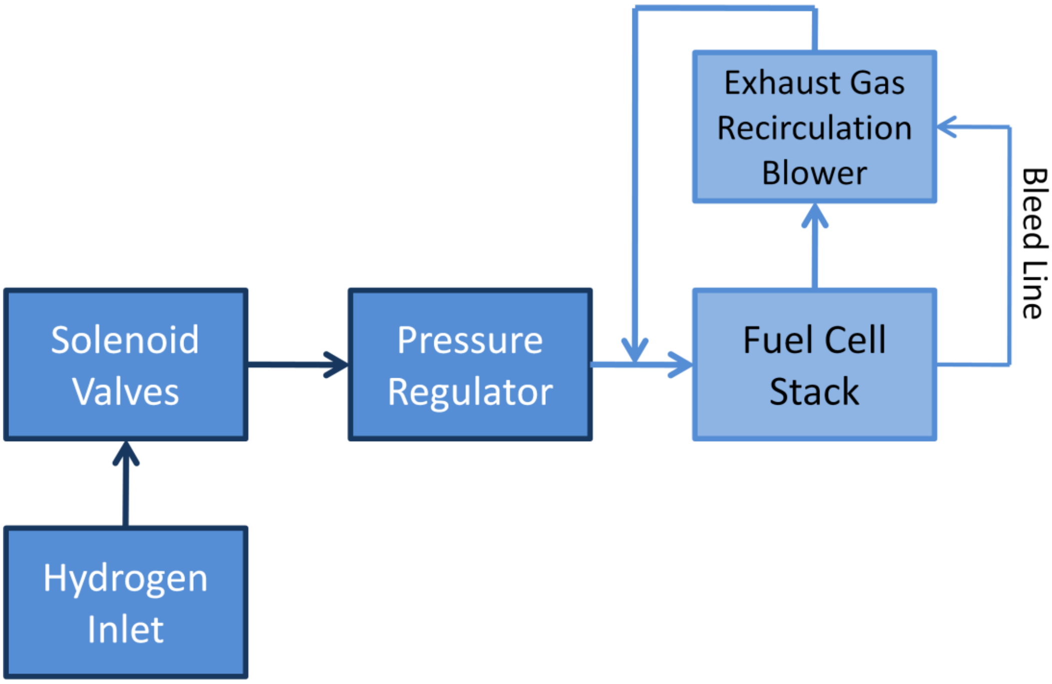

Figure 5.7 Hydrogen circulation diagram

As a part of the safety loop, two solenoid valves (Figure 5.8) are installed. When there is no emergency alarm and all systems are working fine, 24V DC is applied to the (normally closed) valves and hydrogen starts circulating in the system. The valves are connected in series to increase the protection.

Because the working pressure of the hydrogen inside the system is about 1.09 bars, a pressure regulator (Figure 5.8), in the form of a single-stage valve, is needed to reduce it from 5.5 bars.

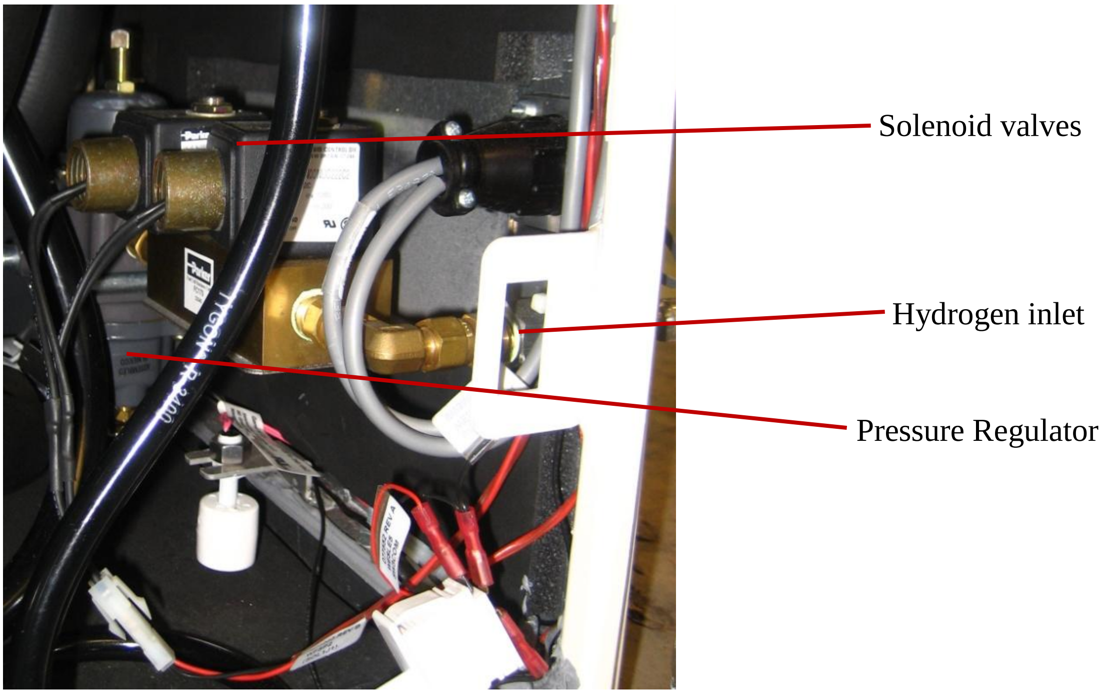

Figure 5.8 Hydrogen inlet with solenoid valves and a pressure regulator.

It is known that not all the gas takes part in electricity generation. There is always some portion that is not used. That is why a special blower, called the Exhaust Gas Recirculation (EGR) Blower, has to be used. It circulates unused hydrogen and water vapor from the anode outlet back to the anode inlet to prevent a buildup of liquid water in the stack channels. Water in this form can block the hydrogen from getting into the anode and therefore decrease the performance of the whole system.

5.5.3 Cooling system

The cooling subsystem is responsible for the management of the fuel cell's stack temperature. Because of the fact that this model of the system is designed to work mainly outside, the cooling subsystem also maintains the enclosure temperature at a level which prevents the components from freezing. The working fluid of this system is a non-conductive heat transfer fluid. It is a mix of uninhibited glycol and distilled water in proportions of 55% glycol and 45% water.

The main components of the cooling system are:

- Coolant pump;
- Coolant ion filter;
- Coolant heater and radiator assembly;
- Thermostat and temperature sensor.

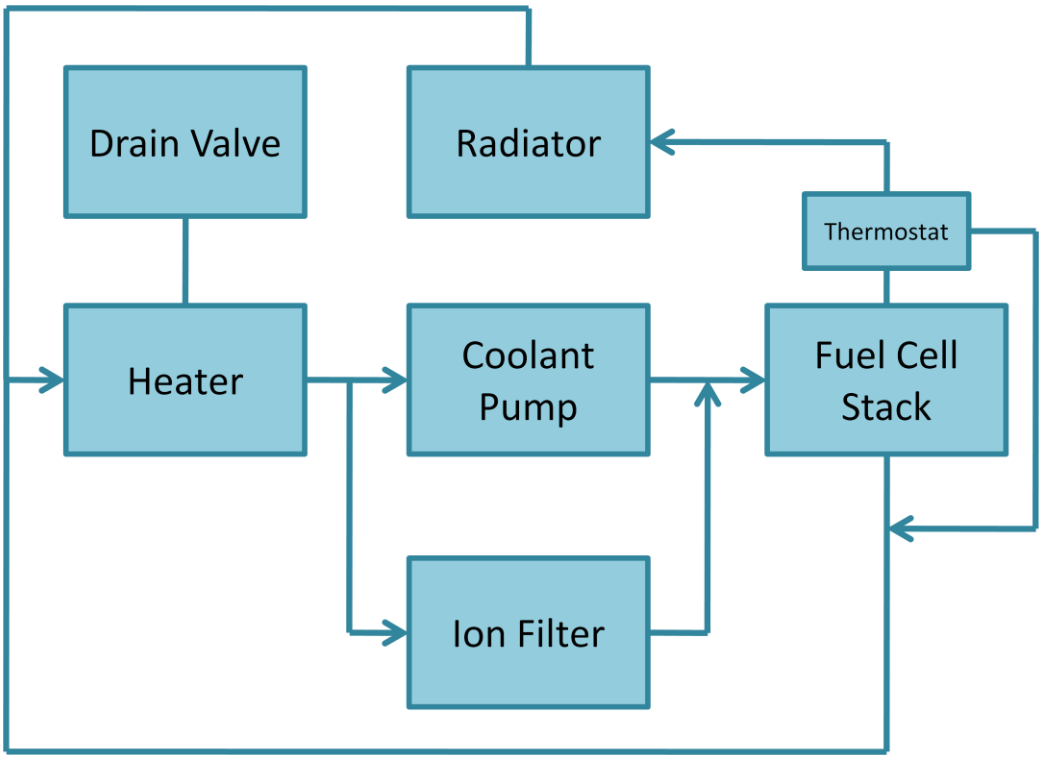

Figure 5.9 Circulation diagram of cooling liquid in the system

The coolant pump circulates cooling liquid through the stack, radiator and coolant system components. It operates when the system is operating or during standby when the internal cabinet temperature is near freezing. To reduce the rate of electrolytic and galvanic corrosion, the coolant ion filter is used to draw ions out of the coolant stream.

Figure 5.10 Coolant ion filter

The coolant heater assembly prevents the system from freezing. When the temperature inside the enclosure drops below 10°C, the 24V DC electric heater is turned on to warm the coolant, which is then used to heat the inside area with help from the liquid-to-air heat exchanger. To monitor the system temperature two sensors located on the heater housing are used. The stack coolant inlet temperature sensor provides coolant temperature for the control system and is used as the control point for the radiator fan and coolant heater. The coolant heater safety sensor sends an emergency stop signal if the coolant temperature reaches 80°C.

The thermostat is used to control the coolant flow through the radiator, which draws heat from the coolant system. When the coolant temperature reaches about 49°C, the thermostat begins to open, allowing the coolant to pass through the radiator where it begins to cool. The thermostat valve continues to open proportionally to temperature increase until it reaches 60.0°C, at which time it is fully open.

5.6 Power distribution

The power distribution sub-module consists of components responsible for providing the electricity at a specific voltage, in this case +48V DC. The fuel cell's output parameters are not very stable, which is why DC/DC converter has to be used to deliver electricity to a DC bus at a desired voltage. There is also an additional auxiliary converter, which changes voltage to 24V DC to supply the system's components with electricity. A fuel cell contactor is provided to cut the DC/DC converter from the fuel cell stack upon the request from the control card. Batteries are also used to deliver power when the fuel cell is not ready to start working.

The way in which the power is delivered to the auxiliary converter depends on the main source of current. If the fuel cell is working (there is a shortage of power to the DC bus), the stack is able to provide power to all the components through the auxiliary converter and control card (Figure 5.11).

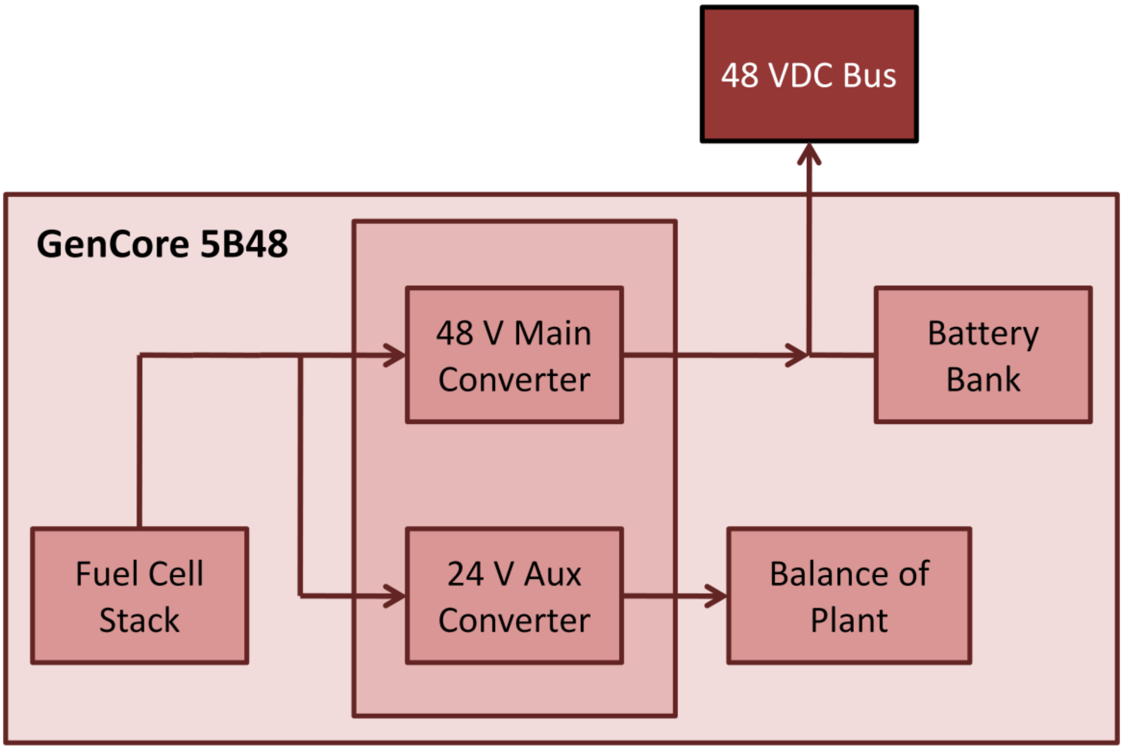

Figure 5.11 Power distribution diagram - fuel cell stack is providing power for auxiliary load.

When power from the grid is available and the DC bus is working properly, the current comes from there or batteries, through the main converter and into the auxiliary one (Figure 5.12).

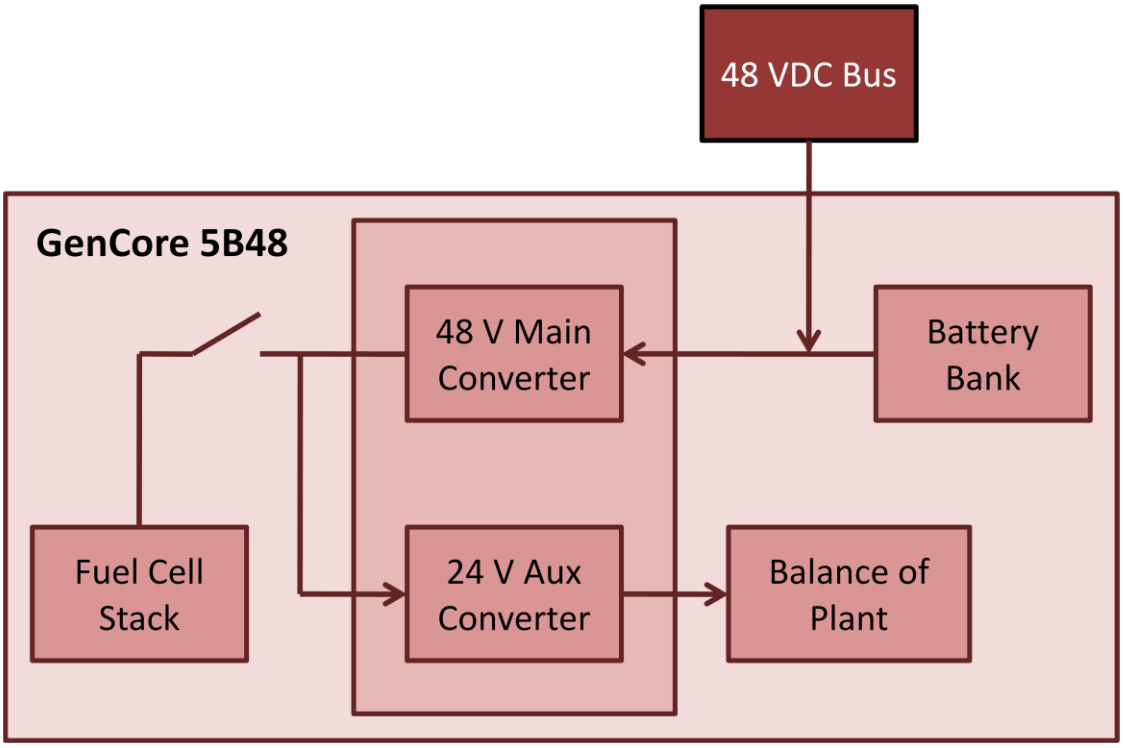

Figure 5.12 Power distribution diagram - DC bus and batteries are providing power for auxiliary load

5.6.1 DC/DC converters

As mentioned above, there are two converters in the system. The 48V DC/DC converter conditions the power output from the fuel cell to provide stable voltage to the DC bus. An auxiliary converter supplies the internal load with 24V DC power. The converter exchanges information with a control card by RS-422 communication protocol. On the front panel of the converter there are three diodes which indicate if converters are working properly and if they communicate with a control card without any problems. On the line between the fuel cell and converters there is also a contactor that connects and disconnects power from the stack as commanded by the control system. It is open when voltage from DC bus is on the expected level, and it closes upon power shortage or voltage drop. When the power is restored to the bus, the contactor opens again and separates the fuel cell from the converter.

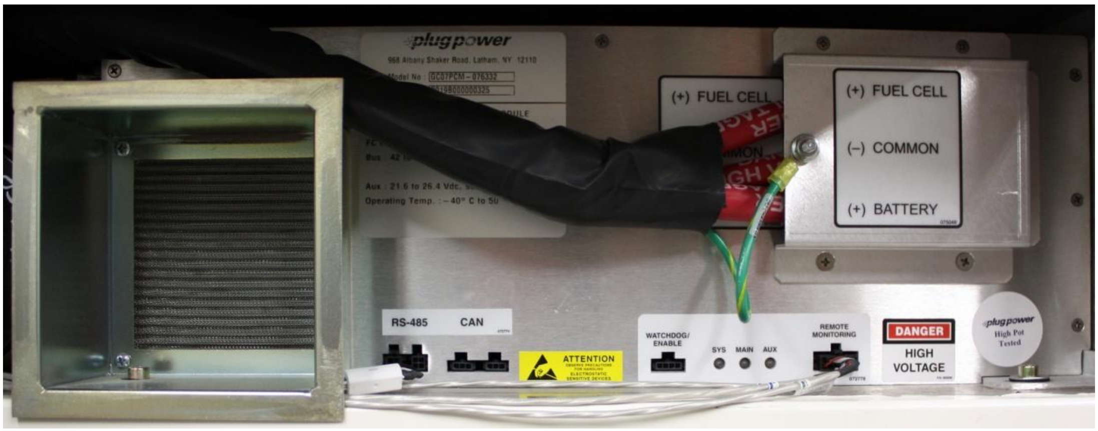

Figure 5.13 Front panel of DC/DC converter. At the bottom three diodes can be seen

5.6.2 Batteries

In GenCore 5B48 there are four 12V batteries connected in series (Figure 5.14). They provide power for a rapid transient load and help with the auxiliary power for the internal components of the system during start-up. On the top of the battery bank there is a temperature sensor, which informs the system about a possible overheating situation.

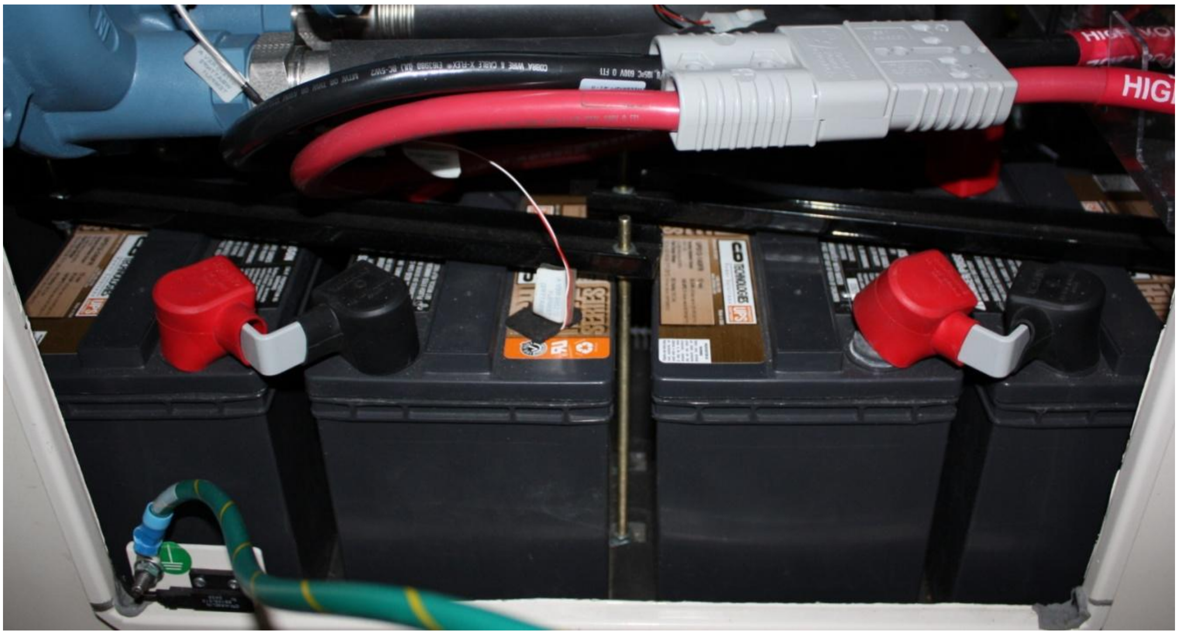

Figure 5.14 Battery bank is situated at the bottom, in the back of the enclosure

5.7 On-board safety

The safety components of the system will be described in more detail in the chapter “Hydrogen safety”; however few of them will be mentioned here.

There are numerous components and devices that are responsible for the safety of the system’s operation. In case of emergency, each one of them triggers an E-Stop signal, which immediately stops the hydrogen flow by closing the solenoid valves and turns off the system.

The Neodym hydrogen sensor monitors fuel cell stack and hydrogen connections inside the enclosure for gas leaks. The sensor suspends system operation when it detects an amount of hydrogen exceeding the 25% lower flammability level or 10,000 ppm.

The other safety device related directly to hydrogen is the inlet pressure switch. It opens, when over pressure is detected and automatically resets when pressure returns to an operating value.

