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Degradation in PEM Fuel Cells and Mitigation Strategies Using System Design and Control

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Additional information is available at the end of the chapter

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Abstract

The rapid miniaturization of electronics, sensors, and actuators has reduced the cost of field sensor networks and enabled more functionality in ever smaller packages. Networks of field sensors have emerging applications in environmental monitoring, in disaster monitoring, security, and agriculture. Batteries limit potential applications due to their low specific energy. A promising alternative is photovoltaics. Photovoltaics require large, bulky panels and are impacted by daily and seasonal variation in solar insolation that requires coupling to a backup power source. Polymer electrolyte membrane (PEM) fuel cells are a promising alternative, because they are clean, quiet, and operate at high efficiencies. However, challenges remain in achieving long lives due to catalyst degradation and hydrogen storage. In this chapter, we present a design framework for high-energy fuel cell power supplies applied to field sensor networks. The aim is to achieve long operational lives by controlling degradation and utilizing high-energy density fuels such as lithium hydride to produce hydrogen. Lithium hydride in combination with fuel-cell wastewater or ambient humidity can achieve fuel specific energy of 5000 Wh/kg. The results of the study show that the PEM hybrid system fueled using lithium hydride offers a three- to fivefold reduction in mass compared to state-of-the-art batteries.

Keywords: sensor networks, degradation, design, control systems, hydrogen storage

1. Introduction

Field sensor networks have many important modern-day applications. This includes monitoring, exploration and mapping of inaccessible and pristine environments. Field sensor networks have deployed for monitoring climate-change, including air quality, water quality and soil erosion (**Figure 1**) [1]. These devices are emerging as important tools in

disaster prediction, including measuring winds in a hurricane, measuring rising seawater from storm surges, inland flooding, sea-erosion, monitoring spread of forest fires, monitoring avalanches, earthquakes, volcanoes and tsunamis [1]. Field sensor networks may also provide timely real-time field data that may feed into computer models for advanced prediction, planning, including timely efforts to evacuate a population and provide post-recovery damage assessment.

Field sensor networks have important applications in the emerging field of precision agriculture (**Figure 1**), where hundreds or thousands of sensors provide periodic monitoring of soil humidity, plant growth, health, and soil nutrition to provide accurate predictions for harvest, enable healthier, higher return on crops and mitigate plant diseases and losses.

In the field of security, field sensor networks have important applications in securing borders, by providing continuous monitoring of border regions including above, below and at ground, for illegal entry, smuggling of people, goods and controlled substances (**Figure 1**, right). There are similar needs to monitor high-security facilities for intruders. For security applications, several hundreds or thousands of modules might be deployed over large areas, including border regions and wirelessly report their data to a base-station.

Another new emerging application is Space Situational Awareness (SSA). There is an ever-growing need to continuously monitor incoming objects from space, including spacecraft debris re-entering the earth's atmosphere and meteors. For this, a camera is mounted to a robotic telescope that scans and tracks incoming objects of interest. Using this footage, it is possible to determine where the object will land and impact the ground and determine its origin/source.

To be practical, once deployed, field sensor network modules need to operate unattended, ideally for years. A key to making these sensor systems practical and ready for wide-scale use is the need for high-energy power supplies.

Significant advancements have been made in the miniaturization of electronic devices, sensors, actuators and radios. However, current power supplies typically depend on rechargeable



Figure 1. Field sensor networks have important applications in environmental monitoring and precision agriculture including monitoring of water, air and soil health (left). They are playing a critical part in continuous observation with emerging applications in border security (right) and space situational awareness.

battery technology and in rare instances, primary non-rechargeable batteries. Current battery technology alone does not meet the needs of many of these field systems due to their low specific energy. This is despite the fact that conventional batteries have made substantial improvements over the past 30 years in terms of specific energy, overall reliability and power density. Furthermore, rechargeable batteries have made significant advances in terms of charge-discharge cycle-life and shelf-life. For long life applications, batteries need to be recharged or replaced often. This presents a major challenge in remote environments with limited accessibility. Significant work is being done to address the energy limits of current batteries [2, 3] but current trends show that batteries cannot meet the high-energy requirements of long duration field sensor networks.

Photovoltaics are another source of power for field sensors but they are bulky, require periodic maintenance such as cleaning of panels and require high solar insolation throughout the year. However, plummeting market prices of solar panels from the late 1990s onwards make them one of the leading options for powering environmental sensors. The challenges remain in powering the sensor when sunlight is not available, including during inclement weather and night time. Another alternative is a wind generator. Wind generators have become attractive due to their low-cost of construction compared to other renewable power sources. Wind generators maybe practical in certain natural environments such as coastlines, mountain passes and flat plains. Due to their large footprint and need for periodic maintenance, they are only promising for certain field applications and climate conditions.

Daily variabilities experienced by both photovoltaic systems and wind power generators, mean that these generators need to be coupled with a battery to store excess capacity and kick-in when there is an input power shortage. However, these rechargeable batteries increase the cost, complexity and reduce system robustness. These rechargeable batteries cannot provide power when there is a prolonged power shortage. Hence, the system needs to be designed to predict these shortages and have sufficient battery capacity to handle them.

Energy harvesting using piezoelectric generators has been another popular choice proposed for field sensors, but have yet to be practically applied. These generators require a steady source of vibrations and are suitable only for a limited number of low-power applications. These limitations identify the need for a high-energy power supply that can provide a steady source of power, rain or shine for long durations, in the order of years.

Here we consider use of fuel cells as high-energy power supplies for low-power field sensor networks. Fuel cells are electrochemical energy conversion devices that convert chemical energy directly into electrical energy [4, 5]. **Table 1** shows common fuel cell technologies. Unlike a battery, fuel cells must be constantly fed with fuel and oxidizer to produce electricity. There are different types of fuel cells based on operational temperature, type of electrolyte, fuel and oxidizer used. Some of the fuel cells listed utilize low-cost fuels such as natural gas, methanol and gasoline. However, they operate at high temperatures and produce CO₂. This makes them unsuitable for use in pristine environments and indoors. Alkaline, Polymer Electrolyte Membrane (PEM) and Direct Methanol Fuel Cells (DMFC) all operate at low temperatures. It

Fuel cell	Electrolyte	Operating temperature (°C)	Electrical efficiency (%)	Fuel oxidant
Alkaline fuel cell (AFC)	Potassium hydroxide solution	15–90	20–60	H ₂ , O ₂
Proton exchange membrane fuel cell (PEMFC)	Proton exchange membrane	15–80	40–70	H ₂ , O ₂ /Air
Direct methanol fuel cell (DMFC)	Proton exchange membrane	15–130	20–40	CH ₃ OH, O ₂ , Air
Phosphoric acid fuel cell (PAFC)	Phosphoric acid	160–220	55	Natural gas, bio gas, H ₂ , O ₂ , Air
Molten carbonate fuel cell (MCFC)	Molten mixture of alkali metal carbonates	620–660	65	Natural gas, bio gas, gasoline, H ₂ , O ₂ , Air
Solid oxide fuel cell (SOFC)	Oxide ion conducting ceramic	800–1000	60–65	Natural gas, bio gas, gasoline, H ₂ , O ₂ , Air

Table 1. Common fuel cell technologies.

should be noted that there exist high-temperature PEM fuel cells [6]. However, Alkaline fuel cells operate at lower efficiencies and require an electrolyte which requires relatively large containers/casing. However, Alkaline fuel cells are known to be reliable having been used as a power source on several spacecrafts [7]. It is the bulky size and low-operating efficiencies that makes Alkaline fuel cells less attractive for sensor networks.

However, two of the remaining technologies including, PEM fuel cells and direct-methanol fuel cells are both attractive for sensor networks. Both operate at low-temperatures and are quiet. PEM fuel cells are relatively more mature and can operate at cell efficiency as high as 60–65%. They react with hydrogen and oxygen to produce electricity. The storage and release of hydrogen is typically a challenge. However, there are new practical solutions that are simple, that offer high specific-energy, low-temperature solutions. Oxygen is obtained directly from the air or pressurized storage tanks or chemical sources.

Direct methanol fuel cells use methanol and oxygen from the air to produce electricity. They tend to have lower efficiencies than PEM, longer start-up times and produce carbon dioxide and water. However, direct methanol fuel cells are attractive, because methanol is relatively easy to produce, store and has higher energy densities than conventional hydrogen storage methods. The main challenge with direct methanol fuel cells is an inherent limitation with the fuel-cell design compared to PEM. Direct methanol fuel cells produce CO₂ as a waste product. This requires an effective ventilation system to prevent build-up of CO₂. CO₂ can build-up in the fuel cell and dissolve in the water to form carbonic acid, a mild source of corrosion and degradation of fuel cell components including the membrane and carbon support layer. A second source of CO₂ induced degradation is from the formation of CO from high enough concentrations of CO₂ around the fuel cell. Together, these sources can cause high rates of cross-over resulting in lower operating efficiencies and unreliability. PEM fuel cells using hydrogen and oxygen are more attractive compared to the other fuel cell technologies for sensor network applications.

However, PEM fuel cells are not widely used in field applications because they face significant hurdles. Firstly, PEM fuel cells are faced with the problem of degradation of their components that result in shortened lives and lower reliability compared to batteries. A second major challenge is the storage of hydrogen [8]. Conventional methods of hydrogen storage are bulky and inefficient, providing only a marginal advantage over current batteries. A third major challenge is that the fuel cell produces lower power compared to batteries. A fourth challenge is that PEM fuel cells have high capital and operating costs. Significant progress is being made in all these areas. Our research addresses the first three challenges.

In this chapter, we present PEM fuel cells as a promising solution to powering sensor networks for long duration. The PEM fuel cell power supply is implemented as a fuel-cell hybrid system, held under controlled conditions to maximize life, maximize cell operating efficiency and minimize component degradation. This method enables the fuel cell power supply to achieve conversion efficiencies of 60–65% and lives of 3–5 years. The fuel cell is supplied with hydrogen fuel from a water activated lithium hydride hydrogen generator that freely extracts water vapor from the air. This method offers a theoretical specific energy of 5000 Wh/kg, more than 40 times conventional lithium ion batteries [9–11]. Our experimental studies show specific energy of 4200 Wh/kg being achieved. Through several case studies, we show that through effective design and control a fuel cell power supply can be superior to conventional batteries for field sensor network module applications.

The remainder of this chapter is organized as follows. Section 2 presents background and related work. Section 3 presents power management, air management and fuel management design and control of the PEM fuel cell power supplies to achieve long life. Section 4 presents several case studies and compares conventional fuel cells technologies and batteries to the proposed technology followed by conclusions in Section 5.

2. Background

In this section, we analyze the major challenges facing fuel cells in order to effectively apply them for field sensor network applications.

Fuel cells have been proposed as power systems for sensor networks. An important factor in their selection addressed earlier in the chapter is that they are clean, are efficient, offer high energy density and are quiet [4, 5]. Most of these properties make them suitable for deployment in sensitive, pristine environments. In contrast, conventional primary batteries pose concern of leakage into the environment. This makes fuel cells a credible choice for environmental sensing. Proposed technologies for powering sensor networks in the field include polymer electrolyte membrane (PEM) fuel cells (**Figure 2**), direct methanol fuel cells (DMFC) and microbial fuel cells [4, 5, 12–14].

