BackyardNet™: Distributed Sensor Network Powered by Terrestrial Microbial Fuel Cell Technology

Keegan G. Cooke[1], Marcus O. Gay, Sage E. Radachowsky, Juan J. Guzman, and Michael A. Chiu
Trophos Energy, Inc., 363 Highland Ave. Somerville, MA, USA, 02144

ABSTRACT

Environmental sensor nodes support services from environmental stewardship to national security and defense. Expansion of high density sensor networks has been inhibited by the poor availability and high cost of long-term power sources. Trophos Energy demonstrates its own wireless environmental sensor network, entitled BackyardNet™, powered by Terrestrial Microbial Fuel Cell (TMFC) technology. When used in conjunction with Trophos' power management electronics, TMFCs offer the potential for robust, long-term power solutions that can service a variety of remote monitoring applications. This paper discusses the technical aspects of the BackyardNet™ demonstration and the assessed viability of TMFC technology as robust power sources for remote applications.

Keywords: Terrestrial microbial fuel cell, remote power, wireless sensor network, pilot project, technical feasibility study

1. INTRODUCTION

Wireless environmental sensor networks can be used in a wide range of applications – from providing enhanced intelligence for military operations to producing high-density micro-climate data to track regional effects of global climate change. These sensor networks, however, are still not widely used within the military or the scientific community due to a variety of technical challenges that have been faced. Many of these challenges, relating primarily to limitations in wireless hardware and software, have been overcome in the last decade – today, a vast range of robust sensor and communications hardware is widely available. However, the one component that continues to limit the expansion of wireless sensor networks is the poor availability of reliable, long-term power sources.

Power supplies for wireless sensor networks typically come in the form of either batteries or on-site energy harvesting technologies. For unattended ground sensors (UGS), Li-ion battery supplies are the default choice and can provide sufficient power for up to 2 years under ideal conditions, after which the unit must be recovered and the batteries must be replaced[i]. Replacing batteries leads to high operational costs and jeopardizes the security of the network in situations where node covertness is essential. To date, on-site energy harvesting technologies in environmental applications have been limited to solar or wind technologies, both of which require a highly visible and highly vulnerable surface expression. This required expression leads to the same problems encountered with batteries: high operating costs associated with necessary routine maintenance along with compromised security. Terrestrial Microbial Fuel Cells (TMFCs) offer an alternative means of energy harvesting for wireless sensor networks and address both the decreased operating cost and the covert feature required for broader dissemination of long-term UGS networks.

Microbial fuel cells (MFCs) have shown great promise as a novel energy harvesting technology that can provide consistent, maintenance-free power for long periods of time, well beyond the lifetime of sensor and communications hardware. In 2007, MFCs were demonstrated to be viable power sources for undersea sensor and communications systems[ii]. Trophos Energy has adapted this aquatic technology to provide long-term power for remote applications in a variety of on-land environments. To test the viability of TMFC technology as a robust, remote power source, Trophos Energy created the first pilot-scale, TMFC-powered, environmental sensor network, called BackyardNet™, which spans the greater Boston area and a variety of locations around the globe. This paper outlines the structure and operation of BackyardNet™ and discusses the assessed viability of TMFCs as power sources for wireless sensor networks.

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[1] Email: keegan.cooke@trophosenergy.com; Tel: 617.440.5597; Fax: 928.597.6582; www.trophosenergy.com

2. MFC BACKGROUND

Microbial fuel cells (MFCs) are bio-electrical devices that harness the natural metabolisms of microbes to produce electrical power directly. Within the MFC, microbes act as a catalyst to break down sugars and other nutrients in their surrounding environment and release a portion of the energy contained within those molecules as electrical current. MFCs remained a laboratory curiosity for nearly a century before the major advances in microbiology and biotechnology in the last decade stimulated significant interest in their commercial potential. This interest has led to the development of environmental MFCs that harness the energy contained within substrates of the natural world, such as soils or sediments. Over the last five years, the scientific understanding of various MFC processes has been greatly enhanced and power generation capability of MFCs, both in the lab and in the field, has risen steadily[iii,iv]. The first field application of an environmental MFC was demonstrated in 2007 by Leonard Tender of the Naval Research Laboratory (NRL), in which an ocean sediment-based MFC was used to power a meteorological buoy[v]. Soil-based MFCs were first explored in 2006, and it was demonstrated that power could be generated from the microbes and the nutrients found within the soil alone[vi,vii]. In 2009, Trophos Energy demonstrated that soil-based MFCs can be used as power sources for wireless sensor networks.