There are also several temperature sensors (stack coolant sensor, enclosure temperature sensor, coolant heater sensor) which open and trigger an emergency stop when a certain temperature is exceeded, preventing the system from overheating.

To protect the system from flooding, a water intrusion sensor is installed. It turns off the fuel cell when the water level inside the enclosure exceeds 3.8 cm.

5.8 Control system

The main purpose of the control system is to manage all the processes happening in the system. It adjusts voltages to all the components, such as blowers or radiator fans, so that the power demand can be met. It also allows communication with the user through a serial cable. A special control card is the main part of this subsystem.

5.8.1 GenCore Control Card

To monitor and maintain all the components of the system, a GenCore Control Card (GCC) is used. It provides the automated control of the system, distributes power between the system's components, establishes communication between components and the user, and governs the E-Stop signals.

There are three operating modes which can be automatically or manually issued by the GCC:

- Manual mode – system can be set to manual mode by the operator through the service interface software, allowing him to manually troubleshoot components;
- System ready – the system monitors the DC Bus voltage for voltage drops and power outages;
- Running state – the systems gets into this state when hydrogen starts to flow through the stack, providing power to the DC/DC converter and the DC Bus.

Figure 5.15 GenCore Control Card

5.8.2 Service Interface Software

Service Interface Software, provided by the producer, is used to communicate, monitor, log and manually control the system from a personal computer or laptop. Communication is done through a RS-232C Serial cable or with the use of a phone line through the modem connection. It is an essential component to system operation. The software is required for system commissioning, troubleshooting, updating, and data retrieval. It is, however, not required for normal daily operation of a GenCore system.

To successfully start communication between the computer and the system, it is important that the GenCore is not connected to the service computer prior to starting it up. It is required to first boot the computer, then start the Service Interface and finally connect the GenCore to the computer.

At the startup, an animation of the processes happening in the fuel cell is shown. When the animation disappears, the computer has established the connection and the software is ready to exchange information with the system.

The main screen should appear, which looks like the one on Figure 5.16:

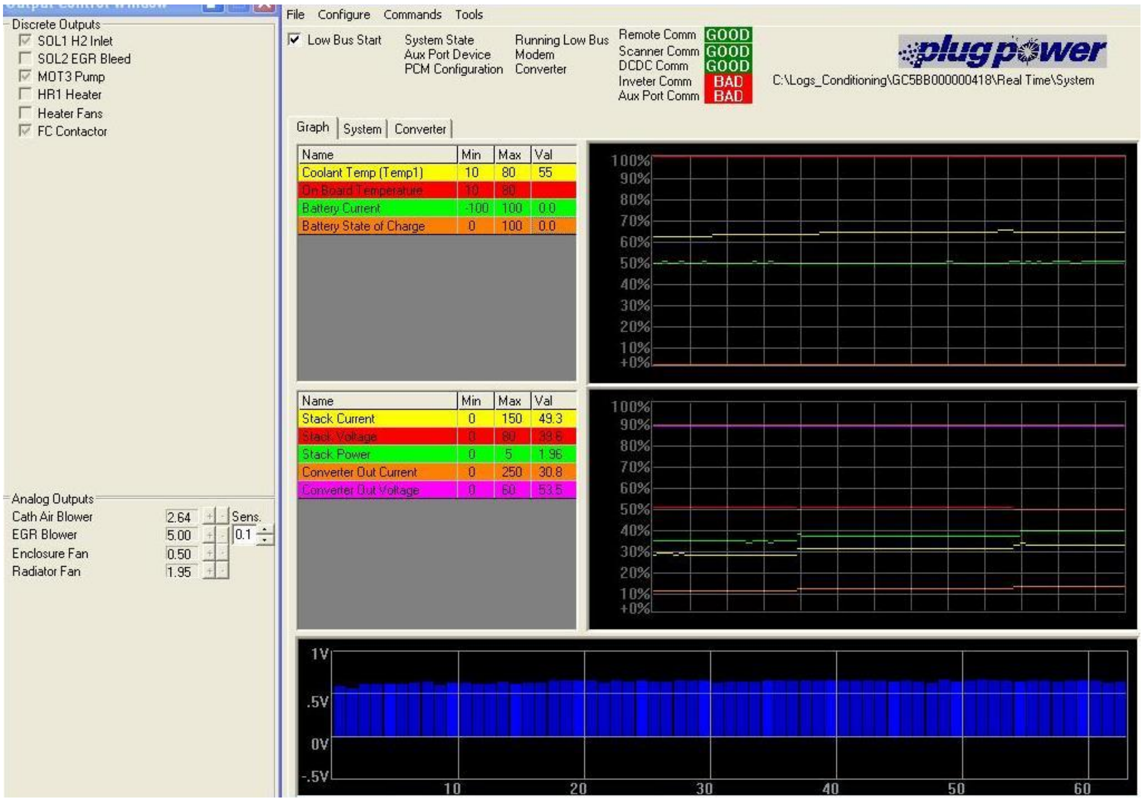

Figure 5.16 Main screen of the Service Interface Software

From the menu bar the operator can configure the system parameters. The important ones are:

- DC Bus set points, which determine when the fuel cell system should start operating, at what voltage and what should be the delay;
- Number and type of hydrogen storage tanks, which is used to properly calculate remaining fuel;
- Configuration of logging – the place where the log file will be stored, the frequency of the logging;

It is also possible to start and stop the system manually, initiate the conditioning cycle, which is usually performed when the system was not working for a longer period of time, and install or upgrade new firmware.

On the left panel, the operator can observe which components of balance of plant are currently working (*Discrete Outputs*) and what voltage they are receiving (*Analog Outputs*) at the moment. In the manual mode, it is also possible to turn these components on and off, and also adjust the voltage to regulate their speed.

On the right (main) panel, the operator can observe the outputs from the system. It is possible to see the current state of the system and check its overall status. In the running condition, *Remote Comm*, *Scanner Comm* and *DCDC Comm* indicators should point at GOOD. Below, there are also three tabs – *Graph*, (shown on Figure 5.16), *System* and *Converter*, which show the parameters and values of all the components in the system in real time.

The *Graph* tab is used to observe the parameters in real time plotted on two graphs. The x-axis is time and the y-axis is percentage of a value – the lowest is 0%, the highest is 100%. The user can choose what values or parameters should be plotted on each graph. Below the main two graphs, there is also a diagram showing voltage on every cell in the fuel cell stack. The voltages should be fairly similar to each other.

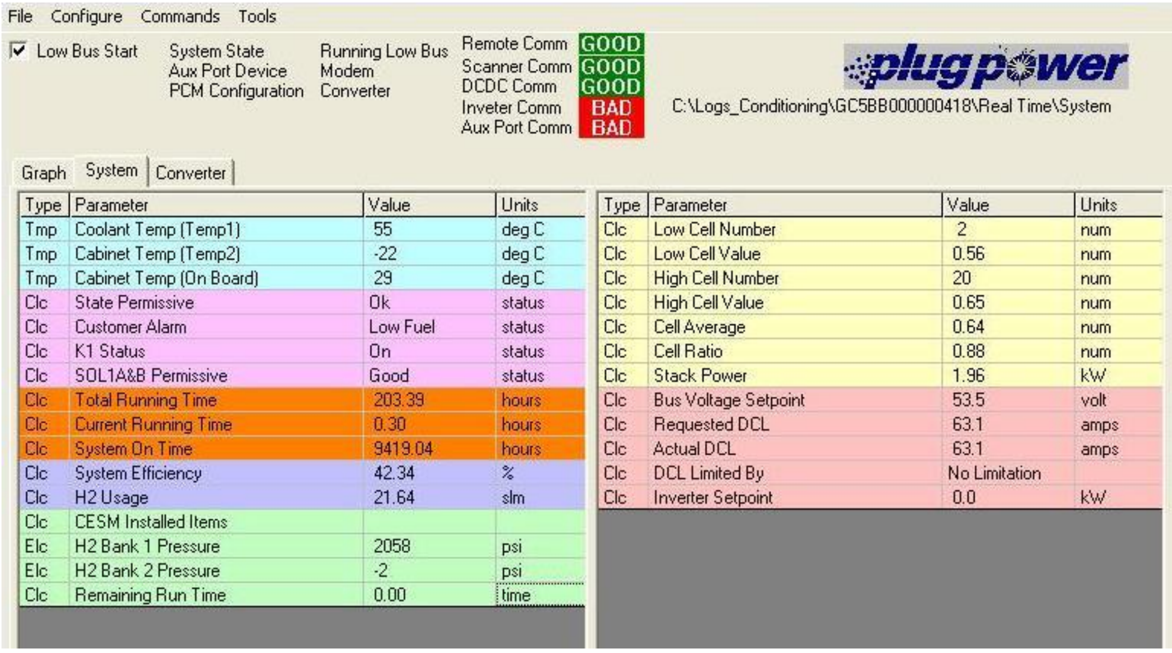

Figure 5.17 System tab view

In the *System* tab (Figure 5.17), the operator can observe parameters from the crucial components of the GenCore system. Coolant and cabinet temperature can be seen on the blue fields. The status of the alarms, contactor and solenoid valves are in pink. Statistics about the running time of the system are in orange, and system efficiency and hydrogen usage are in dark blue. On the green fields information about the chemical energy storage module can be seen. On the other side of the array, the operator can monitor the cell's voltage and DC bus parameters.

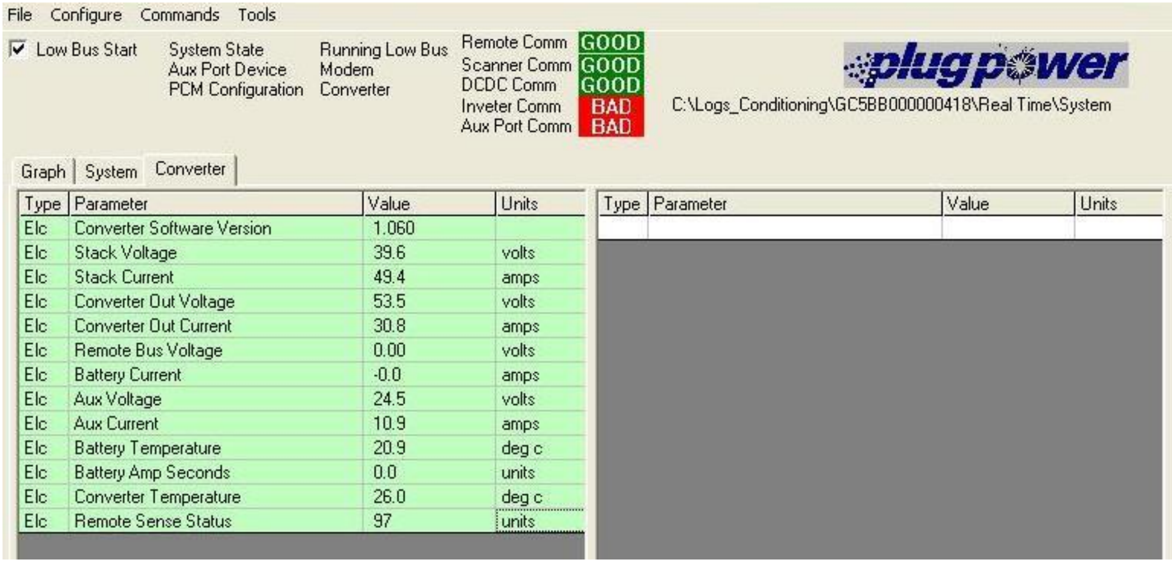

Figure 5.18 Converter tab view

In the *Converter* tab (Figure 5.18), one can find voltages, amps and temperatures related to the fuel cell stack and power distribution module.

5.9 Chemical Energy Storage Module

The Chemical Energy Storage Module (CESM) is the metal case with all necessary safety valves and pressure regulators, which stores hydrogen bottles. The case can store up to six 50 liter bottles with pressurized hydrogen. The bottles can be placed in two rows, 3 bottles each.

Figure 5.19 Chemical Energy Storage Module

For the safety of the working environment, the metal case is isolated with fireproof material, protecting the surroundings in case of fire. There are signs printed on the enclosure, warning that hydrogen under pressure is stored there and it is forbidden to smoke or use fire in close proximity to the module. There is also a main fuel valve, which can instantly block the backup system from receiving the fuel. The safety features of the storage module are described more thoroughly in the chapter “Hydrogen safety”.

CESM is designed to work with hydrogen under pressure of 3000 psi (about 200 bars). At the same time only one bank of 3 bottles is in use. This makes it easier to exchange empty containers with full ones, without any interruption in the operation of the system.

In the standard equipment there are two pressure regulators. The operator has to take into consideration that working units are psi in this case, so it is necessary to recalculate values to bars. One regulator is used to switch sides and measure the pressure in the bottles. It automatically switches to the other hydrogen bank if pressure drops below 100 bars. It is considered that under this pressure the bottles are empty.

The other regulator decreases the working pressure to 5.5 bars, which is the one used to deliver hydrogen to the fuel cell backup power system. The gas gets to the system through the stainless steel hose.

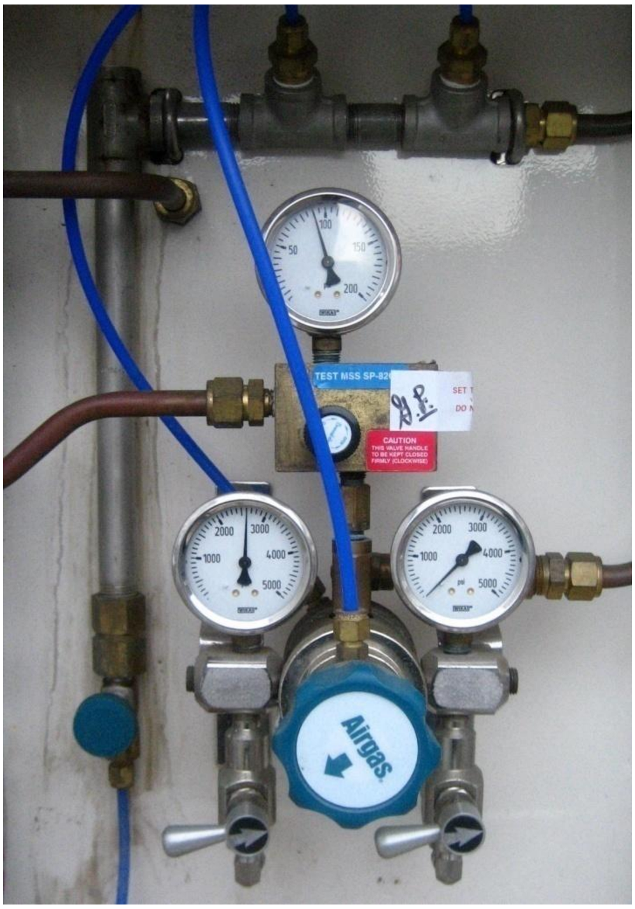

Figure 5.20 Pressure regulators

On each end of the hydrogen bank there is also a pressure sensor, which delivers information about the amount of hydrogen in the bottles to the GenCore Control Card via a special isolated cable. The information is used to monitor the pressure in the storage module and, in case of the danger of hydrogen depletion, to set the Low Fuel Alarm, which can be seen in Service Interface Software.

5.10 Custom DC bus

The GenCore 5B48 Hydrogen Backup Power Fuel Cell System is designed to work with 48V direct current. Because of the lack of this kind of voltage in Innovation Center, a custom DC bus, which was made for the Keflavik Airport Project, was used.

Figure 5.21 Custom DC Bus on site in Innovation Center

The main part of this system is a 48V DC, 600 W power supply, which converts AC power from the grid into a direct current. The diode needs to be placed after the power supply to block the current from getting into the power supply from the side of the fuel cell system. Two fuses are also applied and protect the power supply in case of overvoltage.

There are also two power relays, but in this case one is not connected at all, and the other one is always closed. They were probably used in Keflavik, but it was found that they are not needed in this project.

The DC bus is also equipped with a site disconnect switch, breaker box and a reflector light. The disconnect switch (Figure 5.22) is used to manually disconnect backup system from the DC bus.

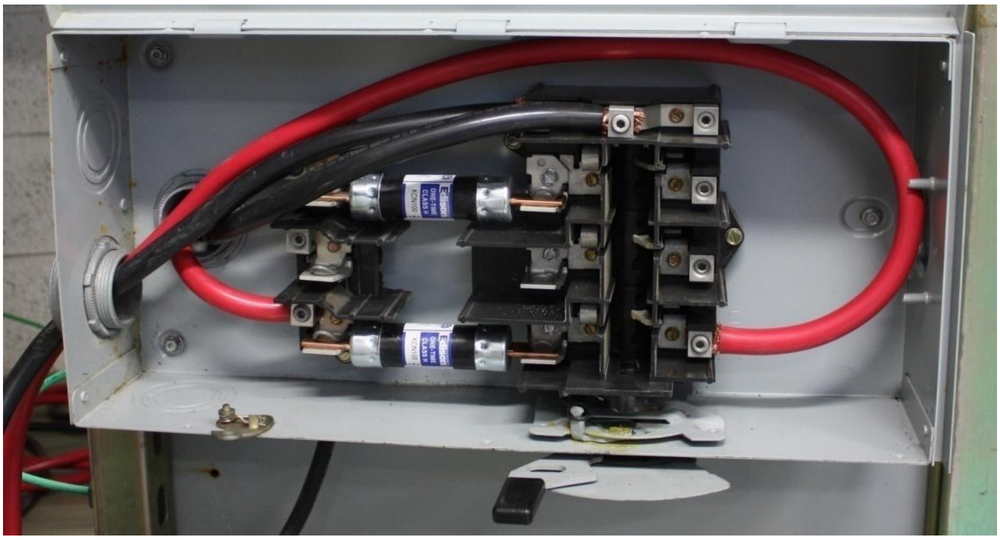

Figure 5.22 Site disconnect switch

The breaker box is a safety element which protects the DC Bus from any anomalies that might happen on the side of the load. It contains fuses, which will automatically cut the power, if any overvoltage or excessive current occur. The user can also turn off and on all the load devices from there. The reflector light was used in the Keflavik Project to illuminate the board containing information about hydrogen, but it was kept to provide additional load during the tests. This light contains 7 light bulbs and draws power of 900W.

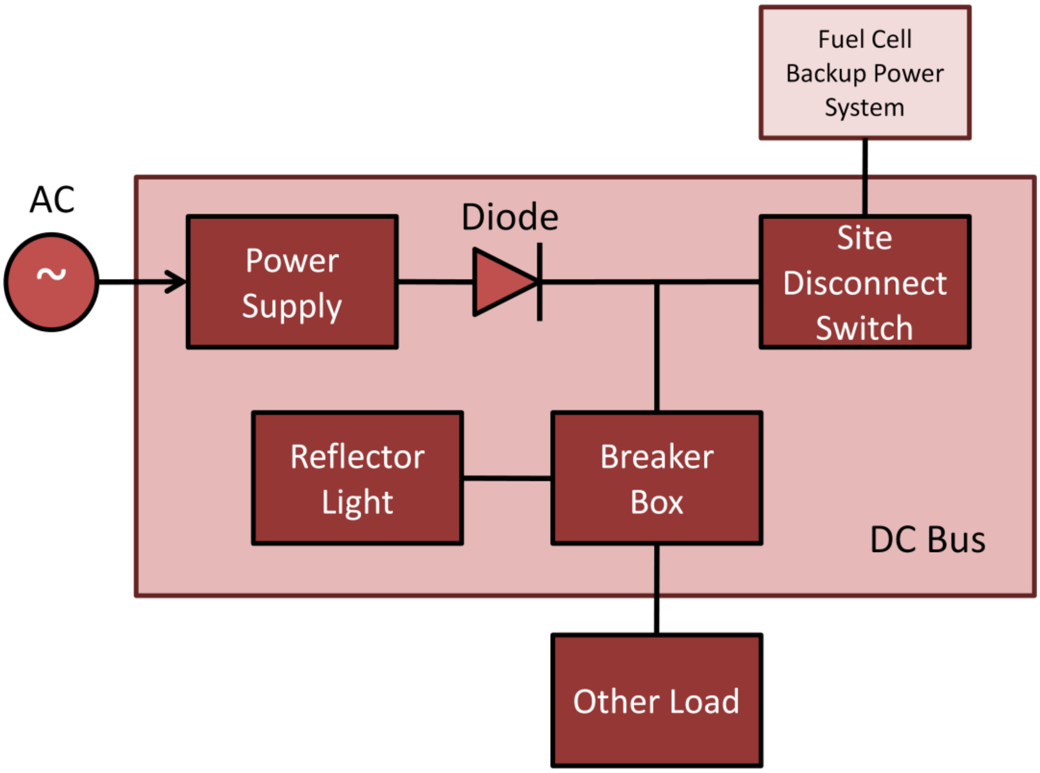

Figure 5.23 Diagram of DC Bus

6 INSTALLATION AND OPERATION OF THE SYSTEM

This chapter focuses on the process of installation and operation of the system. It describes the way the location of the system components was chosen and how the hydrogen infrastructure and electrical connections were made. The last part of the chapter shows the principles of operation of the system.

6.1 Location of the backup system, storage module and DC Bus

The appropriate location of the system is a very important step in a project of this kind. On one hand, the backup system should be easily accessible from all sides and the future testing and presentation location should be close by. But on the other hand, it has to be properly ventilated and free from open flames.

For this project two locations were considered. One was a room with other equipment currently serving mainly as a demonstration for guests and visiting students, therefore it seemed a proper place for the fuel cell system. However, there was not enough space for the system to be accessible from all sides because there was a lot of other devices and machines. Also, the room was not properly ventilated – it was far from the possible location of the hydrogen bottle, and there was a fuse box very close to the system, which, in case of spark, could be dangerous.

The second location proved to be more appropriate. It was a machine shop, with a lot of free space and it was easy to properly ventilate the room, by making a ventilation shaft in the ceiling. It was also closer to the hydrogen storage, and the demonstration and testing site was set up just on the other side of the wall, near the fuel cell. The wall was a natural barrier and protection from sparks that the DC bus could cause.

