NATIONAL ENERGY TECHNOLOGY LABORATORY

Cost-Effective Wireless Application in the Power Generation Market

21 March, 2011

DOE/NETL-2011/1483

U.S. DEPARTMENT OF ENERGY

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March 21, 2011

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Acknowledgments

This report was prepared by Tetra Tech and Sextant Technical Services as subcontractors to Leonardo Technologies, Inc. (LTI) for the United States Department of Energy's National Energy Technology Laboratory. This work was completed under DOE NETL Contract Number DE-FE0004002 and performed under LTI Task 300.02.06.

The authors wish to acknowledge the excellent guidance, contributions, and cooperation of the NETL staff, particularly:

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List of Acronyms and Abbreviations

AES	Advanced Encryption Standard
CBM	Condition-Based Maintenance
CRC	Cyclic Redundancy Check
DCS	Distributed Control System
DO	Dissolved Oxygen
DOE	United States Department of Energy
DSSS	Direct Sequence Spread Spectrum
EM	Electromagnetic
ESR	Equivalent Series Resistance
FHSS	Frequency Hopping Spread Spectrum
FM	Frequency Modulation
GHz	Gigahertz
GSM	Global System for Mobile Communications
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISA	International Society of Automation
LTI	Leonardo Technologies, Inc.
MCU	Microcontroller
MEMS	Microelectromechanical System
MHz	Megahertz
MIT	Massachusetts Institute of Technology
mW	Milliwatt
MW	Megawatt
NEC	National Electrical Code
NERC CIP	North American Electric Reliability Corporation Critical Infrastructure Protection
NETL	National Energy Technology Laboratory
Ni-63	Nickel-63
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
OPC	Open Connectivity
OPV	Organic Photovoltaic
ORNL	Oak Ridge National Laboratory
ORP	Oxidation Reduction Potential
OSI	Open Systems Interconnection

PNNL	Pacific Northwest National Laboratory
PLC	Programmable Logic Controller
PVC	Polyvinyl Chloride
R&D	Research and Development
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RFID	Radio frequency Identification
SCADA	Supervisory Control and Data Acquisition
TEG	Thermo-electric Generator
TDMA	Time Division Multiple Access
UL	Underwriters Laboratories
µW	Microwatt
$\mu W/cm^2$	Microwatts per Square Centimeter
WCI	Wireless Compliance Institute
Wi-Fi	Wireless Fidelity Internet Network
WSN	Wireless Sensor Network

Executive Summary

Wireless sensors, sensor networks, and other wireless technologies are an emerging option for industrial applications, which have traditionally been hard-wired. This report presents the current status of industrial wireless technology and identifies areas limiting its use in coal-fired power plants. The report's conclusion recommends future research and development involvement for the United States Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) Strategic Center for Coal Research.

Most current industry wireless applications involve wireless sensor networks (WSNs) and non-critical applications where there is a distinct cost advantage over hard-wired instrumentation. These applications may include level, pH, or temperature sensors in distant or hard to access areas. For wireless applications to become more widely used in the coal-fired power plant industry, the following issues should be addressed:

- Acceptance of WirelessHART and International Society of Automation (ISA) 100.11a protocols by the industry to allow components from different manufacturers to work together and provide security in control systems.
- Reduction in the cost of wireless components to make them competitive with current wired systems.
- Combination of power sources, including batteries and energy harvesting, with energy-efficient wireless components to improve service life and lower maintenance requirements.
- Improvements in wireless component functioning in the harsh environments found in the power generation industry.
- Improvements in wireless sensor data transmission speed (polling rate).

Considering its mission and resources, the following actions are recommended for the NETL Strategic Center for Coal Research to address the previously outlined issues:

- Continue to monitor competition between wireless protocols as it is a major issue hindering development and implementation of WSNs.
- Evaluate the savings differential between wireless and hard wiring; the cost of WSN devices and associated components is greater for most applications compared to traditional wired systems. It is recommended that NETL:
    - Research alternative materials to reduce component production cost, specifically those related to energy harvesting and storage.
    - Conduct wireless systems evaluation projects to determine the actual cost savings of wireless applications compared to traditional hard-wired applications.
- Become active in advancing research pertaining to the service life of wireless components, which must show long-term reliability to be accepted by industry. The useful life of each component, energy usage, and the life of its power source are critical items to be evaluated. It is recommended that the NETL become active in advancing research which pertains to the following issues:
    - Facilitate development of a battery-powered wireless sensor complete with energy harvesting capabilities to recharge the battery. Vibration and thermal energy harvesting technology should be the focus of research for coal-fired power plant applications. To aid

this development, a software tool could be developed to evaluate the power characteristics of wireless sensors, energy harvesting components, and batteries.

- o Development of more efficient wireless components to reduce power requirements.
- o Conduct projects to analyze the energy efficiency and life expectancy of wireless components.
- o Conduct evaluation projects addressing the need for wireless components to withstand the extreme environments of coal-fired power generation plants.
- o Research improvements in data transmission speed (polling rate), which must be increased by manufacturers for their devices to be used in process automation and other control systems.
- o Develop an on-line tool for use by power generation facilities to summarize the results of these recommended demonstrations and analyses.

1.0 Introduction

Wireless technology is an emerging option for transmitting data in industrial applications and controls, which have been traditionally hard-wired. This report presents the current status of wireless sensors and wireless communication devices as they relate to industrial applications, identifies areas that are limiting their use, and describes how emerging wireless applications and their limitations apply to coal-fired power plants. Finally, it recommends areas for research and development (R&D) and suggests involvement for the United States Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) Strategic Center for Coal Research.

To prepare this report, manufacturers were consulted and white papers, university research, and process-based periodical articles were reviewed. In addition to consulting with manufacturer's representatives, a coal-fired power plant was visited to gain an operations/maintenance viewpoint on wireless sensor technology. A general supervisor in charge of electrical and automation projects for a large power generation company (who requested anonymity) was interviewed and discussed his perspective on the status of wireless technology.

Coal currently provides 48 percent of the electricity generated in the United States. The U.S. Energy Information Administration (2010) estimates that coal will still fill at least 44 percent of U.S. energy needs by 2035 (U.S. Energy Information Administration, 2010). Figure 1.1 presents an overall view of the components and process flow of a typical coal-fired power plant. Successful and efficient operation of a

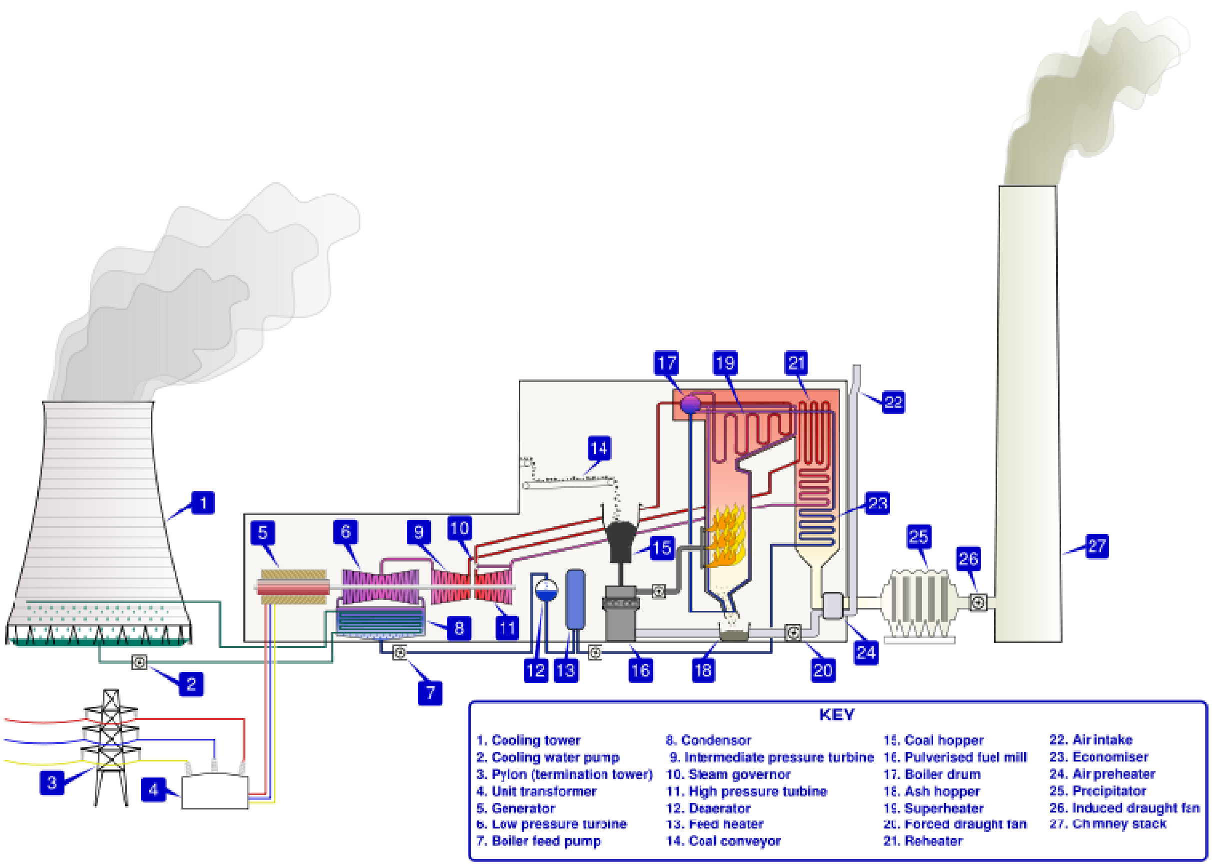

Figure 1-1. Overview of a Typical Sub-Critical Coal-Fired Power Plant (Techsol Systems, 2009)

coal-fired power plant requires that many of these components interact with each other. The improved monitoring and communication of critical readings using wireless devices could significantly improve the operating efficiency of these plants. This increased efficiency could result in greater electrical generation per unit of coal.

Process-related sensors are used by electric power generation plant operators to control plant operations with the least amount of down time. The process information from primary operations within a coal-fired power plant is measured by sensors and then transmitted to an automated control system or to plant operators. The information is used to control these operations, and to control them effectively, this information must be measured and transmitted almost continuously and without outside interferences. Currently, the majority of the information is gathered by wired sensors and communication devices because past wireless devices have not been able to meet the continuous measurement and transmission needs (with minimal interference and no security concerns). Although wireless communications, sensors, and other devices are now emerging as a viable technology for process control, the competitive cost of these systems needs to be proven to the industry for them to be put into use.

Wireless communications and devices are currently used in both consumer and industrial applications. Common consumer applications include wireless internet routers, cellular phones, Bluetooth®, and connections between electronic devices such as gaming consoles. Most current industrial applications of wireless technology involve instrument sensors for which the cost of hard wiring would be considered prohibitive.