2.1 Microbial Fuel Cell Theory

Microbes are ubiquitous in our biosphere, and exist in virtually all habitable soils, sediments, streams, and effluents. Among this diverse assemblage of microbes are particular species with unique metabolic pathways that enable them to reduce (or transfer electrons to) oxidized metals, such as iron oxide, to support respiration. In a sense, these so-called “electrogenic” microbes are able to “breathe” metal compounds much like humans and other organisms breathe oxygen. MFCs employ these unique metabolisms by providing electrogenic microbes with a certain configuration of two inert, carbon-based electrodes placed in environments exhibiting different redox potentials (see Figure 1).

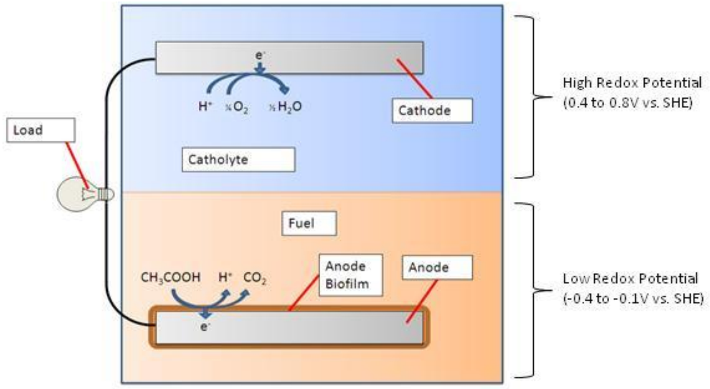


Figure 1. Basic MFC Composition

One electrode, called the anode, is placed in a nutrient-rich, oxygen-poor environment, while the other electrode, the cathode, is placed within an oxygen-rich environment. These two media are typically separated by a proton-exchange membrane that is permeable to protons, but not oxygen. If microbes are present within the anodic media, a biofilm will spontaneously develop on the anode surface. Many MFC researchers inoculate this anodic media with particular species of electrogenic bacteria, such as *Shewanella* or *Geobacter*[viii]. However, for MFCs utilizing natural media such as soils, sediments, or effluents, inoculation is not needed, since these electrogenic species are already abundantly present[ix].

Once a microbial community forms on the anode, its natural metabolic pathways begin to break down the nutrients within the surrounding media, generating highly reduced biomolecules, such as NADH. These highly reduced biomolecules then donate electrons to the anode in one of three ways: 1) direct transfer from the molecule to the anode surface, 2) employing a secondary biomolecule to shuttle the electron to the anode, or 3) transferring the electron through conductive appendages, termed “nanowires”, grown by the microbe[x]. Once the electron has been transferred to the anode, it then travels to the cathode, where it reacts with an oxygen molecule and a proton, a byproduct of electrogenic metabolism, to form water. Thus electrical current is generated, from which one can extract power by simply placing a load between the two electrodes.

The voltage of the MFC is determined by the difference in redox potential between the two distinct electrode environments. When a microbial community forms and begins to respire at the anode surface, the highly reduced biomolecules mentioned above start to accumulate around the anode. This build-up of metabolic byproducts causes the electrical potential of the anode to decrease, typically settling between -0.1V and -0.4V vs SHE (standard hydrogen electrode). The second electrode, the cathode, is placed in a more oxic environment, such as aerated water. The presence of dissolved oxygen gives the cathode a higher electrical potential, typically from 0.4V to 0.8V vs SHE. The working voltage of the MFC is merely the potential of the anode subtracted from the potential of the cathode. It should be noted that MFCs have a theoretical maximum voltage that can be achieved between the two electrodes – approximately 1.2V – since the redox potential of reduced biomolecules has a minimum of -0.4V vs. SHE and the redox potential of oxygen is 0.8V vs. SHE. In order to employ MFCs to power off-the-shelf sensor and communications hardware, Trophos Energy developed proprietary power conversion electronics which up-convert this voltage to 3.5V (discussed in Section 3.1.2).

Power generation from an MFC is continuous, but is limited by the availability of nutrients within the anodic media. In environmental MFCs, such as soil-based TMFCs, nutrients are continuously replenished by the constant decay of fresh plant and animal material, which gives the TMFC a theoretically indefinite lifespan. Researchers of other extant MFC technology have both modeled and demonstrated long-term (multi-year) power generation. For example, Benthic Microbial Fuel Cells (BMFCs) as described by Mark Nielsen et al. of Oregon State University, demonstrate sustainable power density ranging from 10-30mW per square meter of footprint, with peaks as high as 380mW per square meter of footprint [xi]. Recent data collected by Dr. Clare Reimers et al. of Oregon State University has shown negligible consumption of total organic carbon in closed batch aquatic MFCs operated continuously for a period of one year (unpublished). In addition to this abundance of academic literature identifying the persistent nature of environmental MFC systems, Trophos Energy has developed a mass/energy balance model. Using environmental data of substrate chemistry and biogeochemical cycling, we have determined that with appropriate power management technologies, environmental MFCs, differentiated from laboratory closed-cell systems, can last multiple decades.