The fuel cell system presented here is a heavy device – its weight is about 213 kg. To make it easier to move, it was standing on a pallet. When a permanent place for the machine was found, the pallet was removed. To allow water generated at the fuel cell to freely leave the system, three stands were made. This way the system itself was standing about 20 cm above the floor, which made it possible to put the bowl under it and allow water to accumulate there.

Figure 6.1 The backup system standing in the machine shop in Innovation Center

A decision had to be made as to where the hydrogen bottle should be kept. This combustible gas could not be stored inside, so locations outside the main building of Innovation Center were considered.

At the beginning of the project, the location of the Chemical Energy Storage Module used in Keflavik Airport was unknown. Having only a hydrogen bottle would require the construction of a metal case to protect it from the rain, wind and snow. The only possible place to store the bottle, without making any special cover for it, was the area inside the storage shop, which was already used to keep different gas bottles. It was placed just outside the Innovation Center building, where machine shop was. It would, however require making a pipeline about 2 meters above the narrow road, which was sometimes used by cars. That could create a dangerous situation if a truck or higher car accidentally hit the pipe, causing a leak of hydrogen. It would also involve difficulties in the construction of the hydrogen transmission line. The pipe should somehow be fixed so it can resist strong wind, which often occurs in the region.

Luckily the Storage Module was found and brought to the Innovation Center. The chosen location, just outside the machine shop, was considerably safer. The pipes did not have to be laid in dangerous areas, and the required length of transmission line decreased significantly.

Figure 6.2 Chemical Energy Storage Module on site in Innovation Center. The entrance to the machine shop is also shown

The DC Bus was located in a small room, next to the machine shop where the fuel cell system was standing. The room had some tables, which were later used for testing and presentation. The operator could also monitor the system from there using a personal computer, which was standing on one of the tables.

6.2 Changes in storage module

The Chemical Energy Storage Module was obtained from Icelandic Hydrogen. The height of the metal case was extended in 2006 during preparation for the Keflavik Airport Project. The system was designed to work in the United States with slightly shorter bottles. The storage module had to be rebuilt by adding metal plates in the bottom to increase its height to meet the European standards.

Normally two banks, three bottles each, are used to provide fuel to the system (Figure 6.3). Having only one hydrogen bottle required making some changes inside the storage module. One bank was completely disassembled and closed with a pressure sensor, to limit the places where a hydrogen leak could occur. The other one was limited to supplying only one hydrogen inlet and a pressure sensor.

Figure 6.3 Two banks for six hydrogen bottles in the storage module (Top), and interior after the corrections (Bottom) to use with only one hydrogen bottle and limit the places of possible leak

6.3 Construction of the hydrogen transmission line

Because the storage module was placed outside the building, approximately 6.5 meters from the backup system, the conduit provided by Plug Power could not be used due to its length, about 45 cm.

Four sections, 15.5 meters in total, of stainless steel pipes were used to deliver hydrogen from the storage module to the system. The pipes were 6 mm in diameter, 1 mm of which is the metal coating. It was necessary to bend them in few places to avoid obstacles. The hydrogen conduits were connected to each other using a special stainless steel coupler. The assembly of the connector can be seen on Figure 6.4:

Figure 6.4 Hydrogen pipe connector

The rings visible on the left side of Figure 6.4 seal the connection, preventing gas leaks. The proper assembly can be seen on the right side of the figure. The pressure caused by gas flowing through the connector caused the rings to tighten, preventing hydrogen from leaking.

Some adjustments had to be made due to different standards of pipes. European fittings did not match the American outlet from the storage module and inlet in the fuel cell system. Special adapters were made by Jón Hansson from Framtak company, which had a European-style connector on one side and American one on the other.

6.4 Electrical system, DC bus and load design

For the same reason as the transmission line, the connection between pressure sensors in the CESM and backup system had to be redone. A 15.5 meter Ethernet cable was bought and adapted to use with the sensors. The original plugs were used, and the particular lines were soldered to lines in the Ethernet cable.

Two holes in the wall between the fuel cell backup system and DC Bus were drilled to lay the electrical cables connecting these two devices. The DC Bus was connected to the fuel cell through the site disconnect switch.

An additional three cables were used in the DC Bus. One served as a grounding cable, which was connected to the grounding point through an AC grid's socket. The second one was used to provide the power supply with AC electricity from the Innovation Center's electrical network. The last one supplied the load with a 48V DC power.

To provide the simulated bus with a load, eight 24V DC, 60W lights were used. They were connected in the series of two lamps to utilize the 48V voltage. In addition to that, during the tests, a reflector light attached to the DC Bus and two spot lights obtained from Keilir Center of Excellence were used.

It was also necessary to install a power converter, which changed 230V AC from the grid into 110V AC, which was used to power the hydrogen detector.

At the end of the project, a demonstration board was made with two switches, six lights and a block diagram of the system. The switches were used to cut the power from the grid, which simulated a power shortage to the DC Bus, and to turn the load on and off.

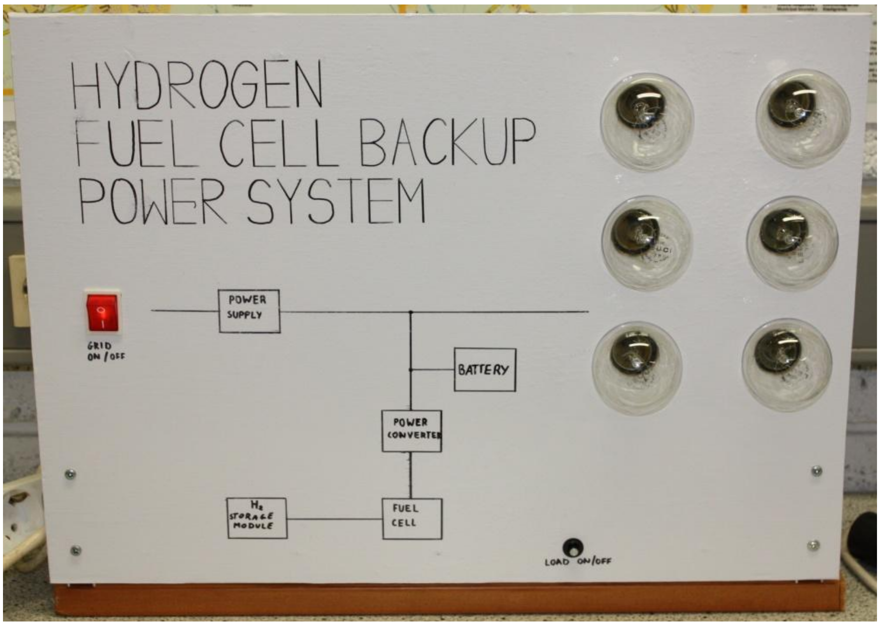

Figure 6.5 Presentation board

6.5 System operation

The first run requires several things to be tested before the backup power system can start operating. First of all the hydrogen bottle has to be connected to the system. In this case, a Chemical Energy Storage Module supplied by Plug Power was used, but any other storage container can be utilized as long as it meets system requirements. Hydrogen was stored outside the building in an easily accessible, but fire-free, place. The bottle contained 99.95% pure hydrogen gas, pressurized to 200 bars. The pressure regulator, which was already included in the storage module, is required to decrease the pressure from 200 bars to 5.5 bars. Gas valves were opened, allowing the gas to flow to the hydrogen inlet in the backup power system. Pipe connections were checked for leaks with a special combustible gas detector capable of detecting hydrogen. The system was placed inside the building, thus proper ventilation was needed. The ventilation shaft was installed in the rooftop, and a hydrogen detector was placed next to it. To be sure that there is only hydrogen in the fuel line, a bleed procedure was performed. The bleed procedure required loosening the screw near the inlet to the system. When the gas detector put next to the bleeding place sensed the hydrogen, the screw needed to be tightened again.

All the electrical connections to the site DC bus have been made. The DC Bus was turned on and was ready for operation and the site disconnect switch was turned off. To turn on the system into a standby mode, it was required to insert the internal battery connector into the mating connector located in the rear compartment and complete the connection with the DC Bus, by closing the disconnect switch. Two lights on the front side of DC/DC converter became green (*MAIN* and *AUX*) and the *SYS* light blinked green every 30 seconds. Having all the lights on DC/DC in the condition described above, and lights on the control card lit green meant, that the system was ready for operation.

Because the software installed on the operating computer was newer than the firmware installed on the system's control card, it was decided to flash the memory of the GenCore Control Card with an updated program. Unfortunately, the attempt to do it failed and, for unknown reasons, the system became unavailable. The SYS light was blinking red, which indicated, that there could be a problem with control card. The efforts to initiate connection with the computer were unsuccessful, and the threat that the card may have to be replaced occurred. However, on the third day of the crisis, after changing a connection cable, and using a different method of flashing the firmware, the connection was established. It was decided that the older software will be used. It had the same potential as the newer one, only the interface was less user friendly.

To make sure that fuel cell will turn on at the correct moment, when there is a power grid failure to the DC Bus, Low Bus Start was enabled in the Service Interface Software and the set point was set according to the nominal DC Bus voltage, which was 53V in this case. The other value that had been set was the start voltage at which the fuel cell system will start operating, which was set to 51V.

The system operates in different states according to the conditions and status of the DC bus. All the states were tested, including ESTOP, which is triggered when there is any malfunction in the hardware or if the safety loop is interrupted. The system's state changing algorithm is shown in the figure below:

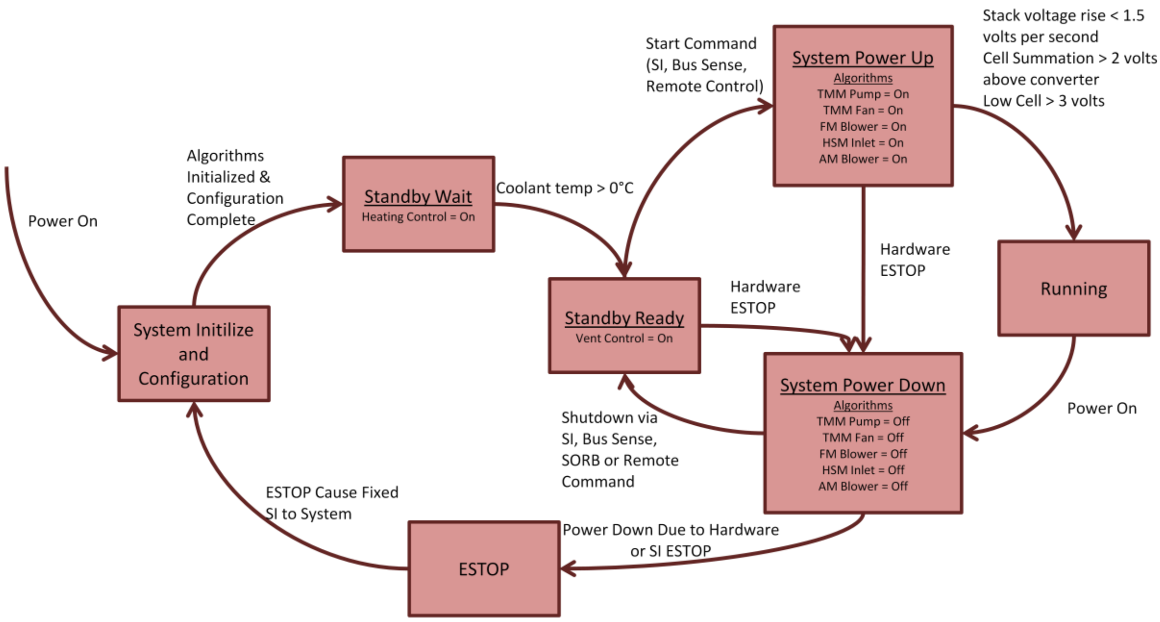

Figure 6.6 GenCore system state change algorithm (Plug Power 2005)

When running the system for the first time after long period of non-operation, it is required to perform a conditioning cycle. The intent of this step is to run the system to ensure proper membrane hydration and raise the coolant to operating temperature (50°C). This requires approximately 55-60 amps of current through the fuel cell stack for approximately 15 minutes. During this cycle the interior of the cabinet was checked for any hydrogen or coolant leaks. After the conditioning cycle was completed the system was ready for tests and operation.

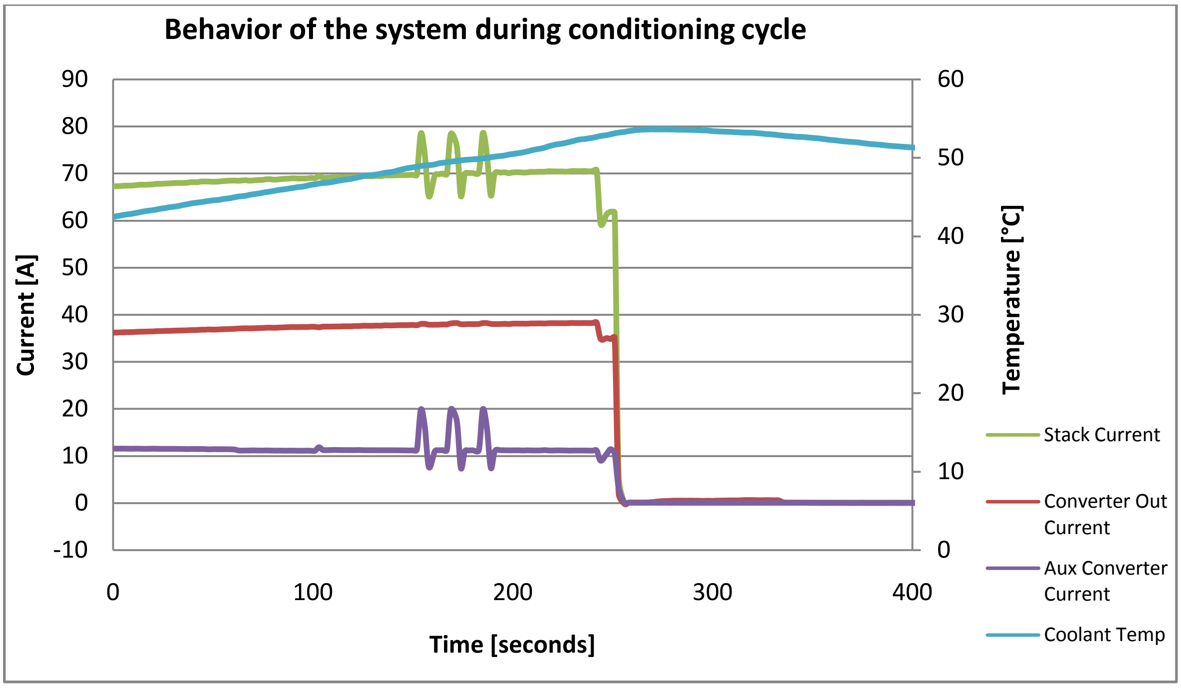

Figure 6.7 Behavior of the system during conditioning cycle

The typical behavior of the system during the power shortage to the DC bus looks as follows. When the power grid failure occurs, the control card of the system detects the voltage drop in the DC bus and will close the fuel cell contactor automatically, allowing the fuel cell to start providing power. However, it takes some time for the stack to start working, which is why during the first 10 seconds all the load is covered by batteries. After a couple of seconds, when the ventilation fan starts working and the solenoid valves open, allowing hydrogen to flow through the system, the fuel cell stack will start generating electricity. The processes can be seen in Figure 6.8.

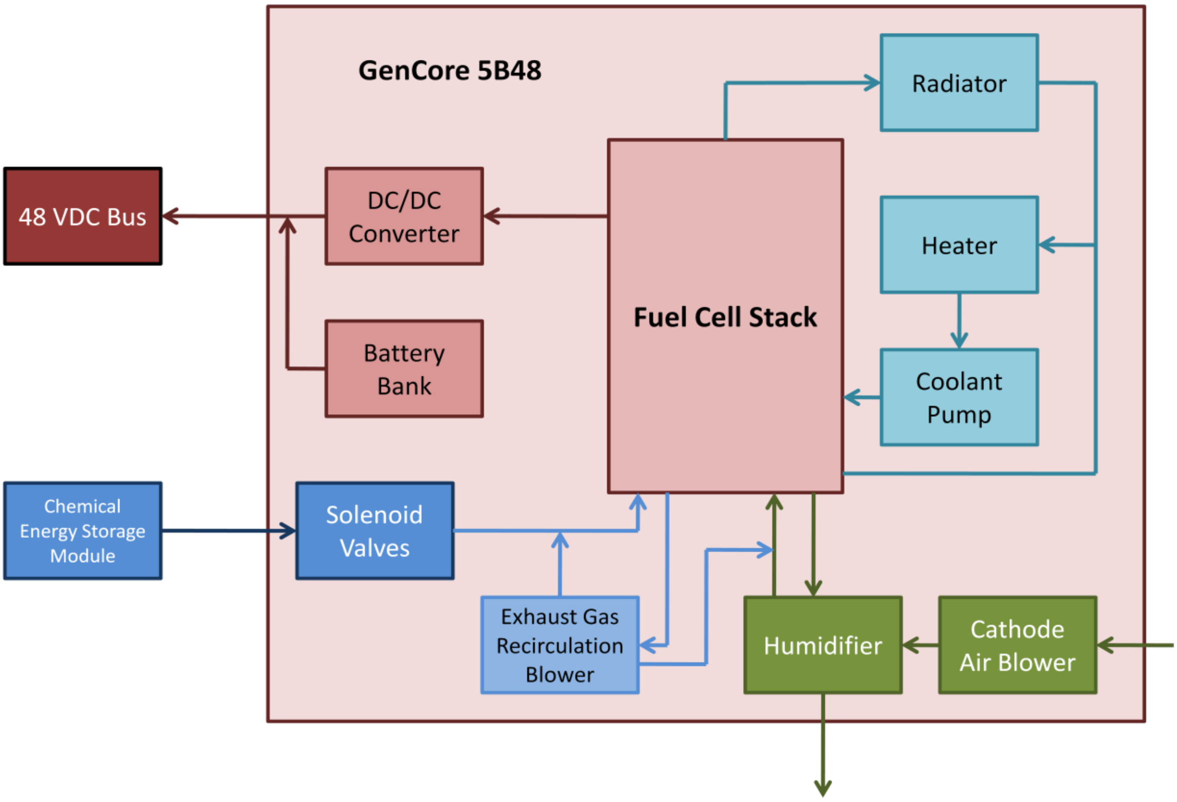

Figure 6.8 Flow diagram of the GenCore 5B48 Backup Power System

Hydrogen (blue color in Figure 6.8) gets to the system through the gas inlet. Then it goes pass the solenoid valves which, in case of emergency, can stop the further flow of hydrogen into the system. Unused fuel is circulated by the exhaust gas recirculation blower and a small part goes to the cathode side to help remove water from the cathode. There is always some hydrogen getting out of the system through the cathode air exhaust, but it is an insignificant quantity.

Air (green) gets to the cathode side with the help of the cathode air blower. The speed of the blower depends on the power demand from the load. The higher the current that needs to be supplied, the faster the blower works. The air that gets out of the stack has some moisture, which helps to humidify and warm the air that gets into the stack. This process happens in the humidifier, just before the air can reach the cathode.

The coolant pump causes the circulation of the coolant (light blue) through the stack, radiator and heater. The radiator is used to draw the heat from the cooling system when the coolant temperature reaches about 50°C. The heater, on the other hand, helps to warm the stack when the cabinet temperature is lower than 10°C, and prevents the system components from freezing.

When the system detects a drop in the voltage, the fuel cell contactor is closed, allowing the current (red) to flow from the fuel cell into the power converter. Electricity generated by the fuel cell is not very stable, which is why a DC/DC converter has to be used. The main converter also has an additional, auxiliary converter which provides 24V DC to the balance of plant components and safety systems. The converter operates on a slightly lower voltage than the one set for the DC bus. The reason for this is that when the power is restored for the DC Bus, the backup system can then detect higher voltage and will stop providing electricity.

When looking at the graphs and data in the Service Interface Software, the operator has to be aware that the fuel cell stack provides power not only for the external load, but also for the auxiliary components in the system (heater, ventilation fan, pumps and blowers). Sometimes the system could work even after the power was restored to the grid. This was because of the minimum running time of the fuel cell, which is 15 minutes. This means that if the power shortage lasted for a very short time, the system was still working. To avoid wasting hydrogen, manual shutdowns were performed to turn off the system.

7 HYDROGEN SAFETY

7.1 Introduction

Safety is an essential element of the emerging hydrogen economy. Currently there are numerous demonstration projects around the world with stationary and mobile hydrogen applications, as well as substantial research activity in hydrogen production, storage, fuel cells and related technologies. In this stage it is important to assess and implement plans for mitigating unintended safety events, determine the cause of the events and evaluate systems to mitigate potential high risk incidents.

Safe practices in the production, storage, distribution, and use of hydrogen are fundamental for the widespread acceptance of hydrogen technologies. A catastrophic failure in any hydrogen project could damage the public's perception of hydrogen and fuel cells (U.S. Department of Energy 2007). Education at all levels – from the general public to consumers to emergency responders – is vital to improve the awareness and understanding of hydrogen properties and its differences from current conventional fuels (Weiner, et al. n.d.).

This chapter introduces the basic issues related to hydrogen safety, such as basic properties, hazards, the need for standardization, and finally a description of the characteristics of safety systems used in the GenCore backup power project as well as certification of the unit.

7.2 Hydrogen properties

Consumers will not accept hydrogen or any new fuel unless it is as safe as our current fuels. Table 7-1 compares some safety related properties of hydrogen and two other commonly accepted fuels, methane and gasoline. Like these two fuel types, hydrogen must be handled appropriately.