Wireless communications have evolved from simple wide area network setups where computers communicate directly with other computers, or microprocessors communicate with other microprocessors, to now include more diverse applications such as process monitoring using simple wireless sensors that communicate via mesh or star networks. A substantial amount of development in wireless capabilities was accomplished by the major equipment manufacturers. Wireless technology has removed the need to hard-wire the process signal back to a control panel; however, replacing the power wire with a reliable power source is still a major issue. Figure 1.2 includes an overview of potential wireless applications within a plant.

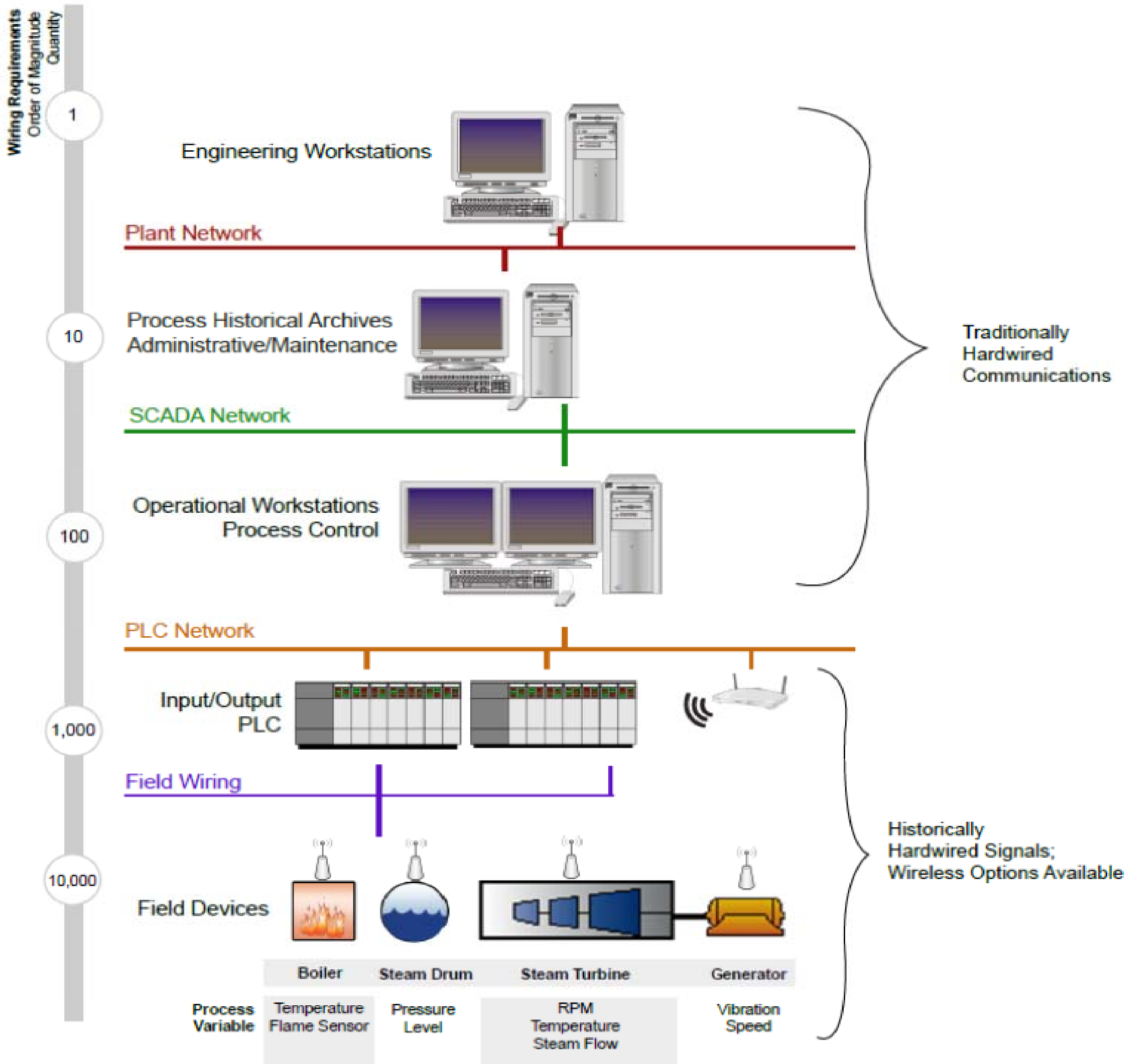

Figure 1-2. Wireless/Wired Application Options

2.0 Wireless Technology

2.1 Background

2.1.1 Wireless Networks

Wireless technology is used in both consumer and industrial applications, with common consumer applications including wireless internet routers and Bluetooth® connections between electronic devices. Most current industrial applications of wireless technology involve wireless sensor networks (WSNs) and non-safety-critical control applications. These applications may include level, pH, or temperature sensors in distant or hard to access areas. Consumer applications are considered easy to install and are routinely used in homes, offices, and restaurants. Industrial WSNs are less common.

Standard consumer wireless connections (Wireless Fidelity Internet Network [Wi-Fi], Bluetooth®, cellular, etc.) are not robust enough for industrial applications. Consumer wireless systems normally use high bandwidth, short transmission distances, high latency, and low response times. High bandwidth use is an inefficient use of resources for industry, and ultimately limits other applications. The longer response and processing times are not sufficient to meet the requirements of process controls in industrial applications. Ultimately, the level of required security determines the bandwidth requirements of the wireless system because increased security uses more bandwidth.

The following details should typically be considered when industrial users evaluate potential implementation of a WSN:

- Higher response time (latency) for obtaining and transmitting an instrument reading and resulting data transmission rates in wireless applications reduce the reliability of continuous data flow. Wireless systems also have a higher possibility of a network failure for control systems. If a response time of between 1 and 10 milliseconds is required, a wired system is currently the only option. A wireless system can be used when minimum response times of between 10 and 100 milliseconds are required, such as for primary process control variables.

- Wireless systems can be a viable option for data collection where wired systems would be too costly or otherwise impractical due to the length of wiring required or when access is difficult. As networks progress from simple corporate setups to more complicated Supervisory control and data acquisition (SCADA), Programmable Logic Controller (PLC), and industrial plant networks, wiring requirements increase drastically. Figure 1.2 shows the wiring requirements in terms of order of magnitude difference in wiring requirements from simple corporate setups to field wiring in an industrial application.

- Wireless systems can be a viable option for non-control applications such as obtaining preventative maintenance or power usage information.

2.1.2 Power

Manufacturers have researched and developed options to remove the need for wired power sources. These options include technologies such as improved energy storage devices and energy harvesting. The current sensor market has relied on batteries as energy-storage devices. The state of battery technology has allowed manufacturers to provide stand-alone simple sensors that transmit information via wireless devices powered by batteries. Battery life has drastically improved over the past few years, and there is continuing research into super and ultra capacitors and thin-film batteries that may provide additional life. Manufacturers currently specify the average life of batteries in wireless applications as 2 to 5 years, but information from actual applications has shown that battery life is 2 years or less. This life span is not acceptable to industry. Although less frequent data collection (sampling) rates have been used by manufacturers to prolong battery life, less frequent sampling rates are still viewed as a deficiency of wireless sensors by many industrial users.

Energy harvesting is a technology that may supplement batteries by increasing their average life. Energy harvesting is based on the ability to generate power from kinetic energy, differences in temperature, or differences in pressure from energy sources that would otherwise be unused or wasted. The most available types of energy for harvesting at coal-fired power generation plants are from vibration and heat. Currently, some energy harvesting prototypes are available, and there are even some sensors that are equipped with energy harvesting capabilities, but these sensors are limited in the types of measurements they can perform and the types of energy they can harvest (Carrabine, 2009). Currently, it is not anticipated that energy harvesting will be able to generate enough electricity for direct use on a continuous basis so that batteries in wireless devices can be eliminated. Energy harvesting, when fully developed, is expected to have the capability of recharging batteries and increase the time between replacements (Jackson, 2010). There are two key concepts that help to define the previous statements regarding energy harvesting and batteries: 1) The energy source is intermittent in most cases, therefore a rechargeable battery will also be required and 2) Not enough energy is typically available from the energy harvesting unit to completely recharge the battery, therefore battery replacement will eventually be necessary. Other technologies could also be applied to facilitate successful application of energy harvesting to wireless devices. These include rechargeable batteries, wireless mesh networks, microelectromechanical systems (MEMSs), small efficient microcontrollers (MCUs), and thin-film batteries.

Industrial process-related sensors have historically been hard-wired from the instrument back to a control panel. Many of these sensors are placed in severe environments compared to consumer applications. A hard-wired connection to sensors located in hazardous, wet, hot, corrosive, or extremely dirty environments can be difficult to install and maintain. These installations normally require special and more expensive materials, such as polyvinyl chloride (PVC)-coated conduit and sealed junction boxes, and higher maintenance frequency and costs.

2.2 Wireless Systems

Manufacturers are seeking to improve wireless applications using various systems such as wireless mesh networks, MEMSs, and small efficient Microcontrollers (MCU),as discussed in the following sections.

2.2.1 Mesh Networks

Wireless mesh networks are communication networks made up of radio nodes called motes. These networks provide a relatively inexpensive means to utilize wireless devices. Each mote transmits, receives, and retransmits signals within neighboring motes. The network is supported by the motes and does not require all of the motes for it to continue to operate. Motes in the network will compensate for other motes in the network if they are no longer working, a concept known as self-healing architecture. The motes are inexpensive, easy to install, and do not require wiring. They also have the potential for low maintenance with the addition of energy harvesting. Figure 2.1 illustrates the topology, or interconnections of the components, of an example wireless mesh network.

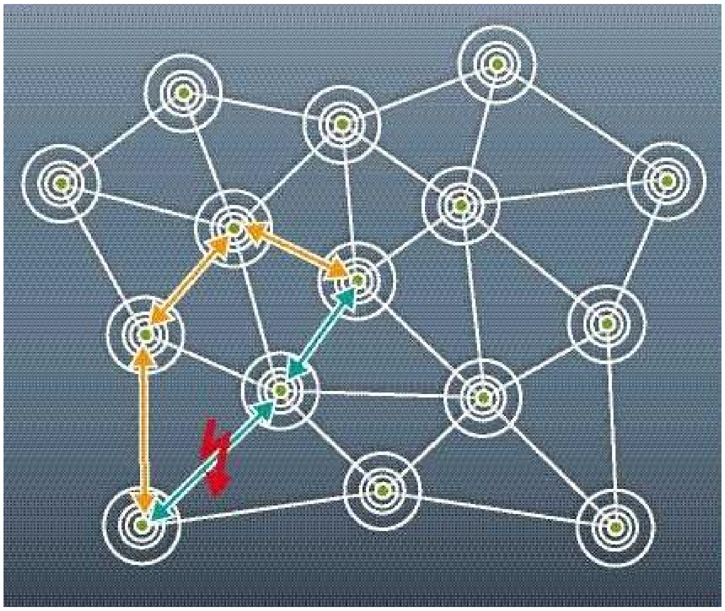

Figure 2-1. WirelessHART Mesh Network Topology (Pepperl+Fuchs International, 2011)

2.2.2 Microelectromechanical Systems

Microelectromechanical Systems (MEMS) are extremely small (20 micrometers), electrically powered, mechanical devices constructed on integrated circuit boards. The capabilities of MEMS sensors have improved as a result of recent improvements in micromachining technology. These improvements have led to smaller sensors that are capable of operating on lower voltages while being more sensitive, rugged, and accurate (Tutle, 2008).