2.2 Terrestrial Microbial Fuel Cell Theory

In the BackyardNet™ project, Terrestrial MFCs (TMFCs) were used to power sensor and communications hardware, as will be discussed in Section 3. The TMFC adheres to the same basic MFC principals as described above, whereby standard topsoil acts as the nutrient-rich anodic media, the inoculum, and the proton-exchange membrane (PEM). The anode is placed at a certain depth within the soil, while the cathode rests on top the soil and is exposed to the oxygen in the air (See Figure 2).

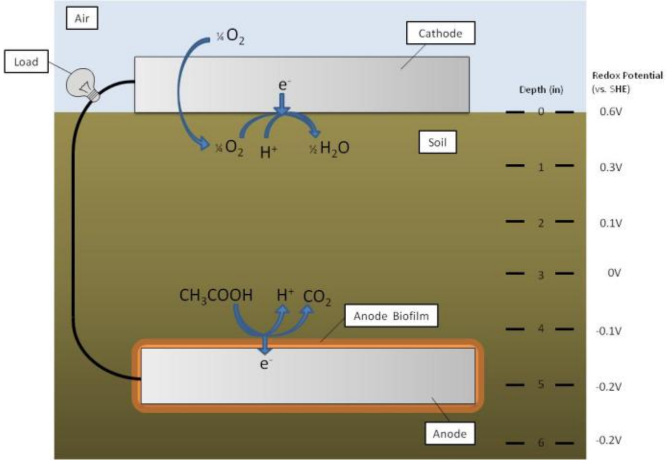


Figure 2. Basic TMFC Composition

Soils are naturally teaming with a complex community of microbes, including the electrogenic microbes needed for MFCs, and are full of complex sugars and other nutrients that have accumulated over millions of years of plant and animal material decay. Moreover, the aerobic (oxygen consuming) microbes present in the soil act as an oxygen filter, comparable to the costly PEM materials used in laboratory MFC systems, and cause the redox potential of the soil to decrease with greater depth, typically leveling at approximately -0.2V vs. SHE. The anode is placed at a depth at which this most negative redox potential exists, which varies depending on soil composition, but typically ranges from 1” to 6”. The cathode, resting on top of the soil, is made of a porous carbon material which allows for the permeation of oxygen and enables the reduction process to occur. The cathode can be then covered so long as there is a means of retaining some exposure to air. Typical voltage potentials achieved in TMFCs are 0.2V to 0.6V vs. SHE for the cathode and -0.2V to 0.0V vs. SHE for the anode. The particular architecture of the TMFCs used in the BackyardNet™ demonstration is outlined in Section 3.1.1

3. BACKYARDNET™ TECHNICAL OVERVIEW

To test the viability of TMFCs as power sources for remote monitoring applications, Trophos Energy developed a pilot-scale UGS network powered by TMFC technology. This network, named BackyardNet™, consists of over 40 UGS nodes that span the Greater Boston area as well as locations in Woods Hole, Colorado, and Rwanda. With the creation of this network, Trophos Energy aimed to achieve the following two objectives:

1. Demonstrate the successful integration of TMFC technology with standard sensor and wireless communications hardware, aided by Trophos Energy’s wireless data acquisition, potentiometry, and power management electronics.
2. Explore the versatility of TMFC technology by collecting statistically significant data on local environmental conditions and correlating this data to TMFC performance.

As will be described in further detail below, each BackyardNet™ node monitors not only TMFC performance, but also four environmental parameters – namely soil temperature, soil moisture, air temperature and air humidity. The nodes were deployed in a variety of environments and climate zones to stimulate varied TMFC performance as a response to the node’s local environmental conditions. Data attained on TMFC power output could then be correlated with data on the four environmental parameters listed above to explore the environmental versatility of TMFC technology. The data collected by each node is transmitted wirelessly to a nearby gateway, where it is stored on a mySQL database, and can be accessed in real time via a Google Maps™ interface. The architecture of BackyardNet™ can be delineated into four distinct unit operations as shown in Figure 3, each of which is described in further detail below.

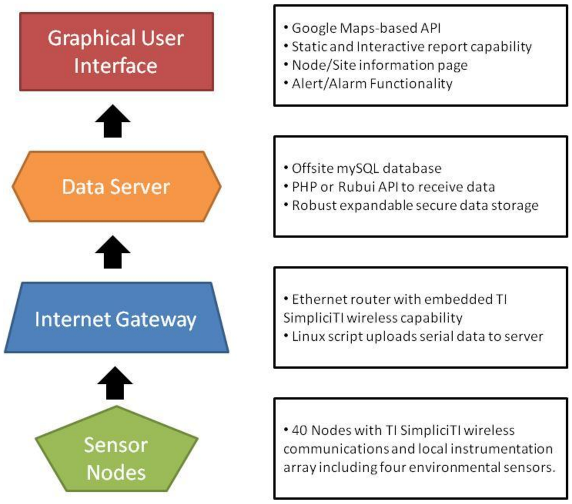


Figure 3. BackyardNet™ Unit Operations

3.1 TMFC-Powered Sensor Node

Each of the BackyardNet™ sensor nodes consists of one TMFC unit, power management electronics, and an applications layer which includes the sensor and communications hardware (see Figure 4). The nodes were designed to collect and transmit data every 15 minutes.