Table 7-1 Physical properties of hydrogen, methane and gasoline (Srnivasan 2006)

Property	**Hydrogen**	**Methane**	**Gasoline**
Molecular weight [g/mole]	2.016	16.04	-
Mass density [kg/Nm^3]	0.09	0.72	720 - 780 (liquid)
Boiling point [K]	20.2	111.6	310 - 478
Higher Heating Value [MJ/kg]	142.0	55.5	47.3
Lower Heating Value [MJ/kg]	120.0	50.0	44.0
Flammability limits [% volume]	4.0 – 75.0	5.3 – 15.0	1.0 – 7.6
Detonability limits [% volume]	18.3 – 59.0	6.3 – 13.5	1.1 – 3.3
Diffusion velocity in air [m/s]	2.0	0.51	0.17
Buoyant velocity in air [m/s]	1.2 – 9.0	0.8 – 6.0	non-buoyant
Ignition energy at stoichiometric mixture [mJ]	0.02	0.29	0.24
Ignition energy at lower flammability limit [mJ]	10	20	n. a.
Flame velocity in air [cm/s]	265 - 325	37 - 45	37 - 43
Auto ignition temperature [^oC]	585	540	228 - 501

Hydrogen is no more or less dangerous than other flammable fuels. In fact, some of hydrogen's differences actually provide safety benefits compared to gasoline or other fuels. It is very buoyant and disperses quickly from a leak. It is non-toxic and non-poisonous, which is also an advantage. Unfortunately, many other aspects of hydrogen are potential safety concerns. Hydrogen is the lightest and smallest element in the universe and is more likely to leak than other gaseous fuels. Hydrogen can embrittle certain steels, resulting in cracks, leaks, and failure. It is odorless, colorless, and tasteless and therefore undetectable by human senses. Hydrogen has a wide range of flammability and detonability limits. The hydrogen ignition energy (e.g., energy required in a spark or thermal source to ignite a flammable mixture of fuel in air) is very low. The flame velocity is high in hydrogen-air mixtures, carrying the risk of a fire transitioning to an explosion in a confined space. For this reason it is recommended that hydrogen refueling and storage be done outdoors whenever feasible, or in well-ventilated indoor areas. Hydrogen burns with a nearly invisible flame and radiates little heat, making fire detection difficult in the daytime.

However, infrared detectors or special heat sensitive paints on hydrogen equipment allow rapid detection. Development of low cost, reliable hydrogen sensors is an ongoing area of research (Srnivasan 2006; Paillere, Studer and Chaudorne 2004-2005; U.S. Department of Energy 2008).

7.3 Hazards

The physical and combustion properties of hydrogen give rise to hazards that must be considered when designing and operating a hydrogen system. Potential hazards should always be identified, analyzed and eliminated or mitigated. These hazards include impacts to:

- People - any hazards that create a risk of injury or loss of life to people must be identified and eliminated;
- Equipment - damage to the equipment or facilities must be prevented; it can be both the cause of incidents and the result of incidents;
- Business interruption - hazardous events may lead to interruptions in providing service or product; the prevention of business interruption is important for commercial entities;
- Environment - any aspect of a natural or built environment that can be harmed due to a failure should be identified, analyzed and damage caused by it must be prevented (U.S. Department of Energy 2007)**.**

Proper design, installation and operation of hydrogen systems allow for control of the potentially hazardous environments and chemical properties associated with hydrogen. One of the major concerns in the use of hydrogen is that of fire or detonation because of hydrogen's wide flammability range, low ignition energy, and flame speed. Other concerns include the contact and interaction of hydrogen with materials, such as the hydrogen embrittlement of materials and the formation of hydrogen hydrides. However, with properly selected materials, the possibility of embrittlement can be avoided. Another concern is related with overpressure of hydrogen gas. This is especially important when dissimilar, adjoining materials are involved. Hydrogen has a significant expansion ratio in its conversion from a liquid at normal boiling point to a gas at normal temperature and pressure. The low temperature of liquid and slush hydrogen bring other concerns related to material compatibility and pressure control. These risks can cause accidents and injuries like: asphyxiation, burn, injury cause by blast and fragments of material, frostbite, and hypothermia. The potential hazards arising from hydrogen properties and design features necessitate a proper hydrogen hazards analysis before introducing a material, component, or system into service (Beeson and Woods 2003).

7.4 Codes and standards

Hydrogen technology struggles with many challenges and obstacles. One of them is the limited availability of necessary uniform international codes and standards. This obstruction slows down the commercialization of hydrogen technology. Internationally accepted codes and standards will be necessary to increase the confidence of local, regional and national officials in the use of hydrogen and fuel cell technology.

Hydrogen has been used for years in industrial applications but established safety parameters were not designed for the hydrogen economy. The historical data used in assessing safety parameters for the production, storage, transport, and use of hydrogen are now several decades old and will need to be re-assessed and re-validated. In addition, there are still only a small number of hydrogen and fuel cell technologies in operation today. Therefore, only limited data are available on the operational and safety aspects of these technologies.

To assure that safe practices for using hydrogen fuel are employed and standardized, there has been a considerable effort by industry and government groups within several countries in recent years to develop codes and standards for hydrogen and fuel-cell systems. (International Partnership for Hydrogen Economy n.d)**.** The international scene for establishing common codes and standards is comprised of a number of United Nation work programs and the International Standards Organization technical committees. Many industry sector organizations and professional organizations conduct work on norms and standards. Globally this type of work is performed by the US proposed International Partnership for a Hydrogen Economy, and by the Society of Automotive Engineers; in Europe, by the European Integrated Hydrogen Project. Moreover, some individual countries have long traditions for such work, and many national standards working groups exist (Sorensen 2005).

Hydrogen codes and standards are being developed to provide the information needed to safely build, maintain, and operate hydrogen and fuel cell systems and facilities, ensure uniformity of safety requirements, and provide local officials and safety inspectors with the information needed to certify hydrogen systems and installation.

7.5 GenCore system safety

In order to limit exposure to potential risk, a number of precautions were taken prior to beginning the activation and characterization of the GenCore fuel cell system. This part of the chapter is a brief summary of the safety measures taken into account and also generally describes safety components and systems used during installation and operation.

7.5.1 Gas supply safety system

The high-pressure (200 bars) hydrogen gas storage was located in an enclosure outside the building. The enclosure was locked and information signs were placed around it. During operation of the GenCore system, the pressure of the hydrogen gas supply piped into the laboratory is limited to about 5.5 bars by a pressure regulator. The gas supply system consisted of three valves: two inside and one outside the enclosure. It also included a safety relief valve, which protects the supply piping to the fuel cell system from over-pressurization due to the failure of a gas cylinder pressure regulator. It is a spring-loaded valve, set to open at 10 bars and specified to relieve the full flow of a failed regulator. In addition, excess flow valve is installed to protect the fuel cell system from a failure of the hydrogen delivery piping. Two pressure gauges indicate pressure of the gas inside the tank and the one delivered to the fuel cell system. The complete gas supply system was bonded to ground potential to prevent any static build up on the metal supply system.

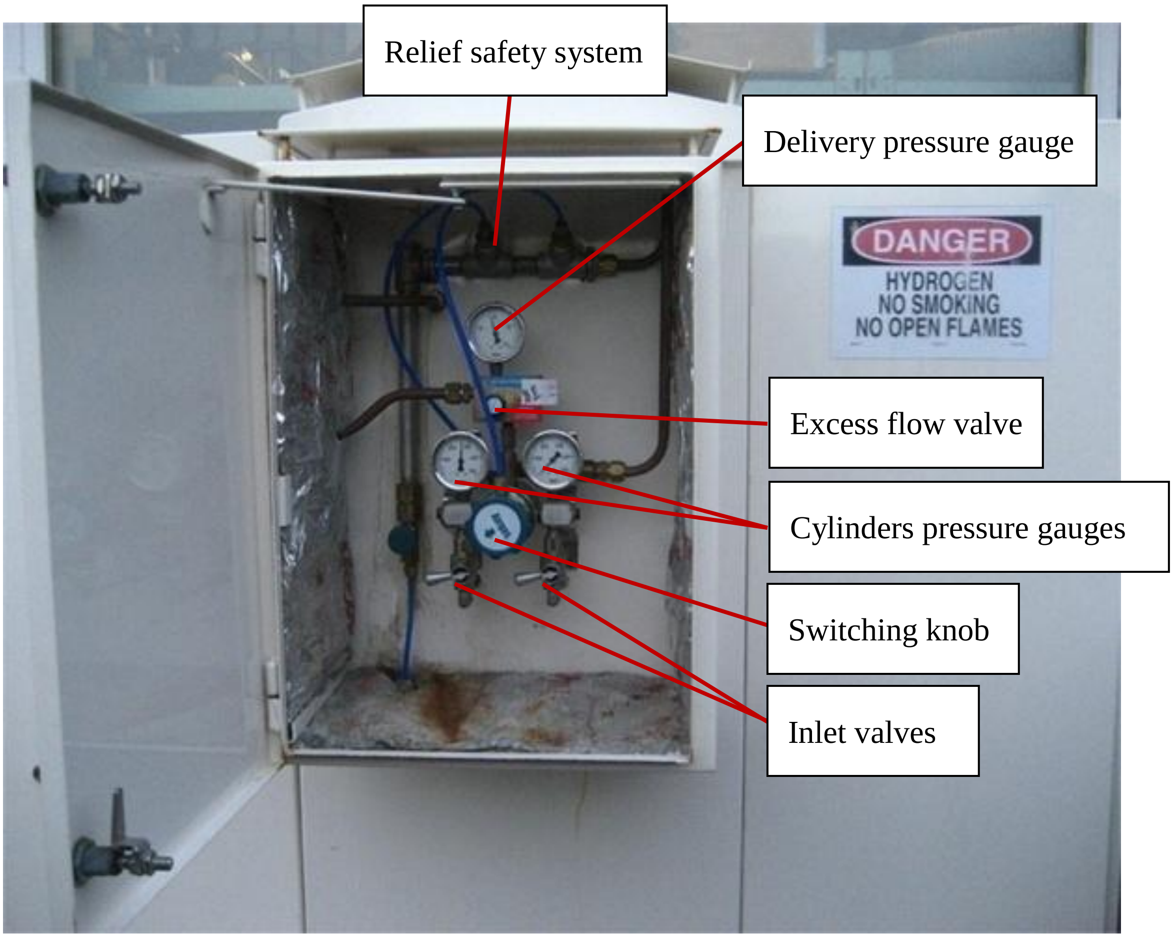

Figure 7.1 Hydrogen supply system

7.5.2 Gas leak detection system

A hydrogen detection system consists of two main sensors. The first one was installed by the manufacturer above the fuel cell stack, inside the enclosure (Figure 7.2). The second one was installed directly above the system on the ceiling, near the vent (Figure 7.3), which was specially made for the system. These sensors consist of semiconductors whose electrical conductivity increases when hydrogen is adsorbed on their surfaces. Conductivity, proportional to the gas concentration, is continuously measured by an electronic circuit. Each of the sensors was checked for correct operation. Using this dual gas detection system helps reduce the risk of an explosive atmosphere developing due to a gas leak. It should be noted that at no time during the testing was the laboratory hydrogen detection system activated due to a buildup of escaped hydrogen gas. The laboratory compartment was well ventilated and as an extra precaution, before system start-up, every connection and fitting was checked with two different manual combustible gas detectors, adapted and calibrated to detect hydrogen gas. Each of these actions was performed with appropriate precautions.

Figure 7.2 Internal hydrogen safety sensor

Figure 7.3 Vent and hydrogen safety sensor installed on the ceiling above the GenCore system

7.5.3 GenCore internal safety systems

The fuel cell's internal safety system incorporates few elements to protect the system and ensure its proper operation. They are components connected to the control system and any interruption in the safety loop by one of these devices will cause the system to stop operation until the fault is repaired and the system reset.

The factory-installed hydrogen safety sensor, which was mentioned above, monitors the fuel cell system for hydrogen leaks within the enclosure. It is located above the fuel cell stack. The sensor suspends system operation if excess hydrogen is detected. The cabinet ventilation subsystem provides air flow to keep the enclosure temperature below its maximum operating temperature, and to ensure there is no hydrogen build-up due to a leak in the cabinet.

There are a few switches installed as a part of the fuel cell safety system, which monitors the system for hydrogen over-pressure, over-temperature in the enclosure, and over-temperature in the coolant subsystem. The hydrogen inlet pressure switch opens when over pressure is detected at the inlet. The trip pressure is set at 0.85 bars and the switch automatically resets when the pressure drops below 0.2 bars. The others are the stack coolant outlet temperature switch and the coolant heater switch. They are bimetallic switches that open when the stack coolant temperature setpoint is exceeded. The trip temperature is 80°C and the switches reset automatically when the coolant temperature returns to below the trip temperature. Another one is an enclosure temperature switch. It is also a bimetallic switch that opens when the enclosure temperature setpoint is exceeded, which is set to 90°C.

In order to prevent possible system flooding, a water intrusion sensor is installed, which shuts down the fuel cell system if the water level in the enclosure is approximately 3.8 cm deep.

The tamper switches are magnetic switches that close in the presence of a magnetic field. The magnet must be in close proximity to the switch (maximum 0.636cm) for proper operation. The tamper switches are used to determine if the front and rear service panels are in their closed positions. Both switches will stop system operation when the front or rear panels are opened. There is a pad shear sensor, a magnetic switch which shuts down the fuel cell system if the enclosure is sheared from the pad.

Finally, there are two LEDs in the rear of the system which indicate system fault or proper operation.

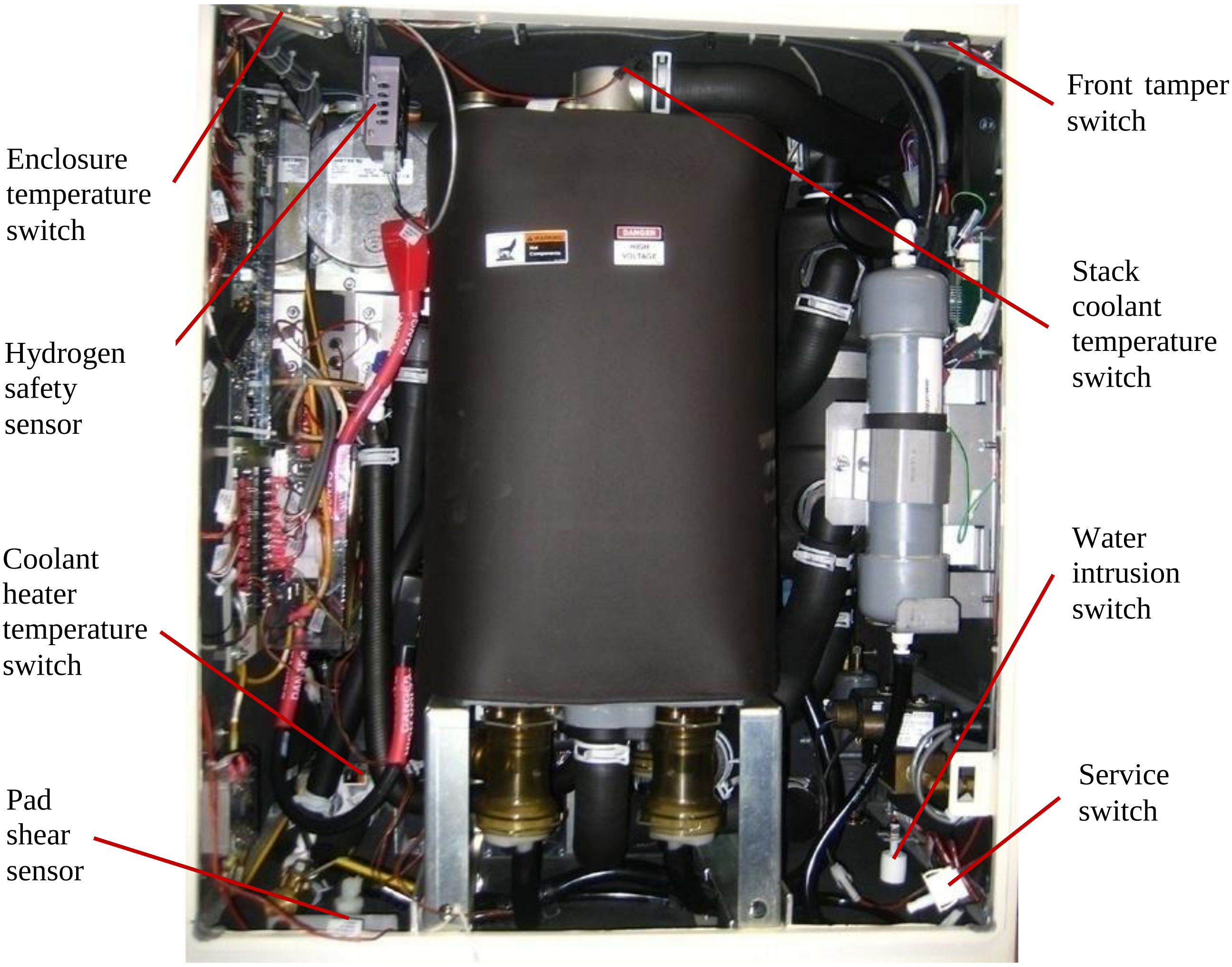

Figure 7.4 Internal safety system components

7.5.4 GenCore certification

The GenCore 5B48 system, tested by Underwriters Laboratories (UL) is in compliance with FCC (Part 15) Class A and Fuel Cell Standard ANSI Z21.83. In addition, it is tested by Telcordia Technologies to the following Network Equipment Building Systems (NEBS) requirements: General Requirements GR-63 (Physical Protection) and GR-1089 (Electromagnetic Compatibility and Electrical Safety) which together constitute NEBS Level 3 compliance testing, along with NEBS GR-487 (Generic Requirements for Electronic Equipment Cabinets).

The following table references the codes and standards that the GenCore 5B48 fuel cell system is manufactured to.

Table 7-2 Codes and standards for GenCore 5B48 fuel cell system

Reference	**Standard or code compliance**
NEBS Level-3	NEBS tested and evaluated
GR-1089	Generic Requirement for Electromagnetic Compatibility and Electrical Safety
GR-63	Generic Criteria for Physical Protection
GR-487	Generic Requirement for Electronic Equipment
UL Classified ANSI Z21.83	Fuel Cell Power Plants
CGA 5.4	Standard for Hydrogen Piping Systems at Consumer Locations, 1999 edition
FCC	FCC Class A, Electromagnetic Emissions Standard, Part 15 of FCC Rules

8 SYSTEM TESTS AND RESULTS

8.1 Introduction

During the operation of the system some basic measurements were taken in order to assess its behavior under a few conditions. This chapter characterizes and evaluates the performance of the GenCore 5B48 unit. The tests included steady-state measurements of primary system properties, fuel consumption, efficiency analysis, cold start-up behavior, transient analysis, and a reliability study. It has to be pointed out that the tested system is a few years old and this can have some negative influence on its overall performance.

8.2 Goals and objectives

The main goals of these tests were to establish system performance, such as electrical efficiency, fuel consumption and fuel utilization efficiency; measure system response during start-up - the most critical moment of a fuel cell backup power system; explore the suitability of the fuel cell system for use in a place of UPS application; and investigate its reliability. The characteristics could vary between fuel cell systems, which is totally acceptable. Each system requires testing in its own right.

8.3 Measurements methodology

The measurements methodology included three parts. The first consisted of the steady-state system response during load switching from 0% to 100% of available load. These tests required a steady-state system, which means that the voltage and current do not change with time. The maximum available load was only about 1.6kW of output power (about 2kW together with power required by balance of plant components), due to limitations in equipment. However, this was sufficient to analyze the performance of the whole system as well as the fuel cell stack, including such parameters as general characteristics, efficiency, fuel consumption, and behavior during cold and hot start-ups. The second part was focused on system transition analysis. It consisted of response time testing during switching from the standby operation into full backup operation, and vice versa. All data was captured by the software provided by the manufacturer and some of it was verified by manual measurements. The last part was an analysis of system reliability and availability, which was based on the study conducted during the one year project at Keflavik International Airport in 2006.

8.4 Results and discussion

8.4.1 Fuel cell stack current-voltage and power measurements

This part characterizes the basic performance of the fuel cell stack used inside the GenCore 5B48 unit and it analyzes stack current-voltage and power curves. All tests were conducted under steady-state conditions. The system was warmed up to about 52-54^{o}C at the fuel cell stack and 28°C inside the cabinet. Additional parameters such as fuel flow rate and pressure were carefully noted.

The result can be seen in Figure 8.1. The voltage decreases and power increases with current, which is normal operation for the fuel cell stack. The reversible voltage of the stack (open circuit voltage) under these conditions was established at 49.9V.

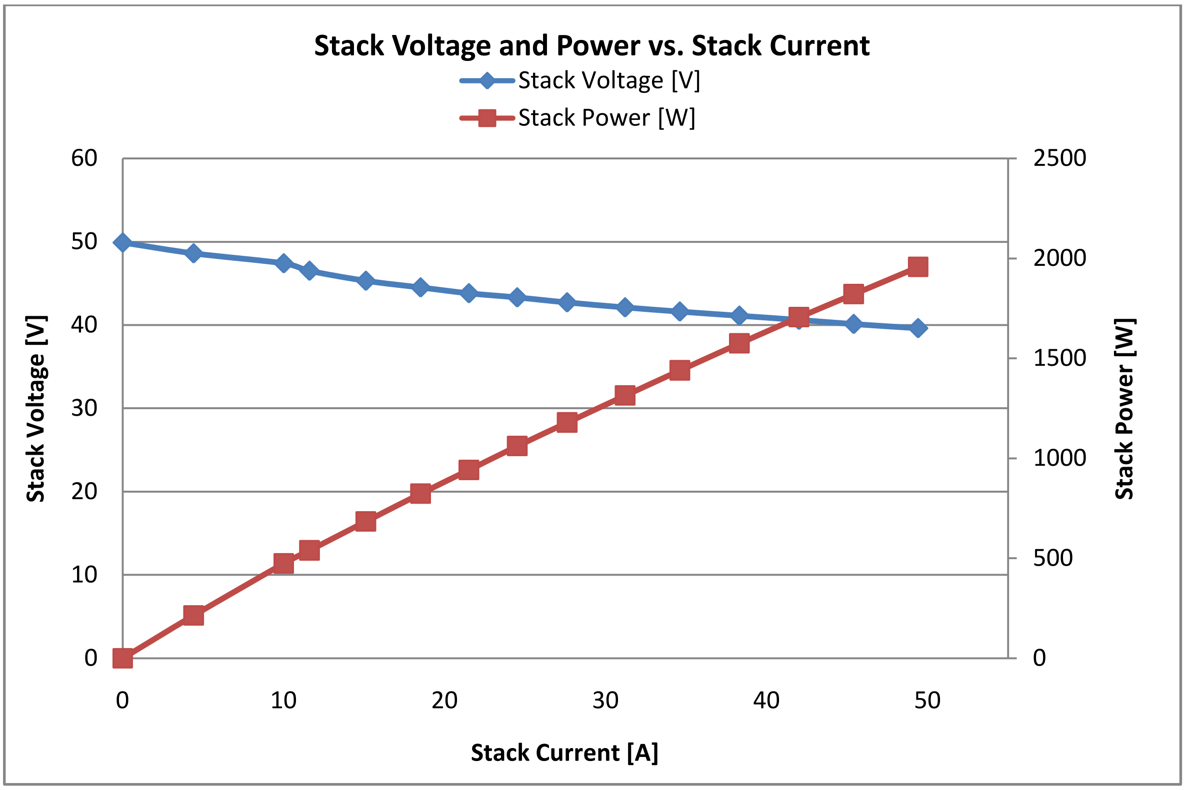

Figure 8.1 Fuel cell stack voltage and power in a function of stack current

Compared to the theoretical values (e.g. from Chapter 4), the obtained voltage-current curve is almost all linear. It is very hard to estimate which part is responsible for activation voltage losses. This measurement was conducted a few times in order to ensure that the results are the same. The conclusion is that the activation losses are very small. The ohmic losses are clearly visible and increase with current. Due to the equipment limitation mentioned before, it was not possible to register if significant concentration losses occur.