2.2.3 Small Efficient Microcontrollers

Small Efficient Microcontrollers (MCU) are computers contained on a single integrated circuit or chip. An MCU contains a processor, memory, clock, and input/output controller. They have been developed to operate on low power while offering acceptable performance for their respective application (Tutle, 2008). The current generation of MCUs has progressed to include ultra-low-power MCUs. Battery life should exceed 10 years for an application involving an ultra-low-power-MCU, which is important because battery replacement costs can be significant (Ostaffe, 2009).

2.3 Energy Sources

Conventional batteries cannot provide adequate power (in the desired space limits) for wireless sensors to provide industry-acceptable data sample rates and battery life. Improved energy storage through the use of thin-film batteries, super capacitors, or hybrid batteries is needed to provide consistent power to wireless sensors.

2.3.1 Conventional Batteries

Conventional or traditional batteries, including zinc-carbon, lead-acid, nickel-cadmium, and alkaline, are used in cars, radios, flashlights, and other portable electric devices. Conventional batteries can be disposable or rechargeable. Their size for the amount of energy they provide, lifespan, energy leakage, and consistency of discharge voltage severely limit their use as a power source for wireless sensors and transmitters.

2.3.2 Thin-Film Batteries

Thin-film rechargeable lithium batteries were developed by the DOE's Oak Ridge National Laboratory (ORNL). Their size along with their ability to be recharged many more times than conventional batteries make them suitable for many different commercial and industrial applications including non-volatile memory, semiconductor diagnostic wafers, smart cards, wireless sensors, radio frequency identification tags, and medical products such as implantable defibrillators and neural stimulators.

The following list presents a brief overview of some of the characteristics thin film batteries that give them an advantage over traditional batteries.

- Able to be manufactured in any shape or size.
- Comprised of all solid-state construction.
- Capable of operating at high and low temperatures (-20°C to 140°C, confirmed by testing).
- Constant cost per area when reducing size.
- Safe under all operating conditions.
- Unaffected by heating to 280°C (Oak Ridge Micro-Energy, Inc., 2010).

The profile of a thin-film battery allows it to be placed directly within a circuit board. They are well suited to wireless applications because they have minimal equivalent series resistance (ESR), which is a resistance value representing the distributed resistances associated with a real capacitor. Minimal ESR allows energy to be stored and removed easily from the battery. The batteries do not self discharge, allowing them to stay at a ready level (Tutle, 2008).

2.3.3 Super Capacitors

Super capacitors are capacitors with maximum available capacitance values. They are capable of holding up to 400 Farads in a single standard case size. Their capacitance density is great enough that they can be used in applications where batteries are normally used (Illinois Capacitor, Inc., Undated)

The advantages of super capacitors include the following:

- 10 to 12 year life consisting of millions of charge/discharge cycles.
- Cycle efficiency of over 95 percent.
- High charge and discharge rates.
- Low impendence.
- Cannot be overcharged.
- Inexpensive, in terms of cost per watt.

Their disadvantages include the following:

- Energy density is one-fifth to one-tenth that of electrochemical batteries.
- Cells have low voltage and must be connected in series to obtain higher voltage.
- Linear discharge voltage.
- High discharge rate (Electropaedia, 2010).

Based on work being done at the Massachusetts Institute of Technology (MIT), nanomaterials are expected to greatly increase the area of capacitor electrodes, which will result in a significant increase in power density (Electropaedia, 2010).

Currently, a super capacitor cannot totally replace a battery but can be used in conjunction with a battery to provide a hybrid battery. The battery is needed as a buffer between the capacitor and the application (Supercapacitor.org, Undated).

2.4 Energy Harvesting

Energy harvesting collects ambient energy that would otherwise be lost for conversion to electrical energy. Normally this energy is not purposely released, but in some cases it is released by design as a means to power remote devices. Vibration, thermal, light, and electromagnetic radiation are all energy resources for which harvesting technology is being developed. The expected power generation rates of these energy harvesting technologies are listed in Table 2.1 (Frank, 2010).

Table 2-1. Expected Power Generation Rates of Different Energy Harvesting Technologies

Energy Source		Maximum Power Harvesting ($\mu W/cm^2$)
Vibration/Motion	Human Activity	4
	Industrial	800
Thermal	Human Activity	60
	Industrial	10,000
Light/Solar (Photovoltaic)	Indoor	100
	Outdoor	100,000
Electromagnetic Radiation	GSM Cellular (900 MHz)	0.1
	Wi-Fi (2.4 GHz)	0.01

$\mu W/cm^2$ – Microwatt per square centimeter.

MHz – Megahertz.

GHz – Gigahertz.

For energy harvesting to be considered for an application, the potential energy source and application must be evaluated. The energy source must have energy that would otherwise be wasted, but it must also be accessible and available on a routine frequency or continuous basis, with the necessary volume to be harnessed effectively.

The wireless applications themselves must also be able to use and benefit from energy harvesting, which typically means that the application should have one of the following characteristics:

- Difficult maintenance or installation access.

- Location or distance from existing power sources and/or communication hubs makes it too expensive or logistically difficult to hardwire.
- A “green” or other environmental or sustainability requirement that must be met.
- A high on-stream time limiting the use of batteries or other power storage devices (Valenzuela, 2009).

The power usage of system components, including MCUs, Radio Frequency Integrated Circuits (RFICs), and power-supply Integrate Circuits (ICs) has been greatly reduced to allow them to be used with energy-harvesting systems. These developments include using control software for power management, data collection, and transmission to avoid excess power consumption.

Because energy harvesting inherently provides small amounts of energy, the integration of energy harvesting, batteries, and wireless sensors should be researched. The standard life of a process sensor is 10 to 15 years. The manufacturers’ estimated battery life is 2 to 5 years, and obtaining this battery life requires reduced functionality in the form of slow sample rates by the sensors. (Frank, 2010).

2.4.1 Vibration

Vibration energy can be harvested at kilohertz levels from machinery, and its capture efficiency is estimated at between 25 and 50 percent. Harvested energy is estimated at 4 $\mu W/cm^2$ for human sources and 800 $\mu W/cm^2$ for industrial sources. Vibrational harvesting requires a vibration source, a fixed connection to the source (frame), a means to capture motion (suspension), and a means for transforming the motion energy into electricity (transducer) (Valenzuela, 2009).

The four means to transform vibration or motion energy into electricity are: (1) electrostatic; (2) piezoelectric; (3) electromagnetic/inductive and (4) magnetostrictive. Electrostatic transformation uses a capacitor consisting of a fixed structure and opposing moving metal structure. The movement from the vibration results in a change in capacitance, which results in a proportional voltage change. Piezoelectric energy harvesting functions by using an existing vibration to place a mechanical stress on certain materials such as crystals. The stress deforms the piezoelectric material producing an electrical charge. In electromagnetic harvesting, captured vibration is used to initiate movement of a magnetic mass through a magnetic field. The resulting change in flux of the magnetic field generates a voltage. Magnetostrictive energy harvesting is based upon the Villari Effect. A ferromagnetic material, referred to as magnetostrictive material, subjected to vibrational induced strain produces a magnetization change which can be converted into electrical energy (Yuan & Wang, 2007).

2.4.2 Thermal

Thermal or heat flux energy harvesting can generate electricity using the thermoelectric effect (Seebeck effect) through which the temperature gradient produced between two dissimilar conductors generates electricity. The estimated efficiency of thermal energy, which is abundant in coal plants, is approximately 3 percent for industrial sources. The estimated harvested power is 60 $\mu W/cm^2$ for human sources and $10 mW/cm^2$ for industrial sources. Thermal harvesting collects energy based on the Seebeck effect or by using a pyroelectric element. The movement of electrons between hot and cold elements through a conductor generates the resulting voltage. The Seebeck coefficient is defined as the voltage generated per degree of temperature difference between two points.

2.4.3 Light

Light energy harvesting converts energy gathered from natural and artificial light sources to usable power. Solar panels are the most known application of this technology. Light or photovoltaic harvesting works by converting photons from incoming light into electricity. In this process, the light is converted directly into electricity through use of the photovoltaic effect. Photons are absorbed and their energy causes electrons to move into an excited state. The excited electrons are then separated spatially and extracted by transporting them to the terminals of a device. The light sources can be either outdoor or indoor. Outdoor photovoltaic cells have been in use for many years. Outdoor light source harvesting efficiencies range from 5 to 30 percent, and power densities can be up to 100,000 $\mu W/cm^2$. Indoor efficiencies are much lower, and power densities also decrease to between 100 and 1,000 $\mu W/cm^2$ due to much lower illumination levels. Indoor applications provide an opportunity for research to optimize light capture (Tartagni, 2009).

2.4.4 Electromagnetic Radiation

Radio Frequency (RF) harvesting captures electromagnetic (EM) radiation, converts it into DC power, most commonly through the use of a floating gate transistor, and conditions the power for use. RF harvesting can be used to obtain EM radiation from anticipated or unknown existing sources such as a Global System for Mobile Communications (GSM), Frequency Modulation (FM), or Wi-Fi or be intentionally broadcast at a specific wavelength to a wireless node. Existing sources use power that is already present but provide low energy density in the $\mu W/cm^2$ range. Harvesting existing EM radiation may raise concerns because of the potential impact on the primary function of its sources (Tartagni, 2009). RF harvested energy can be used for direct power, energy storage in a battery or super capacitor, or to power a passive wireless switch for battery activation. Advantages of implementing RF energy harvesting with wireless applications include extending battery life, embedding the power source in the wireless application or structures, and use within mobile applications (Ostaffe, 2009).

Intentional RF sources are normally dedicated power transmitters, and the available power is engineered for the application. These sources are normally 4 watts or less and can be operated continuously, on demand, or on a scheduled basis. The needs of the application powered by the RF sources, such as energy storage, charging, or device activation, determine how the sources operate. Intentional RF sources may also be operated in a network to provide power over a large area (Ostaffe, 2009). The main concern of intentional sources is the maximum allowable level of transmission of 100 mW (Tartagni, 2009).