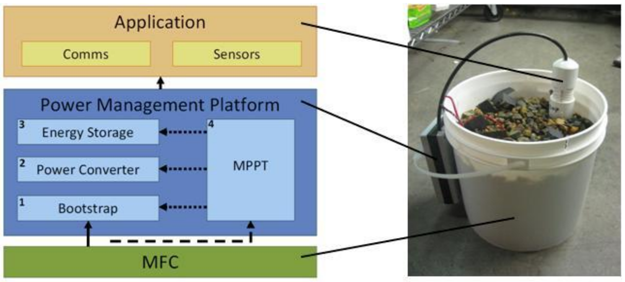


Figure 4. Sensor Node Layout (MPPT = Maximum Power Point Tracking)

3.1.1 The BackyardNet™ TMFC

The TMFCs used in BackyardNet™ employed the basic architecture shown below in Figure 5, whereby a 3-gallon bucket was filled with 5.5” of topsoil prepared with a water content of 0.26 by weight. The anode consisted of an 8” diameter disk of proprietary carbon cloth placed at a height of 0.5” from the bottom of the bucket. The cathode, consisting of an 8” diameter disk of proprietary carbon felt, was then placed on top of the soil. A plurality of 11” x 1” strips of the carbon cloth were then woven throughout the cathode disk to provide extra surface area. A 0.5” layer of river rock was then placed over the cathode to provide surface drainage and protection from environmental challenges, as well as to improve aesthetics, while securing the cathode’s physical connection with the soil. Preliminary laboratory TMFCs of this design exhibited roughly 200uW per unit at 30° Celsius – a power density of 6.17 mW per square meter of bulk anode surface area.

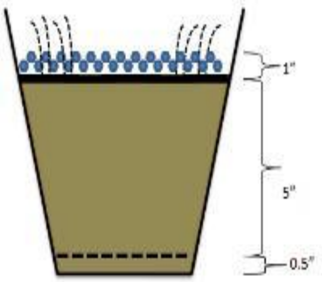


Figure 5. BackyardNet™ TMFC Architecture

3.1.2 Power Management Electronics

Electrical power from an MFC is unique, in that it is a low-current, high-impedance power source, preventing the use of standard off-the-shelf electronic systems. Trophos Energy has developed a power management platform (PMP) that contains sub-components able to boost the incoming electrical potential to a usable voltage in addition to providing energy storage for use in the application. Using a charge-pump boost-conversion topology, the BackyardNet™ power management electronics are designed to take the 300-400mV input potential from the TMFC and upscale convert it to a higher voltage power supply that could be used by the applications layer (above 3V). Moreover, the power converter was designed to output a maximum of 3.5V so as not to overload the applications layer. During in-lab testing, the power converter exhibited a power conversion efficiency above 80% for input voltages ranging from 0.1V to 1V.

3.1.3 Applications Layer

Building upon the Texas Instruments MSP430 microcontroller, the BackyardNet™ nodes’ application layer consists of a proprietary sensor and communications package integrated with the microcontroller's ADC and DI. The custom sensor package consisted of four environmental sensors to measure soil temperature, soil moisture, air temperature, and air humidity. The TI MSP430 chip is well optimized for ultra-low power energy harvesting technologies and this experimental program utilized a custom variant of the TI-Simplicity RF comms protocols.

3.2 Internet Gateway

The BackyardNet™ gateways have locally available power (single phase 110VAC) and Ethernet-based web access through a local residential IP. The necessary TI chipset wireless is received through a comms port with an ethernet router. A linux script was run on the router to process the necessary handshaking for uploading the data-string securely to the data server.