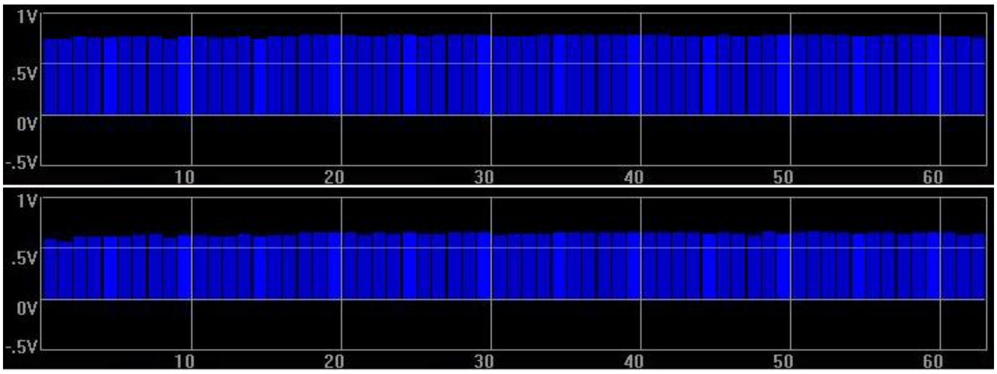

Figure 8.2 Voltages of particular cells under 0.2kW (top) and 1.9kW (bottom) of stack power

During the measurements it was possible to see how voltages of every cell inside the stack change with the change of power (Figure 8.2).

8.4.2 Fuel consumption and fuel utilization efficiency

Hydrogen fuel consumption and fuel efficiency are two of the factors determining the efficiency of the fuel cell stack and all system. The measured fuel consumption at 1kW was 13slm of hydrogen (Figure 8.3). Additionally, Plug Power provides data of fuel consumption for some of the output powers. At 3kW the GenCore unit consumes approximately 40slm and at 5kW – 70slm.

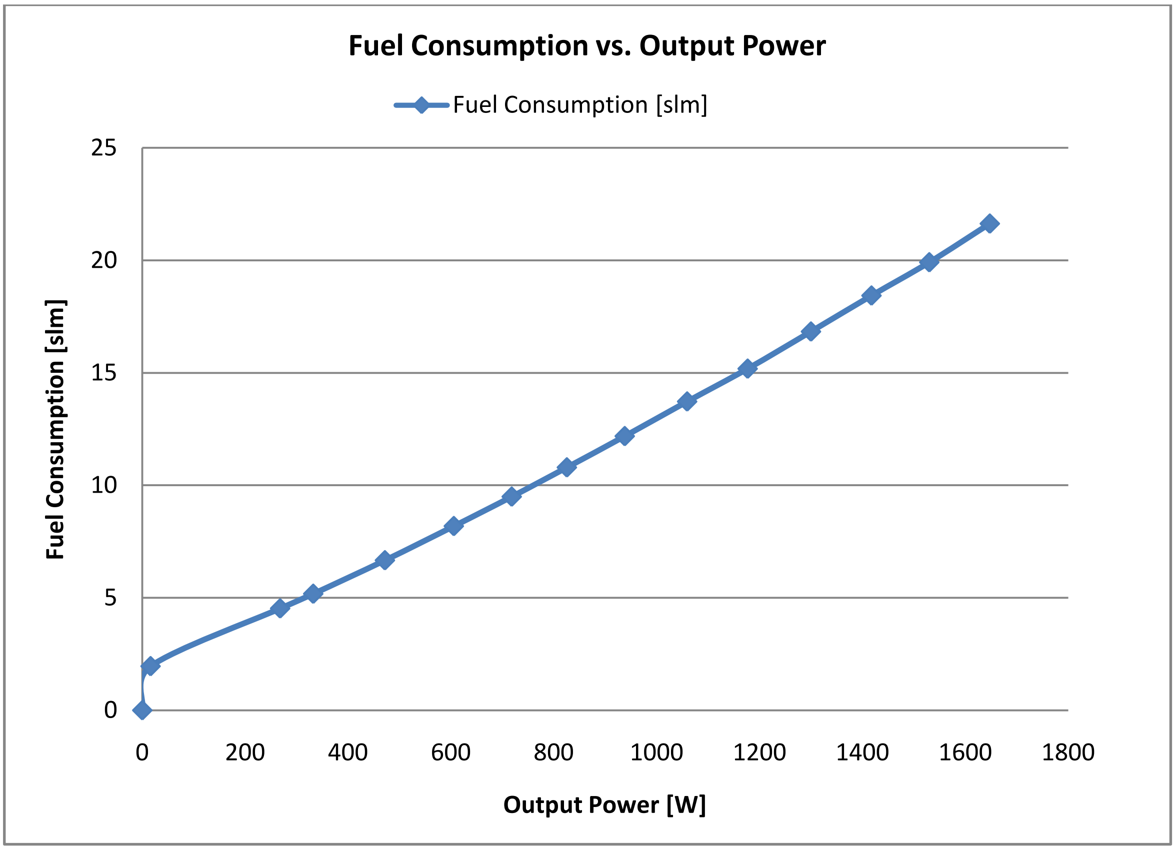

Figure 8.3 Hydrogen consumption as a function of output power

Using 6 hydrogen bottles (50 liters, compressed to 200 bars), the GenCore system is able to provide about 54 hours of continuous operation at 1kW or 12 hours at 5kW prior to refueling.

The fuel utilization efficiency accounts for the fact that not all of the fuel provided to the fuel cell will participate in the electrochemical reaction. During the measurements this aspect was thoroughly examined. Figure 8.4 exhibits the fuel consumption and efficiency as a function of fuel cell stack current.

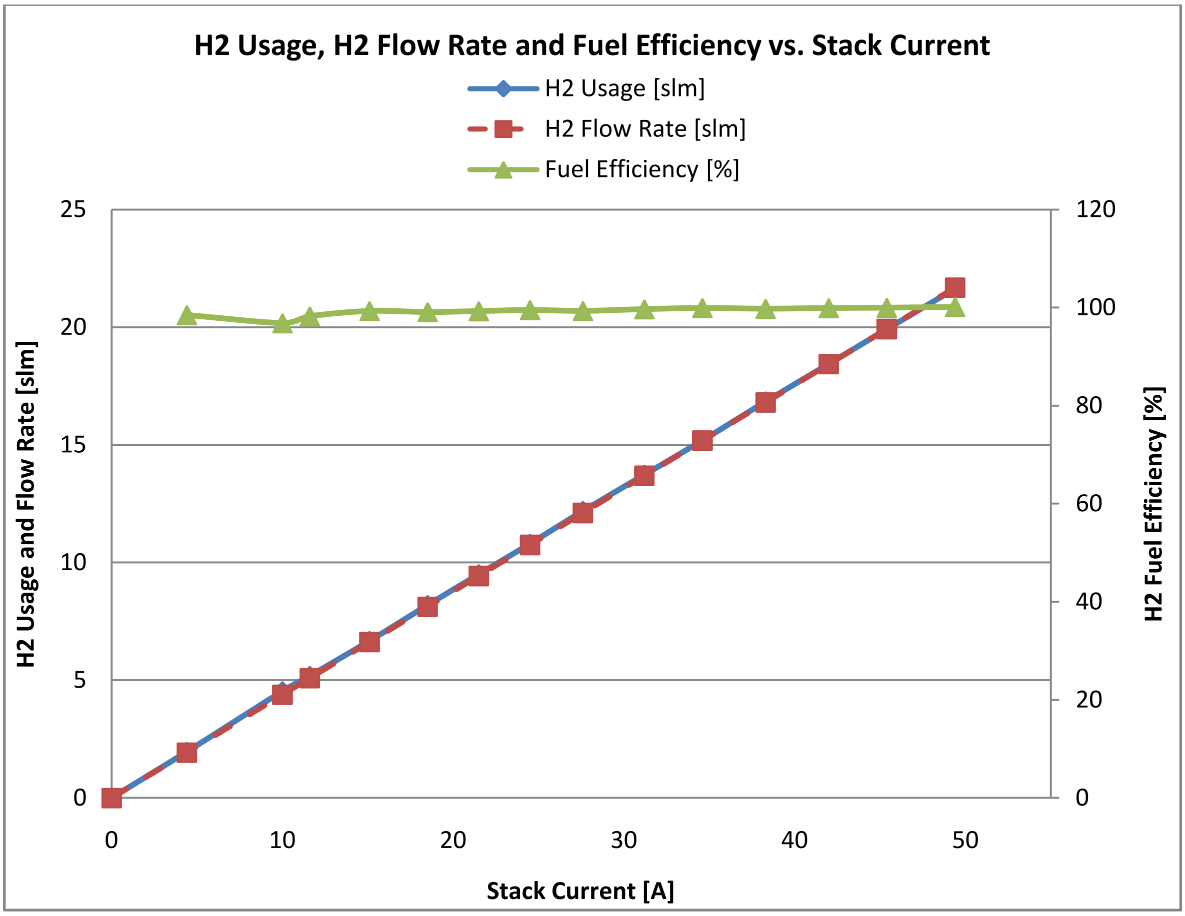

Figure 8.4 Graph of hydrogen consumption and fuel utilization efficiency as a function of fuel cell stack current

It is noticeable that the fuel flow rate changes linearly with a change of current from the stack, thus the fuel consumption is directly related to the power which can be yielded from the stack, and this relationship is linear. The green line on the graph shows fuel efficiency for each measured point. As can be seen, this parameter is very high and on average achieves about 99%. It means that the system does not waste the fuel. The blue line expresses the hydrogen usage in standard liters per minute (slm), which was obtained from the software. It represents the total amount of fuel provided to the stack ($v_{fuel\_provided}$). The red dashed line shows the change of the fuel used by the stack to generate electric current, calculated from the equation:

$$v_{fuel\_flow} = \frac{i}{nF} \times \text{cell number}$$

where: i – electric current, n – number of moles of electrons transferred, and F – Faraday's constant ($96485\frac{C}{mol}$). The unit of the equation above is mol/sec. In order to compare these two values for each point and calculate fuel utilization efficiency, the software units needed to be converted from slm to mol/sec. The ideal gas law was employed to estimate these results:

$$\frac{V}{n} = \frac{R_u T}{P}$$

where: V – volume, n – number of moles, R_u – ideal gas constant ($8.314\frac{J}{K \times mol}$) , T – temperature, P – pressure. The conversion needed to be made using the standard conditions. The approximate data were almost the same as the values calculated using the fuel flow rate equation. This indicates that fuel efficiency of the fuel cell stack is very good. It was calculated as a ratio of the fuel used by the stack to generate electric current versus the total fuel provided to the fuel cell stack:

$$\varepsilon_{fuel} = \frac{v_{fuel\_flow}}{v_{fuel\_provided}}$$

8.4.3 Overall system electrical efficiency analysis

This part involves an energy conversion efficiency analysis of each component separately and the system as a whole. The analysis was conducted based on data captured during load measurements and energy contained in the stored fuel.

The first step was to calculate the overall fuel cell stack efficiency for each point. It may be defined as the ratio of the electrical energy produced by a stack, consuming a certain amount of hydrogen to the theoretical energy content of the same amount of hydrogen. The equation below expresses this relation:

$$\varepsilon_{FC} = \frac{i \times V}{\Delta H_{HHV} \times v_{fuel}} \times 100\%$$

where: i – electric current, V – stack voltage, v_{fuel} - fuel flow rate provided to the stack. The enthalpy of formation was used for liquid water ($285.83 \frac{kJ}{mol}$). The results are shown on the plot (Figure 8.5).

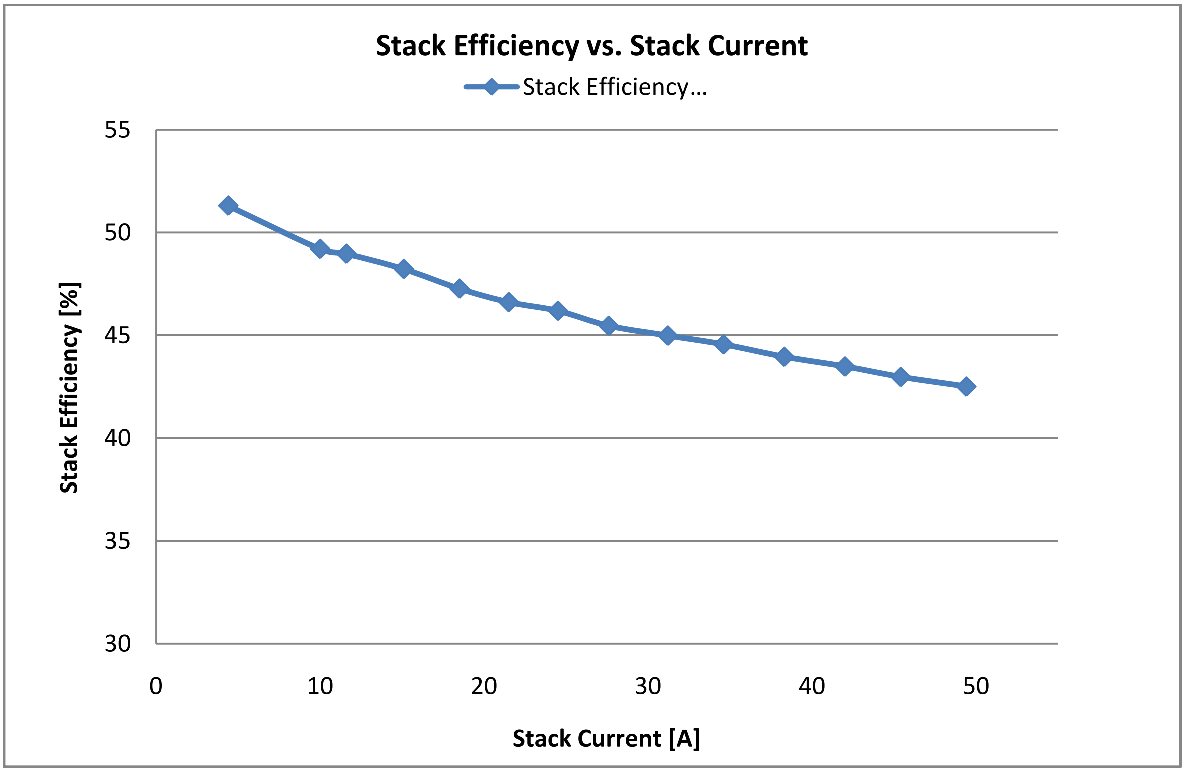

Figure 8.5 Fuel cell stack efficiency

In theory, stack efficiency should decrease while current increases. As can be seen from the graph, the results confirm this theory. For very low power, the stack could exceed even more than 50% efficiency. For 1 and 2kW of stack output power, the efficiencies are about 46.2% and 42.5% respectively.

In a similar manner the overall system efficiency was calculated. Figure 8.6 shows a system efficiency curve and compares it to the fuel cell stack. It can be noticed that fuel cell stack efficiency is higher in every point, and this difference slightly decreases as output power increases. The overall system efficiency increases at low power and after exceeding approximately 1kW it starts to decrease slowly, which is normal behavior of the fuel cell system. The efficiencies for 0.25, 1, and 1.65kW are 27.8%, 36.2%, and 35.8% respectively. It can also be seen that at a very small output power the system is highly inefficient. This is caused due to the parasitic load - power consumed by auxiliary or balance of plant components such as pumps, blowers, heaters, etc., necessary for proper operation of the system. At low output power, the parasitic load is higher than the output load. Figure 8.7 exhibits this relationship.

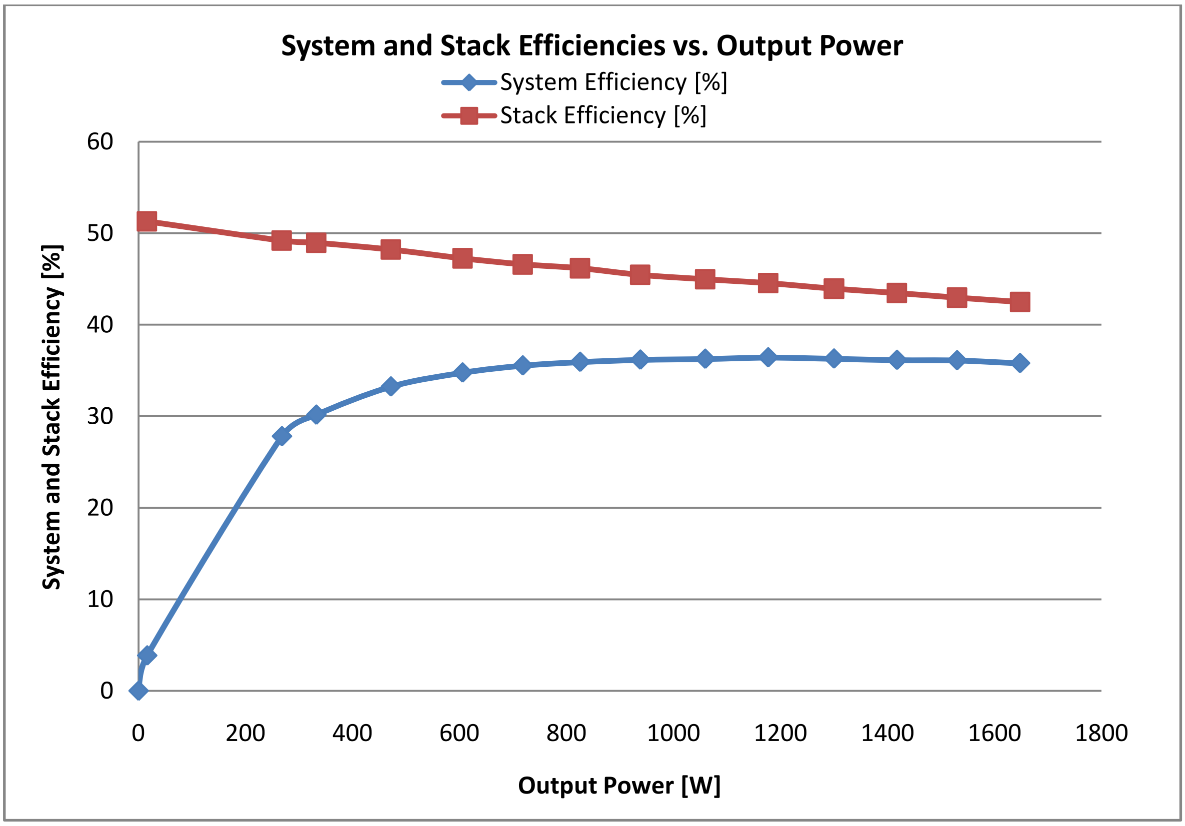

Figure 8.6 Overall system efficiency compared to fuel cell stack efficiency

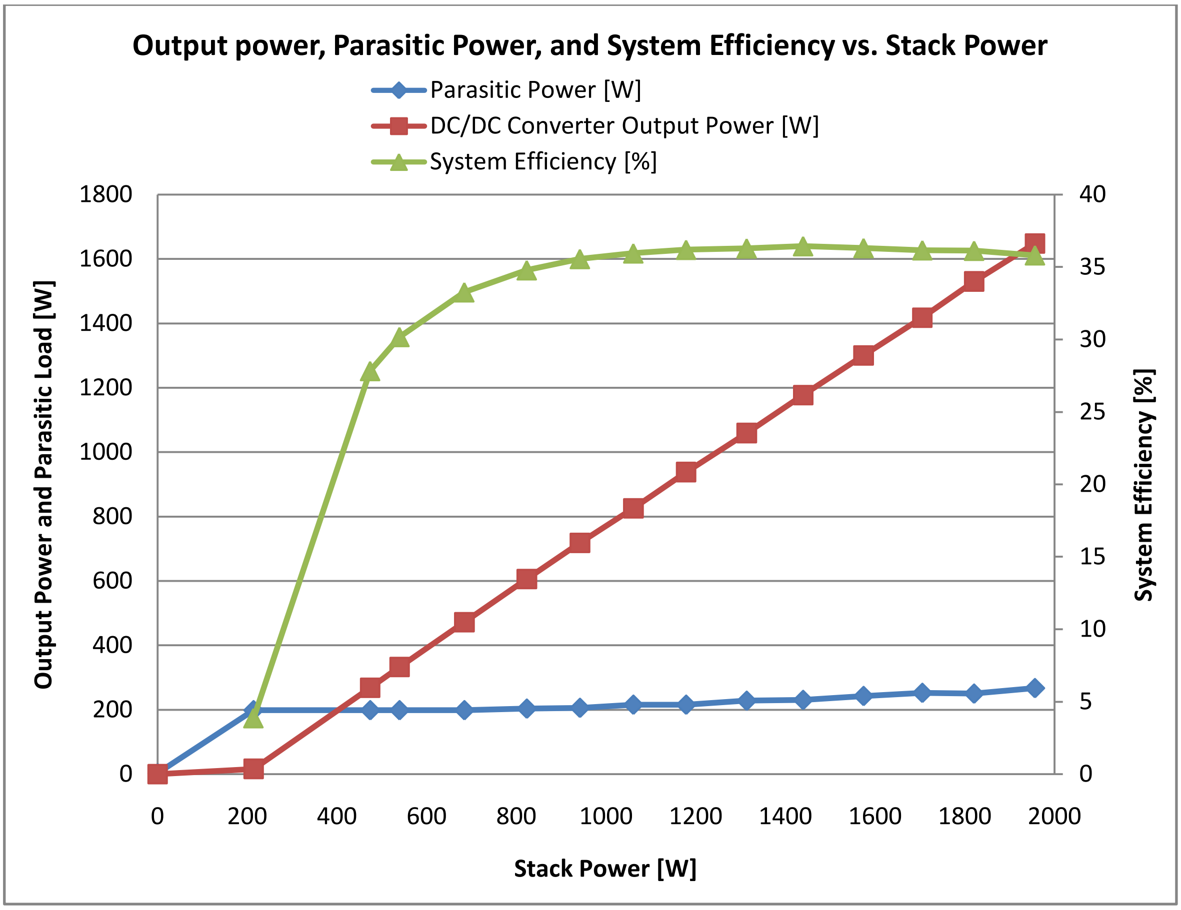

Figure 8.7 System output power and power consumed by balance of plant components as a function of fuel cell stack power

Parasitic load consumed by the power module increases slightly with fuel cell stack output power. If the stack generates more power, it also requires more power for auxiliary devices.