2.1. PEM fuel cell applications

PEM have been proposed as low-power sources for use in the field [10, 15–17]. Impressively, MEMs scale PEM fuel cells have been fabricated and tested for this purpose [18]. These

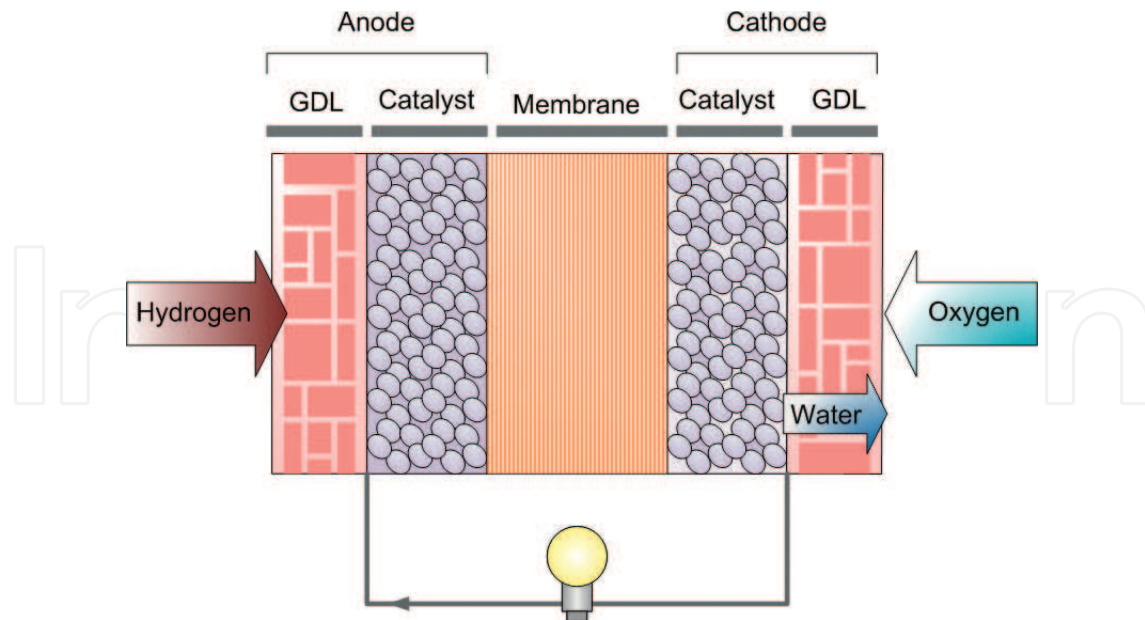


Figure 2. A Polymer Electrolyte Membrane (PEM) fuel cell and its major components.

systems integrate several components of a fuel cell power supply into a chip sized wafer, including the fuel and oxygen source. These fuel cells have been shown to operate for a few hundred hours, though long-life experiments have yet to be tested.

Further, this system trades-off small size for performance, including current density. Control of these fuel cells is performed typically using passive systems that self-regulate fuel dispensation and oxygen flow. Another work by Chraim and Karaki proposes uses of PEMs for sensor networks [15]. One of the major challenges in the implementation of PEM fuel cells for field applications is the storage of hydrogen. Several works have proposed use of metal hydrides from canisters. One approach involves utilizing an ambient power sources to electrolyze water into hydrogen and oxygen [16]. The stored hydrogen and oxygen are fed to a fuel cell providing continuous power [16]. Another proposed application [19] demonstrates a hybrid system where a fuel cell recharges a battery that is in turn used to power a sensor network. The fuel cell in this system is used to keep the battery topped up. Our work identifies some of the additional benefits of this technology particularly to avoid oscillations in fuel cell voltage that limits life.

2.2. Large scale and stationary backup power generation

Current PEM fuel cell control techniques are designed for stationary [20], large-scale power generation applications and use conventional feedback control, gain-scheduling and set-point-tracking approaches towards operating fuel cells [21]. In these configurations, the fuel cell voltage may vary drastically depending on the power demand. Large variation in fuel cell voltage according to our models can substantially shorten life [11]. Fuel cell battery hybrid systems are a promising solution to this problem. In our proposed approach, the fuel cells are small, low-power and operate at constant operating voltage. The fuel cell constantly charges a battery that handles the high and varying loads. The battery protects the fuel-cell from external oscillations

in load that shorten life. In addition, the battery provides a burst of high-power depending on the load demand. A constant operating point simplifies air, fuel and water management, instead of requiring active control methods as in [21].

2.3. Microbial fuel cells

Microbial fuel cells [12] use microbes and their metabolism to generate electricity. They are well suited for swamps, ponds and even reservoirs containing waste water. Although the power density tends to be low, the system benefits from its relative simplicity [12]. A key challenge though is the maintaining the well-being of the microbial organisms to ensure sufficient power is generated. Death of a microbial colony due to disease or change in environmental conditions can have a significant impact on the microbial fuel cell and hence requires periodic human oversight/tending [12].

2.4. PEM fuel cell degradation

PEM fuel cells became the focus of our interest in high-energy power supplies because it is one of the more mature technologies and shows significant potential for both high-energy and long-life applications [4, 5]. A PEM fuel cell membrane electrode assembly (MEA) has several major components that are all subject to degradation (**Figure 2**). They are the gas diffusion layer (GDL), bi-polar plates, the membrane and catalyst layers. The GDL facilitates transfer of input gasses to the anode and cathode. The bi-polar plates have an important role in distributing the reactant gasses to the anode and cathode, conduct electrical current within the cell and help to remove heat from the active area, while preventing leakage of gasses [22]. The anode catalyst layer facilitates the oxidation of hydrogen molecules into protons while the membrane allows for the transport of protons from the anode to the cathode. The cathode catalyst layer facilitates the assembly of protons and oxygen molecules into water via a reduction reaction.

2.4.1. Gas diffusion layer (GDL) degradation

Extensive research has been done to identify the mechanisms that degrade fuel cell components. GDL degradation affects the ability of the cell to absorb reactants. This degradation includes loss of hydrophobicity of the cathode that results in flooding [23] causing loss in performance. Degradation of the GDL can reduce or block gas passageways resulting in choking of the fuel cell. A major source of GDL degradation has been due to mechanical compressions resulting in stress and strains that reduce the micro-pore regions [24]. This reduces gas transport and thus reduces the effectiveness of the GDL. Freeze thaw cycles are well known to damage the GDL as freezing water expands and damages the micro-pores. Another source of damage to the GDL is the loss of polytetrafluoroethylene (PTFE) [5, 24]. PTFE is used to maintain gas passages by repelling water using its hydrophobic properties. The PTFE is weakly bonded to carbon fiber material and therefore high-temperature and humidity can slowly attack and damage the carbon support holding the PTFE. Corrosion of the carbon layers due to oxidation and due to dissolution of the platinum catalyst can slowly erode the PTFE layers. For long duration fuel operations, the major degradation mechanism ends up being GDL degradation particularly the gradual loss of the PTFE [5, 24].

The erosion of the PTFE results in accumulated flooding in the fuel cell [24]. Flooding is known to cause corrosion of various components of the fuel cell including the catalyst [25]. Structural damage, such as from freezing [26], mechanical stress, wear and tear of a GDL can reduce the cell's ability to absorb fuel or oxidizer [27] and thus reducing a cell's performance and resulting in catalyst degradation. However, it should be noted that many of these sources of GDL degradation can be prevented by avoiding such conditions as structural damage, flooding or freezing.

2.4.2. Membrane degradation

Membranes are also subject to degradation and can be classified into three categories, thermal, mechanical and chemical [27–30]. An important source of membrane degradation is due to mechanical stress and strain. The root cause of this degradation is flooding [31]. Membranes once weak are prone to formation of pinholes that result in fuel cross-over and significant reduction in power generated. This is followed by catastrophic failure of the fuel cell [28, 32]. Mechanical stress and strain is known to occur due primarily to humidity and temperature cycling [32]. Humidity is known to impact the mechanical properties of the membrane. With too high a humidity, the membrane curls up and with too little humidity the membrane hardens and dries out. The impact of relative humidity cycling can be severe. It has been shown that a membrane cycled between a Relative Humidity of 30 and 80% faces structural failure after only 100 cycles [32]. A second source of membrane degradation is due to chemical attack [28]. The result from chemical attack is reduced strength of the membrane leading to structural failure.

In addition, membranes can degrade due to migration of impurities, particularly catalyst particles that deposit in the membrane. This can result in local structural weak points that cause pinholes, permitting cross-over of reactant gasses and their direct combustion of the reactants causing loss of power, rapid increase in temperature and fuel cell death [32]. The root cause of the above failure is the particles produced by catalyst degradation in the cathode. Hence in many cases platinum catalyst degradation in the cathode is an important factor in fuel cell durability and life [27]. One cause of catalyst degradation is the dissolution of the platinum particles into ions [27]. The ions either redeposit on large platinum particles (similar to Ostwald ripening) or dissolve and migrate away from the catalyst layer and into nearby regions [33]. Sustained degradation reduces the available catalyst surface in the anode and cathode resulting in loss of power.

2.4.3. Catalyst degradation

In many cases, platinum catalyst degradation in the cathode is an important factor in fuel cell durability and life [27, 34]. One cause of catalyst degradation is the dissolution of the platinum particles into ions [25, 27, 34, 35]. The ions either redeposit on large platinum particles or dissolve and migrate away from the catalyst layer and into nearby regions [33]. Sustained degradation reduces the available catalyst surface in the anode and cathode resulting in loss of power. It also weakens the carbon support structure that holds the platinum and vice-versa through corrosion of the carbon particles [33, 36].

Carbon corrosion is another important source of degradation in a fuel cell [25]. The carbon structure breaks into particles that migrate into the membrane and GDL. The migrating platinum

catalyst and carbon particles weakens the membrane structure as discussed above, causing irreversible structural damage ultimately resulting in tears and pinholes. The fuel cell catalyst is impacted by the oxidation of the platinum particles. Oxidation of the platinum particles results in the formation of surface films of platinum oxide that effectively reduces the available catalyst surface area resulting in loss of power. While oxidation of platinum reduces the surface area, it is also known to protect platinum particles beneath the oxide layer from dissolution.

Early empirical models attempted to capture the effect of catalyst degradation and the resultant power loss based on hours of operation [37]. These models are incomplete and do not account for the fuel cell operational factors that results in catalyst degradation. Several models of fuel cell electrochemical interactions account for platinum catalyst degradation [34, 38]. They capture the physics of the rate of dissolution and oxidation of the platinum particles. These models show the significant effect of fuel cell operating voltage on catalyst degradation [34, 38]. In these studies, the fuel cells are analyzed for conditions where the fuel cell's output voltage is varied in a square wave oscillating between 0.87 and 1.2 V. These conditions are intended to represent oscillatory voltage conditions relevant for PEM fuel cell powered automobiles [34]. It should be noted that voltage oscillation experiments have strong influence on the fuel cell cathode than the anode due to the slower reaction and reciprocal higher resistance of this electrode.

We focused on developing a physical model of fuel cell catalyst degradation that matches existing experimental data, enabling us to make long term predictions of life and performance under field conditions [17, 34]. As discussed above, PEM fuel cells are delicate and require balancing various system parameters such as fuel flow rate, temperature, humidity and operating voltage within a narrow operational window. Operation outside of this narrow window can result in irreversible damage to a fuel cell.

2.5. Hydrogen storage

Another major challenge as noted earlier is hydrogen storage. High pressure and cryogenic storage of hydrogen are clearly impractical for small, low power applications such as sensors networks. A third practical option is the use of metal hydrides. Conventional reversible metal hydrides release hydrogen through changes in pressure or temperature. An alternate option is the use of chemical hydrides that release hydrogen through chemical reaction [39]. While reversible hydrides are valued because of their ability to be recharged with hydrogen, they are not ideal for long-life field applications because they normally have low hydrogen storage densities (defined as the weight of hydrogen divided by the total weight of the hydride) on the order of 1–2% [40]. However, there exists other higher hydrides with much higher yield but they require much higher temperatures, in the order 200–700°C. Achieving such high temperatures for small, low-power devices limits the potential field applications and increases complexity.

