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THE FEASIBILITY OF WIRELESS ENERGY

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Abstract

Research was conducted to investigate the current and future applications of wireless energy transmission. To understand the fundamental theory, progressive innovations, and detrimental effects of this technology within the environment and society, a comprehensive literature review was formed. Electronic questionnaires were distributed, and personal interviews were conducted to obtain detailed descriptions of modern implementation methods within different industries. A survey was also developed to determine public perspectives of the technology. A majority of the surveyed subjects believed that wireless energy will require between 3 and 7 years to integrate completely into society.

Chapter 1

Introduction

Wireless energy transmission involves the exchange of energy without the need for physical connections. The development of this technology started in the late 19th and early 20th centuries, when a number of important innovations in electromagnetic research were made. These advancements established the basic principles that served as the foundation for modern electrical power transport. During the past 20 years, improvements in wireless technologies have led to a revival of related research. Public interest in wireless energy has also increased with the application of Nikola Teslas ideas and inventions [1]. As a result of this, the feasibility of technological implementation merits examination.

Various scientists and inventors contributed to the development of wireless energy. Examining their backgrounds reveals the sources of their motivation and the methods by which they conducted research. The inventions developed during this time were more advanced than anything that had been seen before, solving challenging problems and developing the basic theories that yielded modern technology. These inventors' patents, papers, and experiments effectively describe the practicality and utility of wireless energy propagation.

Three prominent forms of energy transmission are conduction, induction, and radiation. There are various formulas that explain how electrical energy can be transmitted without the use of a physical conductor. Each mode of energy transport has theories that govern how the electromagnetic waves carry energy from a transmitter to a receiver. These fundamental theories show the capabilities and limitations of wireless energy transmission and are briefly explained in Chapters 2 and 3.

Currently, industries and companies are developing wireless technologies to improve the functionality of automobiles, public transportation, and personal devices. When approached, some of these companies commented on their current devices and demonstrated their wireless charging systems. In the United States, government-funded agencies are also conducting energy transmission research. Each industry – commercial or federal – was examined to determine how wireless energy transmission was being incorporated into modern systems. Further considerations comprised the general societal opinion on wireless charging and availability of devices that could benefit from wireless energy transmission. Some common devices were examined to ascertain if and how wireless energy would be beneficial, and a survey was designed to ask questions related to the development and future implementation of wireless technology. This survey also allowed respondents to add their own unguided thoughts.

In light of the survey-takers' concerns about financial and environmental drawbacks, research was conducted to investigate the potential economic and safety risks associated with the use of wireless charging technology. New electric codes and governmental procedures are required to integrate this technology into society. The cost to build, design, and implement a charging system was investigated to determine the impacts of the investment on the economy. The drawbacks and benefits of various charging systems were presented. Another important question addressed was why the public would want to utilize wireless energy. Public perception will influence how much companies invest in wireless technology. There are currently many devices that use electromagnetic fields in their normal operation, which could potentially interact with the field generated by a wireless transmitter. The final issues to address were the environmental and health effects of wireless energy. The effects of electromagnetic fields on cellular, tissue, and mammalian behaviors were discussed. Further analysis was performed to characterize the effects of energy fields on weather patterns. We believe that all of these considerations must be addressed and resolved before the public will accept the implementation of this technology.

Chapter 2

History and Background

The history of wireless energy transmission started with the discovery of electricity over 5000 years ago, but nobody fully understood its applications. After the Renaissance in the 15th century, many scientists completed groundbreaking research that characterized this natural phenomenon. During the 18th, 19th and 20th centuries, other scientists experimented with the application of electricity. Some of these scientists were ahead of their time, and their innovations are still the basis for modern research. In this chapter, we will briefly talk about these scientists and their valuable contributions to the fields of physics, mathematics, and engineering.

2.1 Discovery

2.1.1 Discovery of Electricity

Mankind's understanding of electricity dates back as far as 2750 BCE by the Egyptians, who wrote about the shocks that they received from electric fish, which they called the "Thunderers of the Nile" [2]. Around 600 BCE, Thales of Miletos noted that rubbing a piece of amber with fur caused the amber to attract light objects, such as feathers, straw and pith. However, it is not known if Thales actually discovered this phenomenon or just heard about it from others [3, 4]. Theophrastus later discovered that a piece of jet, a type of natural stone, exhibits similar electrical properties to those of amber. First century naturalists, such as Pliny the Elder, studied the numbing effects of the shocks received from electric fish [5].

Electricity was rarely investigated during the subsequent two millennia until the late 1500s. William

Gilbert, one of the most distinguished doctors of medicine at the time, was sponsored by Queen Elizabeth to further his philosophical research. In 1600, he published *De Magnete*, detailing his investigations of magnetism, which established the foundations for present day magnetic theory. Gilbert studied the effects of friction on electrical charge transfer between lightweight objects, showing that many substances shared this property. He introduced the term "electrics" to classify those substances. The term "electrics" was derived from the Greek word for amber, "elektron" [4].

In the mid eighteenth-century, Benjamin Franklin performed a dangerous experiment, tying a key and a leyden jar to opposite ends of a set of kite strings. The ends of the strings closest to him were kept dry to serve as insulation, but the rest of the string was moistened to provide conductivity. During a thunderstorm, he flew the kite, letting the key fly high up into the air. While the key wasn't directly struck by lightning, Franklin deduced that the Leyden jar was being charged as he noticed that the kite strings were repelling each other. He received a mild shock from the key, confirming that it was negatively charged and that the lightning was of the same nature as the shock received from rubbing amber with fur [4, 6].

2.2 History of Progress in Understanding Electricity

There have been a number of scientists who contributed to the current understanding of electricity. These scientists conducted research in various countries, each exploring and characterizing different aspects of electrical power transmission. After developing mathematical relations that describe these phenomena, researchers demonstrated the application of these concepts by constructing unique devices. The international communication between scientists established an interdisciplinary and strongly supported theory that explains and allows modern wireless charging technology. Looking into the research conducted by early scientists can further one's understanding regarding wireless energy transmission.

2.2.1 Carl Friedrich Gauss

Johann Friedrich Carl Gauss was born on April 30, 1777 in Brunswick, Germany. He was born into a poor family but was a gifted child in the field of mathematics, as he was able to perform complex calculations in his head at a young age [7]. The Duke of Brunswick noticed the young genius and funded Gauss's completion of secondary education at a nearby institution and his subsequent study at the University of Gottingen [8]. At the University of Gottingen, Gauss established a reputation as one of the top mathematicians in Germany and the world. Gauss applied his mathematical expertise to various scientific fields, including astronomy, physics and cartography [7]. Gauss was appointed as the director of the university at the age of 30 and was employed there for the next 47 years [8].