A minor contribution in the overall system efficiency is given by the DC/DC converter. Figure 8.8 shows this plot of DC/DC converter efficiency as a function of its output power. It was calculated as a ratio of converter input power to its output power. The result is very good – in the most steps around more than 97%. The average DC/DC converter available on the market has efficiency between 80% to 98%, depend on the components used.

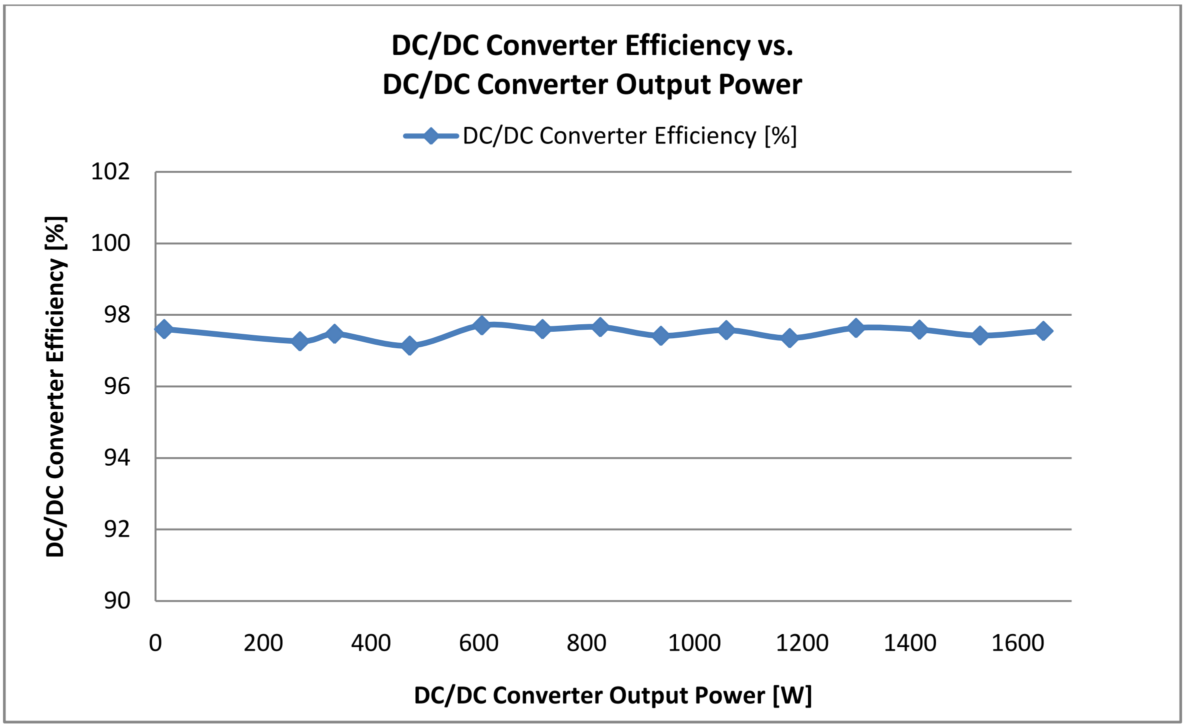

Figure 8.8 DC/DC converter efficiency

8.4.4 Cold startup behavior

So far, all measurements were conducted under steady-state conditions and fixed parameters. During the tests the system was warmed up and prepared to operate. Normally however, the backup power system spends most of the time in stand-by mode waiting for the activation signal. This section describes the system behavior under conditions which change with time. The aim of these tests is to characterize a dynamic response of the system during the so called cold start-up.

Figure 8.9 exhibits how stack power, output power and parasitic/auxiliary power change during the first 28 minutes after system start-up and with changing output load.

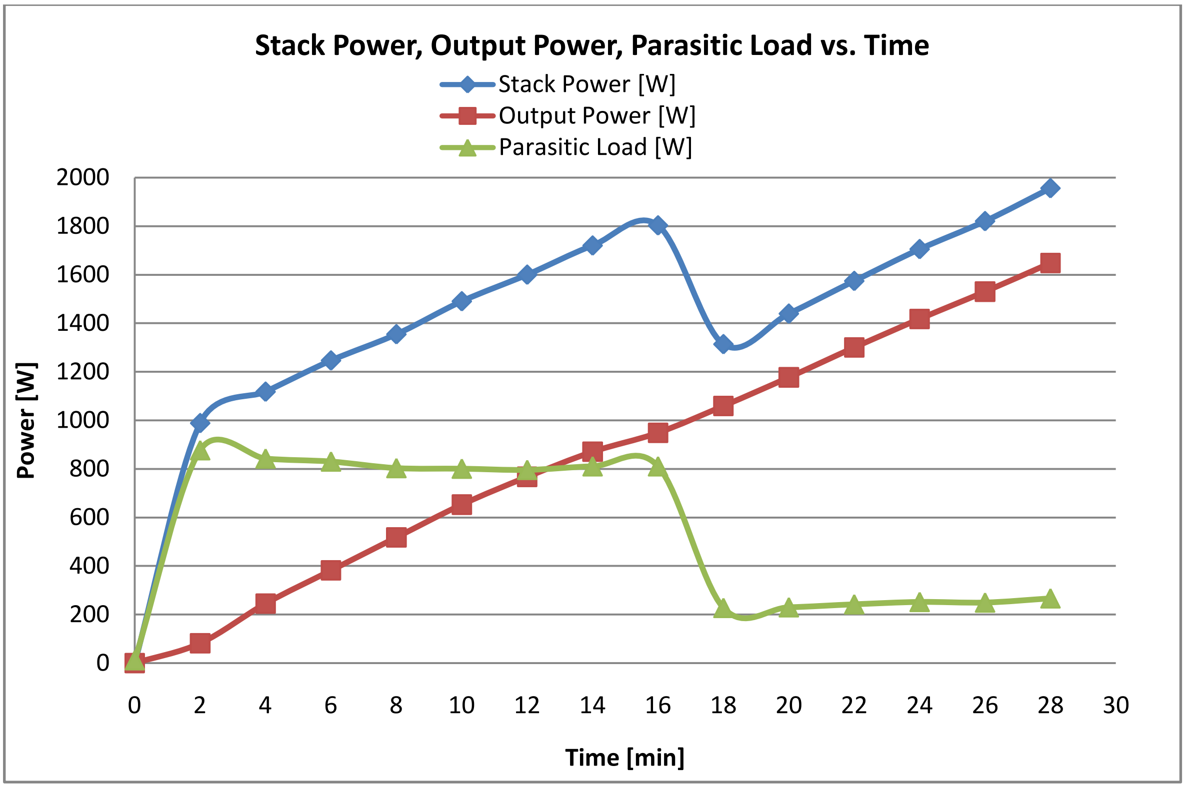

Figure 8.9 Stack power, output power, and parasitic load during first 28 minutes of operation

The output power does not change compared to the results from the previous tests. This is very important information because it indicates that the system is capable of providing the required output power in any initial conditions. However, the auxiliary power changes significantly. During the first minutes of system operation, BOP components require much higher power in order to warm up the system. This power is supplied from the fuel cell stack, as can be seen from the plot. After approximately 16 minutes, when the unit is warmed up and ready for further operation, the parasitic power drops. Of course, everything depends on the weather conditions and ambient temperature, etc. Figure 8.10 points out how temperatures inside the unit change.

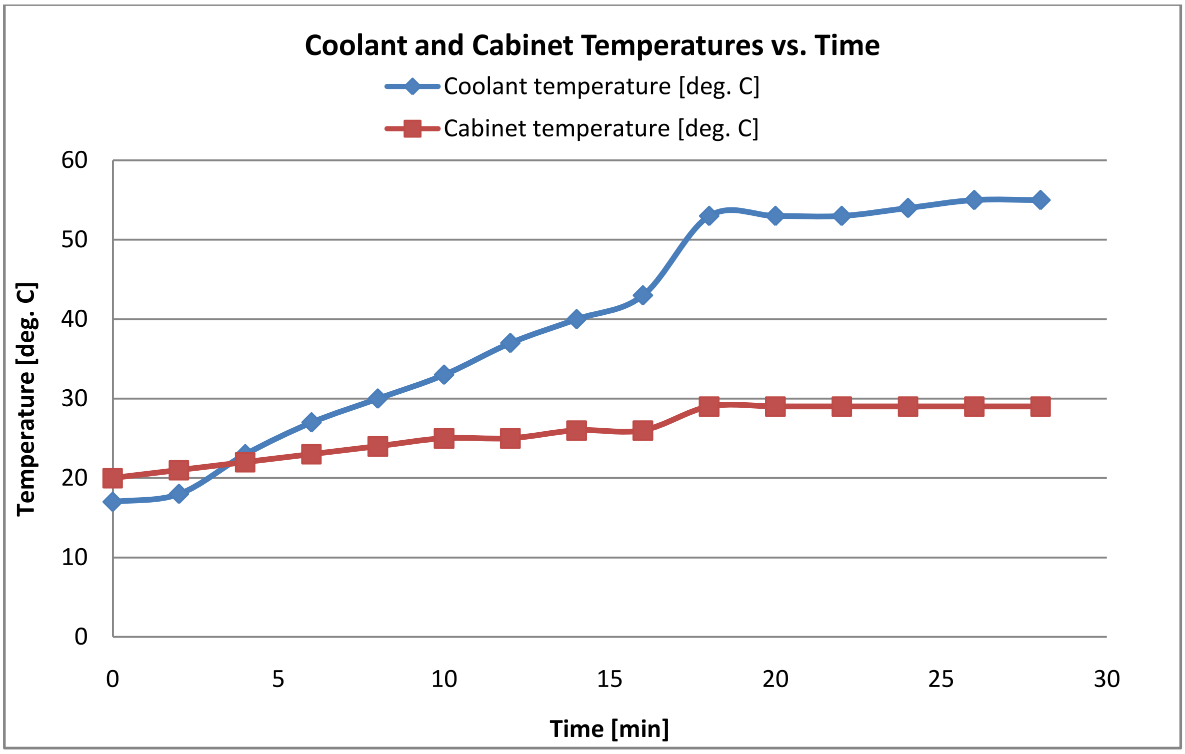

Figure 8.10 Coolant and cabinet temperatures during first 28 minutes of operation

Figure 8.11 indicates that during these first few minutes, system fuel consumption is much higher and its efficiency lower because of the higher auxiliary power requirement.

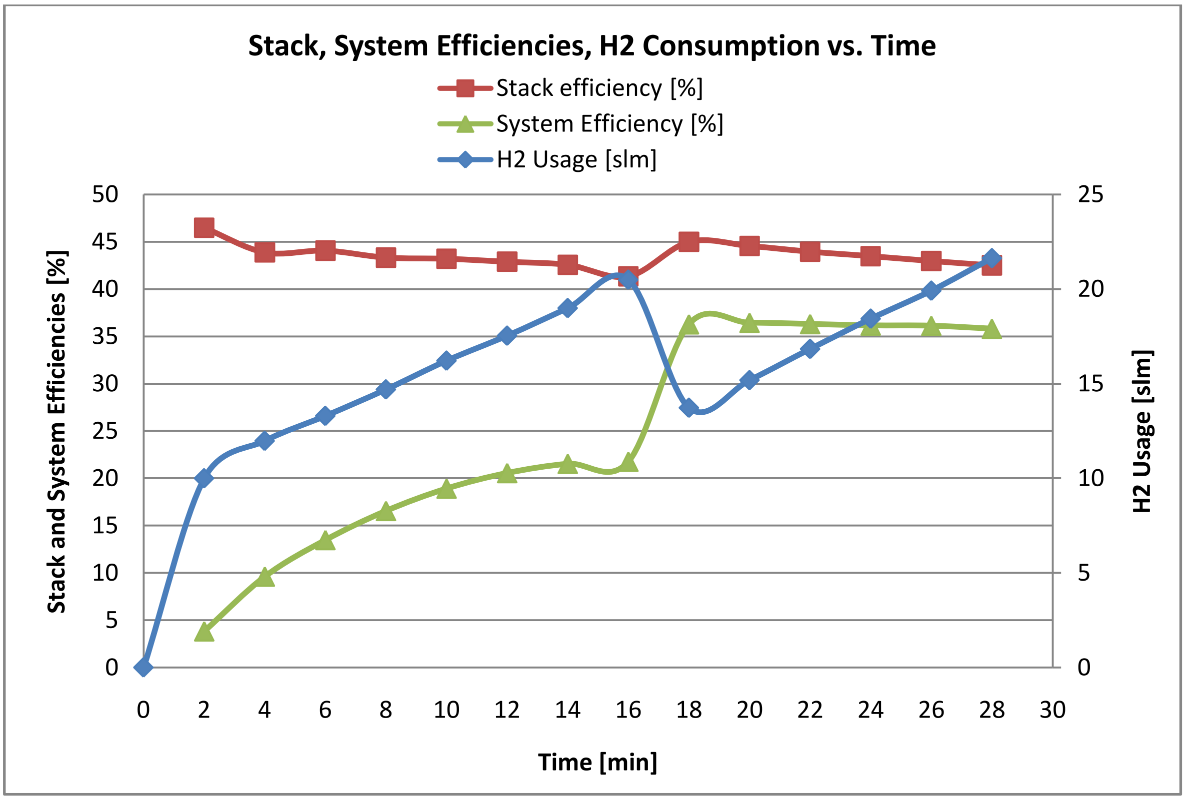

Figure 8.11 Fuel cell stack efficiency, system efficiency, and fuel consumption during first 28 minutes of operation

8.4.5 Transition analysis

The purpose of this test was to measure the behavior and parameters of the fuel cell stack and the whole system during instant startup, when a step change in power demand occurred.

Each step started from cutting the power to the DC Bus. At the same time the load was applied to the system. After a few seconds of operation on the batteries, the fuel cell stack started working and took over the load. It was necessary to wait some time for the system to stabilize.

Usually, after a minute, the internal heater fan turned on; this resulted in an increase in power demand. The fuel cell was then turned off manually. Fifty second breaks between each step were allowed for the system to go to a complete stop.

There were three steps, each one of them was a bigger power demand for the system. Respectively, 27% (500W), 50% (900W) and 100% (1800W) of available load was applied to the fuel cell stack.

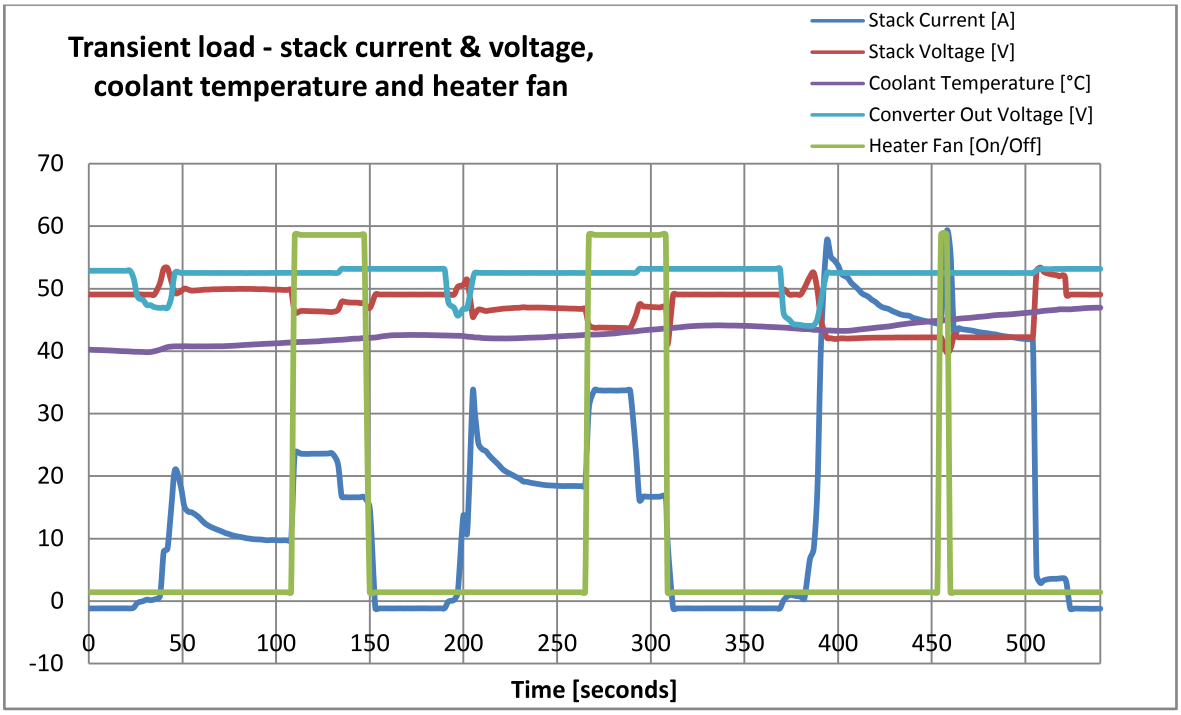

Figure 8.12 Stack parameters over time during the test

Figure 8.12 shows the timeline of the test with a stack current, stack voltage, converter out voltage, coolant temperature and heater fan status on the Y axis. A spike can be seen each time the fuel cell stack starts working. It is the result of a sudden drop of voltage due to an increase in power demand. After one minute of operation the heater starts working, drawing more current from the fuel cell.

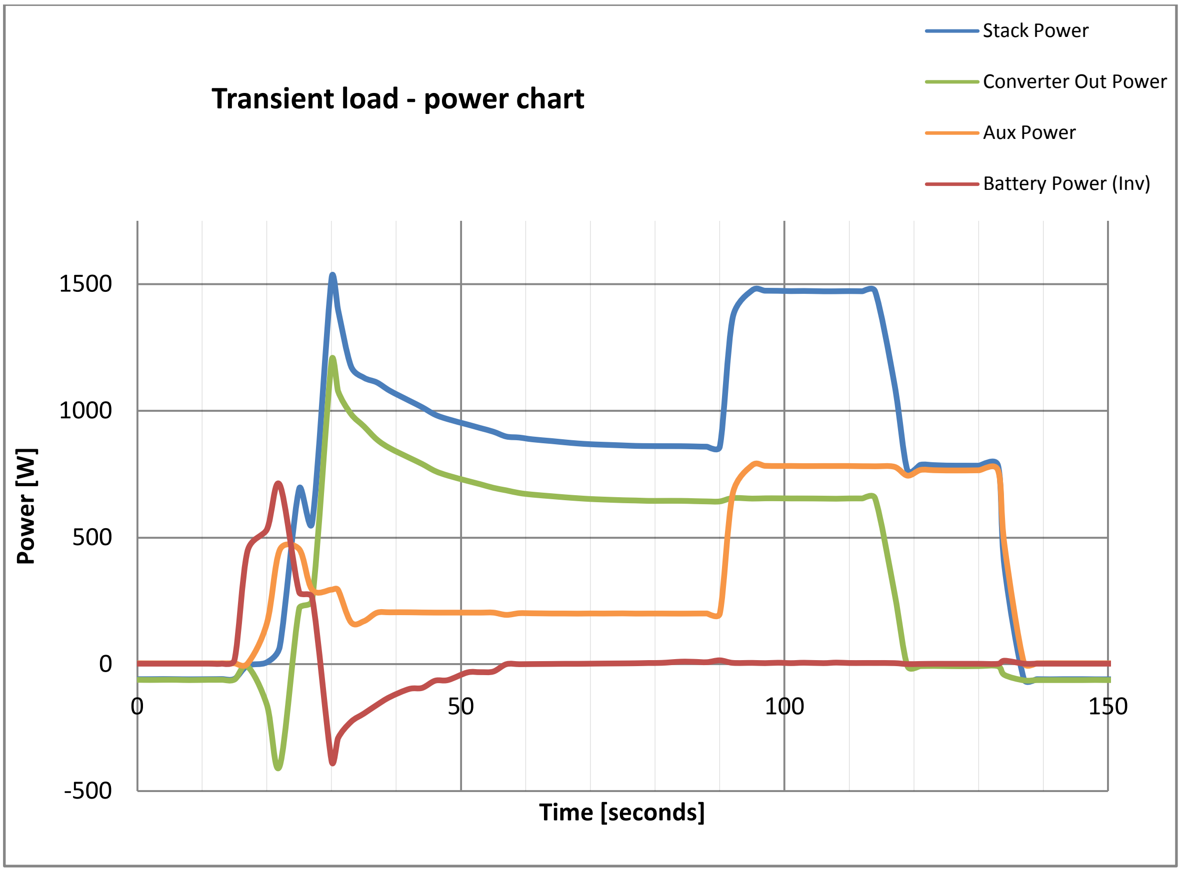

Figure 8.13 Behavior of the battery and system components

On Figure 8.13 a single transient test is shown. The moment of power shortage to the DC Bus can be seen in the increase in battery power. Batteries cover the demand of the load for about 10 seconds; then the fuel cell stack is ready to take it over. The negative power of the batteries reflects their charging during first 30 seconds of fuel cell operation. The increase in auxiliary power is due to the heating system being started to heat up the coolant to the operating temperature. The heater was still working even after the power demand was decreased to zero.