Anticipated ambient sources have a reliable concentration of RF energy that is expected to be available on a regular or intermittent basis. These sources may be totally separate from or incidental to the application in which the harvested energy will be used and were not designed for powering the application. The sources provide RF energy in excess of their intended application to allow harvesting without impacting the application. Examples of these sources are radio, television, and mobile-base station transmitters or areas with large concentrations of mobile phones.

Unknown ambient sources are not designed sources of RF energy and are unrelated to the wireless application. The wireless application user has no control over and may have little or no knowledge of their operation. Examples are microwave radio links or mobile radios. These sources still provide a useable source of continuous or intermittent RF energy in the mW and µW range (Ostaffe, 2009).

The energy harvesting and micro battery products industries appear to be entering into a growth phase. Successful applications for these products have been developed for the automotive, consumer electronic, building, and military markets (Frank, 2010).

2.5 Protocols and Security

Wireless network components are designed and manufactured by different companies, and for these components to work with one another, communication standards and protocols are established. These standards and protocols dictate the network structure and how the data are transmitted. The three emerging protocols for wireless industrial automation are WirelessHART, ISA-100.11A, and China's WIA-PA. The organizations developing these protocols plan for them to be adopted by the International Electrotechnical Commission (IEC). WIA-PA is anticipated to become China's national protocol. The protocols are meant to provide reliable and secure wireless operation for non-critical monitoring (critical monitoring typically utilizes a wired sensor), alerting, and supervisory control applications. ISA-100.11A has lower data latency, superior battery life capabilities (accomplished by not forcing field devices to route data as part of the meshing scheme), and easier integration with current internet protocol (IP) networks (wired or wireless) than WirelessHART. However, slow arrival to market (2 years after WirelessHART) has stunted potential early adoption of ISA-100.11A. Both ISA-100.11A and WirelessHART provide low data rate connectivity, adequate system security, and the ability to work well within industrial environments that have high noise and interference. The two protocols are not currently interoperable and have technical differences and different commercial manufacturer support, which may lead to a slow convergence. The long-term convergence of the WirelessHART protocol with the ISA-100.11a protocol is currently a popular topic with the International Society of Automation (ISA), which has developed a standards subcommittee to foster development of a converged protocol named ISA-100.12.

The two primary WSN protocols used in the U.S. industrial market today are WirelessHART and ISA-100.11a. WirelessHart currently appears to be the most widely accepted protocol. However, the ISA-100.11a protocol appears to be more efficient in transmitting information.

WirelessHART and ISA100.11a were designed for industrial performance by using input from end-users, customers, and technical experts. Prior to the ratification of WirelessHART and ISA100.11a, the communications methods between the device and gateway and device to device were vendor dependent. This issue led to vendor products that were not compatible with other vendors' products. Although there is not one clear protocol, there are two widely accepted protocols that can be implemented regardless of vendor. These protocols allow support to multiple (few to hundreds) field devices in a single network with viewing capabilities that can be managed from a single network manager.

All industrial protocols use the Open Systems Interconnection (OSI) seven-layer model as their design base. The IEEE 802.15.4 radios used by the industrial wireless protocols use the lower two layers (physical and data link) of the OSI model. This allows all protocols to use the same radio while still being unique.

To ensure that all manufacturers' systems will work in the global environment, the 2.4 GHz frequency is used. It is available in all countries but is also used for cellular phones and other devices such as remote control toys. The demand for this bandwidth is an area that will have to be addressed by these protocols (Verhappen, 2010)

In addition, wireless network security must ensure that the network can recognize the system's wireless signals. It must discern these signals from tramp or malicious signals from other systems that could disrupt operations. Data security is addressed in the wireless protocols and standards (Verhappen, 2010)

WirelessHART, ISA100.11a, and WIA-PA are discussed in more detail in the following sections.

2.5.1 WirelessHART

The International Electrotechnical Commission (IEC) approved the WirelessHART protocol as a full international standard on March 26, 2010. WirelessHART, now known as IEC 62591, is a backwards-compatible, cost-effective approach to wireless communications that supports industry requirements for simple, reliable, and secure wireless communication. WirelessHART is backwards compatible with wired HART devices, which allows common configuration tools and user familiarity with the estimated 25 million HART field devices currently installed. WirelessHART is available for measuring pressure, flow, level, temperature, vibration, pH, valve position, float switches, and universal adaptors to retrofit existing instruments with wireless capability. WirelessHART relies on the use of wireless access points and data gateways to send transmitter data to host applications connected to a high-speed backbone or other existing plant communications network. The gateway acts as a data server (usually using open connectivity [OPC]) and can be used in a redundant fashion. Current products have a network size standard of a maximum of 100 devices per wireless gateway with update times of 10 seconds, and 50 devices per wireless gateway with update times of 5 seconds.

WirelessHART uses a time-synchronized, self-healing, mesh architecture, and in the U.S. operates at 2.4 GHz ISM band using the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard with a data rate of 250 Kbps. The IEEE 802.15.4 standard is used for the physical and media access layers of the WirelessHART protocol. Each WirelessHART field device forms a network and also can act as a signal repeater. The original transmitter sends a message to its nearest neighbor, which passes the message on until the message reaches the base station and the actual receiver. In addition, alternative routes are established in the initialization phase. If the message cannot be transmitted on a particular path due to an obstacle or defective receiver, the message is automatically passed to an alternative route. Thus, in addition to extending the range of the network, the flat mesh network provides redundant communication routes to increase reliability.

Communication within the wireless network is coordinated with Time Division Multiple Access (TDMA), which synchronizes the network participants in 10-millisecond time frames. This enables a very reliable (collision-free) network and reduces the lead and lag times during which a station must be active.

To avoid jamming, WirelessHART uses Direct Sequence Spread Spectrum (DSSS). All 15 channels as defined in IEEE 802.15.4 are used in parallel. WirelessHART uses channel hopping sequences to reduce the chance of interference with other networks, such as 802.11g/g, that operate in the same ISM frequency band. Channels that are already in use are blacked out to avoid collisions with other wireless communication systems. Other methods of providing robust security are the use of industry-standard 128-bit Advanced Encryption Standard (AES) encryption, device authentication, and rotation of encryption keys to join the network.

2.5.2 ISA-100.11a

ISA100.11a is an open-standard wireless networking technology developed by the ISA100 Committee of the ISA. The ISA100 committee was formed in 2005 to establish standards that will define procedures for implementing wireless systems in the automation and control environment, with a primary focus on field level applications. The committee is made up of more than 400 automation professionals representing end users, wireless suppliers, Distributed Control System (DCS) suppliers, instrument suppliers, Programmable Logic Controller (PLC) suppliers, technology suppliers, system integrators, research firms, consultants, government agencies, and consortia.

In 2009, the ISA Automation Standards Compliance Institute established the ISA100 Wireless Compliance Institute, also known as the WCI. The ISA100 Wireless Compliance Institute owns the 'ISA100 COMPLIANT' certification scheme and provides independent testing of ISA100-based products to ensure that they conform to the ISA100 standard. In May 2009, the ISA100 standards committee voted to approve ISA100.11a, and in September 2009, the ISA officially released the ISA100.11a standard. Current products have a network size standard of a maximum of 50 devices per wireless gateway with update times of 5 seconds, and 10 devices per wireless gateway with update times of 1 second.

2.5.3 WIA-PA

WIA-PA is proposed by the Shenyang Institute of Automation, Chinese Academy of Sciences, and is based on IEEE 802.15.4. Its network supports a hierarchical network topology and is a hybrid of star and mesh networks. The first layer is a deployment of touring and gateway devices in a mesh topology. The second layer is where routing and field and handheld devices are connected. It is based on the OSI seven-layer model but only defines the data link sub-layer, network layer, and application layer. Network interconnections are made through the WIA-PA gateway.

The WIA-PA protocol specifies five types of devices, the host computer, gateway device, routing device, field device, and handheld device (Verhappen, 2010). WIA-PA is not currently envisioned by the U.S. wireless industry to be used in the industrial market outside of China; however, for U.S. manufacturers to sell their services in China, they will have to be compatible with WIA-PA.

2.5.4 Security

Security is of utmost importance in wireless transmitter implementations, especially at mission-critical facilities such as power plants. Both ISA100.11a and WirelessHART manufacturers have implemented some of the most advanced security methods currently available, namely the end-to-end session utilizing the AES 128-bit encryption method. These sessions ensure that messages are enciphered such that only the final destination can decipher and use the payload created by the source device.

Security and privacy for network communications is accomplished through encryption, verification, authentication, key management, and other open industry standards best practices. At a minimum, manufacturers are employing several communication techniques that provide multiple levels of security. Methods include frequency hopping spread spectrum (FHSS) or DSSS. The FHSS technique modulates the data signal with a carrier signal that periodically “hops” across a band of frequencies from 902 MHz to 928 MHz. Other methods include Cyclic Redundancy Check (CRC), checksum coding and password protection. More recently, manufacturers have included the AES method, which is incorporated into both of the leading protocols, ISA100.11a and WirelessHART.

Both the ISA100.11a and WirelessHART protocols are being developed to address the concerns and impending requirements of the North American Electric Reliability Corporation Critical Infrastructure

Protection (NERC CIP) standards and ISA99 standards. These standards are being developed to deal with the security of the electrical grid and cyber security.

The essential work of the NERC CIP regarding the electricity sector, as noted on their website, includes the following actions:

- Protecting – includes physical security, cyber security, emergency preparedness and response, business continuity planning, and recovery from a catastrophic event, with emphasis on deterring, preventing, limiting, and recovering from terrorist attacks.
- Deterring – to dissuade one from even trying.
- Preventing – to cause an attempt to fail.
- Limiting – to constrain consequences in time and scope to something less than what they would have been otherwise.
- Recovering – returning to normalcy quickly and without unacceptable consequences in the interim.

The ISA100 committee is mandated to work within the ISA99 and ISA standard. The ISA99 standard is for industrial automation and control system security. It includes two completed parts, the Part 1 standard, Security for Industrial Automation and Control Systems: Concepts, Terminology and Model, and the Part 2 standard, Security for Industrial Automation and Control Systems: Establishing an Industrial Automation and Control Systems Security Program. The current working group is developing the standard, Technical Requirements for Industrial Automation and Control Systems (Verhappen, 2010).

There is little doubt that the later developed ISA100.11a protocol is more robust, has lower latency, and higher security standards than WirelessHART, but questions regarding product certification and general slowness to market have caused confusion among end users. The quick adoption and 2-year head start of WirelessHART has added to the confusion of whether ISA-100.11a will make headway in the competitive market place. Companies such as Nivis, headquartered in Atlanta, Georgia, have recently developed hardware and software applications that allow co-existence of WirelessHART and ISA-100.11a devices. This hardware and software may ease the need for one protocol.