Gauss's work in magnetism and electromagnetism established a fundamental theory upon which modern research has been developed. In 1831, Gauss worked closely with Wilhelm Weber and invented a device called a magnetometer, which could measure the magnetic field in a given area. This instrument was used by several researchers to investigate the natural magnetic properties of the Earth. While employed by the Czar of Russia in 1832, Gauss and Weber proposed the feasibility of telegraphy and demonstrated the practicality of this innovation by inventing primitive wired communication devices, which operated by sending electrical signals that moved a metal bar at the receiving end [9]. Gauss simultaneously studied the movement of magnetic fields and compared them to wave functions [10]. He published a total of three papers regarding his work with Weber on magnetic fields and the study of geomagnetism [11].

Gauss also formulated an alternative to Coulomb's law, which states that the total electric flux through a closed surface is proportional to the net electric charge within that surface [12], *i.e.*

$$\oint_S \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\epsilon_0} \quad . \tag{2.1}$$

Here $\mathbf{E}$ is the electric field vector, q is the total enclosed charge, and ϵ_0 is the electric permittivity of the vacuum. The integral in Eq. (2.1) is a surface integral and the vector $d\mathbf{A}$ points along the normal of the surface.

In addition to his seminal work on electricity and magnetism, Gauss was one of the greatest mathematicians in history, and he helped develop several branches of mathematics, including differential geometry. He continued to make innovations until his death on February 23, 1855. After his death, many of his unpublished works were discovered.

2.2.2 André-Marie Ampère

Born on January 20, 1775, French physicist and mathematician André-Marie Ampère is regarded as one of the fathers of electrodynamics. At only 13 years old, he had already submitted his first academic paper in mathematics. In 1820, after Hans Ørstead demonstrated the magnetic effects of electricity, Ampère began developing a working mathematical and physical theory to model the relationship between magnetism and electricity. This work, known as Ampère's Law, established the foundation of electrodynamics [13]. Unlike Gauss' law, which refers to a closed surface and the volume enclosed by it, Ampère's law refers to a closed loop and the surface it encloses [13], and is stated as

$$\oint \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \mathbf{I}_{\text{encl}} \quad , \tag{2.2}$$

where $\mathbf{B}$ is the magnetic field vector, μ_0 is the magnetic permeability of the vacuum, and $\mathbf{I}_{\text{encl}}$ is the current enclosed by an arbitrary closed curve. The integral in Eq. (2.2) is taken over this closed curve where the infinitesimal segment $d\boldsymbol{\ell}$ points along the direction of the current.

Ampère's other accomplishments include the development of measurement techniques for electricity and Ampère's Theorem. This theorem shows a relationship between an electric current and the strength of a magnetic field. Ampère's theories became fundamental for 19th century developments in electricity and magnetism and were applied by scientists such as Faraday, Weber, Thompson, Maxwell, and many others [14]. As a recognition of Ampère's many contributions to the field of electricity, the ampere was established as a standard unit of electrical current measurement by an international convention [15].

2.2.3 Michael Faraday

English scientist Michael Faraday was born on September 22, 1791. Born into a poor family, Faraday only received a basic formal education. During his teen years, Faraday spent his bookbinder apprenticeship educating himself by reading a wide range of scientific books [16]. In 1812, after seven years as a bookbinder, Faraday attended a series of lectures by chemist Humphry Davy at the Royal Institution. After spending a few weeks working as Davy's assistant, Faraday requested a permanent position at the Royal Institution, but was rejected. Not long after, one of the Royal Institution's laboratory assistants was dismissed for brawling with the instrument maker. Faraday was offered the job, and while he considered it to be more of a "chief bottle washer" than working as a chemist, he perceived this offer as his chance to contribute to the scientific world [17].

In 1821, Davy and British scientist William Hyde Wollaston attempted to design an electric motor, but results ultimately showed failure. Faraday started doing research on the subject, and learned that Ampère had already modified Ørstead's idea of a "one-way" effect induced by electric current on a magnet, asserting that the magnets also acted on currents. Ampère thought that there was a Newtonian attraction/repulsion between the two wires, whereas Faraday thought it could be more complex [17]. His work on the subject of electromagnetic rotations was published in 1821 [16]. In 1831, electromagnetic induction was discovered independently by both Michael Faraday and Joseph Henry. However, as Faraday was the first to publish the results of his experiments, credit went to him for the discovery. His experiment involved passing current through one of two insulated wires wrapped around an iron ring. He hypothesized that once current was flowing through the first wire, a “wave of electricity” would travel through the ring and cause the other wire to feel the electrical effects [17]. As Faraday caused current to pass through the first wire, he noticed a transient current pass through to the other wire when the battery was both connected and disconnected. Faraday realized that the induction was caused by the change in magnetic flux that occurred each time he connected or disconnected the battery.

Faraday’s law of induction is the quantitative expression of these experiments, and explains the relationship between a changing magnetic flux (either by a change in the magnetic field or the area of interest) and the induced voltage, $\mathcal{E}$, *i.e.*,

$$\mathcal{E} = -\frac{d\Phi_B}{dt} \quad . \tag{2.3}$$

In this relation, Φ_B is the magnetic flux, and t denotes time.

2.2.4 James Clerk Maxwell

James Clerk Maxwell was born on June 13, 1831 in Edinburgh, Scotland. At the age of 14, Maxwell wrote his first research paper about the mathematical geometry of ellipses [18]. Maxwell had many different research interests in physics, including electromagnetic waves. During his tenure at King’s College, some of his most influential works were completed in electromagnetics and studies of color [18]. Maxwell wrote two papers about electromagnetic fields and was the first to create a color photograph [19]. He also worked on thermodynamics, applied probability, kinetic theory of gases, fluid mechanics, and astronomy [18].

Maxwell is most known for his work titled “Treatise on Electricity and Magnetism” [20]. Inspired by the previous work of leading physicists, Maxwell used his analyses to explain how light could be considered an electromagnetic wave [20, 21], and derived four fundamental equations that described electromagnetic fields in any situation. Equations (2.4) through (2.7) represent these formulas as they would act in a vacuum; they can also be modified for any medium [12],

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \quad , \tag{2.4}$$

$$\nabla \cdot \mathbf{B} = 0 \quad , \tag{2.5}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad , \tag{2.6}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \quad . \tag{2.7}$$

Here ρ, $\mathbf{J}$, and ∇ represent the charge, current densities, and divergence operator respectively. Wireless energy transmission and the theory of induction can both be explained by these four equations [12]. The first equation is Gauss's law of electricity, which explains how electric fields act around electric charges. The second equation is Gauss's law of magnetism. The third equation is Faraday's law of induction, which explains how a changing magnetic flux can generate an electric field [12]. The final equation is an extension of Ampère's law, which describes how a current and a changing electric field can create a magnetic field. The equations above show how a variation in one of the fields creates changes in the other field, which leads to the formation of electromagnetic waves [12]. These equations are crucial to the understanding of energy propagation in the form of electromagnetic waves.