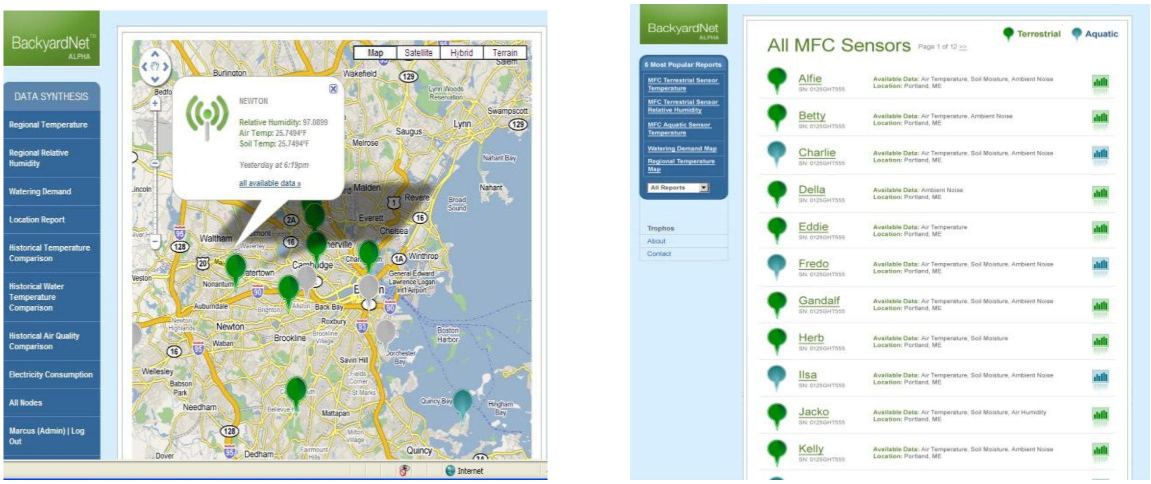
3.3 Data Server

The BackyardNet™ Data Server takes the form of a mySQL database that stores both the incoming data from all the sensor nodes and user-provided information about each node. This mySQL database contains two tables:

1) The **nodeinfo** table stores information about the node itself, such as the deployment location of the node (in latitude and longitude coordinates), contact person for the node, etc.
2) Data from all the nodes are appended into the **nodedata** table. Data can be sorted based on node ID or other information during analysis.

3.4 Graphical User Interface (GUI)

The data collected on the data server is made available in real time via a custom Google Maps™ interface, as shown in Figure 6, which is featured on the BackyardNet™ website (contact authors for access). With this GUI, users are able to observe the most recently collected data, preview archived data, and run spatial and temporal graphical reports against any of the monitored variables. The interface visually distinguishes active and inactive nodes, and allows the user to hover over a particular node to display its most recently collected data.



NEWTON
Relative Humidity: 97.0899
Air Temp: 25.7494°F
Soil Temp: 25.7494°F
Yesterday at 6:19pm

All MFC Sensors Page 1 of 12 >>

Alfie SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Ambient Noise Location: Portland, ME
Betty SN: 0125GHT555 Available Data: Air Temperature, Ambient Noise Location: Portland, ME
Charlie SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Ambient Noise Location: Portland, ME
Della SN: 0125GHT555 Available Data: Ambient Noise Location: Portland, ME
Eddie SN: 0125GHT555 Available Data: Air Temperature Location: Portland, ME
Fredo SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Ambient Noise Location: Portland, ME
Gandalf SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Ambient Noise Location: Portland, ME
Herb SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture Location: Portland, ME
Ilsa SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Ambient Noise Location: Portland, ME
Jacko SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Air Humidity Location: Portland, ME
Kelly SN: 0125GHT555 Available Data: Air Temperature, Soil Moisture, Ambient Noise Location: Portland, ME

Figure 6. BackyardNet™ GUI Layout

4. BACKYARDNET™ PROJECT RESULTS

As mentioned in Section 3, the BackyardNet™ project encompassed two primary goals:

1. Demonstrate the use of TMFC power by standard sensor and wireless communications hardware, via the integration of Trophos Energy's wireless data acquisition, potentiometry, and power management electronics.

2. Explore the versatility of TMFC technology by collecting statistically significant data on local environmental conditions and correlating this data to TMFC performance.

The following subsections discuss the successes and challenges experienced against each goal.

4.1 Employing TMFC Power

Successes:
BackyardNet™ was built and launched in July of 2009. Throughout its deployment, BackyardNet™ has demonstrated the successful integration of TMFC technology with standard sensor and wireless communications hardware, aided by proprietary power management electronics. As mentioned in Section 2.1, raw MFC voltages are too low (typically below 0.4V) to be used by most off-the-shelf hardware and therefore must be up-converted. As shown in Figure 7, Trophos Enegy's power management electronics successfully converted the low voltage coming from the TMFC to a voltage that could be utilized by the applications layer (above 3V). Notice in Figure 7 that the output voltage from the power converter never exceeds 3.5V, which was an intentional design consideration to safeguard against overloading the sensor hardware as described in Section 3.1.2.