Hydrolysis is the reaction of chemical hydride with water to produce hydrogen [10, 39]. However, popular water activated metal hydrides including sodium borohydride (NaBH_4) [41] and magnesium hydride (MgH_2) [42] have low hydrogen content, low-reliability and require expensive catalysts. Alternatives such as calcium hydride do not require catalyst but have low yield. Our research has focused on lithium hydride (LiH) which has higher net hydrogen content by mass than calcium hydride. Hydrogen can be released by exposing lithium hydride to

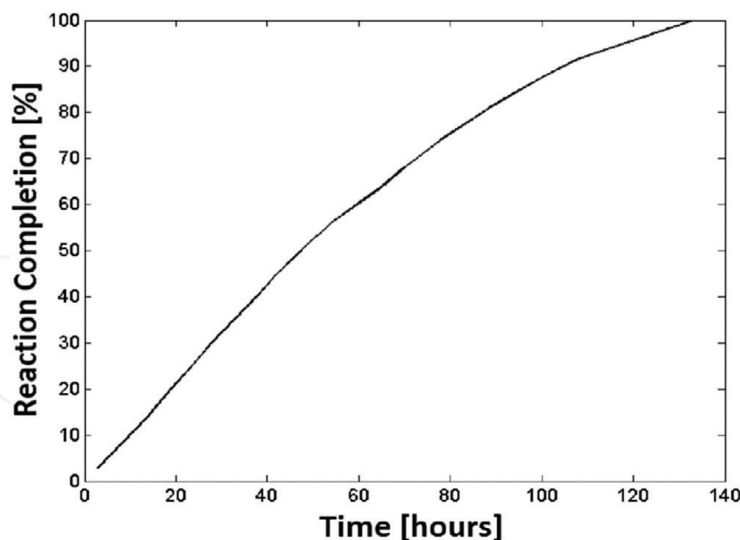


Figure 3. Lithium hydride hydrolysis reaction with water. The reaction can achieve reaction completion [10].

water releasing the hydrogen from the hydride and stripping water of its hydrogen. Lithium hydride unlike other water activated hydrides requires no complex mechanisms or catalysts to start, control and complete the hydrogen release reaction [10, 39]. Our experimental studies show that water activated lithium hydride can achieve 95–100% reaction completion rates with excess of water (**Figure 3**) [10].

3. Fuel-cell design for sensor networks

3.1. Fuel cell degradation

Fuel cell degradation is an important factor in the design of the fuel cell power supply. Fuel cell degradation is impacted by operating conditions, including operating voltage, temperature, humidity and voltage oscillations [17]. Using the catalyst degradation model developed in [11, 17], we determine the effect of operating conditions on fuel cell life.

The model is run and we quantify the effect of each operating condition on fuel cell life, while keep other conditions constant. Use this model; we obtain life predictions for the fuel cell. Next, we fit an analytical expression to these life prediction curves and use the expression to extrapolate fuel cell life under field conditions.

Figure 4 shows that fuel life exponentially increases for lower voltages. To achieve 3 years of life, the fuel cell would have to operate at 0.8 V or less. According to the model, increased voltages accelerates dissolution of the platinum catalyst, thus reducing its electrochemically active surface area. However, operating at high voltages increases the fuel cell conversion efficiency, but also results in less power output. These conflicting factors need to be considered to determine a suitable operating voltage.

Typically, all but the simplest of electrical devices have varying electrical loads. The work in [17] analyzed the effect of voltage fluctuations on fuel cell life. The results show a linear

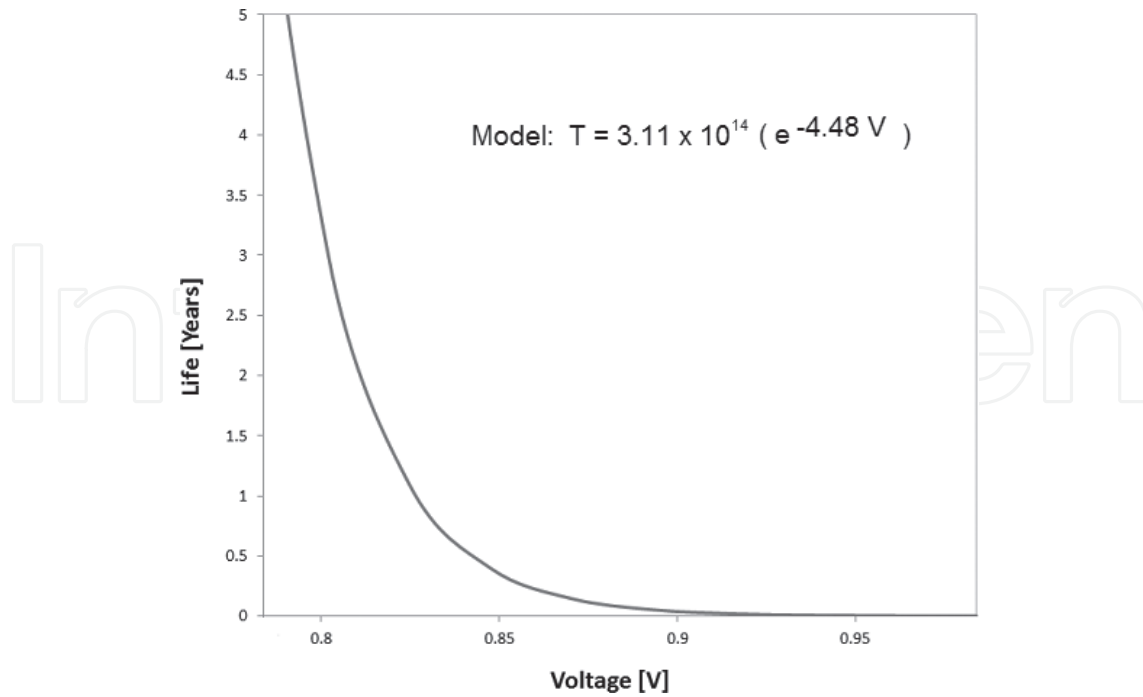


Figure 4. The predicted effects of operating voltage on fuel cell catalyst life (cathode humidity 50%, temperature 25°C).

reduction in catalyst life for a linear increase in voltage oscillation amplitude. To understand the full impact of voltage oscillations, the percentage reduction in life needs to be multiplied to the expected life in Figure 5 to obtain an absolute effect on life.

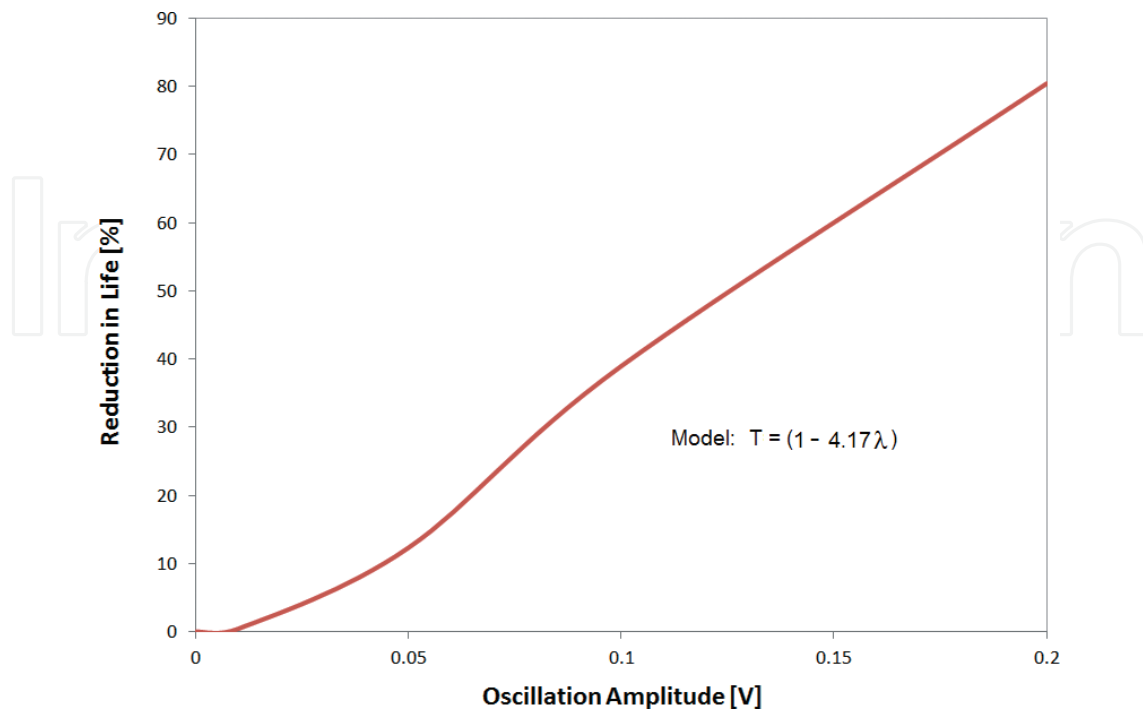


Figure 5. The predicted effects of voltage oscillation on fuel cell catalyst life.

The effect of temperature on fuel cell performance is critical for field devices, where temperatures will vary over the course of a day and over seasons. The effect of temperature on fuel cell catalyst life is shown in **Figure 6**. For increased temperature, an exponential decrease in life is predicted by the model. For example, operating at 0.8 V, the life of the catalyst is 4.5 times shorter operating at 60°C than for 15°C. Low temperatures decrease catalyst degradation and increases life, but can produce other problems such as increased condensation resulting in flooding.

Humidity is an important operating parameter for fuel cell catalyst life. The effect of cathode humidity on the catalyst life of an air breathing PEM fuel cell is shown in **Figure 7**. As seen, life is significantly shortened when the relative humidity approaches 0, while a peak occurs at 10% relative humidity. Further increase in humidity is less substantial.

This result is caused by varying rate of platinum oxide formation due to cathode humidity.

Based on the degradation models we produce a combined equation to predict the effect of fuel cell catalyst life. This equation for τ_{clife} in years presumes each operating variable has an independent effect on the life of the fuel cell catalyst. The equation is given below:

$$\tau_{clife} = a_V e^{-k_V V} a_T \cdot e^{-k_T T} \cdot (a_h \ln h + k_h) \cdot (1 - a_\lambda \lambda) \quad (1)$$

The equation considers the effect of operating voltage, operating temperature, operating humidity and voltage oscillations. The list of variables used and their respective values are shown in **Table 2**.

For field applications, ambient temperature and humidity may change over the course of a day and over the seasons. Next, we model the impact of humidity and temperature oscillations on

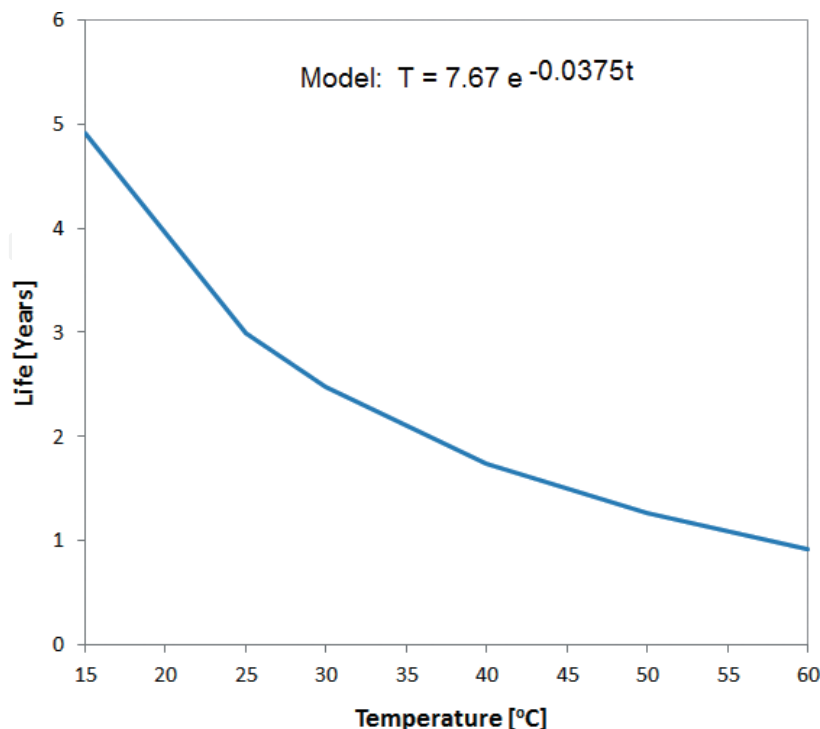


Figure 6. The predicted effects of temperature on fuel cell life.