2.2.5 Heinrich Rudolph Hertz

Heinrich Rudolph Hertz was born February 22, 1857 in Hamburg, Germany [22]. During his adolescent years, he constructed his own galvanometer and spectroscope. Hertz had a strong enthusiasm for physics research and was dedicated to working in a laboratory [22]. His doctoral work was on the induction of rotation spheres [22]. Hertz was one of the first researchers to prove that Maxwell's electromagnetic equations described real-world phenomena by demonstrating oscillatory inductive action over a distance. He also proved Maxwell correct by finding the speed of inductive propagation across space and by determining that electromagnetic waves could be reflected.

Hertz developed a theoretical wave function that showed how electric and magnetic fields formed between the induction coils, and showed experimentally that electromagnetic waves created by coils travel at the same speed as light [23]. Hertz's experiments on the generation of radio waves became the basis of wireless communication and power concepts.

2.2.6 Nikola Tesla

Nikola Tesla was born on July 10, 1856 in Austria-Hungary. He is a well-known inventor best known for developing transmission of electricity via alternating current. While at the University of Prague in 1879, Tesla started working on the concept of using a rotating magnetic field in an induction motor. These ideas led to the first uses of alternating current [24], and eventually into polyphase induction motors, which are still used today. In 1884, Tesla moved to the United States, where he met Thomas Edison, to promote his new motor. Edison realized Tesla's potential and hired him to work on improving his direct-current dynamos [1]. While employed by the Continental Edison Company, Tesla built a prototype of his idea for rotating magnetic fields, creating the first alternating current system without a communicator [1]. In his spare time, Tesla continued to work on ideas and inventions based on alternating current, which led to an intellectual dispute between Edison and Tesla. Tesla found financial assistance from George Westinghouse, owner of the Westinghouse Electric Company in Pittsburgh, Pennsylvania, while Edison got support from J.P. Morgan. The intellectual war between the two inventors lasted until 1893, when the performance of alternating current convinced the operators of the Niagara Falls power plant—the biggest electricity-producing plant of the day—that alternating current was the future of energy generation [25].

Tesla had over twenty patents in this area of electrical engineering, ranging from electro-dynamo machines used in efficient power generation in the Niagara Falls project to wireless transmission. His next major work relating to the field of wireless energy transfer was in 1897. The patent he filed for the transmission of electrical energy stated that air could be used as a conductor if the pressures inside the vessel are low enough or the temperatures high enough, but the resistance of air is still high compared to normal conductors. The previous statement is not true for pulsating currents generated by an alternating system due to the change in the properties of the air causing arcing between the terminal and brushes in a spherically or cylindrically shaped device [26]. This arcing causes ionization within the air over an expanded area. Tesla stated that this transmission method is viable for use in precise and industrial scale equipment for any distance.

Tesla designed a transmitter and a receiver for wireless energy transfer that consisted of two towers located any distance apart. The transmission and receiving towers contained coils that created an electric and magnetic field system within the transmission tower that ionized the air outside the tower—commonly known today as a Tesla coil. He claimed that the apparatus was designed to be portable for oceanic or atmospheric uses, and that higher elevation (since air is thinner) of towers improved transmission.

Tesla tested his ideas of wireless energy transfer by building massive towers— 80-foot wooden structures with a 142 foot metal poles—containing Tesla coils, and performed numerous experiments at his laboratories in Colorado Springs, Colorado [27]. He also worked on transmission of power by the use of subsonic frequency signals transmitted in the region between the livable atmosphere and the ionosphere, and calculated that the optimal transmission frequency in this region was around 8 Hertz—which was proven to be correct in the 1950's. The concept of power transmission in the ionosphere was proven correct after his death, but during his time, the technology did not exist to effectively utilize his discovery [27]. After returning to New York, Tesla was able to get financial support to continue his work on wireless energy

Figure 2.1: A photo of WardenClyffe tower. Source: Wikimedia Commons.

transfer, and in 1901 construction of a new power plant and a transmission tower—known as WardenClyffe tower—began. Construction was delayed on the project as the country fell into a financial panic and all funding for the project disappeared after Tesla stated that WardenClyffe was non-profit. He ended up submitting a patent for the aerial tower design he used at WardenClyffe [27]. The patent is based on the basic structure for the Tesla coil used in the experiments in Colorado Springs with minor variations [28]. Wardenclyffe was abandoned for many years and then later partially destroyed by marines during the breakout of World War I as the government felt that German U-boats could use the tower as a landmark.

Nikola Tesla was an important figure in the development of wireless power transmission, as he developed many of the basic ideas, principles and equipment for transmission of power through a natural medium. Tesla's ideas were far ahead of his time, and continue to be an inspiration in the area of wireless energy transmission.

2.2.7 Guglielmo Marconi

Guglielmo Marconi was born on April 25, 1874 in Bologna, Italy, and studied physics at the technical school at Leghorn Lyceum. Marconi was highly interested in Hertz's and Lodge's work with electromagnetic waves [29]. In 1894 he started experimenting with wave transmission, and using induction coils, spark gap oscillators and dipole antennas, he was able to transmit signal over a distance of 2.4 kilometers [30, 31], and in 1897 he received his first patent. It took several years for him to receive public recognition for his invention. During the 19th century, mathematicians predicted that electrical wave transmission would be limited by the curvature of the Earth [29]. In 1901, Marconi defied this concept by transmitting from England to New Foundland, a distance considered out of transmission range. Research on the movement of electrical waves around the Earth and through the atmosphere grew after this transmission [31]. During World War I, Marconi researched short wave electrical transmission and discovered that a more focused, stronger signal could be produced with less energy input. Information security could also be improved as more reflectors were used on the antenna, creating less wave dispersion. In 1932, Marconi's company established the first worldwide wireless transmission grid for telegraphy [30]. Marconi was awarded many prizes throughout his life, including the 1909 Nobel Prize in physics for his work in wireless communications [29].

2.3 Conclusions

Ever since the discovery of electricity almost 5000 years ago, mankind has always been interested in electricity. This interest increased in the 19th and 20th centuries, as many leading scientists and inventors wanted to obtain a better understanding of electricity. Building on Gauss's earlier work on electricity Ampère created his law regarding electron movement. Concurrently, Faraday took a different approach and discovered the mathematics behind inductive electrical transmission. Based on the work of his fellow scientists, Maxwell was able to develop a set of four equations that explain how electrical and magnetic fields work together. His equations were proven to be correct by Hertz, by the use of a spark gap transmitter experiment. Nikola Tesla studied many of these great scientists' works and used the principles that they founded in many of his revolutionary inventions. His research ranged from electrical motors and dynamo-induction systems to the Tesla coil and wireless energy transfer. Marconi also took the experiments of Hertz and the ideas of Tesla, and used them to develop wireless communications. All of these scientists and inventors used each other's findings as stepping stones toward the better understanding and development of theories and inventions related to wireless energy transmission.