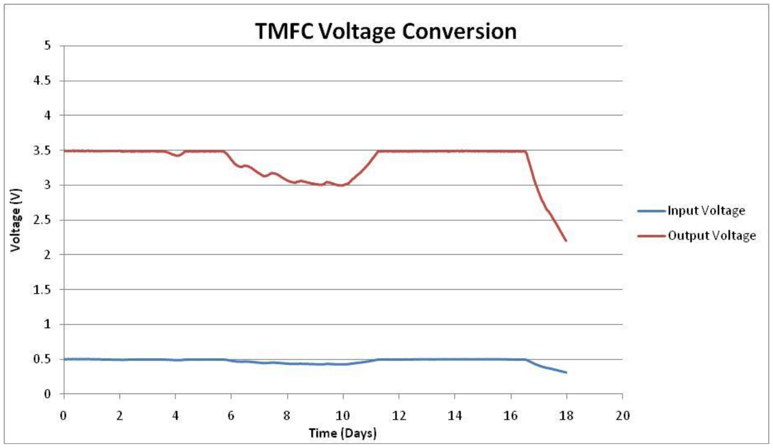


Figure 7. Typical voltage conversion for BackyardNet™ nodes

Across the board, much success was seen with the low-power electronics designed and built by Trophos Energy for the BackyardNet™ project. It was demonstrated both in the laboratory and in the field that the sensor node, including the power management board and applications layer, could function on less than 30uW with a 15 minute sampling/transmission rate. Moreover, laboratory tests showed that between sampling, the quiescent power draw from the complete sensor node electronics was less than 15 uW.

Challenges:
While the performance of the power management electronics remained consistent and functional throughout the duration of the BackyardNet™ project, the performance of the actual TMFC units was much more staggered and unpredictable. Figure 8 shows the power generation from ten TMFC units over the course of their deployment. While most of the TMFC systems continued to generate power throughout the duration of their deployment, as indicated by the continued data collection after Day 100, many TMFC systems failed within the first three weeks. Moreover many of the nodes that did remain functional did not generate enough power to maintain the 15 minute sampling rate after their deployment, some falling to a sampling rate of once per day, indicating an average power generation below 30 uW.

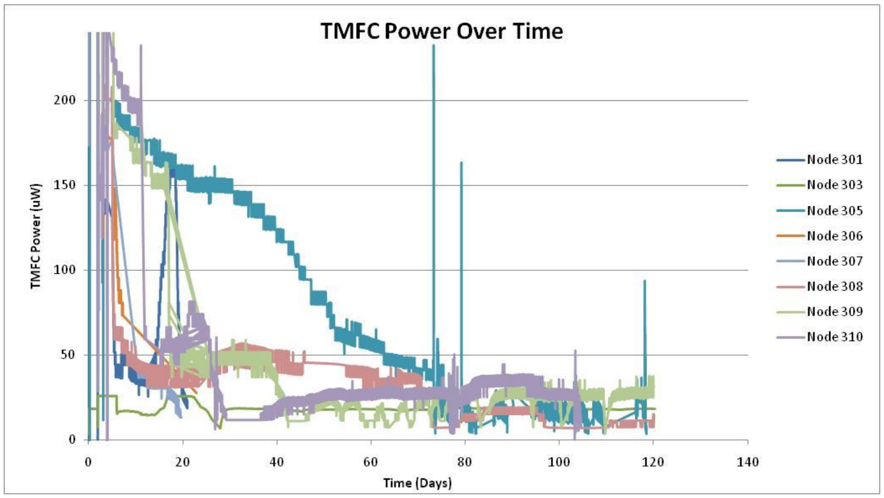


Figure 8. BackyardNet™ TMFC performance over time

The cause of the staggered and generally poor performance of the TMFC nodes was deduced to be primarily a function of both the soil water content and the temperature of the TMFC, as will be discussed in further detail in the next section.

4.2 Correlating TMFC Performance to Environmental Conditions

As mentioned previously, each sensor node employed four environmental sensors which collected data on soil temperature, soil moisture, air temperature, and air humidity. With these sensors, the aim was to uncover correlations between these four environmental parameters and TMFC power output.

Challenges:
Many challenges were faced with the environmental sensors incorporated into the BackyardNet™ sensor nodes. More than two-thirds of the sensors exhibited faulty readings, likely due to both poor manufacturing quality as well as mishandling during integration. With the remaining functional sensors, very few correlations with TMFC power output could be found. Those that were found are included in the discussion below.

Successes:
While the environmental data collected by the BackyardNet™ sensor nodes proved to be unfruitful in correlating TMFC performance to environmental conditions, progress was nevertheless made in the lab. In conjunction with the BackyardNet™ project, Trophos Energy conducted in-lab experimentation to characterize the impacts of certain environmental parameters on TMFC performance. Through this work, it was discovered that the water content of the TMFC's soil has a dramatic impact on TMFC performance.

4.2.1 TMFC Soil Water Content

As shown in Figure 9 below, there is a water content threshold of approximately 0.24 (by weight) which must be exceeded in order for the TMFC to function. Beyond this point, power generation increases dramatically with increased water content. While the actual value of the water content threshold does vary slightly depending on the composition of the soil, the essential requirement is that the soil must be at or above field capacity for the TMFC to perform reliably.