Several manufacturers are delaying certain equipment releases until one protocol is adopted. WirelessHART is the defacto protocol at this time; however, the ISA-100.11a protocol has benefits that cannot be discounted (e.g. easier integration with current IP networks and superior battery life) (Jackson, 2010).

2.6 Industrial Environments

Coal-fired power plants contain process areas where sensors must withstand severe environmental conditions. Table 2.2 contains some examples of these areas within a coal fired power plant.

Table 2-2. Severe Environmental Conditions within a Coal Fired Power Plant

Environmental Condition	Application within a Coal Fired Powerplant
High Dust	Coal, ash, or lime handling
High Moisture	Scrubbers or water treatment
Corrosive Areas	Acid/Caustic use, corrosive gases from combustion and high temperature in combustion areas, proximity to steam lines or vents

Additional requirements must be met for wireless sensors to be used in National Fire Protection Association (NFPA) classified areas. These areas have the potential hazard of fire or explosion due to the elements in the surrounding atmosphere or vicinity. Sensor applications for these environments can be very expensive. The National Electrical Code (NEC) divides hazardous locations into three classes:

- Class I locations are areas in which there are or may be high concentrations of flammable liquids, gases, or vapors.
- Class II locations are areas that contain combustible dusts.
- Class III locations are areas that contain easily ignitable fibers or filings.

Instrumentation commonly used in factory automation and process industries including coal-fired power plants typically requires adherence to Underwriters Laboratories (UL) Class I, Division 1 or 2. For areas where ignitable substances such as gases, vapors, or liquids are likely to exist only under abnormal conditions, as classified under Class I, Division 2, instrumentation rated for the area should not require an explosion-proof housing. For areas where these substances can exist under normal conditions, as classified under Class I, Division 1, instrumentation must be contained within a suitable explosion-proof housing, contained within a suitable purged housing, or rated as intrinsically safe.

Wireless products are available with Class I, Division 2 ratings that can be incorporated into this type of hazardous location without the need for expensive explosion-proof housings. Presently, most manufactures such as Emerson “Rosemount” and Honeywell and other large suppliers of wireless instrumentation offer intrinsically safe wireless instruments for Class I/II/III, Division 1.

Manufacturers are developing some wireless applications for wet, corrosive, high-temperature, and NFPA classified environments, but the selection is limited. There is continuing government and academic research into these areas.

2.7 Available and Emerging Commercial Products

A number of WSN products are currently available for commercial application. The major manufacturers include Emerson, Honeywell, Yokogawa, ABB, Siemens, Micropelt, GE, KCF Technologies, Adaptive Energy, Perpetuum, and Texas Instruments. These products include the radios, sensors, and energy-harvesting components. Some examples of available sensors are temperature, pressure, level, sound, corrosion, position, flow, pH, and vibration. A sensor from Emerson that will measure dissolved oxygen (DO), oxidation/reduction potential (ORP), nitrates, and ammonia is expected to be released in the near future. Appendix A, Table A.1, identifies many of these emerging products and their features.

2.8 Application within a Coal-Fired Power Plant

Coal-fired electrical power generation plants are the most common type of power plant in the world, and because of their complex nature, lend themselves to the use of high-level control automation systems. Most of the plants use complex DCSs with centralized computer-automated control systems that allow efficient operation of complex systems while minimizing staffing needs compared to traditional hard-wired control systems.

One such plant is the Karn-Weadock power plant located in Essexville, Michigan, run by CMS Energy (CMS Karn). The CMS Karn plant uses Emerson's Ovation Expert Control System™ to help control the 2,100-megawatt (MW) complex. CMS Karn currently has 22 Emerson wireless transmitters using the WirelessHART protocol, with a plan to deploy more wireless transmitters as funding becomes available. Currently, signals monitored via wireless transmitters using the WirelessHART protocol to seamlessly integrate into the Emerson Ovation DCS include cooling water flow, make-up water flow, service water flow, condensate pump discharge pressure, house service water pump discharge pressure, caustic tank temperature, generator oil pressures, extraction steam pressure, soot blower air pressure, combustion control air pressure, house service air pressure, and several others. The staff is comfortable with the performance and reliability of the installed instruments and plans to deploy additional vibration sensors on cooling towers and fuel-handling tail pulleys. The staff also plans to add wireless sensors to record important operational parameters in secluded areas that would otherwise require an operator to take manual measurements at periodic intervals. Additional wireless sensor integration will also help to reduce personnel presence in potentially hazardous areas.

An anonymous general supervisor of another large coal-fired generation company suggested to the authors that there are several areas of concern regarding wireless sensor systems that need to be resolved before these systems can be widely used in operational control systems. These concerns include:

- Security of the information transmitted within the WSN and from the wireless sensor to the controller.
- Standardization of protocols and standards that allow wireless components from different manufacturers to work together.
- The current cost of individual sensors makes them too expensive compared to wired components.
- Data transmission rates and data readers must be compatible for wired sensors to be used in process automation applications.
- Reliable power sources are needed for the sensors. Several years of life is a desirable time frame.
- Sensors typically need to be capable of operating in severe environments including those common to the power industry. Many of these environments are dirty, dusty, wet, corrosive, and have high temperatures or have hazardous conditions.

3.0 Wireless Technology Needs

Although today's wireless technology provides non-mission-critical functionality, wireless systems of the future are anticipated to be more reliable and to perform mission-critical monitoring and control functions. Maintenance requirements for these systems will be minimal, whether for battery replacement, verification of sensor calibration, or any activity to sustain system performance. To reach this level of performance, certain technology gaps must be overcome.

The main technology gaps present within WSNs are related to three areas. The first gap relates to the power requirements of the sensors and radios exceeding the life of stand-alone power sources (batteries), specifically, the inability of components to preserve battery life while utilizing low power sources such as energy harvesting devices. It is anticipated that end users will begin to require increased data transmission rates on the order of once per second or more which will significantly impact battery life. A related problem is used battery disposal and replacement requirements associated with large WSNs, which also reduces the acceptability of WSN deployment to the industry. This gap is also making it difficult for wireless sensors to be relied on to play critical roles in control and automation systems. Energy harvesting is expected to decrease this gap; however, the current technology lacks the ability to supply ample power.

The second gap is the lack of a clear industry wide accepted wireless protocol. There are efforts to develop a converged protocol, but competing protocols have divided manufacturers and are standing in the way of WSN and controls adoption for many potential end users.

The third gap is cost. Although the total installed cost of a wireless node is typically lower compared to a wired node (including wiring and installation), it is not low enough. It is the authors' opinion that in order for wireless to be strongly considered as an alternative for a wired system the cost would need to be on the order of 50 percent less. Areas for cost improvement are unit housing and packaging, increased competition between manufacturers, the price and availability of materials required to produce energy harvesting components, and limited production capabilities. Production capabilities are limited due to the lack of an effective manufacturing process for energy- harvesting components and effective large-scale manufacturing processes that would result in increased component availability and the ability to take advantage of economies of scale.

The effects of these three technology gaps related to energy usage, protocols, cost, and use in critical applications are discussed in further detail below.

3.1 Energy Usage

WSNs are able to provide more flexible installation options and cheaper per node costs than a traditional wired system. However, unlike wired installation options, wireless sensors must make efficient use of a limited power source (most commonly a battery). Most of the power use in a wireless sensor is related to data transmission. For example, the power draw in sleep mode may be in the range of a few microwatts, but the power draw in transmit mode could be more than several hundred milliwatts. As previously mentioned, the most common power source for a wireless sensor node is a battery. Most of the current commercially available wireless transmitters use a C size lithium ion battery. A typical lithium ion battery loses on average 20 percent of its charge capacity per year which equates to approximately 800-1200 charge cycles before it needs to be replaced. The ultimate service life of these batteries will depend upon the frequency of transmissions. Super capacitors also show promise for use as power sources for WSNs due to their longevity and ability to quickly charge and discharge (Jackson, 2010).

A range of low power components with power draws so low that they can be measured in microamps were developed in response to the need for longer battery service lives. These components include microcontrollers, digital signal processors, RF transceivers, and MEMS sensors. However, they do not provide the performance needed for the use of wireless devices for process control.

Thin-film battery technology, also referred to as "battery-on-a-chip," could potentially allow common objects to capture and store enough energy to complete measurements and RF transmissions, a concept known as "pervasive power." However, additional developments in energy harvesting conversion efficiencies will be needed to further decrease the gap between wireless components and effective power sources and allow thin-film batteries to be used to their full potential (Murray, 2009).

The viability of wireless sensors for use in control systems is now being considered in the power generation and other industries. Initially, the most feasible wireless technology applications were considered for non-control measurements because of power constraints. For many critical control applications, the sensor or control instrument is required to be powered continuously, which would inevitably lead to high levels of battery consumption. One specific example of a critical control application is a control valve or actuator. A control valve or actuator would most likely require a defined failure position where continuous power is applied to a spring to keep a valve either open or shut until the measurement is deemed to fail. If this control valve or actuator were allowed to "go to sleep" to conserve power, it would automatically enter its failure position and disturb the process. A potential solution to the problem surrounding this one application would be a locally powered wireless control valve or actuator if there was a readily available power source. According to an industry representative, a WirelessHART-based product to perform wireless valve and actuator controls with a local power source will be introduced in the near future (Rezabek, 2010).

Energy harvesting technology is being developed and used to supplement battery life (Jackson, 2010). A major issue associated with development of energy harvesting units on a large scale is related to the price or availability of certain materials and a lack of effective production processes. For example, piezoelectric materials, which produce electricity from stress on materials from vibration, most commonly use lead composites. However, the use of lead is met with reservation because of its potentially hazardous characteristics. An alternative material for this application is bismuth telluride, but increased use of cadmium telluride in solar harvesting applications has decreased the availability of telluride resources (Frost and Sullivan, 2009).

Newly developed WSN components continue to cut power requirements while battery and energy-harvesting technologies continue to increase their respective efficiencies; however the gap between power availability and power requirements is still large. Before WSNs can effectively be integrated for long-term deployment, this gap must continue to decrease.

3.2 Protocols

Many WSN users see the need for a convergence of WirelessHART and ISA100.11A protocols. A survey conducted by ControlGlobal.com revealed that 54 percent of respondents are not able to decide on implementation of a WSN due to competing protocols. Some of these respondents are even looking for completely different alternatives to WSNs. Some WirelessHART and ISA100 supporters do not feel that a convergence would be difficult if the equipment suppliers would work together. Pat Schweitzer, the cochair of ISA100, stated, “Technically there is no issue. Both base [specifications] were developed under the same premise. One is constrained only by the applications layer that was adopted. The base networking is almost the same. The better question is can the supplier community ever come together to meet the users’ expectations” (Boyles, 2010).