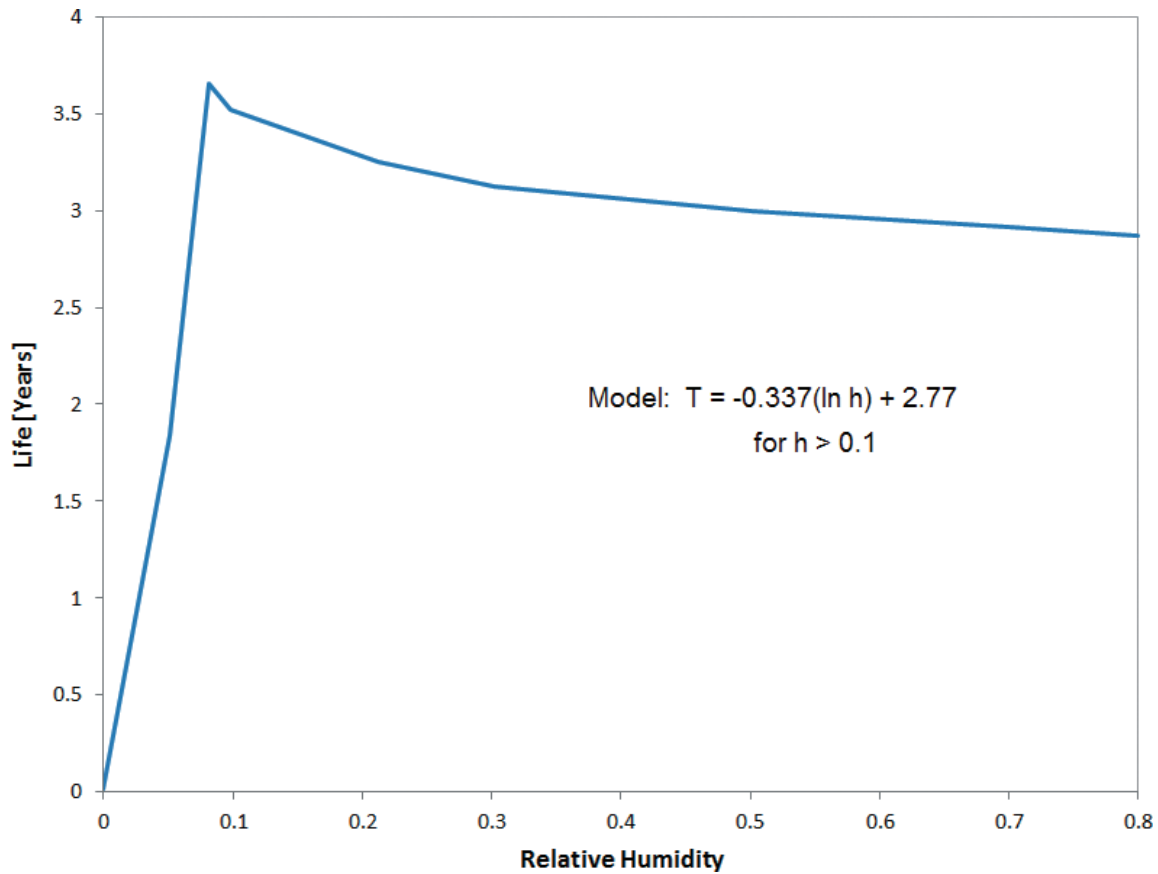


Figure 7. The predicted effects of humidity on fuel cell life.

the life of the fuel cell membrane. A second degradation phenomenon modeled is degradation of the membrane due to humidity cycling given below. Based on the experiments from [32] and others, the PEM fuel cell membrane can only withstand a finite number of humidity cycles that result in stress loading culminating in mechanical failure of the membrane.

$$\tau_{mlife} = \Delta t_{hosc} \cdot \frac{b_{memb}}{RH_{max} - RH_{min}} \quad (2)$$

where Δt_{hosc} is the humidity cycling period, b_{memb} is a membrane specific constant and is 0.02 for Nafion NR111 [32], RH_{max} and RH_{min} is the maximum and minimum relative humidity.

The total life of the fuel cell is then modeled as the following:

$$\tau_{life} = \min(\tau_{clife}, \tau_{mlife}) \quad (3)$$

where τ_{life} is the expected life of the PEM fuel cell. In summary, the expected life is the minimum of the catalyst life presented earlier and life of the membrane due to humidity cycling. These factors independently impact the fuel cell. Catalyst degradation begins with performance degradation of the catalyst and finally results in catastrophic loss, while membrane degradation results in mechanical damage to the membrane that results in the formation of pinholes and ends up in catastrophic loss.

Variable	Value
a_v	3.11×10^{14}
a_T	7.67 years
a_h	-3.37×10^{-1}
a_λ	4.173 V^{-1}
k_h	2.77
k_v	-4.48 V^{-1}
k_t	$-3.75 \times 10^{-2} \text{ C}^{-1}$

Table 2. Fuel cell catalyst life model parameters.

Figure 8 shows the maximum and minimum daily temperatures expected throughout the year in Negev, Israel. **Figure 9** shows the maximum and minimum daily humidity expected in Negev. Using these varying temperature and humidity conditions, we can predict the net effect on life of a fuel cell power supply in the field. We presume the fuel cells operating at 0.78 V and voltage oscillations are at 0.2 V. Using ambient temperature and humidity (in other words no environment control) the expected fuel cell life is 0.27 years (**Table 3**).

Next, we set the fuel cell to operate at 10% humidity and operate the power supply 5° above dew point. The annual maximum and minimum dew point in Negev, Israel is shown in **Figure 10**. By effectively lowering the operating temperature and humidity, we expect to increase the life of the fuel cell. In addition, lower operating humidity also reduces the chances of flooding. The resultant fuel cell life is 2.2 years (**Table 2**).

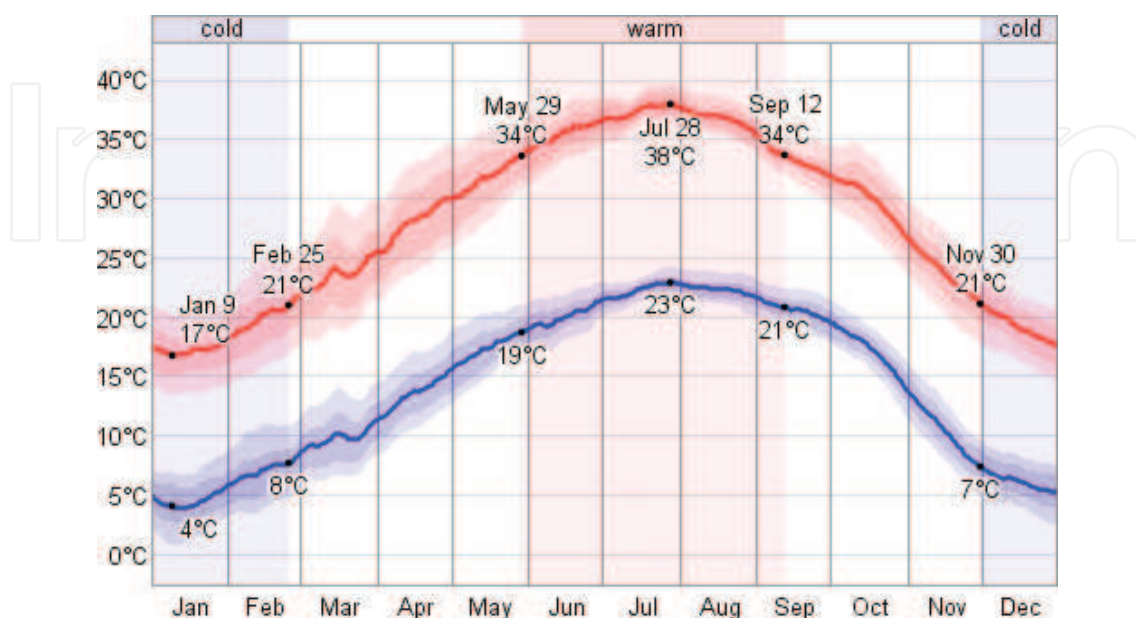


Figure 8. Annual daily maximum and minimum temperature in Negev, Israel.

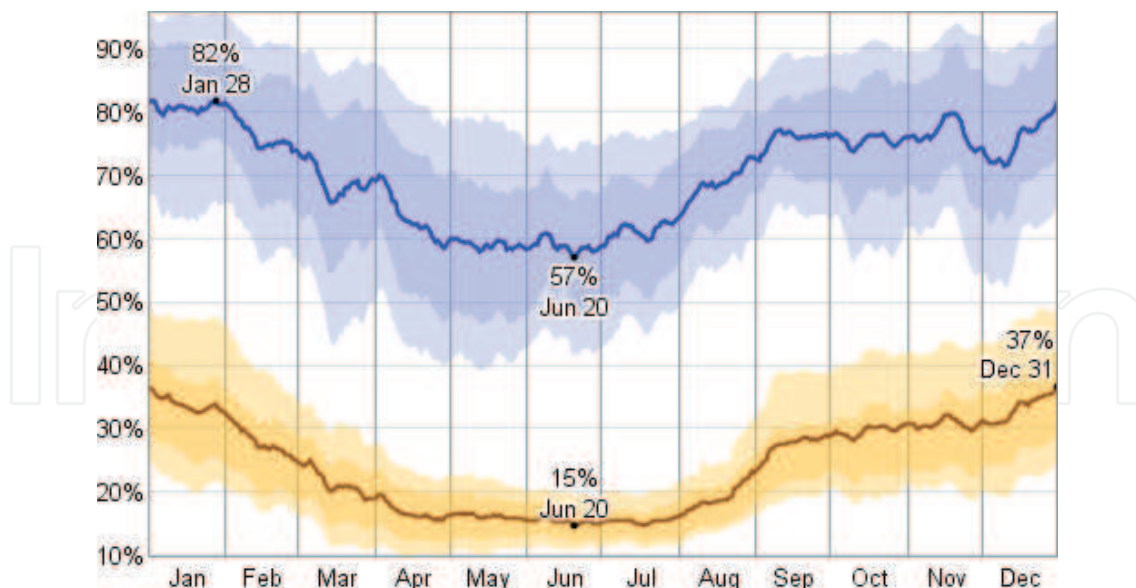


Figure 9. Annual daily maximum and minimum humidity in Negev, Israel.

Furthermore, we can reduce voltage oscillations experienced by the fuel cell system to 0.02 V. Our studies show that we can minimize oscillations to 0.02 V further extending life to 12.2 years (Table 2). By effectively controlling the humidity, temperature, operating voltage and voltage oscillations we can extend the operating life of the fuel cell.

In the following section, we describe how we implement fuel cell control systems to achieve long life. A block diagram of the fuel cell power supply is shown in Figure 11. The fuel cell power supply consists of several important components, a hydrogen generator system, fuel cells, humidity and temperature control, air management system and power management and control. In the following section, the power management system will be analyzed.

3.2. Power management

The proposed fuel cell power supply consists of a fuel cell-battery hybrid system. The fuel cell constantly charges a battery and the battery/fuel cell system periodically powers an electrical load. By having several fuel cells in series, the net voltage can be set high enough to charge a battery without use of additional electronics. Otherwise, a step-up DC-DC converter is required. The DC-DC typically introduces voltage oscillations that can by our analysis result in degradation of the fuel cell power supply [11, 17]. It also decreases the efficiency of the system due to voltage conversion losses.

Conditions	Predicted fuel cell life (years)
Operating voltage 0.78 V, 0.2 V oscillation, No environment control	0.27
Operating voltage 0.78 V, 0.2 V oscillation, 15% Humidity, +5°C dew point	2.2
Operating voltage 0.78 V, 0.02 V oscillation, 15% Humidity, +5°C dew point	12.2

Table 3. Fuel cell catalyst life comparison for field sensor network.