This behavior of the system can be explained by the fact that it was mainly designed to work outside. The temperature inside the cabinet had to be high enough to prevent the system components from freezing. Also, coolant temperature had to be increased to 50°C, which is the operating temperature for this system.

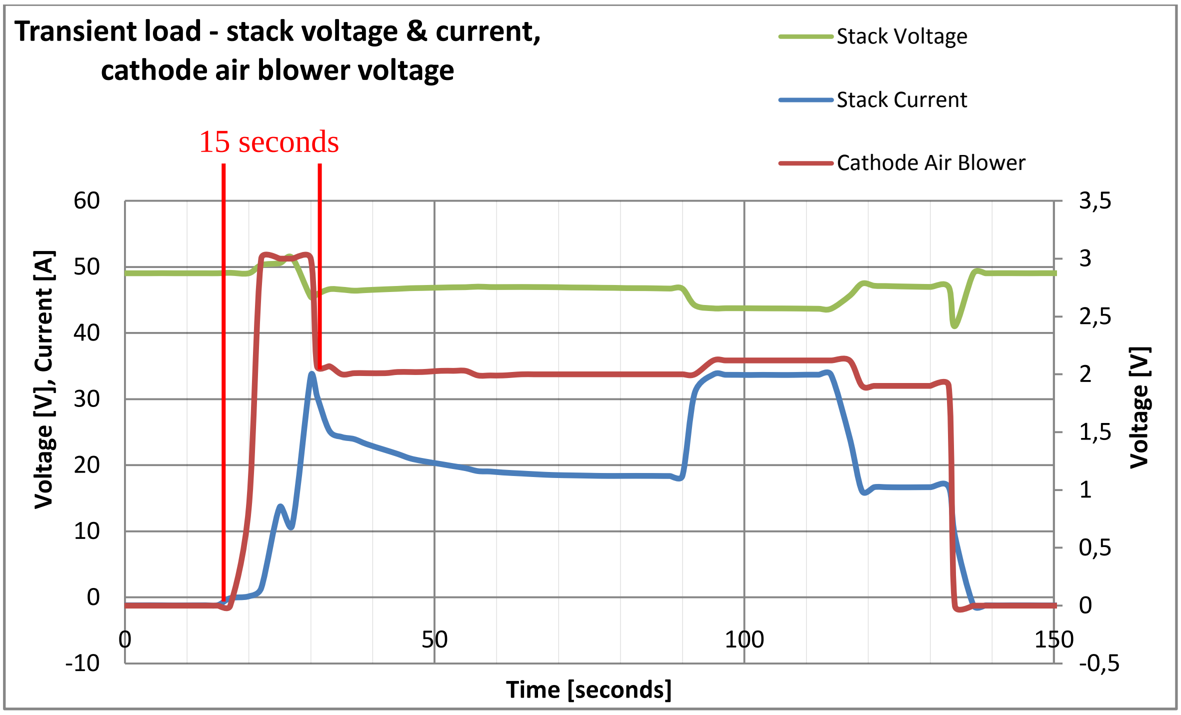

Figure 8.14 Behavior of the fuel cell stack

In Figure 8.14 the behavior of the fuel cell stack can be seen. The voltage applied to the cathode air blower is proportional to the current which is drawn from the fuel cell, thus also to the power generated by the stack. Also, drops in voltage can be seen as the power demand increases.

The fuel cell behaved very well in this test, and proved to be a reliable backup power source. The time from the moment of power shortage to full power was about 15 seconds. Also, one has to account for the delay that can be set in the Service Interface Software, which was 1 second in this case. The delay is meant to prevent the fuel cell from unnecessary startups, for instance when the voltage drop lasts just milliseconds.

8.4.6 System reliability and availability

The limitation of time and hydrogen fuel did not allow conducting accurate availability and reliability tests of the system, however this kind of study with exact the same unit was done during the 12 month demonstration project at the Keflavik airport. It was reported that the GenCore unit achieved a reliability of 96.8% and availability of 79.9%.

Table 8-1 Availability and reliability of the system during one year demonstration project at the Keflavik airport (LOGANEnergy 2007)

Month, year 2006	Scheduled Starts	Attempted Starts	Actual Starts	Availability*	Reliability**
January	12	12	12	100.0%	100.0%
February	56	56	56	100.0%	100.0%
March	62	59	58	93.5%	98.3%
April	60	35	34	56.7%	97.1%
May	62	53	52	83.9%	98.1%
June	60	38	34	56.7%	89.5%
July	62	62	62	100.0%	100.0%
August	62	62	58	93.5%	93.5%
September	60	57	56	93.3%	98.2%
October	62	37	33	53.2%	89.2%
November	60	36	35	58.3%	97.2%
December	62	54	53	85.5%	98.1%
TOTAL	680	561	543	79.9%	96.8%

* Availability = Actual Starts / Scheduled Starts

**Reliability = Actual Starts / Attempted Starts

The obtained results were inadequate, especially for this kind of application. The majority of the issues affecting the performance of the system were related to the hydrogen sensor, electronics, and software. There were also several hardware issues related to the external equipment used to simulate the DC bus application, such as a failure of the relay and power supply. There was also an extended outage due to the construction crews accidentally severing the underground electrical connection between the fuel cell and the airport terminal. The unit proved to be reliable as long as the cabinet heater circuits were fully operated. The malfunctions of this element caused the fuel cell stack to be affected by cold weather and it had to be replaced by a new one. It happened on July 1st, 2006 (LOGANEnergy 2007).

The lesson learned was that the site at which the system is installed needs to be properly protected, and also the reliability of the entire fuel cell system depends not only upon the reliability of the fuel cell stack, but also upon the reliability of all the other components within the unit. Every component may affect the reliability of the stack. A failure of one of these devices can lead to abnormal system operation and even to premature damage (Feitelberg, et al. 2005).

9 COST ANALYSIS

9.1 Introduction

The economics may not always be the dominant driver in selecting a power generation system, especially for backup power, but are always a very important consideration. Initially, when first introduced to the market, the fuel cells were offered at a price point that was prohibitive to wide-scale deployment. In recent years however, the price of the fuel cells has declined dramatically to one that may be competitive with existing backup power solutions due to advancements in manufacturing, technology and volume of production.

This chapter focuses on a cost analysis of fuel cell systems for emergency power applications. It tries to define general trends in backup power system prices and provides an overview of some of the cost models. Finally, it analyzes the costs of the GenCore unit and compares it with some other products available on the market.

9.2 Is the fuel cell solution cost competitive?

There is no simple answer to this question. It depends on the requirements of the specific application. For example, if a relatively long run time is required (e.g. ≥ 8 hours) and using an engine generator is considered unacceptable, then a fuel cell solution may be attractive, especially where the average power requirement is relatively small (e.g. ≤ 20kW). The main reason for this is that the cost of batteries is a function of the energy required, whereas the cost of fuel cells is determined primarily by the power required. In other words, adding additional hydrogen storage is cheaper than adding more batteries. This is why telecommunication applications, and others with similar demands, look especially attractive for this solution, since there are many instances in which highly reliable backup power is required and the average power output is relatively small, but the run time requirements are relatively long (Perry and Strayer 2006)**.**

A number of studies have been published on the costs of backup power technologies and their comparison. The output results vary from study to study, and one shows a positive case for fuel cell and the next does not. What this means is that there are currently no definite rules on costs, with different systems from different manufacturers having different cost structures. When making an economic model or comparing the costs of different systems, it is important to take into consideration the Total Cost of Ownership (TCO), which can consist of the following elements:

- Capital cost;
- Installation/startup costs;
- Maintenance costs;
- Engineering costs;
- Fuel costs;
- Saved energy (offsetting fuel costs);
- Disposal costs at the end of life.

Some examples of the studies are included below.

Using a number of assumptions, APC modeled the TCO for generators, fuel cells and micro turbines. Given the cost data for equipment, installation, maintenance and energy, the TCO calculations were made for various technologies and operating modes in a 10 year lifetime, 250kW data center. The results are shown in Figure 9.1.

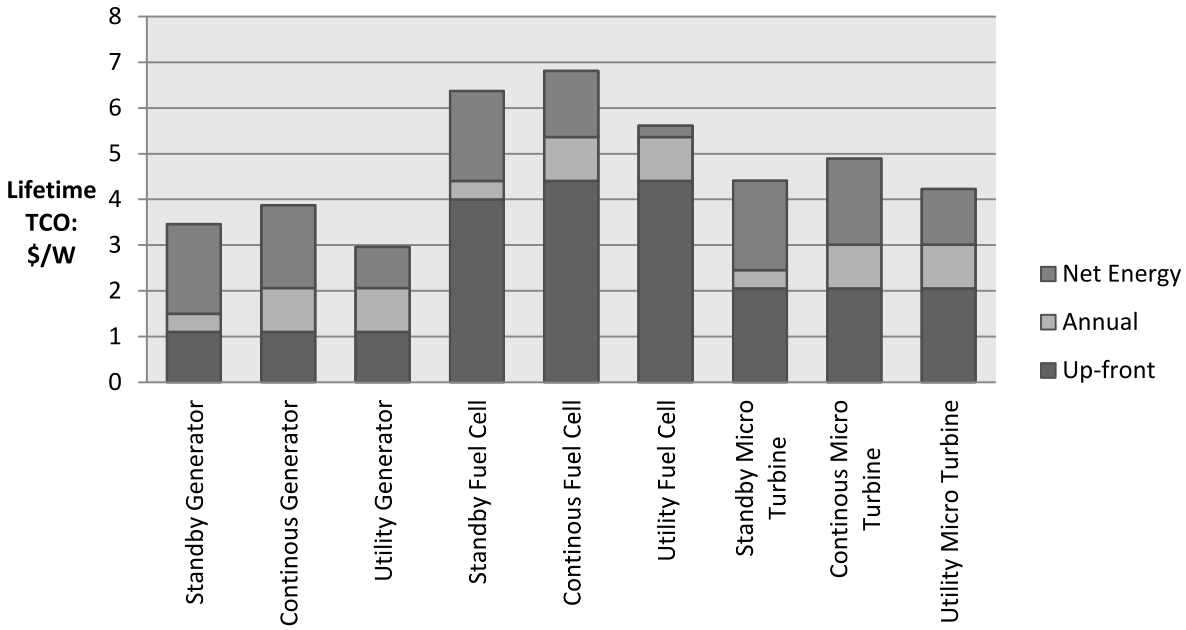

Figure 9.1 Power generation system TCO for various technologies and modes operation

What this figure shows is that under all conditions, fuel cells come out most expensive compared to rival technologies (American Power Conversion 2003)**.** It must be underlined that this model was made in the year 2003 and the data are not up-to-date, especially for new technologies. Technological innovations, research and development have dramatically reduced the costs of these solutions till now.

Another cost evaluation was conducted by the Bureau of Reclamation (BOR) during the tests of fuel cell backup power system in one of their sites, Pole Hill Power Plant, Colorado (chapter 2). BOR predicted the lifecycle cost of both storage batteries and fuel cell systems. Costs were calculated based on a 1kW load using a 7% discount rate and 4% inflation. The results are summarized in Table 9-1.

Table 9-1 Economic evaluation of fuel cell vs. VRLA battery over 10-year period made by BOR

	Runtime (hours)	**Initial Cost**	**Maintenance Costs**	**Replacement Cost**	**Total Cost**	**Fuel Cell Saving**
VRLA Battery	8	$13,400	$11,900	$5,000	$30,300	-24%
	24	$18,800	$11,900	$9,600	$40,300	6%
	48	$29,000	$15,400	$17,500	$61,900	39%
	72	$39,200	$17,100	$25,300	$81,600	54%
Fuel Cell	72	$31,700	$5,100	$900	$37,700	

The initial costs of the battery shown in the table include the cost and installation of the battery and its monitoring system. The monitoring system precludes monthly and quarterly maintenance. Battery maintenance costs shown in the table include onsite inspection every 6 months and capacity testing every 2 years. The battery is replaced on a 5-year schedule. Fuel cell costs include the cost and installation of the fuel cell, an outdoor enclosure, 7-year warranty, and on-site inspections and maintenance performed at 6-month intervals. The initial fuel cell cost is slightly greater than an equivalent battery for run times less than 72 hours. However the costs over 10 years will provide significant savings for run times greater than 8 hours. For the runtime period equal to 8 hours or less, the battery solution is less expensive (Myers and DeHaan 2005).

Plug Power, as a one of the world leader in fuel cell backup system production, also provides its own cost evaluation. A fuel cell system capable of supplying up to 5kW of power has an installed initial cost of $17,000 - $20,000. A battery backup system with equivalent power output typically has an installed initial cost of $15,000 - $19,000. Based upon a cost analysis, the initial capital cost of the battery solution may be lower than the initial cost of the fuel cell solution. However, ownership cost diverges sharply, with the lifetime ownership cost of battery backup nearing double that of the fuel cell system.

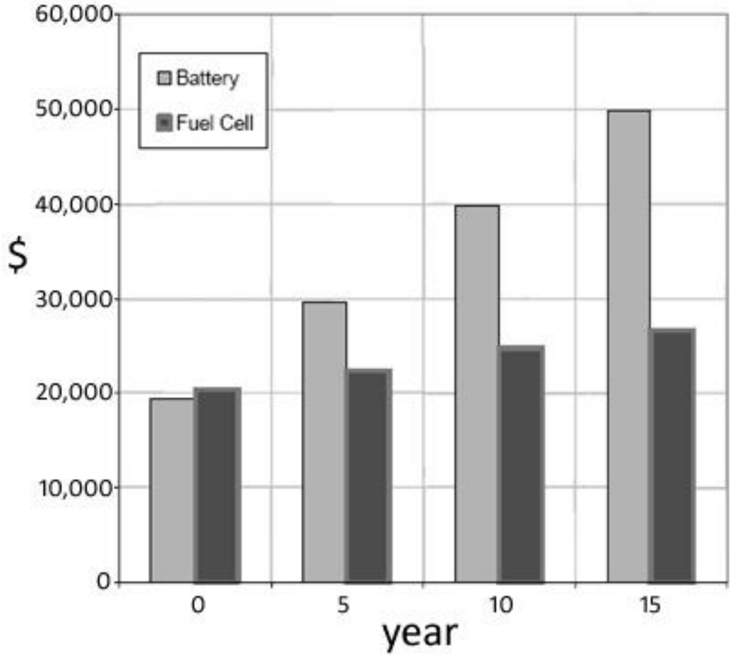

Figure 9.2 Cost comparison of battery installation and fuel cell technology made by Plug Power

These cost differences are primarily due to the heavy maintenance and replacement schedules associated with the battery backup system (Egbert n.d.; Plug Power n.d.)**.**

In a study for the U.S. Department of Energy, Battelle Memorial Institute analyzed lifecycle costs of emergency response radio towers, comparing fuel cells with 2kW battery-only backup of 8 hours and 5kW battery-generator backup of 52 hours, 72 hours, and 176 hours. Calculations assume a 5-year battery replacement schedule. Fuel cell systems with tax incentive prices were calculated with benefit of tax credit of up to $1000/kW.

Table 9-2 Net present value of total cost of backup power systems for emergency response radio towers

Runtime (hours)	**Outdoor Installations**			**Indoor Installations**		
	Battery/ Generator	Fuel Cell without tax incentive	Fuel Cell with tax incentive	Battery Only	Fuel Cell without tax incentive	Fuel Cell with tax incentive
8				$19,037	$14,023	$12,136
52	$61,082	$61,326	$56,609			
72	$47,318	$33,901	$32,014			
176	$75,575	$100,209	$95,491			

As shown in Table 9-2, on a lifecycle basis, fuel cells can provide service at substantially lower total cost than current technologies when runtime capability of up to three days is sufficient. The higher cost of the 176-hour fuel cell system results from the cost of hydrogen storage tank rental (Mahadevan 2007).

The explanation for the discrepancies between the different studies is the difference in the assumptions behind them. All of these costs are case-by-case and therefore potential adopters have to work the economics on an individual approach.

In summary, at this time fuel cell backup power systems are only cost effective for configurations requiring extended autonomy only. There are no significant differences between fuel cell and battery units in initial costs but they occur during system lifetime. With fuel cell technology, some costs can be dramatically improved by reducing periodic maintenance and subsequent costs associated with personnel providing emergency overtime. Fuel cell manufacturers also offer recycling programs for backup power systems that eliminates disposal issues. Finally, prices for fuel cell technology decrease constantly.

9.3 Project cost evaluation

Table 9-3 exhibits current prices for three of the most popular backup power systems on the market. It can be seen that, compared to the provided output basis, these prices vary a lot. It can be said which solution is the least expensive there is no point. Each of these systems offers very unique features and manufacturers try to attract customers with different services.

Table 9-3 Cost comparison of three fuel cell backup systems

	APC (InfraStruXure)	**ReliOn (I-1000)**	**Plug Power (GenCore 5B48)**
List price (2006)	$40,000 for the 10 kW system	$8050 per 1 kW system	$15,000 for the 5 kW system
Installed price (2006)		$31,000	$26,000

This project was based on a Plug Power GenCore 5B48 that was used in 2006 during a one year demonstration program at the international airport in Keflavik, Iceland. The Keflavik project costs included:

- Plug Power 5 kW GenCore: $14,915;
- Product training - GenCore (2 people): $5,000;
- Shipping: $3,992;
- Installation electrical: $5,074;
- Installation mechanical & thermal: $7,023;
- Instrumentation, data package: $1,494$;
- Site Prep, labor materials: $3,225;
- Technical supervision/Start-up: $3,500;
- Installation travel & Per diem: $18,154;
- Maintenance labor: $45,760;
- Hydrogen fuel: $4,097.

The total installed cost of the demonstration was $62,377. Actual operation and maintenance cost was $45,760. In total, including hydrogen fuel: $112,234 (LOGANEnergy 2007).

High cost was related to the specific purpose of that project as well as a few problems during unit installation and operation. In the case of the project described in this thesis, the overall cost is much lower and beside the unit itself, it is related only to hydrogen fuel, electrical installation and adaptation of the system to operate inside the building.

10 SUMMARY AND CONCLUSIONS

Availability and reliability of the power source are the core aspects of energy security. The market for backup power systems is predicted to increase in line with the increase in electricity grid instability in areas such as North America and Europe, as well as the growing development of nations like South Africa. Fuel cell technology has entered this application sphere because it offers a number of advantages over incumbent systems. At present, this technology is used when its benefits, such as reliable and extended operation in remote areas, overcome the main disadvantage of high capital costs. Fuel cell usage is growing fast in the backup power and especially UPS sector, with the expectation that it will continue to grow. So far, the only real market option is the PEM fuel cell. The vast majority of manufacturers works on this type of unit and has built up solid initial distribution networks for their products.

The GenCore 5B48 hydrogen fuel cell backup power system described here has a lot of advantages, which were illustrated in this report, but it has also some disadvantages.

One of them, which was discovered during this project, occurred while trying to update the firmware of the GenCore Control Card. The procedure caused some problems and the system failed to re-initiate after the first attempt at an update. It occurred that the reset button placed on the main board of the card was not working properly. After several tries the control card was restarted by connecting and disconnecting the battery power to the system. Old software had to be installed to start the fuel cell. This two-day failure showed how hard it can be to fix the system if any serious errors occur. Most of the components are non-serviceable and have to be ordered directly from Plug Power. This could compromise the project and leave it with no results.

Another disadvantage is that the 5B48 system is not designed to work inside buildings. This results in unnecessary startups of the heating system, which raises the temperature of the coolant to operating level (50°C). The fuel cell sometimes worked when the DC bus was already receiving power from the grid, providing power to the heating system to bring the temperature of the coolant up. It was caused by the operation algorithms, which require the system to run at least 15 minutes before the shutdown. It is also possible that the power supply included in the DC bus, which should serve as the power source for the auxiliary load of the fuel cell during standby mode, was insufficient. The power demand of the components could sometimes go up to 800W, whereas the power output of the supply was just 600W.

The Service Interface Software could have been designed better. First of all, it had troubles when only one bank of the hydrogen bottles was used in the Chemical Energy Storage Module. This caused the Low Fuel warning to appear, even if there was still pressure in the bank currently connected to the system. The user interface was not perfect – the layout of the windows could have been more user friendly. It also lacked the conversion to metric units (bars, meters, etc.). Logging was not reliable, and setting the interval to, for instance, one second, did not guarantee, that it would save the data during that time.

Unfortunately it was not possible to check the updated software, due to the reasons described above, and most of these mistakes could have been corrected in the newer versions of the software. The system evaluated and tested in this project is an old model, constructed in 2004. Since then, much progress in the development of fuel cells and fuel cell systems was made; therefore most of these disadvantages could have been corrected in the updated versions.

Realization of any project always requires some safety precautions. In case of work related with an alternative fuel type, this rule is especially true. During this project a few safety actions were taken. They included technical aspects, such as installation of safety systems and components. Where possible, each of these components was tested, and all of them fulfilled their tasks. One of the additional goals was spreading awareness and education among people in the workplace, which is particularly important when dealing with new technology.

Measurements and obtained results describe the primary and most important features of the system, such as electric characteristics, efficiency, fuel usage, operation during start-ups, and reliability. However, in order to fully characterize the GenCore system, a few more tests should be done to establish the operational limits and investigate problems in the safety of the system. These tests should be based on simulations of out of tolerance and system failure scenarios, such as operation under extremely bed environmental conditions, operation under much higher load than can be supplied, failure or malfunction of any system components, behavior under the low pressure hydrogen gas, overpressure, or no gas supply, and a few others. These kinds of tests were not performed due to limitations in equipment but also in project budget and time.

The cost of the system is always a very important aspect, especially for the commercially emerging and new technologies, which have to compete with existing and well understood ones. Hydrogen fuel cell systems have a real chance to win this competition in a few emergency power application sectors.