A new subset of the ISA100 committee, known as the ISA100.12 committee, was established in 2005 to create a converged ISA100 committee that would potentially include all of the competing protocols. These efforts may be stifled due to a clear divide within the ISA100 community. One group feels that the convergence of protocols is necessary, but the other group feels that convergence is not useful or practical. Instead of convergence, it has been suggested that the competing protocols just need a way to coexist and work together within the same space without interference. One suggestion made by Jean-Pierre Hauet of KB Intelligence was to “develop backbone routers which allow transparent communication between sub-nets” (Boyles, 2010).

3.3 Cost

The ControlGlobal.com survey mentioned above also found that many potential industry users feel the cost of WSNs is too high. One of the greatest costs associated with WSN nodes is the actual packaging; the radio costs are relatively low and the gateway costs can be spread throughout a large part or the entire network. Potential end users also may not be making a fair comparison between the entire installed cost per node of wired compared to wireless systems. Bob Karschnia, Vice President of Wireless at Emerson, stated, “The cost of a wireless measurement point needs to be compared to the total cost of wiring the same point. Studies have shown that the installed cost is reduced by 50 to 80 percent. Time savings are also a huge factor, not only the actual billable hours that are saved, but also the longevity of the overall project. […] The best way to evaluate pricing is through some sort of conjoint where tradeoffs are made, because those are the decisions that customers really make. At this point in the adoption curve, lower prices would not increase the adoption rate at all. Additionally, economies of scale will kick in as volumes rise, and this will help with pricing.”

As the technology develops more and the market continues to grow, more competition between suppliers will inevitably lead to price decreases (Boyles, 2010).

4.0 Research and Development

4.1 Department of Energy (DOE) Sponsored Research and Development

The Department of Energy (DOE) currently funds research and development (R&D) projects that will ultimately lead to improved capabilities of wireless sensor and controls networks in power plants. These projects focus on topics such as improving battery characteristics, increasing sensor capabilities for harsh environments, improving efficiency and reducing costs for power plants, and developing new energy harvesting technologies. Ongoing DOE R&D projects include the following:

- ***Decreasing Battery Recharge Time to Minutes Instead of Hours.*** The Pacific Northwest National Laboratory (PNNL) is currently researching the use of Vor-x^{TM}, a graphene material, in the manufacturing of batteries. Graphene, an ultra-thin sheet of carbon atoms, has been shown by PNNL to improve the power and cycling stability of lithium-ion batteries while maintaining their power storage capabilities (Vorbeck Materials and Princeton University, 2010).

- ***Extend Lifetime of Plastic Solar Cells.*** The National Renewable Energy Laboratory (NREL) has partnered with Solarmer Energy, Inc., to test their new plastic solar cells against 360 other organic photovoltaic (OPV) devices. These OPV devices are the energy harvesting components of the plastic solar cells. The manufacturing of these new plastic solar cells is estimated to cost less and can be performed faster than the current devices on the market today (Solarmer Energy, Inc. and DOE NERL, 2010).

  Battery-Free Wireless Sensor Network for Advanced Fossil-Fuel Based Power Generation. NETL is sponsoring this project at the University of Puerto Rico Mayaguez to develop and characterize high-temperature sensing materials with dielectric response to physical and chemical exposure. This project consists of research into a battery-free wireless sensing mechanism to develop novel wireless sensors and sensor networks for physical and chemical parameter monitoring in harsh environments (University of Puerto Rico, Mayaguez, 2007 to 2011).

  Online, In-Situ Monitoring Combustion Turbines Using Wireless Passive Ceramic Sensors. NETL is sponsoring this project at the University of Central Florida to develop wireless, passive, ceramic microsensors for in-situ temperature and pressure measurement inside combustion turbines. The sensors would operate in high-temperature (greater than 1,300°C) and elevated-pressure (300 to 700 psi) harsh environments. Specifically, this project is working to develop a set of high-temperature, wireless, passive, ceramic, MEMS sensors for online real-time monitoring applications in turbine systems where they are required to survive extremely harsh work conditions (University of Central Florida, 2010 to 2012).

- ***Energy Harvester Powered Wireless Sensors for Extreme Temperature Environments.*** NETL is sponsoring this project by KCF Technologies, Inc. involving wireless sensing, powering of sensors, their use in high-temperature environments, and their limitations. The temperature problem is being addressed using: (1) temperature control of electronics in high- temperature environments; (2) high-temperature tolerance of thermal and vibration energy harvesters; (3) conditioning and reliably supplying voltage to wireless sensors; and (4) energy harvester mechanical robustness (KCF Technologies, Inc., 2010).

Ultra-High Temperature Distributed Wireless Sensors. NETL is sponsoring this project by Prime Research, LC, and Virginia Tech to develop wireless sensor technology capable of operating at very high temperatures and in highly corrosive environments. This research includes eliminating the need for cables connecting to the sensors. The technology related to the project will include recent developments in radio frequency identification (RFID), high-temperature materials, and frequency selective metamaterials (Prime Research, LC and Virginia Polytechnic Institute, 2009 to 2010).

A Novel Wireless Sensor Network with Advanced Prognostic Algorithms for Condition Based Maintenance of Critical Power Plant Components. NETL is sponsoring this project by Signal Processing, Inc., the University of Texas at Arlington, and General electric which evaluates the development of two mutually dependent functions, distributed data acquisition and real-time data interpretation. This project combines a WSN with an advanced diagnostic and prognostic capability to monitor and assess critical power plant components (Signal Processing, Inc., University of Texas at Arlington, and General Electric, 2007 to 2011).

Self Powered Wireless Sensor System for Power Generation Applications. NETL is sponsoring this project by Wireless Sensor Technologies, LLC which focuses on the development and demonstration of a highly reliable waste heat-enabled power supply and wireless sensor system for power generation applications. CBM systems significantly improve the effectiveness of maintenance programs for complex systems by optimizing the timing and focus of the maintenance. The project looks to minimize the associated costs and to improve the application of CBM sensors to existing plants and equipment. The CBM system and its individual temperature and pressure sensors are being effectively used in the development phases of power plant equipment such as gas and steam turbines. This system includes a unique power supply that uses waste heat from the plant equipment. In addition, the system eliminates most system interconnects through its wireless networked architecture of individual sensor nodes. The program devises a self-powered wireless sensor system for power generation applications that is enabled for operation using a semiconductor thermo-electric generator (TEG)-based power supply (Wireless Sensors Technologies, LLC, 2010 to 2011).

Wireless Seebeck Power. NETL is sponsoring research by Physical Optics Corporation to identify a new type of power harvesting that will support the wireless sensors used in power plants. Currently, large amounts of energy are lost from vibration and heat. The project will look at developing technology that can collect this energy to allow wireless sensors to operate without using wired power or requiring periodic battery replacement. Specifically, the project will evaluate the development of a new class of thermo-electric nanodevices (Physical Optics Corporation, 2010 to 2011).

- ***Galfenol Energy Harvester for Wireless Sensors.*** NETL is sponsoring this project by Techno-Sciences, Inc. which involves retro-fitting a compatible wireless sensor system for real-time monitoring of power plant processes without having significant integration related issues and/or requiring reconfiguration of the wireless system. The device is based on an innovative use of the magnetostrictive effect. The device has the potential to outperform devices using the conventional piezoelectric approach (Techno Sciences, Inc., 2010 to 2011).

4.2 University Research and Development

Active R&D areas related to wireless sensor applications, power supplies, and energy-storage devices are diverse and include energy efficiency to reduce sensor and network power requirements, improved energy harvesting devices, improved operability, and demonstration of the capability of wireless applications for process control applications. The following presents a brief overview of some current university R&D in these areas. This list was compiled through review of industry publications, internet news releases, and university web pages.

Decision Support Systems for Large-Scale Networks. The Florida Institute of Technology is researching means for improving connectivity and coverage as the network deployment area increases. To accomplish this goal, they are developing a decision support system for the stochastic or random deployment of large-scale WSNs (Kostanic, Otero, & Otero, 2009).

Software Updates for Wireless Networks. The University of Pittsburgh is researching software update management for WSNs. The project's goal is to make the updating of sensor software faster and more energy efficient (Li, Weijia, 2010).

High Demand Applications. The University of De Pau's (Spain) Liuppa wireless network team is researching the use of wireless networks in more demanding applications including video surveillance, robot-sensor interaction, and collaborative planning for complex processing tasks using real-time collected data (University of De Pau, 2010).

Materials for Energy Storage. Washington State University used super-high pressures to develop a new compact material capable of storing highly condensed amounts of energy. This material will be developed into several different applications potentially including an energy storage device (Yoo, Choong-Shik, 2010).

Nanomaterial Energy Cells. Louisiana Tech University researched and published "Light and Thermal Energy Cell Based on Carbon Nanotube Films." This research involves a piezoelectric cantilever coated with a carbon nanotube film that converts distortions into electrical energy. When the film absorbs light and/or thermal energy, it causes the cantilever to bend back and forth repeatedly causing the piezoelectric material to generate power as long as the light and/or heat source is active (Que, 2010).

Sensor Longevity. Research teams from Cornell University and Holst Centre, part of the nanoelectronics research center Imec, in the Netherlands, conducted research into increasing sensor longevity. Two methods were researched, both relying on piezoelectric power generation in which a MEMS cantilever converts mechanical motions into electrical power. Cornell created a piezoelectric generator using a small amount of nickel-63 (Ni-63). The Holst Centre created a wireless autonomous temperature sensor powered by an aluminum nitride vibration harvester (Adee, 2010).

- **Thin-Film Voltaic Technology.** Several institutions are involved in research with thin-film photovoltaic technologies, including Arizona State University, Massachusetts Institute of Technology (MIT), University of Delaware-Institute of Energy Conversion, Imperial College of London, Colorado State University, Ecole Polytechnique Federale de Lausanne, and Helsine University of Technology (Zervos & Kahn, 2010).

- **Nanomaterials for Energy Harvesting.** Stevens Institute of Technology has developed nanogenerators and is working on miniature energy harvesting technologies using piezoelectric nanowire- and nanofiber-based generators that have the potential to power wireless electronics, portable devices, stretchable electronics, and implantable biosensors (Stevens Institute of Technology, 2010).

4.3 Equipment Vendor Research and Development

Equipment vendors are conducting R&D in the following areas:

- **Energy Efficiency and Power Storage.** Current technology allows for a 3- to 5-year battery life without recharging for most common instruments, depending on application and data update rates. Lower power usage and improved energy sources to increase the "maintenance interval" of the sensors to something approaching the effective lifetime of the sensor are currently being developed.