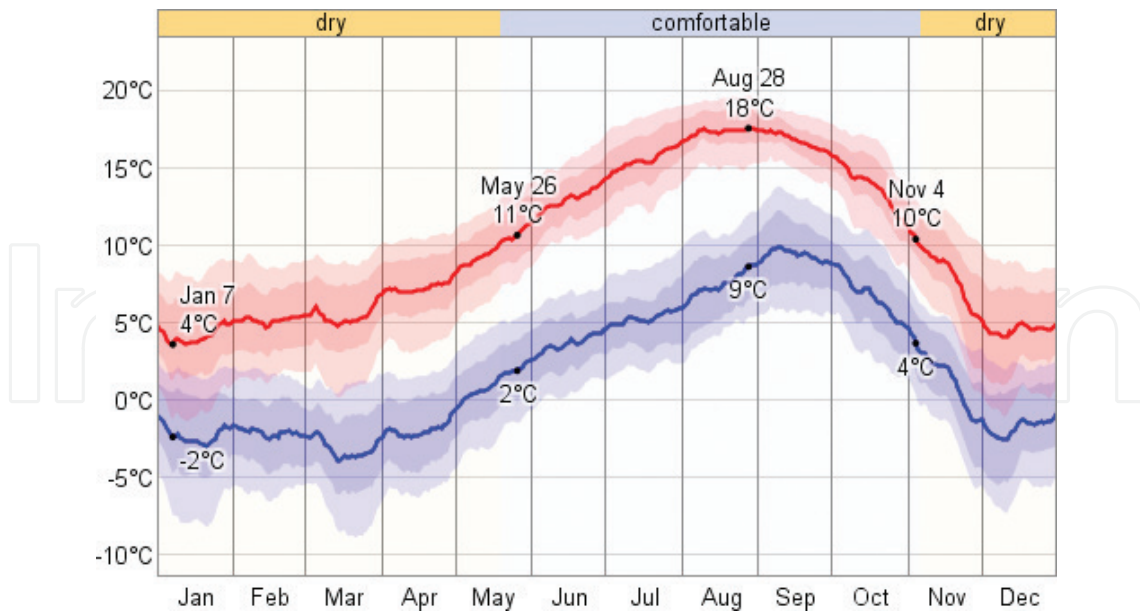


Figure 10. Annual daily dew point temperature in Negev, Israel.

Without the DC-DC converter, the system is simpler and more efficient. In addition, a variable resistor circuit is included in the circuit. This variable resistor circuit is activated and used during start-up and shutdown, to ensure the fuel cell is at proper voltages at all times and to avoid fuel starvation. The variable resistor ensures the fuel cell maintains a constant voltage during start-up and shutdown. Finally, an electrical load is connected to the circuit and periodically turned on at a set duty cycle or on-demand.

First, the average power required of the fuel cell needs to be determined. Second, an operating voltage range must be selected for the cells. For sensor network applications, we wish to maximize both the life and fuel cell conversion efficiency to minimize hydrogen fuel consumption. The operating efficiency of a fuel cell given as a function of voltage is [4, 5]:

$$\lambda_{FC} = 0.81 \text{ V} \quad (4)$$

A third constraint is that the fuel cells need to have matching output voltage to charge the battery. This is to avoid a specialized battery charging circuitry. A battery charging circuitry would add additional complexity to the system, and be a source of voltage oscillations and it will further reduce system efficiency due to conversion losses. However, the trade-off is that the fuel cells need to be designed to be in a matching series configuration, with a high enough voltage to charge the battery.

A battery needs to be selected that has enough capacity so that when the load is powered, it does not result in a substantial voltage drain from the battery. This is once again to avoid voltage oscillations that degrade the fuel cell. This expected change in voltage due to loss of charge can be calculated from integrating a voltage-battery charge curve.

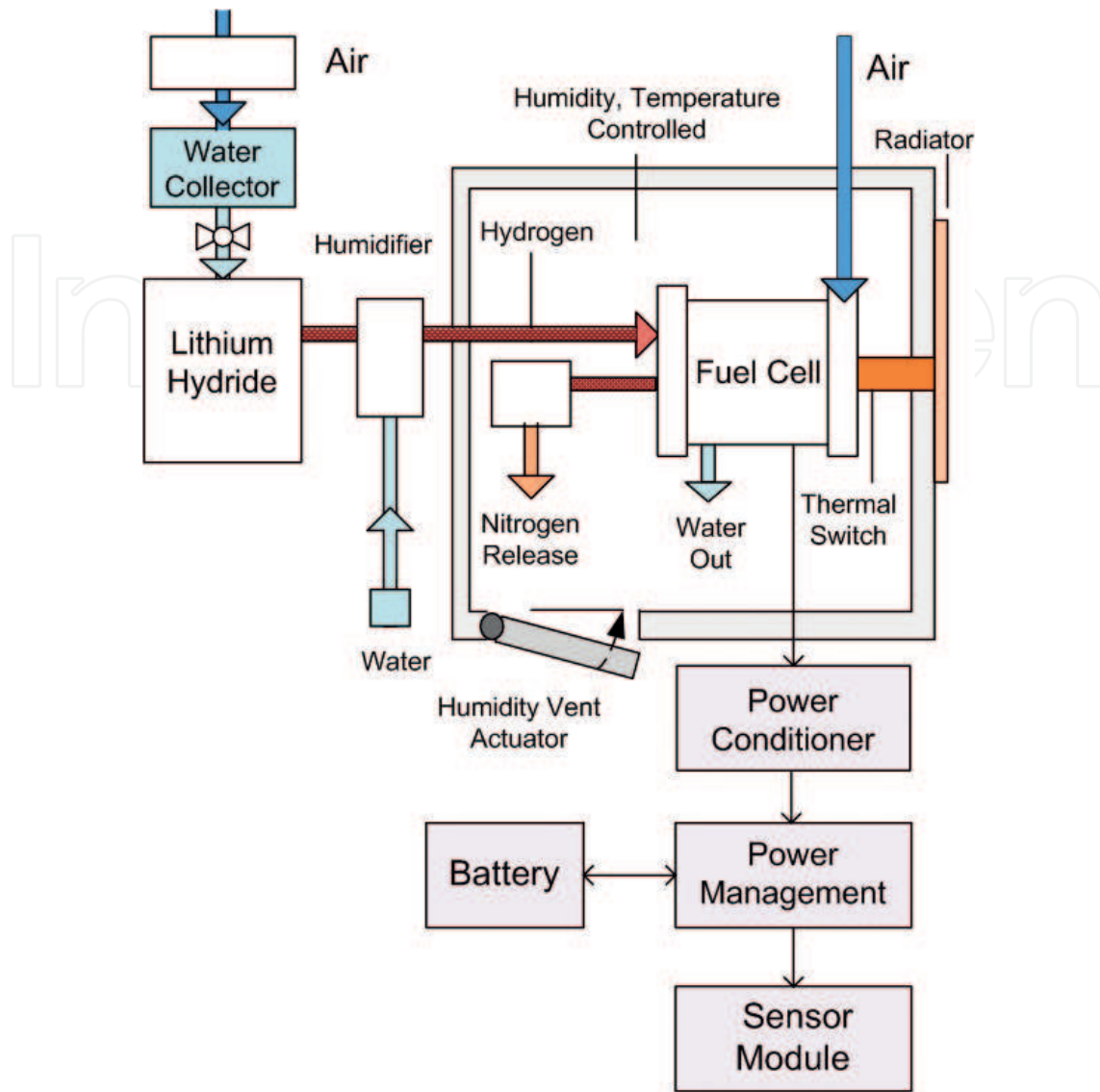


Figure 11. Proposed fuel cell power supply.

A power control system monitors the fuel cell output voltage and the battery (see Figure 12). Once the voltage drops just below operating voltage range, the control system would divert output power from the fuel cell to charge the battery until the net voltage reaches the upper boundary of the operating voltage range.

3.3. Air and water management

The purpose of the air and water management system is to ensure oxygen is delivered to the fuel cell cathode and ensure inert gasses such as nitrogen don't build-up in the anode. We assume that air-breathing PEM fuel cells are used; hence the oxygen is freely extracted from the air. However, it is critical that the air entering the cathode maintains a proper humidity to ensure smooth operation of the fuel cell. This requires that the air humidity not be too low or

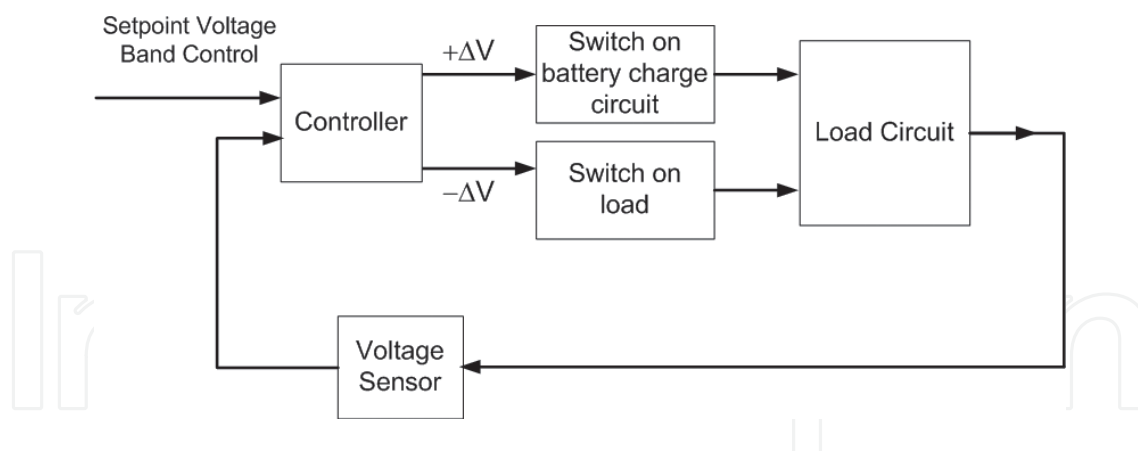


Figure 12. Proposed fuel cell voltage control system.

too high. Improper water management can result in loss of performance, prolonged flooding and shortened life [31, 43]. The effect of humidity on catalyst degradation from [11, 17] is shown here. The results show that humidity needs to be well above 10% to avoid accelerated degradation. However, the humidity also cannot be too high, otherwise this might cause flooding that blocks pores in the GDL and result in reduced power output due to fuel starvation, oxygen starvation or both. In addition, excess flooding may cause damage to the membrane and GDL [43]. For the micro-fuel cells considered here, this maximum humidity cannot exceed 70%. It is found that most of the waste water from the fuel cell exits the cathode. Therefore, this waste water needs to be carefully disposed to prevent the cathode from reaching the maximum humidity.

A second objective as noted earlier is to prevent build-up of inert gases such as nitrogen in the anode. The fuel cells as noted earlier are configured in a dead-end anode mode. This typically maximizes fuel utilization, but at a cost of build-up on nitrogen on the anode. If this is left uncontrolled, a fuel cell will starve of hydrogen and drop in voltage. The net effect is that this degrades the fuel cell catalyst and limits life. A conventional method of removing the nitrogen is using a purge valve that is actively controlled. The valve periodically opens and closes to dispose of the nitrogen build-up according to a predetermined schedule [21]. However, this requires active electronics and valves and results in some loss of hydrogen, between 10 and 15% for small scale systems. For low power systems, methods to avoid the active electronics and valves can both simplify the system and increase overall efficiency.

In our work, we focused on designing a passive membrane to continually purge nitrogen. This is done using sufficiently thick foam, which lets nitrogen through but also some hydrogen. The thickness of the foam is varied using empirical methods to let out enough nitrogen. This is done by varying the foam and its thickness to ensure minimal voltage drops in dead-end mode.

Through this design process, our work suggests, that nitrogen can be effectively purged in small scale systems with estimated hydrogen leakage losses of up to 5%.

3.4. Thermal management

As noted earlier, maintaining the fuel cell at a controlled temperature can substantially decrease fuel cell degradation. It avoids build-up of hot-spots, drying and reduction in

humidity. In our studies, we presume the fuel cell power supply is at above freezing temperature. The proposed thermal controller is shown in **Figure 13**. In this controls approach, a thermal switch is introduced. The system works by operating within a temperature set-point band. In an active setup, a temperature sensor is used to take readings and feed the signal to a thermal-switch actuator, while in a passive setup; thermal expansion of the material is used to close the switch. When there is too much heat, the thermal switch is closed and is used to radiate the heat to an external radiator. When the switch is open, internal heat generated from the fuel cell is recirculated.