Chapter 3

Modern Theories

The development of Maxwell's equations led to a greater understanding of electric and magnetic fields, forming the basis of modern wireless technologies. In this chapter, we will briefly review three common methods of energy transfer: conduction, induction and radiation.

3.1 Conduction

The most common mode of electrical power transfer in modern technology is the transmission of current through electrical wiring. Electrical wiring is generally made from highly conductive elements, such as copper or aluminum, which facilitate the flow of electrons across neighboring atoms. This type of energy transfer is highly efficient in short-range applications such as circuit board assembly, but the cost and use of material both increase proportionally with increasing transfer distances.

As stated above, electrical wiring is usually composed of a single metal like copper. In 1984, the United States Department of the Interior conducted a geological survey to measure the composition of U.S. soil. U.S. soil, on average, contains 25 parts per million (ppm) of copper, with an overall range between 1 and 700 ppm of copper [32]. In this survey, the most abundant element was silicon, which had an average soil concentration of 310,000 ppm. The small concentrations obtained in the study demonstrate that the earth does not have the same characteristics and composition as electrical wiring; the earth also contains several insulative elements like carbon and bromine. Although the earth contains mixtures of individual elements that hinder or promote electron transfer, various types of rocks and crystals allow metal ions to diffuse through them. Elevated subterranean temperatures increase the mobility of various metallic ions through crystal structures such as quartz.

In 1951, J. Verhoogen of the University of California, Berkley, California determined the electrical conductivity of quartz crystals by replicating the subterranean environment in which the crystals are formed [33]. Within this controlled system, heated to 500°C, a specific metal salt layer was attached to a quartz plate. These two layers were physically isolated by platinum foil. Connected to a 350-volt D.C. power source, copper electrodes generated a potential gradient across the salt and quartz plates, driving sodium ions through the quartz. The movement of the ions, in the form of electrical current, was then measured by a galvanometer. The experimental apparatus also included a supplemental silver Coulomb meter that measured the total amount of charge that flowed through the quartz crystal. The control of various parameters and the measurement of electrical quantities lead to a quantization of quartz crystal conductivity [33].

As experimentally demonstrated by Verhoogen [33], crystals like quartz facilitate metallic ion diffusion through their structures when exposed to an electric potential gradient. These changes in conductivity within crystals are caused by the piezoelectric effect – the internal conversion of electrical energy into physical motion and vice versa. Various materials within the earth, such as zinc oxide and barium titanate, are capable of transmitting and storing electrical energy [34]. In a heterogeneous environment, the absorption of electrical energy at the molecular scale promotes the transfer of ions through piezoelectric crystalline structures, forming a relationship between the conductivity of the crystal and the flow of electrical current. Because natural quartz crystals can both store and transfer electrical energy with high efficiency, they are incorporated into various types of microelectronic circuits and devices.

Quartz and other crystals are abundant at and below the Earth's crust; however, these complexes are not the only materials that can be converted into electrically conductive mediums. Piezoelectric compounds in the soil release electric fields in response to applied pressure; some crystals, depending on their geometric shapes, can focus the radial electric fields on a single point [35]. When exposed to a large enough electric field, the surrounding air, despite being a physically stable insulative mixture of compounds, can be magnetically ionized and electrically conductive [36]. It is important to note that as the elevation increases at a constant separation distance, the energy required to polarize the gas decreases. After the applied potential exceeds the breakdown voltage of the surrounding air, the air particles are broken apart into ionic fragments by the overwhelming energy. Due to large differences in polarity and ionic charge, plasma and neutral air do not interact. Over time, these unstable ions begin to decompose and produce free radical particles that recombine with other molecular fragments. From this reformation, different combinations of molecules arise [35].

Although several types of plasma are produced by an atmospheric polarization, they are all electrically polarized and consequently conductive. These ionized molecules are in a higher-energy state than a gas and move freely through space [37]. However, when an electrical source produces a high enough voltage difference across a length of atmosphere, absorption of the energy contained in the electric field causes the release and flow of valence electrons, inherently inducing an electrical current. The formation of plasma, like the use of a copper wire, provides a medium that facilitates the movement of electrons via electron de-localization.

The ability to transform several natural materials into electrically conductive mediums shows that the Earth itself can facilitate long-distance power transmission. According to Nikola Tesla, man-made mechanisms are needed to generate "electrical oscillations of the required character" and convert the signals into "vibratory energy capable of penetrating into the distance" [38]. After the signals are emitted from the power source, a device must be designed to receive and store the energy. During this transfer between devices, the signal must be modified to not interfere with and prevent interference from other types of energy. A combination of atmospheric and subterranean conduction can be used to transport this electrical signal from the transmitting source to the receiving device. Because the molecules in the troposphere are at a higher altitude and lower pressure, the tropospheric breakdown voltage is less than that of the atmosphere. Therefore, if an insulated power source generates enough charge to ionize the troposphere, the unaffected atmospheric air acts as an insulator that maintains a potential difference between the earth and troposphere [28]. Continuously applying an oscillating signal that has a magnitude at or above the breakdown voltage of the troposphere depolarizes and re-polarizes tropospheric molecules. Maintaining the ionization of the troposphere subsequently causes the continuous movement of electrons and ions - electrical current - across great distances. The current then moves in all directions throughout the troposphere and upper plasmic layers but cannot reach the ground due to the insulating atmosphere. To harvest the energy held within this current, a conductive connection must be made between the troposphere and the ground [39]. Whether the power source provides alternating or direct current, this global power transfer system resembles a simple, stable circuit with a potential being applied across a load resistor analogous to the receiving tower.

3.2 Induction

Faraday's law of induction describes an electromotive force transferable between contactless circuit elements. Proper utilization of this induction facilitates conversions between electrical and mechanical energy. In the years since Faraday's discovery and the unification of Maxwell's equations to modern electrodynamics, different approaches to and applications of induction have been studied.

Nikola Tesla demonstrated that passing a high frequency current through insulated terminals caused an electric field gradient across the insulation. By placing a receiver between the terminals, a capacitance acting as a voltage divider is formed, such that the receiver is powered at any location between the terminals [40]. Notably, in Tesla's experimentation with such a system, it was determined that luminescent tubes would be illuminated with or without the presence of electrodes, but only with the use of a phosphorescent material or a condenser coating. However, it was also observed that significant extraneous phenomena were caused by this field. Insulated conductors, when approached with grounded conductors, induced forceful sparks, and telephone speakers in powerful fields would often begin to emit a tone [41]. Additionally, Tesla noted that "the electrostatic effects diminish nearly with the cube of the distance from the coil, whereas the electromagnetic inductive effects diminish simply with the distance" [41]. Thus, electrostatic induction proves viable for localized lighting applications, yet unsatisfactory for projecting energy over distance.