- **Energy Harvesting.** Energy harvesting technology is being developed to supplement batteries and to provide charging capabilities with the goal of extending the life of the battery to match the life of the sensor. This goal is becoming more realistic as microcontrollers, radios, and protocols become more powerful and efficient and as energy harvesting technologies increase their ability to capture and utilize minute amounts of energy. As noted in Table A-1, the most common energy harvesting sources are vibration or thermal energy.

- **Additional Sensor Measurements.** Common measurements of sensors currently on the market include temperature, level, pressure, vibration, position, flow, current, voltage, power, pH, and weather parameters. Development of emerging and developing technologies to measure corrosion, oxidation/reduction potential (ORP), conductivity, acoustics, stress, seismic activity, acceleration, and other parameters is ongoing.

- **Sensor Network Monitoring.** A sensor network is unlikely to crash outright, but as some nodes die and others generate noisy or corrupt data, the measurements of the overall system may become inconsistent. Ongoing work to judge the health of the network and more importantly the health of each individual sensor is critical to determining the state of the overall WSN.

- **Wireless Sensor Network Software.** Current R&D of software to setup, integrate, and monitor complex WSNs is a top priority for wireless sensor manufacturers. Each manufacturer currently uses its own set of software tools to assist the integration engineer in setup, integration, and most importantly the real-time health of the wireless network and individual sensors.

5.0 Conclusions and Recommendations

A number of gaps must be addressed for WSNs to be adopted for routine use in the power generation industry and for industry use in process automation and control systems. These issues and barriers include the following:

- The WirelessHART and ISA100.11a standards need to be accepted by the US industry and able to co-exist and communicate with one another in order to allow components from different manufacturers to work together and to provide security in the control systems.
- The cost of wireless components needs to be reduced to make them competitive with current wired systems.
- Power sources, including batteries and energy harvesting devices, need to be combined with energy-efficient wireless components to improve service life and to lower maintenance requirements.
- Improvements are needed in the functioning of wireless components and reduction of signal interference in the harsh environments found in the power generation industry.
- Improvements are needed in data transmission speed (polling rate) of wireless sensors.

Considering the mission and resources of the NETL Strategic Center for Coal Research, the following recommendations are made:

- Competition between wireless protocols is a major issue hindering development and implementation of WSNs. It is recommended that the NETL continue to monitor this issue.
- The cost of wireless sensor network devices and associated components is greater for most applications when compared to traditional wired systems. The savings differential between wireless and hard wiring needs to be evaluated. It is recommended that NETL:
    - Research alternative materials for use to reduce component production cost. Specifically those related to energy harvesting and storage.
    - Conduct wireless systems evaluation projects to determine actual cost savings of wireless applications versus traditional hard-wired applications.
- The service life of wireless components must show long term reliability to be accepted by industry. The useful life of each component, energy usage, and the life of its power source are critical items to be reevaluated. It is recommended that the NETL become active in advancing research which pertains to the following issues:
    - A battery powered wireless sensor complete with energy harvesting capabilities to recharge the battery should be developed. Vibration and thermal energy harvesting technology should be the focus of the research for coal fired power plant applications. To aid this development a software tool could be developed for use to study various tests. The software would evaluate the power characteristics of wireless sensors, energy harvesting components, and batteries.
    - The development of more efficient wireless components to reduce power requirements is needed.
    - Evaluation projects to analyze the energy efficiency, operating performance, and life expectancy of wireless components should be conducted.

- Wireless components must be capable of handling the extreme environments of coal fired power generation plants. It is recommended that the NETL conduct evaluation projects in this area.
- Data transmission speed (polling rate) must be increased by manufacturers for their devices to be used in process automation and other control systems. It is recommended that the NETL research improvements to these devices.
- Results of these recommended evaluations and analyses should be summarized in an on-line resource tool for use by power generation facilities.

REFERENCES

Adee, S. (2010). Wireless Sensors That Live Forever. *IEEE Spectrum* , http://spectrum.ieee.org/semiconductors/devices/wireless-sensors-that-live-forever.

Bloodgood, C. (2009). *Wireless Technology Delivers Value to the Power Industry.* Phoenix: Honeywell International, Inc.

Boyles, W. (2010, August 10). *Wireless Field Devices are Shipping, but Adoption Questions Remain*. Retrieved August 2010, from Control Global: http://www.controlglobal.com/articles/2010/Wireless1008.html

Carrabine, L. (2009, November 05). *designworldonline.com.* Retrieved 2010, from design world: http://www.designworldonline.com/articles/4933/11/Are-Wireless-Sensor-Networks-Really-Ready-for-Industry

Electropaedia. (2010). *Supercapacitors*. Retrieved December 2010, from mpoweruk: http://www.mpoweruk.com/supercaps.htm

Frank, R. (2010, August 5). *Making Energy Harvestings Promise of Free Energy a Reality.* Retrieved 2010, from electronicdesign.com: http://electronicdesign.com/content/print.aspx?topic=making_energy_harvesting_s_promise_a_reality

Frost and Sullivan. (2009). *Energy Harvesting Materials - The Road Ahead.* Research and Markets.

Illinois Capacitor, Inc. (Undated). *Supercapacitors*. Retrieved December 2010, from Illinois Capacitor: http://www.illinoiscapacitor.com/pdf/Papers/supercapacitors.pdf

Jackson, R. (2010, January 14). *Developments in Harvesting Energy for Wireless Sensor Networks*. Retrieved July 2010, from Design World: http://www.designworldonline.com/articles/5257/12/Developments-in-Harvesting-Energy-for-Wireless-Sensor-Networks.aspx

KCF Technologies, Inc. (2010). *Energy Harvester Powered Wireless Sensors for Extreme Temperature Environments.* KCF Technologies, Inc.

Kostanic, Otero, & Otero. (2009). *Development of a Simulator for Stochastic Deployment of Wireless Sensor Networks.* MelBourne Florida: JOURNAL OF NETWORKS.

Li, Weijia. (2010). *SOFTWARE UPDATE MANAGEMENT IN WIRELESS SENSOR NETWORKS.* University of Pittsburgh.

Murray, C. J. (2009, March 19). *Energy Harvesting Gets Real*. Retrieved September 2010, from Design News: http://www.designnews.com/article/print/189768-Energy_Harvesting_Gets_Real.php

Oak Ridge Micro-Energy, Inc. (2010, November 22). *Oak Ridge Micro-Energy Inc.* Retrieved November 24, 2010, from http://www.oakridgemicro.com/tech/tfb.htm

Ostaffe, H. (2009). RF Energy Harvesting Enables Wireless Sensor Networks. *Sensors Mag* , 3.

Pepperl+Fuchs International. (2011). *WirelessHART*. Retrieved January 2011, from Pepperl+Fuchs International: http://www.pepperl-fuchs.com/cps/rde/xchg/global/hs.xsl/10028.htm?rdeCOQ=SID-1F9D24A1-D3C86527

Prime Research, LC and Virginia Polytechnic Institute. (2009 to 2010). *Ultra-High Temperature Distributed Wireless Sensors.* Prime Research, LC, Virginia Polytechnic Institute.

Que, D. L. (2010, October 8). *Louisiana Tech researchers design, fabricate innovative energy harvesting device*. Retrieved 2010, from e! Science News: http://esciencenews.com/articles/2010/10/08/louisiana.tech.researchers.design.fabricate.innovative.energy.harvesting.device

Rezabek, J. (2010, May 5). *Users Will Have to Exert Their Influence with Suppliers to Get Control in the Field Implementd in WirelessHART*. Retrieved August 2010, from Control Global: http://www.controlglobal.com/articles/2010/WirelessControl1005.html

Physical Optics Corporation. (2010 to 2011). *Wireless Seebeck Power.* Physical Optics Corporation.

Signal Processing, Inc., University of Texas at Arlington, and General Electric. (2007 to 2011). *A Novel Wireless Sensor Network with Advanced Prognostic Algorithms for Condition Based Maintenance of Critical Power Plant Components.* Signal Processing, Inc., University of Texas at Arlington, General Electric.

Solarmer Energy, Inc. and DOE NERL. (2010, June 21). *NREL Launches Partnership with Solarmer Energy to Extend Lifetime of Plastic Solar Cells*. Retrieved October 2010, from National Renewable Energy Lab: http://www.nrel.gov/news/press/2010/861.html

Stevens Institute of Technology. (2010, July 9). *Miniature Energy Harvesting Technology Could Power Wireless Electronics*. Retrieved 2010, from Science Daily: http://www.sciencedaily.com/releases/2010/07/100709131308.htm

Supercapacitor.org. (Undated). *Super Capacitors and UltraCapacitors New Energy Storage*. Retrieved December 2010, from Super Capacitors: http://www.supercapacitors.org/

Tartagni, M. (2009). *EAS Future Trends in Devised, Technologies, and Systems.* Europe: CATRENE.

Techno Sciences, Inc. (2010 to 2011). *Galfenol Energy Harvester for Wireless Sensors.* Techno Sciences, Inc.

Techsol Systems. (2009). *Products*. Retrieved November 2010 , from Techsol Systems: http://www.techsolsystems.com/products.html

Tutle, D. (2008, December 11). *Energy Harvesting Synergies.* Retrieved 2010, from electronicdesign.com: http://electronicdesign.com/content/print.aspx?topic=energy-harvesting-synergies20221

U.S. Energy Information Administration. (2010). *International Energy Outlook 2010.* Washington, D.C.: U.S. Energy Information Administration.

University of Central Florida. (2010 to 2012). *Online, In Situ Monitoring of Combustion Turbines Using Wireless, Passive, Ceramic Sensors.* University of Central Florida.

University of De Pau. (2010). *Wireless Sensor Network Research at Liuppa, University DePau*. Retrieved from http://web.univ-pau.fr/~cpham/PROJETS/WSN/Home.html: http://web.univ-pau.fr/~cpham/PROJETS/WSN/Home.html

University of Puerto Rico, Mayaguez. (2007 to 2011). *Battery-Free Wireless Sensor Network for Advanced Fossil-Fuel Based Power Generation.* University of Puerto Rico Mayaguez.

Valenzuela, A. (2009, August 1). *Batteryless Energy Harvesting for Embedded Designs.* Retrieved 2010, from eetimes.com: http://www.eetimes.com/General/DisplayPrintViewContent?contentItemId=4008326

Verhappen. (2010, 4 07). *Industrial Wireless Worries: Security and Standards Delay Adoption and User Affinity.* Retrieved 12 2010, from controldesign.com: http://www.controldesign.com/articles/2010/WirelessSecurityIN10Q2.html

Vorbeck Materials and Princeton University. (2010, July 13). *Battery research could lead to shorter recharge time for cell phones*. Retrieved October 2010, from U.S. Department of Energy Pacific Northwest National Laboratory: http://www.pnl.gov/news/release.aspx?id=807

Wireless Sensors Technologies, LLC. (2010 to 2011). *Self Powered Wireless Sensor System for Power Generation Applications.* Wireless Sensors Technologies, LLC.