3.4.1. Thermal storage system for cold environments

For cold environments, the field sensor module needs to be specially designed to capture excess heat during the daytime and release this heat during night-time. This strategy keeps the field sensor module at or above the operating temperature at all times. In Polar Regions, there is lack of daylight for several months at a time and hence an effective thermal storage system will need to have captured ambient heat a few months in advance. Our own experience in developing photovoltaic sensor networks for measuring snow height in Greenland shows that an effective low-risk strategy is to run the sensor module in a hibernate mode and conserve as much heat as possible [44, 45]. However with a fuel cell power supply, our Greenland sensor network would have operated unhindered even during the dead of winter. These operational limitations encourage efforts to develop practical thermal storage solutions.

In **Figure 14** we present a Thermochemical Energy Storage System (TESS) that we have demonstrated in the laboratory. TESS captures external heat from the environment during daylight and releases it during the night time, when the external temperatures plummet. One potential material for thermal storage is lithium chloride (LiCl). Dry LiCl is exposed to stored waste water from the fuel cell. The waste water is absorbed and forms a hygroscopic solution with the LiCl. This process releases heat which is used to keep the sensor module within operating temperatures. The lithium chloride salts maybe reused for thermal storage simply by exposing the lithium chloride water solution to high external heat. The water boils off and the

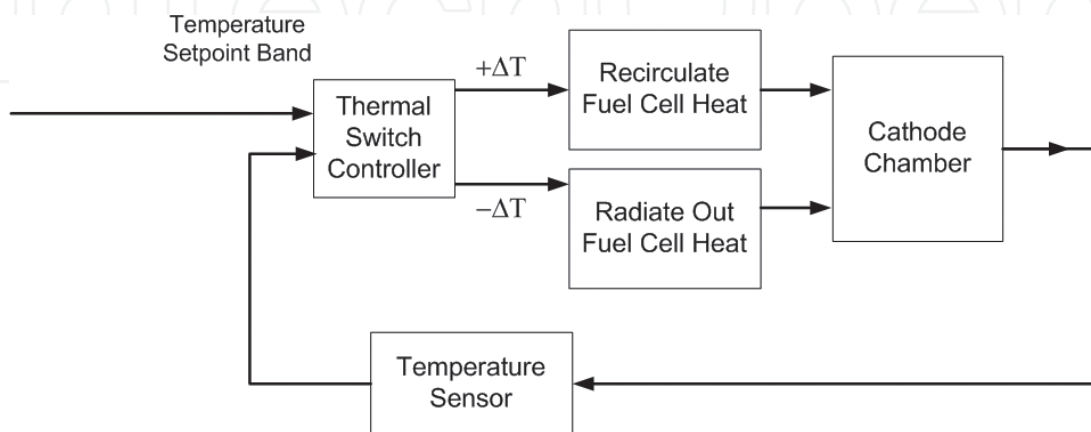


Figure 13. Proposed fuel cell thermal control system.

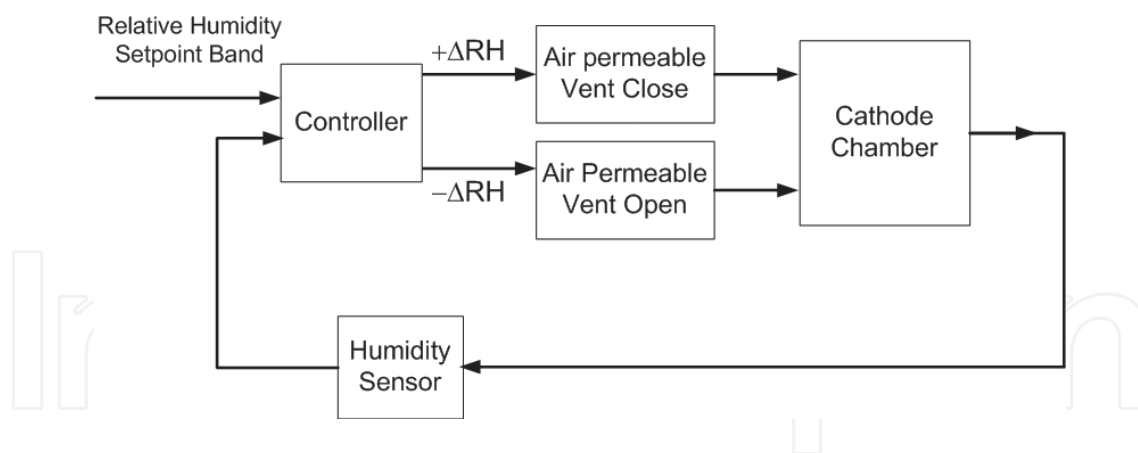


Figure 15. Proposed fuel cell humidity control system.

earlier can be made passive utilizing humidity sensitive material that can expand or contract (i.e. open or close) a vent. However, our laboratory studies shown these methods are unable to achieve humidity control within $\pm 10\%$ relative humidity.

3.6. Fuel management

Here it is shown that lithium hydride is ideal for storage and release of hydrogen. Hydrogen can be released by exposing the hydride to water, releasing the hydrogen from the hydride and stripping water of its hydrogen according to the following reaction:



Lithium hydride unlike other water activated hydrides requires no complex mechanisms or catalysts to start, control and complete the reaction [10, 39]. Our experimental studies show that water activated lithium hydride can achieve 100% reaction completion rates (see **Figure 3**). Another appealing feature of water activated lithium hydride, for PEM fuel cells is that in theory, it produces enough waste water for activating the lithium hydride. When exhaust water from a fuel cell is reused for producing more hydrogen using a lithium hydride generator, the reaction achieves a theoretical 25% hydrogen storage efficiency or 5000 Wh/kg specific energy [9–11] (40 folds higher than lithium ion batteries).

Based on the experiments performed, a semi-empirical model is developed of the hydrolysis of thick layers of lithium hydride for design of a lithium hydride hydrogen generator [10]. The model predicts the total volume of hydrogen produced at a given time, for a given humidity, volume, and exposed surface area of lithium hydride. Using this model, we have developed a lithium hydride hydrogen generator design that can achieve reaction completion.

3.7. Control of hydrogen generator

Several control strategies have been developed to produce the required hydrogen at high operating efficiencies. Active control strategies had been initially pursued to achieve a desired hydrogen pressure. A small peristaltic pump drawing an average power of 10^{-2} mW is used

to periodically dispense droplets of water exposed to the hydride to produce hydrogen for a 50 mW system (**Figure 16**). However, for low-power sensor network applications there is a need to simplify the system and increase its reliability by minimizing control electronics and actuators. Our work focuses on passive lithium hydride hydrogen generators, that are simpler and more appropriate for low-power because they don't have active control components that would otherwise require electrical power.

A passive control system works by exploiting the physics of a material or structure to perform control (**Figure 17**). The proposed concept is to control the output hydrogen pressure. The mechanism works by letting in water vapor through Nafion™ membrane layer that produces hydrogen, which increases hydrogen pressure. The Nafion™ lets water vapor cross from a point of high vapor pressure to a point of lower partial pressure, but prevents the escape of hydrogen. The partial pressure of water vapor inside the chamber is low because it readily reacts with lithium hydride to produce hydrogen. This setup in effect allows the lithium hydride to passively extract water vapor from the surrounding. Once the unit reaches the target pressure, a latex diaphragm expands and seals the Nafion™ preventing further transport of water vapor.

A cross-section view of a passive lithium hydride generator is shown in **Figure 17**. (A) Generator consists of two opposing compartments that allow for pressure communication between them. (B) Water vapor either produced at the fuel cell's cathode or from the environment enters through the Nafion™ sheet. (C) The water vapor reacts with the lithium hydride. The generated pressure travels to the upper chamber and inflates the latex membrane. (D) The rate limiting mechanism occurs when the latex membrane presses against the Nafion™, greatly reducing the amount of water vapor entering the system. (i) Latex membrane fully contracted, allowing water vapor to enter the system. (ii) Latex membrane fully expands at target pressure stopping any more water vapor from entering the system.

The passive hydrogen generator is designed not to carry water on board. Instead, it extracts water vapor from its surroundings. This design is tested for long duration to produce hydrogen for a fuel cell power supply in [10, 11]. The generator was designed to not carry water on-board. While passive lithium hydride generators relying on liquid water have been developed, this generator is unique in its ability to use water vapor from the atmosphere or fuel cell exhaust [9, 10].

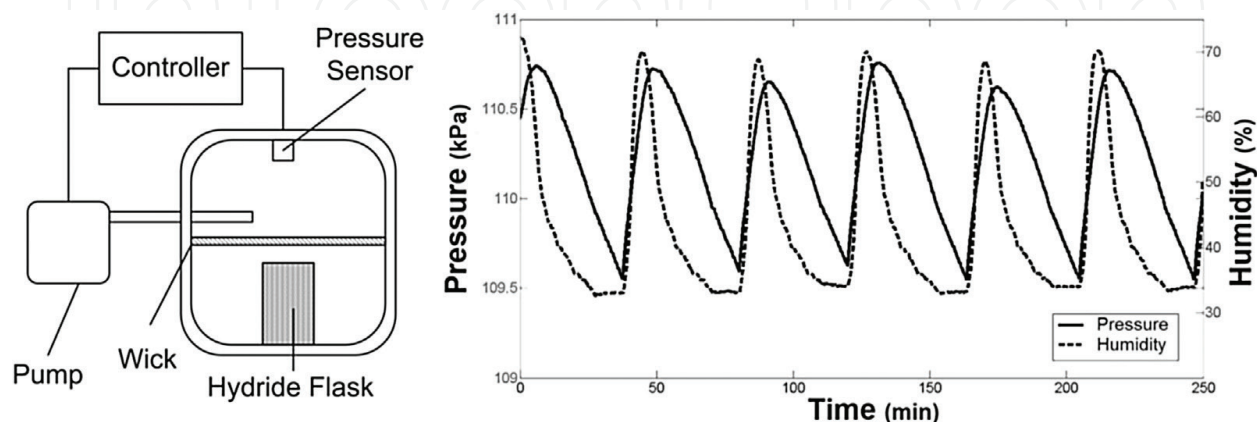


Figure 16. Active control system used to control hydrogen generation and hydrogen pressure at 1.1 Bar [10].

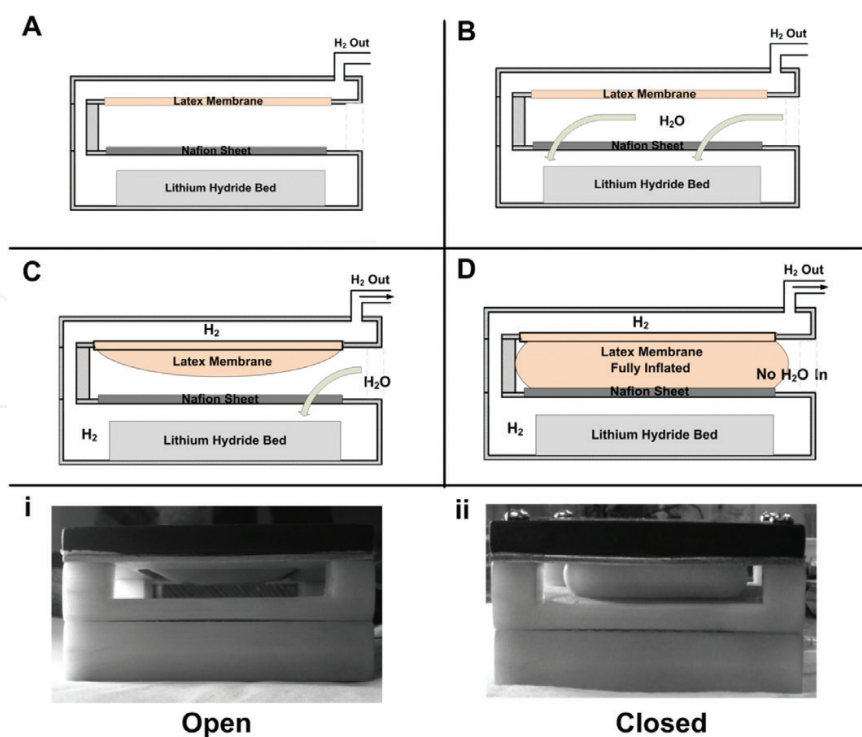


Figure 17. Passive lithium hydride hydrogen generator design.