In commercial applications, specifically resonant mutual induction is commonly utilized [42]. This involves a set of mutually inductive coils, each designed to operate at a resonant frequency. Radio frequency identification (RFID) systems utilize a powered coil in the tag reader to detect and measure nearby identifying coils, which do not contain any power source of their own but couple to the reader's resonant coil. Electrical transformers, used in long-distance power transfer and high-voltage circuitry, utilize internal inductive coupling to raise voltage and lower current (and vice versa) for more efficient energy transfer. Most relevantly, devices with no internal power supply can be wirelessly charged or powered by coupled induction; for instance the startup company WiTricity specializes in commercialized wireless power, with systems significantly more efficient than batteries [42].

3.3 Radiation

Far-field wireless energy transmission relies upon the ability to transfer energy over great distances with minimal loss; which necessitates significant efficiency. Radiative energy transmission utilizes high directivity to offset its drawbacks; antennas, while limited in directivity by diffraction, can be geometrically optimized in matching the transmitted beam of energy to its receiving medium. The Rayleigh criterion describes the relation between radiation diffraction and distance

$$\sin\theta = 1.22\frac{\lambda}{D} \quad . \tag{3.1}$$

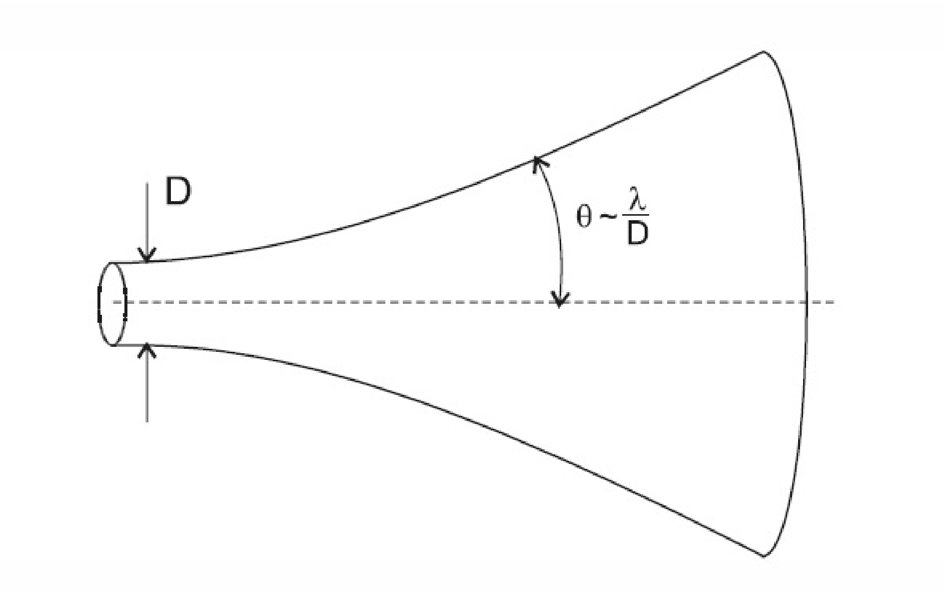

Figure 3.1: Illustration of Rayleigh criterion diffraction.

This criterion states that electromagnetic radiation must diffract as it travels through space because the beam must pass through an aperture, which, at a shorter transmitted wavelength, will result in a more focused beam width [12]. This is not the only factor as infinitely short wavelengths cannot optimize the beam width. However, atmospheric disturbances also account for losses in beamed power; light undergoes Rayleigh scattering, governed by an scatter coefficient α defined as

$$\alpha_{scatter} \propto \frac{1}{\lambda^4} \quad . \tag{3.2}$$

Shorter wavelengths are subject to greater diffraction in the atmosphere [43]. From considering the implications of the Rayleigh criterion and Rayleigh scattering equations, it is evident that only a finite optimal wavelength for radiative transmission exists (See Figure 3.2).

Microwave transmissions are not particularly hindered by significant attenuation loss due to Rayleigh scattering because the transmitted wavelengths tend to be long enough to mitigate this effect. However,

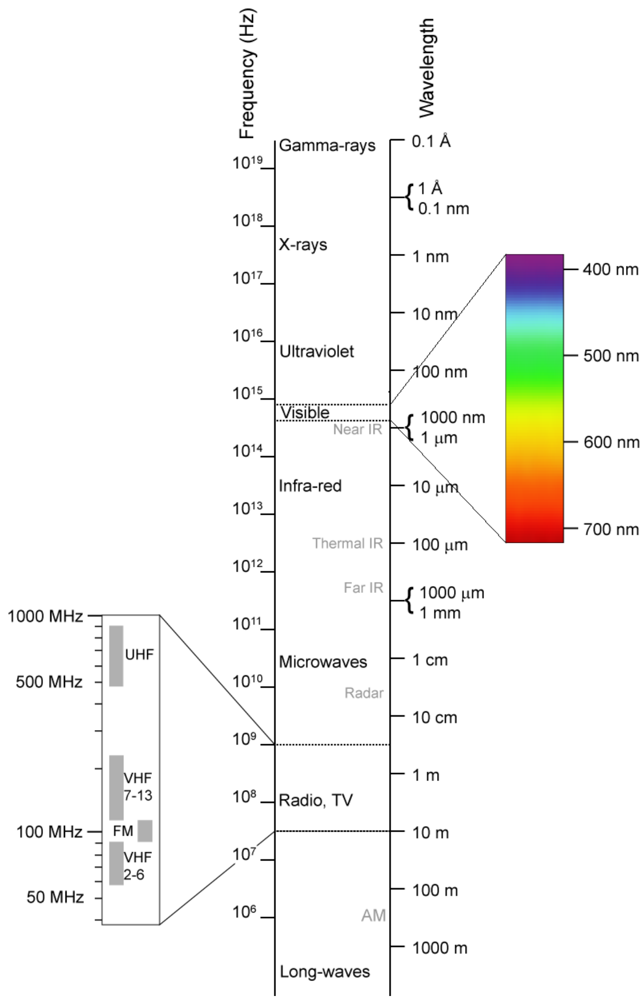

Figure 3.2: This diagram shows the electromagnetic spectrum ranging from wavelengths lower than one angstrom to one thousand meters. In Eq. (3.1), angular spread of radiation is minimized by wavelengths at the top of this diagram, while in Eq. (3.2) it is minimized by wavelengths at the bottom of the diagram. Thus, when accounting for both, minimal spreading must be found at a non-zero, finite wavelength within this spectrum.