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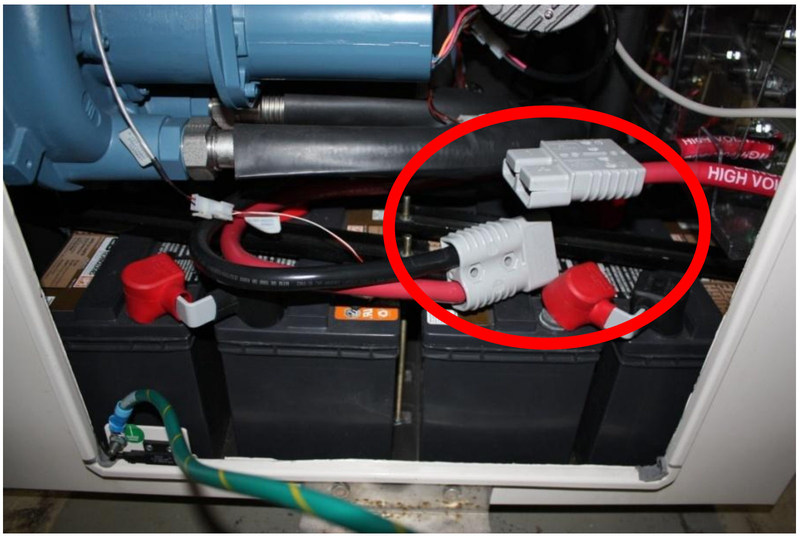
APPENDIX A

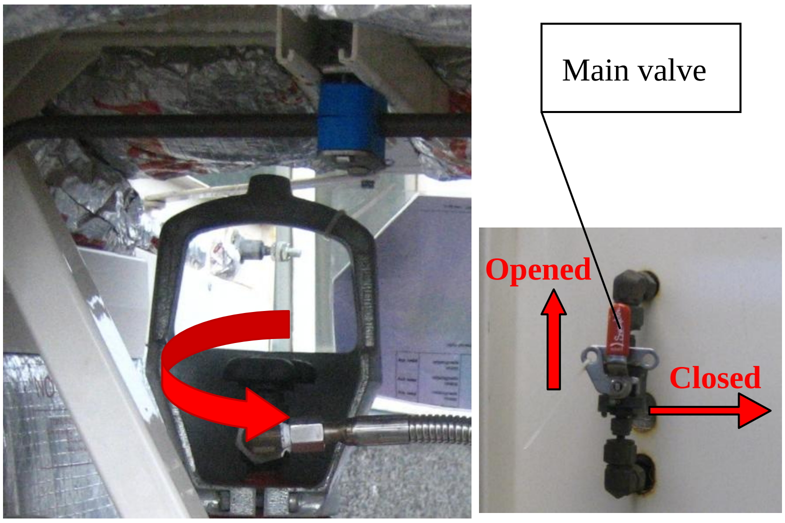
Operation manual

1. Open all doors in the system (front and back, with batteries).
2. Make sure the system is powered down:
    a. the connector and corresponding socket in the back of the system are disconnected;

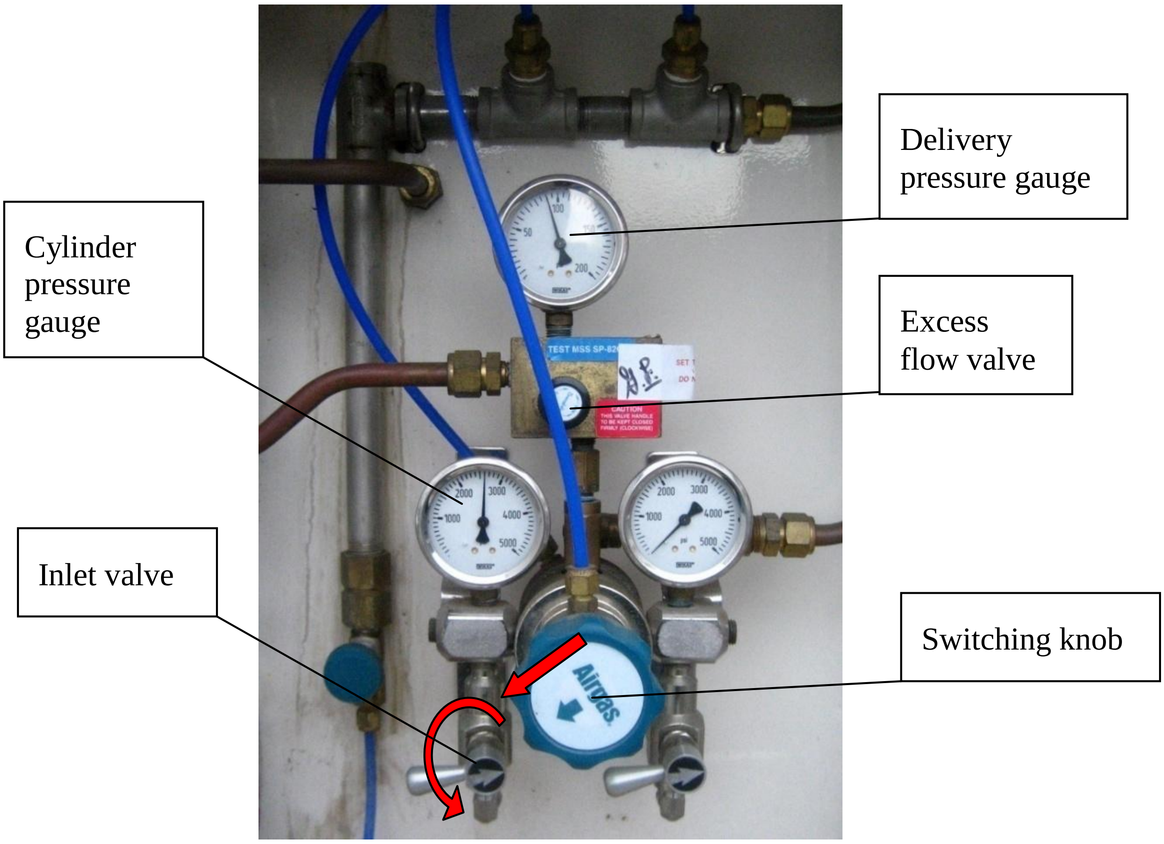


    b. fuel cell is isolated from the DC Bus – site disconnect switch is positioned on the **off** side (left).

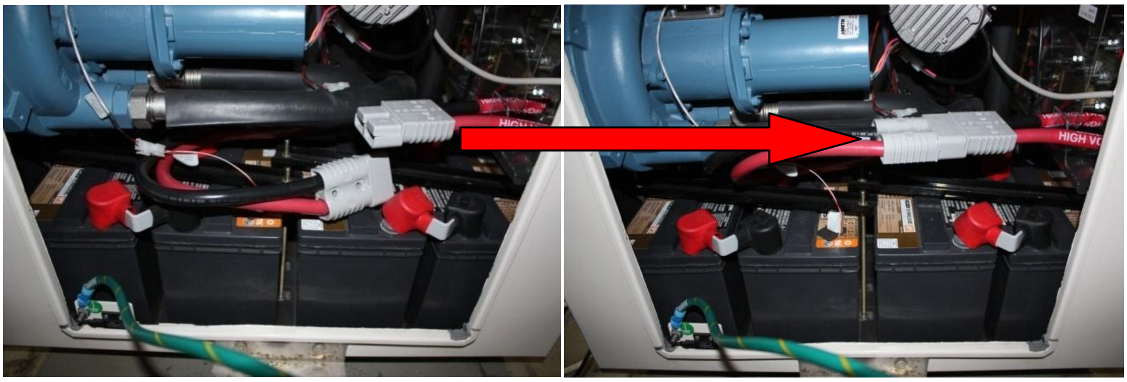
3. Make sure that there is a bowl to gather the exhaust water from under the fuel cell.
4. Before opening any valves, one should be sure that the outside main valve is in the closed position. To provide hydrogen to the system several valves have to be opened:
    a. Valve on the hydrogen bottle;



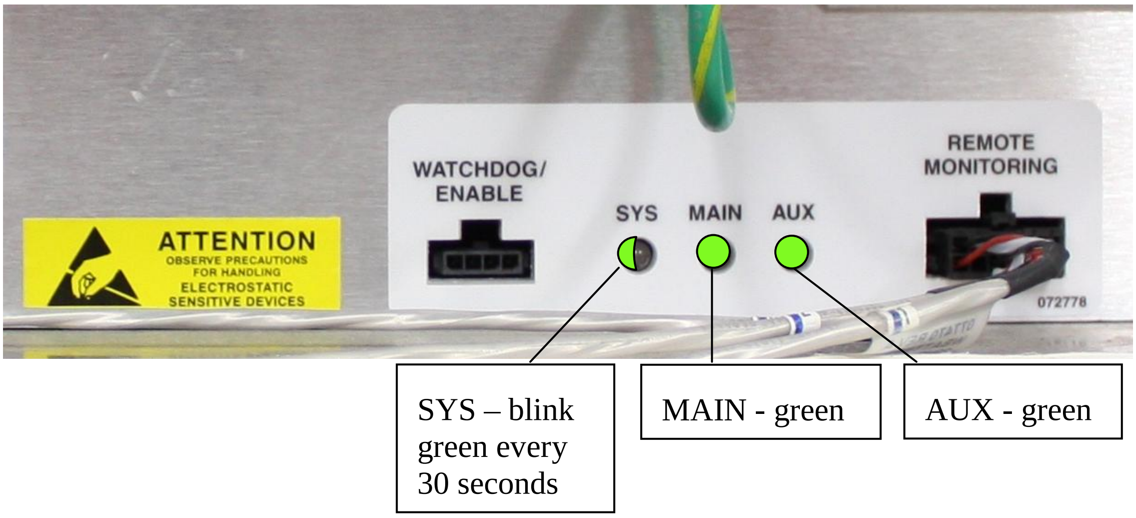
    b. Valves and gauges in front of the Chemical Energy Storage Module – the arrow on the left inlet valve should point up and the switching knob should point left. The cylinder pressure gauge should show no less than 1400 psi, which is half of the maximum pressure of the bottle. The delivery pressure gauge should show about 80 psi. If the fuel cell system is not used for some time, it may be necessary to open the excess flow valve for a few seconds. When the pressure goes back to operating values, the outside lockout valve (4.a) should be opened.



5. With the hydrogen flowing to the system, it is now time to turn it on.
    a. The matching plug has to be inserted into the battery socket in the back of the fuel cell. This will start the system.

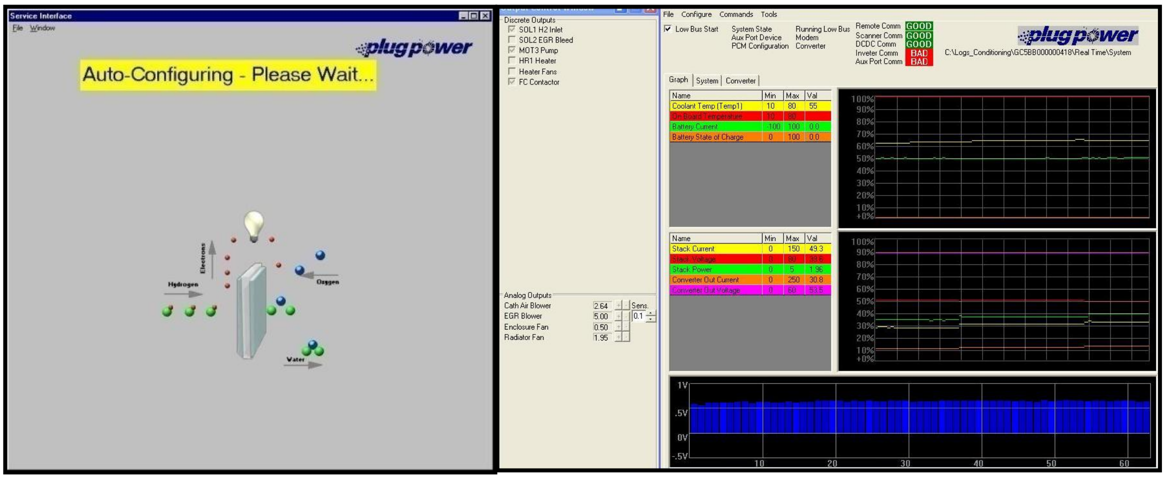


    b. Now, the lights on the GenCore Control Card should be green, also the led lights on the DC/DC converter in front of the fuel cell system should be lit up in this configuration:



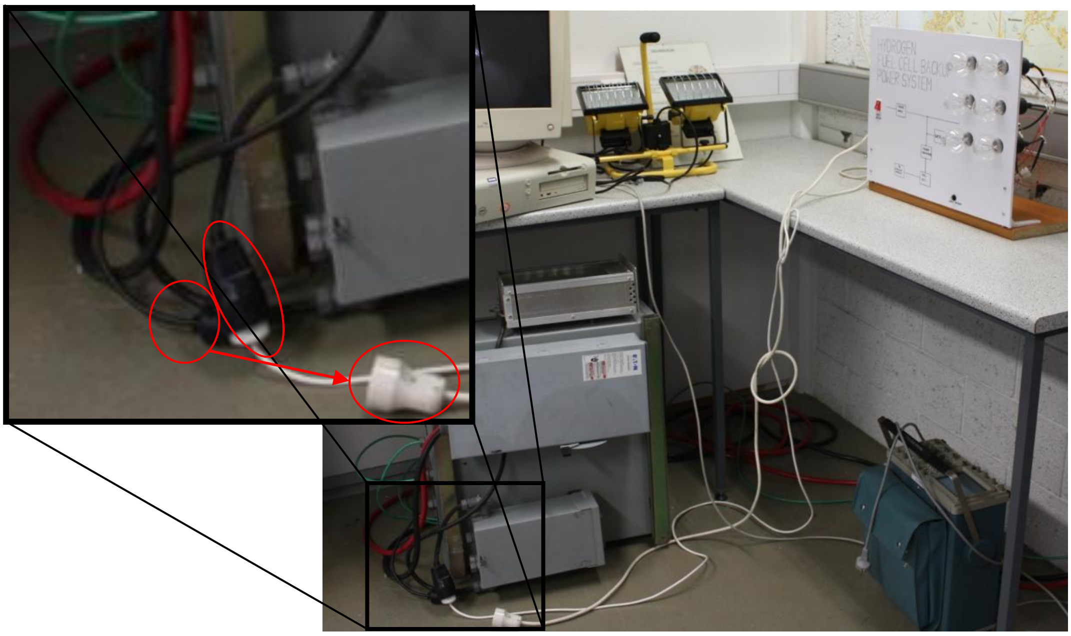
    c. It is also necessary to connect the system to the DC Bus by closing the site disconnect switch.

6. The Fuel Cell System should now be ready for operation. To properly turn it on a few actions are necessary.
    a. First of all, a personal computer or laptop with RS-232C serial port is needed to connect the system to the computer. The software is installed on the computer in the room where DC Bus is. The serial cable needs to be plugged in to the first serial port in the back of the computer. There is also a shortcut to Service Software Interface on the desktop. The splash screen with fuel cell animation should appear for a couple of seconds after starting the program. It should disappear, and the main window of the software should now be visible.

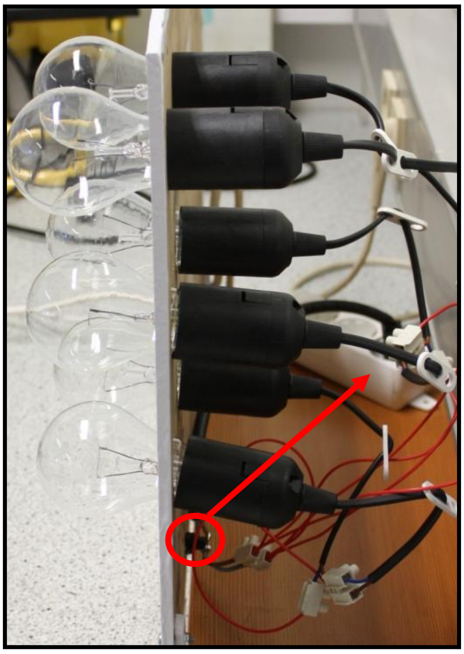


Splash Screen   Main Window

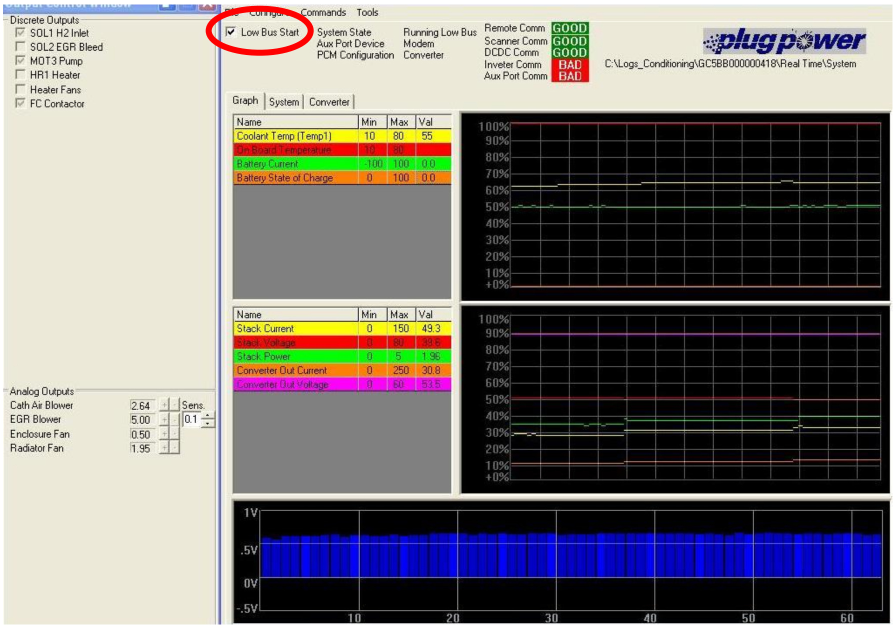
    b. Some errors can occur (low fuel error and/or data transfer error). From our experience it seems that these can be neglected, as they are connected to a different configuration of storage module.
    c. It is now necessary to turn on the power supply in the DC Bus. To do this, a cable from the demonstration board must be connected to the corresponding socket in the DC Bus. At the same time, the output cable from the fuse box of the DC Bus has to be connected to the cable coming out from the power divider behind the demonstration board, where the load will be connected.



d. The cable from the main switch on the demonstration board has to be plugged in to an ac grid and the cable from the load on/off button has to be plugged in to the power divider in the back of the demonstration board.

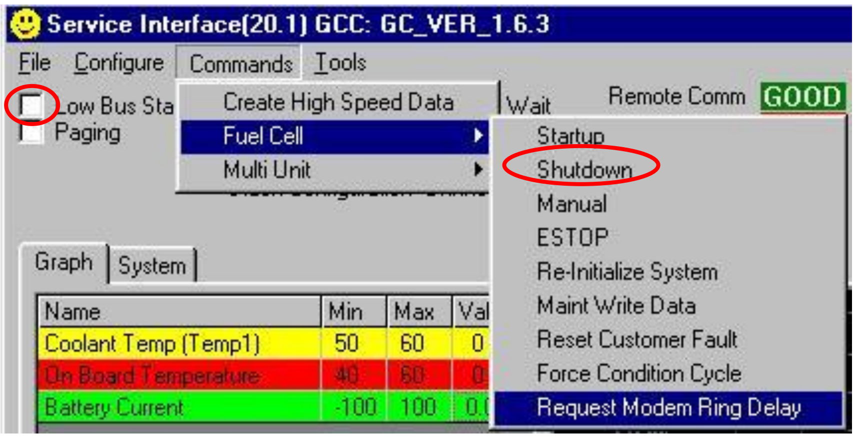


e. Switching the grid switch on the demonstration board will turn on the power supply of the DC Bus. The lights can also be turned on and off, but the fuel cell will not start yet. The Low Bus Start option has to be ticked in the service software interface for the fuel cell to be able to provide power to the load in case of grid failure. For other options of the software, refer to the *Service Interface Software Manual.*



7. To simulate grid failure, the grid switch on the demonstration board has to be turned off and the lights should be turned on. With the Low Bus Start option enabled, the batteries of the system will start providing power to the load. After few seconds, when the fuel cell is ready, it will take over the load.

8. The system is designed in such a way that it has to work for at least 15 minutes to automatically power down in case of power returning to grid (Main grid switch turned on). In order to shut it down manually, the *Shutdown* option has to be picked from *Command* → *Fuel Cell* menu. After that, it is a good idea to unmark the Low Bus Start option.



9. The software can be closed now, and the RS-232C cable can be disconnected from the computer.
10. Now all the systems have to be powered down.
    a. The DC Bus has to be disconnected from the grid by turning off the Grid switch (refer to point 6.d) on the presentation board;
    b. The Site disconnect switch has to be switched to the *off* position (2.b);
    c. The System batteries have to be disconnected from the corresponding connector in the back of the fuel cell(5.a);
    d. The main lockout valve on the Chemical Energy Storage Module has to be turned into the *closed* position (4.a), the inlet valve can be closed (4.b) and the main cylinder valve has to be closed (4.a).

APPENDIX B

Plug Power GenCore 5B48 Hydrogen Fuel Cell Backup Power System parameters

Attribute	Description	Specification
Performance	Rated Net Output	0 to 5000 W
	Adjustable Voltage	+46 to +56 V DC
	Operating Voltage Range	+42 to +60 V DC
	Operating Current Range	0 – 109 A
	Maximum load drawn from DC Bus when system is in standby	800 W
	Nominal load drawn from DC Bus when system is in standby	25 W
Alarm	Digital Output Alarm	24 V DC (maximum) at 0.05 A (by means of an opto-coupled MOSFET)
Fuel	Gaseous Hydrogen Supply	99.95% Dry
	Pressure	5.5 barg ±1 barg
	Fuel Consumption	36 slm at 3000W 64 slm at 5000W
Operation	Ambient Temperature	-40°C to 46°C
	Relative Humidity	0% to 95% Non-condensing
	Altitude	-60m to 1.8km
Physical	Dimensions	112cm x 66cm x 61cm)
	Weight	213kg
Emissions	Water	Maximum 2 liters per hour
	CO, CO_2, NO_x, SO_2	<1ppm
	Audible Noise	60db @ 1m