Additionally, lithium hydride generators have not been experimentally validated for long periods of time or with a hybrid PEM fuel cell system. Based on the lessons learned, an experimental system was built to demonstrate the fuel cell power supply for field sensor networks.

4. Application case studies

Consider a ball shaped sensor network node (Figure 18) with a 10–20 cm radius [11]. The node consists of four interchangeable modules, a central CPU module containing electronics and wireless-radio, a power module consisting of either fuel cells or batteries and a payload module to house sensors. The payload module may contain temperature, humidity/moisture, vibration, accelerometers, chemical, light sensors and cameras. These nodes periodically communicate to neighboring nodes and a central base station. Hence, they will be low-power devices that intermittently operate at high power to operate their payloads or communicate data. Each node will require a minimum 10 mW for standby power. It is assumed the sensor modules consume 500 mW average. These nodes need to operate for 3–5 years unattended, without any periodic maintenance and have a mass less than 30 kg, so that it may be easily carried and deployed on site.

It is assumed that the field sensor is deployed in a temperate, desert or tropical location, operating continuously, where the temperature varies between 15 and 40°C and humidity varies between 0.15 and 1.0. In colder climates, the sensor node will require heaters to maintain the fuel cell temperature at 15°C or higher.

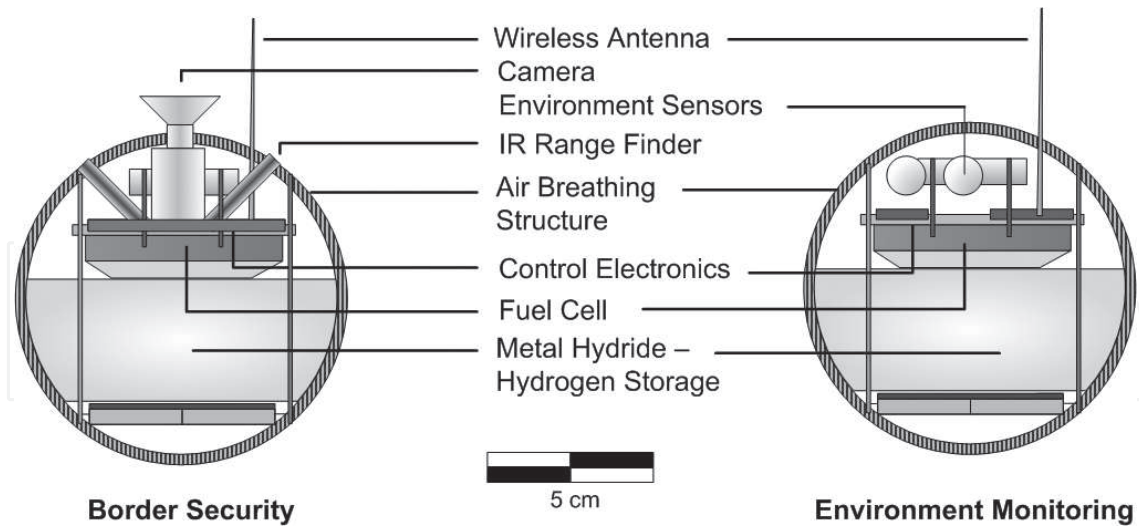


Figure 18. Layout of field sensor nodes for application in border security (left) and environmental monitoring (right).

Figures 18 and 19 shows the sensor node assembled in two different configurations for three different applications. These applications include (1) Environmental monitoring of air quality and pollution readings, (2) Border security for illegal crossing and smuggling and (3) Space Situational Awareness (SSA) monitoring of incoming falling objects and meteorites from the sky in remote locations.

For these three different applications, there are different payload sensors. The key difference between the three applications is the operational duty cycle. For environmental monitoring, the duty cycle can be low, utilizing environmental sensors (air, CO₂, temperature, humidity, soil moisture) that are typically low power devices with data being gathered periodically at duty cycles of 0.1 or less. For border monitoring and security applications, the power supply needs to be fully operational and sensors constantly operating thus requiring a high duty cycle. These sensors may have an infrared range finder, ultrasonic range finder and cameras.

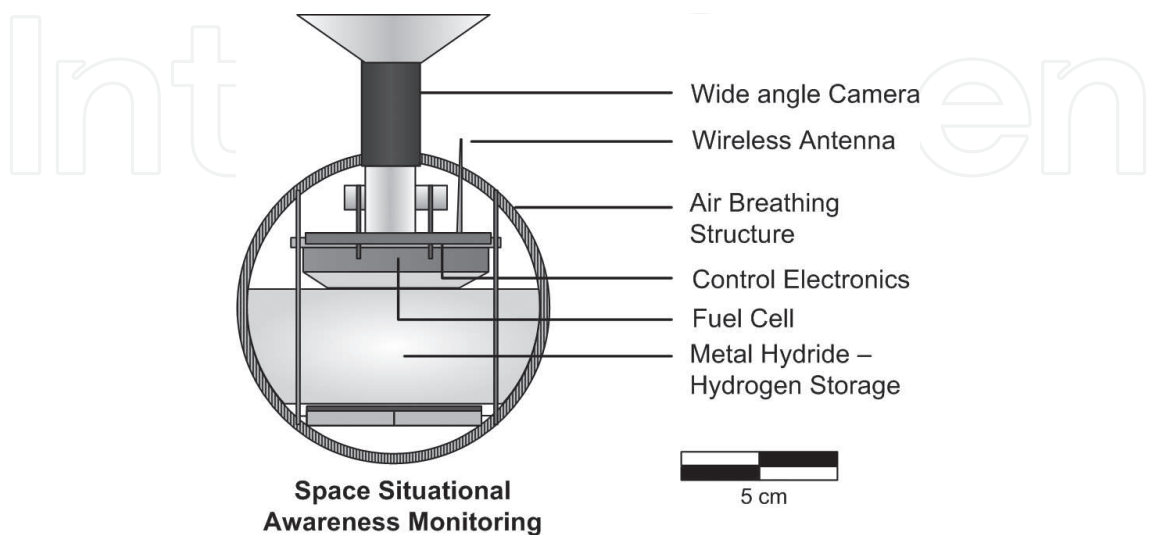


Figure 19. Layout of field sensor for applications in space situational awareness.

It is presumed that a state-of-the-art field system is developed consuming an average power of 0.5 W. However, the actual peak power consumed maybe higher and dependent on the choice of sensors and applications. For SSA, a camera sensor needs to be active and enter a high frame-rate mode when an incoming object is detected.

4.1. Battery

First batteries are considered as power supplies for these nodes. Batteries self-discharge, where stored energy is lost at a fixed rate modeled as a geometric series. It is further assumed that the last 20% of the stored energy cannot be used. The mass of a battery power supply required is:

$$M_{bat} = \frac{\alpha E(T)(1 - r^T)}{\rho_{bat}(1 - r)} \quad (6)$$

Where, M_{bat} is the total mass of the battery power supply required for T years of life, α is the capacity margin, r is the self-discharge rate, ρ_{bat} is the energy density of the battery, $E(T)$ is the energy required to power a payload device for T years according to a given duty cycle. The energy densities, self-discharge rates and mass of the battery power supplies are shown in **Table 4** [11].

A sensor module weighing more than 30 kg or more lacks scalability to hundreds or even thousands of modules owing to the high cost and logistics required for deploying/moving them and installing them. Ideally, the sensor module and power supply needs to have low mass that enables them to be carried in backpacks, mules and deployed in off-grid environments.

4.2. PEM fuel cell

Next, the proposed PEM fuel cell power supply concept is compared against batteries [11]. The mass of the fuel for the PEM fuel cell power supply is given by:

$$M_{fuel} = \frac{E(T)}{\rho_{fuel} r} \cdot \ln \left| \frac{0.5 - \frac{1}{r}}{T + 0.5 - \frac{1}{r}} \right| \quad (7)$$

where M_{fuel} is the total mass of the fuel for T years of life, ρ_{fuel} is the specific energy of the fuel, $E(T)$ is the energy required to power a payload device for T years for a given a power profile, r is the power degradation rate of the fuel cell power supply for a specified operating point. In addition, the dry mass of the power supply excluding the structural shell is given in **Table 4**.

Technology	Specific energy (Wh/kg)	Self-discharge/degradation (% per month)
Alkaline	110	0.5
Lithium ion	140	5
Lithium CR	270	0.17
Lithium thionyl chloride	420	0.08
LiH fuel cell	5000	0.12

Table 4. Power supply technology characteristics.

The lithium hydride fuel has a volume of 0.7 g/cm^3 . Based on these factors, the shell consists of two aluminum spheres, 1 and 1.5 mm thick, each with enough internal volume to hold the lithium hydride fuel.

The energy density of the fuel is given as follows:

$$\rho_{\text{Fuel}} = \rho_{\text{LiH}} \cdot \lambda_{\text{FC_EH2}} \cdot \eta_{\text{LiH_RC}} \quad (8)$$

Where, σ_{LiH} is the usable quantity of hydrogen energy released from the lithium hydride hydrolysis reaction (presuming water reuse), $\eta_{\text{LiH_RC}}$ is the percentage reaction completion of the lithium hydride reaction and $\lambda_{\text{FC_EH2}}$ is the efficiency of the fuel cell system.

The total efficiency of the fuel cell is calculated from the following:

$$\lambda_{\text{FC_EH2}} = \lambda_{\text{FC}} \cdot \lambda_{\text{FC_stack}} \cdot \lambda_{\text{Purge}} \quad (9)$$

Where λ_{FC} is the chemical to electrical efficiency of the individual fuel cells and is related to the operating voltage of the cell, V/V_{LHV} where V_{LHV} is 1.23 V, $\lambda_{\text{FC_stack}}$ is the fuel cell stack efficiency and is 0.95, λ_{purge} is the losses due to nitrogen purging and is 0.95. Our work shows that operating each cell at 0.78 V, giving it a $\lambda_{\text{FC}} = 0.63$ is a good trade-off between efficiency, life and power output. To supply peak system power and avoid oscillatory voltage seen by the fuel cell, the battery handles the high and varying power of the load.

To generate the average power required this requires 5 fuel cells. This design vastly simplifies the fuel cell control electronics. The fuel cells are assembled in this configuration to avoid a DC-DC convertor. With each fuel cell operating at 0.78 V, 5 are assembled in series to obtain a nominal volt of 3.9 V. Note, that the mass calculated accounts for the extra fuel required due to losses from degradation and to ensure the fuel cell provides the energy required at the end of T years. **Table 5** shows the mass breakdown of the fuel cell power supply. The power supply consists of the fuel cell, lithium hydride fuel storage system, power control electronics and other components for air and water management. The lithium hydride fuel produces hydrogen with the addition of water extracted from the air.

4.3. System comparison between batteries and fuel cells

We first compare the proposed system with batteries. **Figure 20** shows the mass of the power system vs. average power of 0.5 W for 5 years of operation at 100% duty cycle. For very low power, batteries provide an advantage, because of the additional overhead mass required for

Component	Mass (grams)
Fuel cell and electronics	100
Sensor payload	80
Computer	50

Table 5. Dry mass breakdown for fuel cell powered sensor module.