the Rayleigh criterion necessitates a receiving antenna proportional to the longer wavelength, and as such, proposals for microwave transmission over long distances, in both atmosphere and space, must account for large transmitting and receiving antennas. However, rectifying antennas (rectennas), which convert microwave radiation to direct current, facilitate high-efficiency conversion of microwave radiation into direct current, with some rectenna designs averaging 84% efficiency [44]. This efficiency, in combination with the limited effect of in-atmosphere Rayleigh scattering, implies the potential for efficient energy transfer. Research and experimentation indicate the feasibility of efficiently broadcasting solar power from an orbiting satellite to a rectenna on the surface of the earth [45]. Using collimated monochromatic laser light in the vicinity of the visible spectrum yields a lesser diffraction limit from the Rayleigh criterion. In space, this can be utilized to form a narrow transmission beam over a large range. In the atmosphere, laser power is limited by Rayleigh scattering, which can lead to complete transmission failure in heavy weather. Evidently, efficient long distance laser transmission is only feasible in space, and as such, research continues to progress in this field. NASA has expressed an interest in powering satellite payloads using high-power fiber lasers [46], and has also proposed the use of focusing optics to partially offset the Rayleigh criterion diffraction [47].

While laser transmission in space thus far has yielded positive theory, further limitations in atmospheric use, such as gas absorption, weather and topographical conditions, deny the likelihood of terrestrial use. Despite the lack of radio frequency interference from lasers, a complication implicit in microwave transmission, lasers pose greater health risks. Microwave receivers are expected to have a large diameter and disperse the imminent energy across a large area, optimizing human safety. However, lasers necessitate precise control of direction. Even the milliwatt laser diodes, used in common consumer applications, can cause blindness due to unintentional exposure; the kilowatt lasers necessary for large-scale transmission would cause significant bodily damage in short periods of time, with such effectiveness that another application is in directed energy weapons [48].

3.4 Conclusions

There are many theories to describe the interactions of electrical and magnetic fields. Conduction consists of physical connections that use copper or other conductive materials. Recent research regarding quartz crystal technology shows improvements in transmission efficiency. Induction charging uses electromagnetic waves to create fields that power devices in close proximity. This system applies Faraday's law and

Maxwell's equations to understand how the fields transfer energy between points. These equations were used by Tesla to create some of his first inventions in electrical engineering. Currently, induction is the most common form of wireless energy in the commercial industry. Radiation is a form of long-range energy transmission using electrical and magnetic fields. Defined by the Rayleigh criterion, this transmission method is governed by the diffraction caused by the atmosphere. Energy transfer by radiation can be improved with the use of different types of antennas and lasers operating on the microwave frequencies of the electromagnetic spectrum.

Chapter 4

Modern Use and Development

Wireless energy research is being conducted in academia and throughout different commercial sectors. A variety of companies have started to make progress on both small and large scales, ranging from cell phones to cars and buses. With easier access to energy, small devices can become more portable, and transportation systems can become less reliant on fossil fuels. In this chapter, we will review some of these recent developments.

4.1 Small Electronics

Music-playing devices, such as Apple's iPod Touch and Creative's Zen, could benefit from wireless energy. However, replacing the battery with a wireless charging coil is not completely feasible at the moment—it would require a wireless power source to be present wherever someone would want to use it. A near-term solution is a combination of a wireless charging coil and battery.

Currently, companies like Duracell are offering special cases for products like the iPod Touch that contain coils for inductive charging when used with their Powermat charging pads [49]. Products like this allow older devices to be modified with wireless charging attachments. This type of adaptation is a good solution for older devices, however, having to purchase a case can be expensive and make the devices more cumbersome. Therefore, the combination of a smaller battery with an internal induction coil provides a more elegant integration of wireless charging into existing technology.

Larger speakers such as those in home theater systems allow the consumer to connect a music-playing device wirelessly to a sound system. Eastern Acoustic Works has constructed speakers that contain signal-emitting amplifiers, eliminating the need for longer connections between separate external modules [50]. The inclusion of amplifiers within the speakers permits direct signal inputs to these speakers without the use of a mixing board. The ability to power these devices wirelessly demonstrates benefits similar to those shown by wireless signal propagation. Wireless energy transmission from the power source to the speaker will increase system mobility and remove the need for long-distance wiring. The integration of contactless, inductive charging into large-scale sound systems reduces the overall cost of power supplies by replacing heavy power cables and guaranteeing complete mobility of speakers within an effective radius.

Cell phones often perform the same functions as music-playing devices, however, added communication capabilities establish mobile power supplies as a necessity for operation in critical situations. Installing a resonant coil in the back panel, for example, would be a simple way to develop a wireless charging system. The main obstacle to overcome would likely be the need for a large-scale shift towards wireless charging. In order for the wireless receivers in phones to be feasible, enough of the population would need to support wireless charging, and owners of these phones would need to have adequate access. Research conducted by AcuPOLL®Research, Inc. states that "nearly half of consumers [surveyed] indicate that they would wait two years for [the] product if they could have the [wireless charging] technology built into electronic devices. Still, about one-third would be willing to buy adapters; about one-quarter would buy the stand alone charger [pad] and use them until they replace their devices with ones with embedded technology" [51]. The inherent convenience incentivized the subjects of the survey to consider spending more money on wireless technology, implying that the infrastructural shift toward wireless power may be aided by transitional technologies.

Since the development of embedded computing, battery technology has failed to develop as quickly as the electronics it powers. Furthermore, higher-speed processors and computationally intensive programs diminish phone batteries remarkably quickly because of their inherently higher power consumption. A future application of wireless charging devices could, in theory, be to continuously power phones, eliminating the need for a battery or including only a small battery for use between coverage locations. One limitation on this is the necessity of long-range distribution of energy; the infrastructural shift involved would require an enormous allocation of resources.

One of the most significant innovations in the computer industry over the past decade was the development of the laptop. The laptop is a type of computer that is more compact than a desktop and facilitates work on the go. Laptops have been manufactured for the past twenty years with continuous increase in memory storage, processing power, and battery life. A major complication in most laptops is the dependency of processing speed and functionality on power supply. Several computer companies are improving the battery capacity, but the microprocessors are also becoming faster and require more energy to perform higher-level tasks. The compromise between performance and battery life will always be an issue with laptops.

Laptops in the future could use inductive charging to recharge the batteries if the coils can produce enough electrical power to recharge the system. Modern corded laptop battery chargers use transformers to decrease the outlet voltage and increase input electrical current, producing electrical power that charges the battery [52]. The replication of transformer operations and the production of sufficient electrical power are the primary functions being considered in wireless energy transfer research. Several laptop companies are developing devices that could be inserted into the charging port of the laptop, facilitating wireless charging capabilities. The eventual progression could lead to lightweight coil and battery systems that can be used anywhere. The average laptop battery weighs about 1.5 pounds; this weight could be decreased because most batteries are composed of lithium-ion cells, which are heavy due to their composition of lithium metal, graphite, and a lithium salt solution [53]. The replacement of a battery with an induction coil may decrease the overall weight of the laptop and maintain charging capabilities.