It should be noted that Figure 9 includes data from TMFCs employing soils infused with various levels of super-absorbent polymer (SAP). SAPs are known for their remarkable ability to absorb and retain moisture are used in many laboratory and field applications. The incorporation of SAP in the TMFC increased the total water holding capacity of the soil, allowing higher water contents to be achieved without over-saturating the soil. You will notice in Figure 9, that the addition of SAP seemed to simply extend the trend of increased power generation as a function of increased soil water content. The implications of SAP in future TMFC designs will be discussed in Section 5.

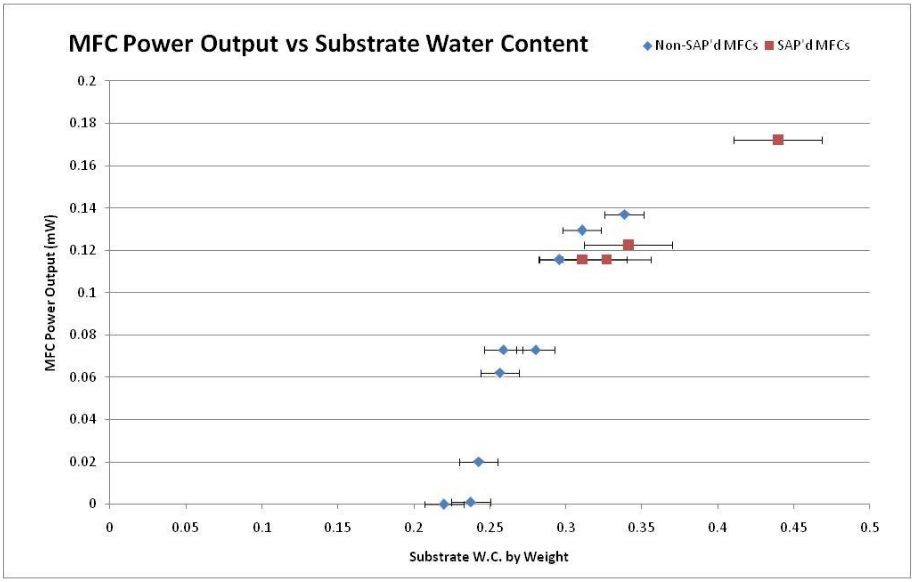


Figure 9. Power output vs. substrate water content (W.C)

It should be noted that this high dependence of TMFC performance on soil water content was exhibited in the data collected by the BackyardNet™ nodes themselves. As shown in Figure 10, after the TMFC began its initial ramp in the first 16 Days of deployment, power seemed to plateau and eventually fall dramatically. This decay in power coincides with a steady drop in soil water content. Notice in the chart that power generation approached zero as the soil water content approached 0.24, just as the laboratory experiments suggested.

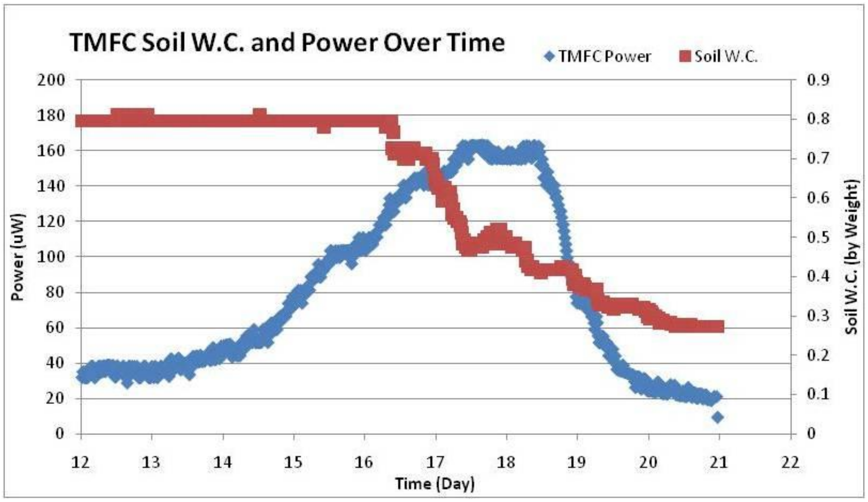


Figure 10. Impact of soil water content on BackyardNet™ nodes

Soil water content has such a dramatic impact on TMFC performance due to the fact that it impacts nearly all the chemical processes that make the TMFC function. For all MFCs, power generation is limited by the rates at which different chemical processes occur at each electrode. These include, but are not limited to, the rate at which new nutrients diffuse to the anode, the rate at which bacteria can metabolize these nutrients, the rate at which metabolic waste products diffuse away from the anode, and the rate which protons diffuse to the cathode. The presence of water significantly facilitates all of these processes. Other research has shown that the presence of water catalyzes the proton reduction reaction that occurs at the cathode.[xii] All the processes listed above are especially restricted in highly complex, semi-solid media such as soils, thus rendering the water that is present within the soil to have such a crucial role in TMFC performance.