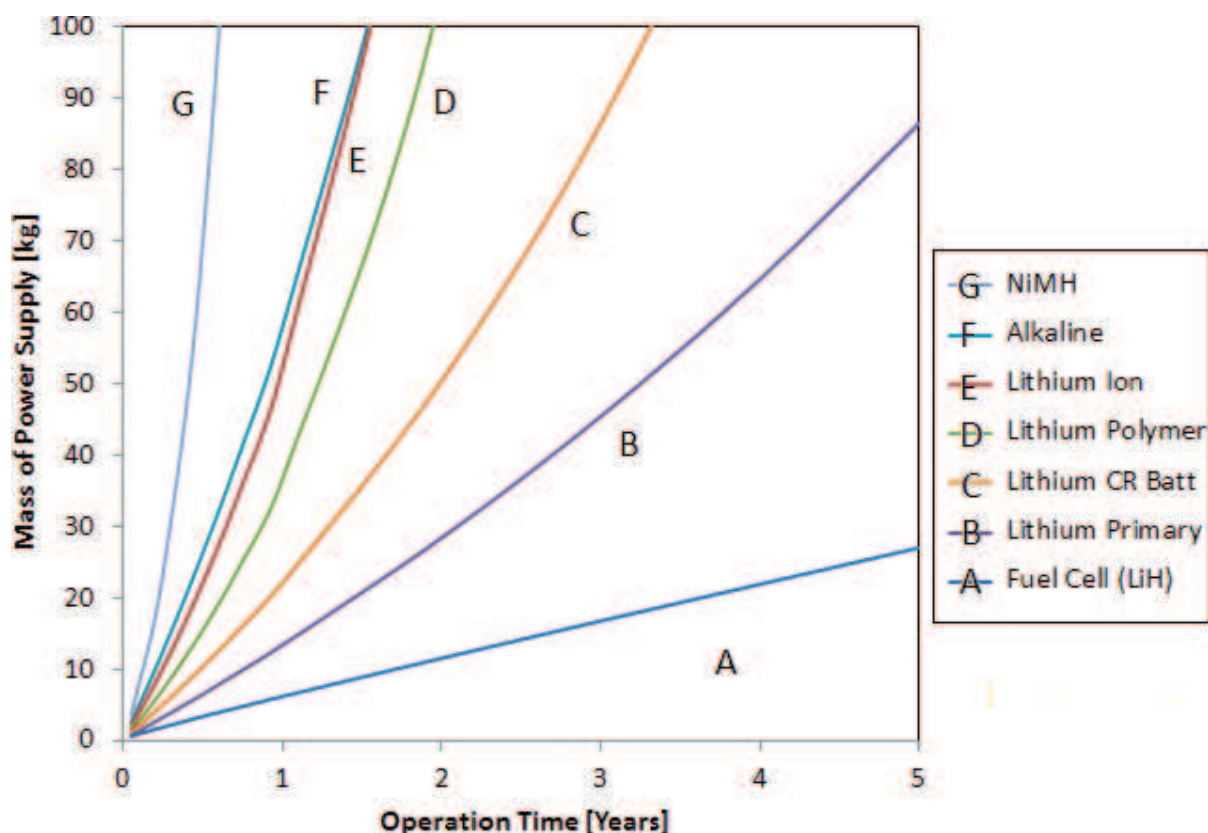


Figure 20. Comparison of field sensor power supply technologies for up to 5 years of operation, 0.5 W and 100% duty cycle.

the fuel cell power supply. The advantage for the fuel power supply is apparent when the system requires high energy. Fuel cells using lithium hydride shows a 50-fold advantage in terms of mass compared to lithium ion batteries, a seven fold advantage over Lithium CR batteries and a threefold advantage versus lithium thionyl chloride batteries. It should be noted that the rechargeable batteries weigh tens or hundreds of kilograms. For a network of hundred or thousand nodes, most of the batteries considered are not feasible.

We also compare the proposed fuel cell power supply with previously reported fuel cell storage technologies (Figure 21). These previously reported numbers are extrapolated to the required energy for mission lifetime. This includes a PEM fuel cell powered using sodium borohydride and direct methanol fuel cells (DMFC). For these comparisons, the dry mass for these fuel cell configurations is assumed to be the same as the concept fuel cell system presented here. In addition, the operating efficiency of DMFC is lower at 40% and it outputs carbon dioxide that needs to be vented. DMFC offers a simpler approach to fuel storage; however, challenges exist with fuel cell life, due to build-up of carbon monoxide and low operating efficiencies. We presume these challenges have been overcome. The major difference is the mass and volume of the fuel and container.

Overall, for high duty cycle applications (see Figure 22), the proposed fuel cell power supply offers a compelling advantage over other energy storage technologies. A LiH fuelled PEM fuel cell power supply of 78 kg can be fully operational for 5 years at 100% duty cycle and supply

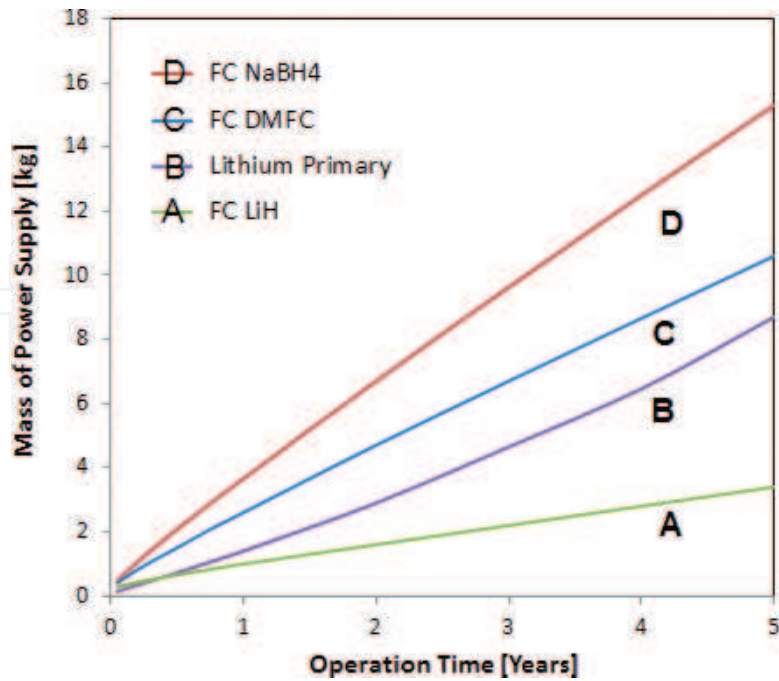


Figure 21. Comparison of fuel cell and battery technologies for field sensor power supply. The system is compared for up to 5 years of operation, 0.5 W and 10% duty cycle.

2 W of power. In comparison, a lithium thionyl chloride primary battery system would weigh 360 kg. Overall, the proposed power supply offers a 4.6-fold mass advantage over the best battery technology and 5.25-fold advantage over DMFC.

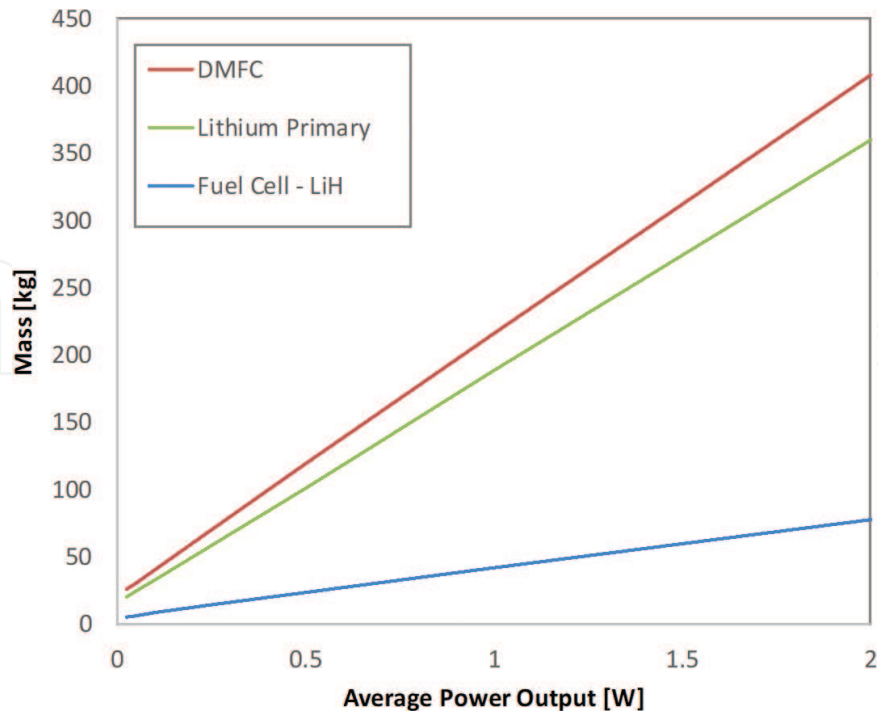


Figure 22. Comparison of leading fuel cell and battery technologies for field sensor power supply. The system is compared for up to 5 years of operation with 100% duty cycle.

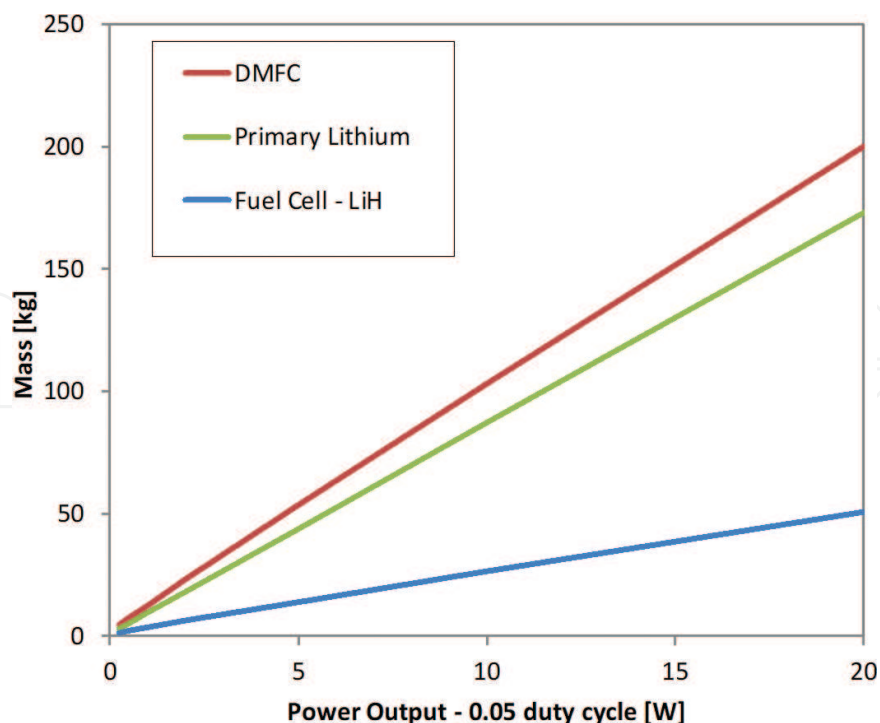


Figure 23. Comparison of leading fuel cell and battery technologies for field sensor power supply. The system is compared for up to 5 years of operation at 5% duty cycle.

In another scenario (**Figure 23**), we consider powering a field sensor at 5% duty cycle for 5 years. This is equivalent to operating a sensor for 3 seconds every minute. The proposed fuel cell power supply can power a 20 W field sensor and have a total mass of 51 kg. In comparison, the lithium thionyl chloride battery would have a mass of 173 kg. The advantage of the lithium hydride fuel cell system is reduced mass for long duration missions. Overall, the presented lithium hydride fuelled PEM fuel cell offers a substantial advantage over conventional batteries and other fuel cell and hydrogen technologies. These results present a promising pathway towards field testing and evaluation of the proposed concept. For higher duty cycle applications, the proposed system shows an increased advantage over conventional technology. The mass advantage approaches nearly fivefolds over lithium primary batteries. This shows the promise in this technology for high-energy, remote, off-grid applications.

5. Conclusions

Field sensor networks are being applied to environmental monitoring, border security and infrastructure monitoring tasks. Current sensor modules rely on solar power augmented by rechargeable batteries. These systems are bulky and due to extended inclement weather may stop working. Fuel cell power supplies offer a compelling alternative. They can keep a sensor network fully powered for years at a time, utilizing very little fuel and is clean, quiet and highly efficient. We present a fuel cell design framework for achieve long-life operations by minimizing the effects of catalyst degradation, while maximizing operating efficiency and performance. Using these techniques, we identified operating conditions that will enable fuel

cells designed in a hybrid system to achieve more than 5 years of life, by performing temperature, humidity and voltage management. We then extrapolated the capabilities of this proposed fuel cell technology and compared them to state-of-the-art fuel cell and battery technology. The results show that the proposed technology requires substantially less mass and can be enabling for several applications, where hundreds or thousands of modules need to be deployed in the field.

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