In 2009, Dell launched a series of laptops, Latitude Z, which included a 35- to 45-millimeter coil to charge the device. This coil received energy from a charging stand that was provided with the laptop. The Latitude Z used technology created by eCoupled, and charging required between 3 and 4 hours. There was also discussion about charging without the need for contact, but this was not possible with this model of laptop because the coil system was not designed for that scenario [54]. Unfortunately, very few of these laptops were sold because people did not recognize the benefits of the wireless charging system; the stand took up a substantial amount of working space, and there was a $200 price increase to install the coil and buy the stand [55].

Intel also has been working on wireless charging technology for their Ultrabook line, claiming that these laptops consume less power during charging and utilize a charging pad comparable in size to a charging cord. The company has predicted that these chargers will be used to simultaneously charge a smartphone and a laptop. These Ultrabooks will be released to the public in late 2013 [56]. The fast-approaching projected deadline for the distribution of wireless charging technology demonstrates that companies have developed and tested feasible and cost-efficient charging apparatuses [57].

Although corporate organizations have produced specific products, research within academia has provided methods to improve the efficiency of wireless energy transmission. The work of Prof. Shu-Yuen

(Ron) Hui's team is one such example. Prof. Hui has earned several awards from the Institute of Electrical and Electronics Engineers based on his development of light production methods, wireless charging interfaces, and Qi (the first wireless power standard). As a result of his investigation into wireless charging, Professor Hui has produced a series of patents that together demonstrate the feasibility of inductive energy conversion [58–60]. These patents describe small, adaptable apparatus that are compatible with various devices and successfully shield, produce, and receive electromagnetic energy.

A key component in maximum inductive signal transmission is the use of materials to prevent electromagnetic interference (EMI). The Hui Lab tested the functionalities of various materials that can reject external EM noise and concentrate internally generated signals. The tested materials were used to coat an inductive printed circuit board (PCB) transformer. The efficiencies of no shielding, ferrite metal, conductive metal, and combinations of the two metals were measured as a function of generated magnetic field intensity. The results show that the ferrite and conductive metal composite most effectively shielded the coated device from EMI.

The Hui lab subsequently tested the ability of the coatings to reject EMI at different frequencies. With increasing alternating current frequency, the efficiency of all three tested coatings increased. The conductive metal sheet had the lowest efficiency gradient over high frequencies; the low metallic resistance alone induced a small eddy current that drew power from the output magnetic field. The ferrite material by itself demonstrated over 90% power delivery efficiency at MHz-range frequencies, whereas the ferrite and conductive composite caused nearly no loss of power during delivery [58].

The EMI shielding technology was then incorporated into an inductive charging station that can power multiple devices that incorporate receiving adapters. Within this platform design, a charging module draws its power from a standard AC wall outlet to generate a high frequency signal, producing a magnetic field that can detected by a charging receiver. In the charging circuit, an embedded PCB composed of offset coils produces a uniform magnetic flux that is directed toward the charging surface by an EMI backing [59]. The Hui lab subsequently engineered a receiving unit, which uses an inductive coil to create a rapidly changing potential gradient and produce an alternating output current. This energy can be stored in a AC-to-DC conversion circuit to transmit a charging signal to the device [60]. The combination of energy shielding, generating, and receiving devices describes the benefits and shortcomings of most commercialized apparatus, addressing performance optimization challenges within the entire industry.

4.2 Transportation

Companies have been gradually recognizing the economic and environmental advantages of wireless energy. They have started to make progress on both small and large scales, ranging from cell phones to cars and buses. With easier access to energy, small devices become more portable, and it becomes easier to use alternatives to fossil fuels.

Qualcomm Incorporated, derived from “Quality Communications”, specializes in radio transmission and microprocessors. They pioneered Machine-to-Machine (M2M) communications in 1988, when they launched a system called OmniTRACS, which was “a satellite-based data communications system for the transportation industry that enabled truck fleet operators to effectively track and monitor their vehicles in the field”. In 1989, Qualcomm was the first to demonstrate making a cellular phone call using Code Division Multiple Access (CDMA) technology. They demonstrated basic packet data services, such as Transmission Control Protocol/Internet Protocol (TCP/IP), over CDMA in 1993, and CDMA was adopted as a wireless standard by the U.S. Telecomunications Industry Association. Qualcomm started developing wireless chipsets in 1995, and in 2000, they created the first CDMA chipset that integrated GPS [61]. Recently, Qualcomm has partnered with British luxury car company Rolls Royce in its investigation of wireless technology transmission with its “Halo” technology [61].

In response to this demand for innovative charging solutions, WiTricity, founded in 2007 by Marin Soljacic and a team of Massachusetts Institute of Technology (MIT) physicists, was established as a private company that has developed wireless charging apparatuses for small devices and automotive vehicles [62]. The developed technology uses coupled coils that resonate at a specific frequency to transfer energy via a continuous, dynamic magnetic field [62]. The technology utilizes a dynamic magnetic field that non-radiatively transfers energy based on proximity, reducing both radial emission energy loss and potential adverse environmental effects. As a precautionary consideration, the company’s systems are designed to detect any parasitic coupling—loss of power absorption due to interfering metals—and immediately shut off power flow.

During a personal interview we conducted with Mr. Colin McCarthy, a representative of WiTricity, the advantages of the company’s patented system were discussed. He demonstrated the technology by using a set of large induction coils to power an industrial work light, explaining that the medium on which the platforms are placed does not matter; only the placement of metallic objects between the emitting and receiving coils impacts the energy transmission efficiency. Furthermore, the emitting and receiving coils must be tuned to resonate with each other, increasing power transmission efficiency. The casing that surrounds each coil is made from a polymeric material that is meant to withstand large compression forces and protect its contents. After the demonstration, Mr. McCarthy described the various regulations that guided the design and implementation of this technology. The incentive to use this technology in the automotive industry is to eliminate the need for a heavy physical cord that connects the outlet power to the car battery. He speculated that this wireless energy transmission system will be integrated into automobiles within the next three years.

Concurrently, electric vehicle manufactures, such as Tesla Motors, have utilized design methods that reduce energy consumption, increase speed-based performance, and even regain lost energy. The vehicles manufactured by Tesla Motors run completely on electric power with no direct dependence on fossil fuels [63]. Immediately after its establishment, Tesla Motors developed an electric sports car. Since then, the company has produced a greater variety of vehicle types. Currently, the Model S, a mid-sized sedan, is on the market; the Model X, an SUV, will be commercially available in 2014 and the BlueStar, a prototype sedan, will be released in 2015 [64]. Tesla Motors has also designed its automotive suspension systems to minimize environmental energy loss and resistance to movement.