World Coal Institute. (2003). *The role of coal as an energy source.* London: World Coal Institue.

Yoo, Choong-Shik. (2010, July 8). *Washington State University Create Super Battery*. Retrieved 2010, from Energy Harvesting Journal: http://www.energyharvestingjournal.com/articles/washington-state-university-create-super-battery-00002429.asp?sessionid=1

Yuan, F. G., & Wang, L. (2007). *Energy harvesting by magnetostrictive material (MsM) for powering wireless sensors in SHM.* Bellingham: International Society for Optics and Photonics.

Zervos, H., & Kahn, B. (2010, Q2). *Thin Film Photovoltaics and Batteries 2010-2020*. Retrieved 2010, from IDTechEx: http://www.idtechex.com/research/reports/thin_film_photovoltaics_and_batteries_2010_2020_000239.asp

Appendix A

Wireless Sensor & Energy Harvesting Devices Characteristics/Performance										
Manufacturer	Market Availability	Wireless Measurement	Intended Market	Power	Hazardous Environment Capable	Standard/ Protocol	Functionality	Transmission Characteristics	Advantages/ Disadvantages	Additional Information
1. Emerson Smart Wireless	Released	• Temperature • Level • Pressure • Vibration • Position • Flow • pH • Float Switch • Universal Adaptor	Universal application	Advanced power management with 3-7 year battery life	Yes	• Open standards (IEC approved) • WirelessHART protocol	• Advanced encryption standard (AES-128) • Anti Jamming • Mesh Network • Channel Hopping • Time Sync Messaging	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 wireless standard emphasizes efficiency (low power) rather than speed	• Eliminates conduit • Allows continuous remote monitoring and remote instrument calibration • Robust wireless network that sacrifices speed for reliability	Current battery technology has limited the need for energy harvesting for industrial applications.
2. Honeywell Wireless	Released	• Temperature • Level • Acoustic • Pressure • Discrete input • Corrosion • Position • Flow • pH • Float Switch • Universal Adaptor	Universal application	Advanced power management with 5-10 year battery life	Yes	• Open standards (IEC approved) • ISA100.11a protocol	• Advanced encryption standard (AES-128 codified) • Mesh Network • Channel Hopping • Time Sync Messaging	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 DSSS wireless standard emphasizes efficiency (low power) rather than speed • Frequency Hopping Spread Spectrum (FHSS) – user select	• Eliminates conduit • Allows continuous remote monitoring and remote instrument calibration • Robust wireless network that sacrifices speed for reliability	Wireless multiplexer can be used in stack monitoring applications.
3. Yokogawa	Released	• Temperature • Pressure	Universal application	Advanced power management with 5-10 year battery life	Yes	• Open standards (IEC approved) • ISA100.11a protocol	• Advanced encryption standard (AES-128 codified). • Mesh Network • Channel Hopping • Time Sync Messaging	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 DSSS wireless standard emphasizes efficiency (low power) rather than speed	• Eliminates conduit • Allows continuous remote monitoring and remote instrument calibration. • Robust wireless network that sacrifices speed for reliability. • Increased security standards over WirelessHART	
4. ABB	Released	• Universal Adaptor to upgrade current ABB transmitters to wireless, other products are being developed	Universal application	Advanced power management with 3-7 year battery life	Yes	• Open standards (IEC approved) • WirelessHART protocol	• Advanced encryption standard (AES-128) • Anti Jamming • Mesh Network • Channel Hopping • Time Sync Messaging	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 wireless standard emphasizes efficiency (low power) rather than speed	• Eliminates conduit • Allows continuous remote monitoring and remote instrument calibration. • Robust wireless network that sacrifices speed for reliability	Asset Vision configuration software – enhanced ease of use.
5. Siemens Sitrans	Released	• Temperature • Pressure • Flow • Universal Adaptor	Universal application	Advanced power management with 3-7 year battery life	Yes	• Open standards (IEC approved) • WirelessHART protocol	• Advanced encryption standard (AES-128) • Anti Jamming • Mesh Network • Channel Hopping • Time Sync Messaging	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 wireless standard emphasizes efficiency (low power) rather than speed	• Eliminates conduit • Allows continuous remote monitoring and remote instrument calibration • Robust wireless network that sacrifices speed for reliability	
6. Emerson Smart Wireless	Emerging	• Dissolved Oxygen (DO) • Oxidation Reduction Potential (ORP) • Nitrates • Ammonia	Universal application	Advanced power management with 3-7 year battery life	Yes	• Open standards (IEC approved) • WirelessHART protocol	• Advanced encryption standard (AES-128) • Anti Jamming • Mesh Network • Channel Hopping • Time Sync Messaging	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 wireless standard emphasizes efficiency (low power) rather than speed	Not provided	
7. ABB/ Micropelt	Project in Joint Development	• Temperature	Universal application	Thermal energy harvesting	Unknown	• WirelessHART protocol	Unknown	Unknown	• Eliminates conduit • Allows continuous remote monitoring • Temperature gradient of 30°C between the sensed medium and ambient air required	Maintenance-free power supply, contains two Micropelt Thermogenerators MPG-D651
8. Micropelt/ Royal Dutch Shell	Field Test in Progress	• Pressure	Universal application	Thermal energy harvesting	Unknown	• WirelessHART protocol	Unknown	Unknown *(transmits data once per minute)*	• Eliminates conduit • Allows continuous remote monitoring	Field test combined a Micropelt TE-Power PROBE Thermoharvester with an IPS thin film battery to create a buffered perpetual power source for a prototype Rosemount wireless pressure transmitter

Wireless Sensor & Energy Harvesting Devices Characteristics/Performance										
Manufacturer	Market Availability	Wireless Measurement	Intended Market	Power	Hazardous Environment Capable	Standard/ Protocol	Functionality	Transmission Characteristics	Advantages/ Disadvantages	Additional Information
9. GE Energy Bently Nevada	Released	• Vibration	Universal application	• Advanced power management with minimum 2 year battery life • Vibration Energy Harvesting option available	Yes	• Open standards (IEC approved) • ISA100.11a protocol	• Advanced encryption standard (AES-128) • Time Synchronized Mesh Protocol (TSMP) • Mesh network • Direct Sequence Spread Spectrum (DSSS) frequency hopping	• Low speed, 2.4 GHz radio frequency • IEEE 802.15.4 wireless standard emphasizes efficiency (low power) rather than speed	• Eliminates conduit • Allows continuous remote monitoring. • Robust wireless network that sacrifices speed for reliability • Energy Harvester requires installation on constant speed asset • Energy Harvester frequency must be matched to machine speed • Reduced battery life at extreme temperatures (<-20°C and >60°C)	Communication node supports up to four of any mix of vibration and/or temperature transducers. WiTry Kit includes pre-configured laptop with System1 Software loaded. Software can remotely monitor battery life. Interoperable with sensors from multiple vendors.
10. KCF Technologies	Released	• Temperature • Pressure • Vibration	• Power Generation Facilities • Refrigeration & HVAC • Printing Paper & Pulp Processing	• Vibration Energy Harvesting • Up to 15 years of service life	No	ZIGBEE protocol	• Advanced encryption • Star Type Network	• Low speed, industrial, scientific and medical (*ISM*) radio bands • IEEE 802.15.4 wireless standard emphasizes efficiency (low power) rather than speed • Sensors transmit data approximately every two minutes	• Eliminates conduit • Low power consumption enables sensor placement in infrequently accessed areas • Limited range – nodes to be placed within 75 feet or less of transmitter/receiver • Magnitude of vibration should be between 2mm/s and 10mm/s • Recharge of one node and restart of monitoring software required if all nodes unpowered for significant length of time.	This is a Power Harvesting Sensor Demonstration Pack complete with: • USB dongle receiver/transmitter for host Ultra-mobile PC (UMPC) • Software installed on the UMPC for sensor network and data display and archiving • Set of three integrated wireless sensors, each including: o Vibration power harvester o Temperature sensor (in housing) o Acceleration sensor o Port for external pressure sensor • Ratio-metric pressure sensor • One Magnetic Base
11. Honeywell Wireless	Not Provided	Not Applicable – Energy Harvesting Unit Only	Not Provided	Energy Harvesting	Not Provided	Not Applicable	Not Provided	Not Applicable	Not Provided	
12. Yokogawa	Not Provided	Not Applicable – Energy Harvesting Unit Only	Not Provided	Energy Harvesting	Not Provided	Not Applicable	Not Provided	Not Applicable	Not Provided	
13. Siemens Sitrans	Not Provided	Not Applicable – Energy Harvesting Unit Only	Not Provided	Energy Harvesting	Not Provided	Not Applicable	Not Provided	Not Applicable	Not Provided	
14. KCF Technologies	Released	Not Applicable – Energy Harvesting Unit Only	• Power Generation Facilities • Refrigeration & HVAC • Printing Paper & Pulp Processing	Thermal Energy Harvesting	Unknown	Not Applicable	Not Provided	Not Applicable	• Reduces installation and lifecycle costs (battery replacement) • Limited power output (1.75mW Max.)	Provides a cost effective power source for wireless sensors for a range of industrial monitoring applications
15. Adaptive Energy	Released	Not Applicable – Energy Harvesting Unit Only	• Industrial • Structural • Vehicular	Vibration Energy Harvesting	Unknown	Not Applicable	Not Provided	Not Applicable	• Makes the end application independent from the finite lifetime of batteries and the physical challenges of running power lines	• Provides a self-powered intelligent sensor solution when combined with today's low power microelectronics (MCUs) • When combined with wireless sensor product it creates a longer lasting, autonomous product with significantly lower installation and maintenance costs

Wireless Sensor & Energy Harvesting Devices Characteristics/Performance										
Manufacturer	Market Availability	Wireless Measurement	Intended Market	Power	Hazardous Environment Capable	Standard/ Protocol	Functionality	Transmission Characteristics	Advantages/ Disadvantages	Additional Information
16. Perpetuum	Released	Not Applicable – Energy Harvesting Unit Only	• Industrial monitoring • OEM products • System integrator products	Vibration Energy Harvesting	Yes	Not Applicable	• High reliability • Hermetically sealed • Certified intrinsically safe	Not Applicable	• Offers flexible design integration into OEM and system integrator products to minimize design efforts and shorten “time to market” cycles • Provides an efficient way to integrate energy harvesting into existing products.	• PMG FSH is designed with highly efficient drive circuitry for charging an external storage device up to 4ma at 5V while reporting power levels via a standard 3-pin IEC connector • The PMG17 range of energy harvesters convert the most prevalent “twice-line-frequency” machine vibration into useful electrical energy • Provide entirely maintenance free operation of wireless sensors • Optimized to give the highest power output on the typical industrial machines