4.2.2 TMFC Temperature

Much like water content, temperature also affects virtually every chemical process of an MFC. It has a particularly significant role in determining the metabolic rates of microbes, since the physiologies of microbes have evolved within a certain range of temperatures – any temperature above and below this range can inhibit microbial respiration dramatically. Among the in-lab studies conducted in conjunction with the BackyardNet™ project was an experimental regime aiming to characterize the effect of temperature on MFC performance. You can see in Figure 11 that TMFC power generation exhibits an exponential relationship with temperature in the given range (0-25°C), whereby power generation doubles every five degrees Celsius. It should be noted that temperatures beyond 35° Celsius are expected to have a detrimental effect on TMFC performance, since this is beyond the suitable range for soil-based microbial metabolism.

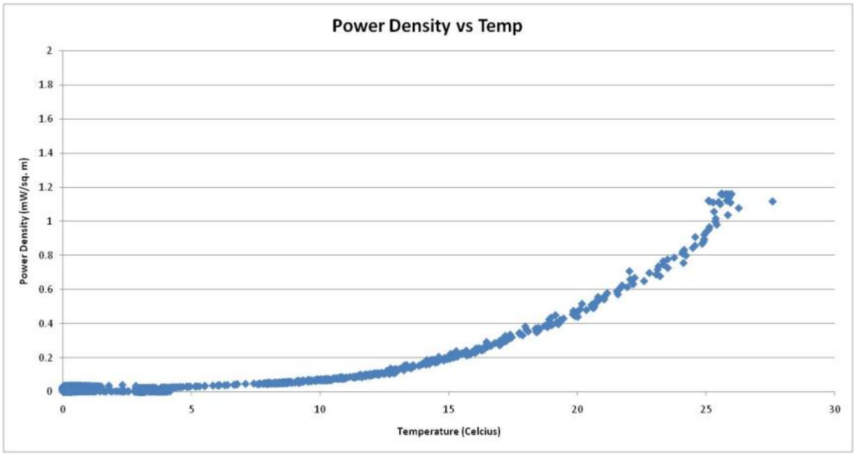


Figure 11. Impact of temperature on TMFC performance

The range of temperature in this study was chosen to represent that which the BackyardNet™ nodes might encounter throughout the course of their deployment. This trend was uncovered in October 2009, right as winter was approaching the New England area. Upon observing this curve, it was decided that TMFC nodes would have to be brought indoors (above 10°C) at their respective locations in order for the power generation to be sufficient for the sensor and communications package.

5. CONCLUSION

The BackyardNet™ project demonstrated the successful integration of TMFC technology with a pilot scale environmental sensor network. With the aid of Trophos Energy's power management electronics, power from the TMFCs was converted into a form usable by standard sensor and wireless communications hardware. This proprietary power management technology proved to be robust and highly efficient (above 80% for all relevant voltages). While this aspect of BackyardNet™ demonstrated great success, the operation of the actual TMFC systems posed many challenges. This project has demonstrated that there are still technical hurdles to be overcome before TMFCs can be deemed a viable power source for most wireless sensor networks. According to the findings of this study, the use of TMFC technology is currently limited to very wet and warm environments, such as tropical areas and marshes, due to the dramatic dependence of power generation on both soil water content and temperature.

To augment detrimental impacts associated with these two variables, and therefore expand the applicability of TMFC technology, Trophos Energy is currently exploring possible improvements in TMFC design. This includes further incorporation of super-absorbent polymers (SAPs) within the TMFC soil, as was suggested in Section 4.2.1. The addition of SAP not only increased the water holding capacity of the soil, thus increasing power generation, but also increased the TMFC's resistance to harmful desiccation events that seemed to have inhibited power generation for many of the BackyardNet™ TMFC systems. The incorporation of SAP into the TMFC architecture seems to be a promising design modification for improving the viability of TMFCs as remote power sources in a range of environments.

Other design enhancements are currently being investigated to augment the detrimental impact of winter temperatures on TMFC performance. These include placing the TMFC anode at a greater depth within the soil to experience a constant temperature throughout the year. According to the present findings, a constant temperature of 10°C may enable the TMFC to produce reliable levels of power throughout all seasons of the year, while still exhibiting a reasonable footprint and remaining cost-effective.

In conclusion, the BackyardNet™ pilot project proved to be an invaluable tool in rapidly assessing the viability of TMFCs for market today, while illuminating components that require further development. As new insights continue to emerge in the fields of microbiology, material science, and electrical engineering, the power generation capability of MFCs, both in the laboratory and in the field, continues to increase. With enhanced TMFC materials and architectures, this nascent technology may still prove to be a viable power source for long-term, remote monitoring applications throughout the varied climates of the world.

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