Some corporations have begun to use electric charging mechanisms in other forms of transportation, such as trains and airplanes. Bombardier is a transportation-based company that predominantly produces airplanes and trains and has recently started manufacturing buses. Bombardier comprises two divisions: aerospace and ground transportation. The aerospace division constructs aircrafts for private and commercial services clients. All parts, maintenance, training, technical support, and online services are provided by the company.

The ground transportation division develops terrestrial transportation systems, including rail (trains and cable cars) and motor systems (buses and taxis). The rail infrastructure uses control and propulsion systems that are designed and built by Bombardier [65]. Bombardier is currently investigating wireless energy transmission through their subsidiary, Primove. Even though Primove is Bombardier's main focus toward wireless energy technology, Bombardier as a whole is conducting research in this area [66]. The company sees this as an investment opportunity to help expand its global presence, while also increasing general standard of living by increasing safety and making electrically run trains more aesthetically pleasing. This concept is shown with their products, the MITRAC and its E-mobility solutions, which conserve energy [67, 68].

Bombardier's project director, Mr. Christian Guay, answered our questions regarding this technology.

He stated that the company produces airplanes, trains, and induction charging systems. Mr. Guay explained that Bombardier has been conducting research into different types of wireless charging. Examples of charging research can be founded on Bombardier and Primove website [69]. When asked the question regarding the implementation of wireless technology over the next ten years, Mr. Guay stated that in two years he expects that wireless charging will be introduced into mass transit systems. After five years, he expects wireless energy transmission in cars and within ten years, throughout all forms of transportation. Some of the obstacles towards implementation he observes are the infrastructure of current cities, acquiring the needed funding from mass transit to convert to a wireless system, and acceptance of magnetic field charging from the public due to the risk of electromagnetic interference. He chose not to answer the question regarding the effective range of transmission. He also recommended that our group conduct more research into Primove.

Primove was established in 2003, in Mannheim, Germany; in 2010 and 2011, projects were initiated to design and implement devices that charge trams and buses. Although these two types of vehicles establish transportation by different means, Primove has developed unique instrumental adaptations that facilitate the universal implementation of wireless charging technology.

The major vehicles that have been outfitted with wireless charging systems are the European trams and buses. These two charging supply systems are almost completely identical because they are both underground and are supplied power via high-voltage power lines. However, the tram charging source is located under railroad tracks, and the bus charging source is placed under pavement [70]. Underneath these charging systems, magnetic metal sheets are inserted to deflect subterranean electromagnetic waves that are naturally generated by the Earth, consequently minimizing energy losses during transfer between the sending unit and onboard receiving unit. Although these charging units are meant to supply energy to vehicles passing over them, the emitted energy is dissipated and wasted if there are no vehicles directly above the charging sources. To prevent the potential loss of energy, pressure-sensitive cables are used to detect a vehicle's location relative to that of the underground charging pad. When the vehicle is above the charging pad and the surrounding sensor cables, the sensors send a signal that activates the charging pad, inductively charging the vehicle as it passes. After the vehicle has passed the charging station, the cables experience no pressure and send a signal that deactivates the charging pad. These underground charging stations serve as reliable and intelligent systems that effectively transmit power through various types of terrain and minimize energy waste with sensor signal timing [69].

Adaptive systems that convert emitted electromagnetic field into electrical signals can be attached to undercarriages of trams and buses. These charging modules are large, planar platforms that have inductive receiving coils that are large enough to generate a substantial alternating electrical current which is converted to a direct current. Via a physical wired connection between the receiving platform and the vehicle battery, the direct current transfers energy to the battery, powering the entire vehicle [70].

These charging systems for buses and trams introduce two types of charging: dynamic charging and static charging. While the vehicle is stopped directly over a charging pad, the receiver is stationary in the magnetic field, causing static charging that provides a rapid recharge rate. However, the vehicle's movement over the charging pad surface causes dynamic charging because the receiving pad is still traveling parallel to the emitting coil through the magnetic field. This combination of stopping and traveling over consecutive charging pads provides an energy-efficient method of maintaining vehicle battery life [69].

The ease of device construction and rarity of system malfunctions together reduce the repair costs needed to maintain the systems, having a positive impact on the consumer. The requirement and replacement of fewer components in these wireless charging apparatuses reduce the cost of repair needed to keep the transportation systems running. The smaller upkeep expenses for the transportation agencies consequently allow transportation fares for consumers to decrease without reducing the agencies' profits. The use of fewer components to make the wireless charging pads decreases the overall weight of the vehicle, inherently increasing the maximum passenger capacity. The ability to carry more passengers per trip also contributes to reduced fare and expenses [71]. In order to gain more insight, we contacted Primove for an interview. Unfortunately, we did not receive any response from the company.

In response to societal needs that depend on electronics, a variety of companies has focused on improving methods of mobile energy transport to increase device reliability. These organizations have brought innovation to the transportation industry on various levels, improving systems such as the individual car and the entire tram system. These methods of wireless charging reduce vehicular dependence on oil and consequently give alternative energy providers (wind, solar, and water) the opportunity to contribute electrical power.

4.3 Government Use

Numerous government-sponsored and independent labs around the country perform research in wireless energy transfer technology, among many other fields. While the private sector is commercializing the process, the product of the laboratory is often oriented towards defense and private contracting.

The Defense Advanced Research Projects Agency (DARPA), one of the government's branches focused on accelerating research and development of defense-oriented technology, has been pushing for research in wireless technology. The focus of their research desires has been short-range wireless transmission. Particularly, allowing utilization of wireless power within a two meter range would reduce US Army and US Marine Corps' reliance on various batteries for their portable electronics in the battlefield while simultaneously improving upon the existing energy-to-weight ratio [72]. Having a higher energy-to-weight ratio could prove critical in combat scenarios, where a common limiting factor is the amount of equipment a soldier can carry. Additionally, having a centralized distribution system would optimize the process of powering individual devices by bypassing the necessity of matching proper battery types to their respective devices.

The focus of research at Oak Ridge National Laboratory (ORNL), similar to that of WiTricity, is the use of magnetic resonance coupling to charge electric vehicles. Because the technology implemented is magnetic resonance, field strength decreases linearly with the scalar displacement, allowing high efficiencies; a 4kW transfer at 10 inches was demonstrated at 92% efficiency [73]. In addition to their research into wirelessly charging electric vehicles, ORNL is planning future research into the process of integrating the wireless power input with the electronics of the vehicle, including communications and a grid converter, and the chassis of the vehicle, necessitating proper field shaping and shielding [73].

In 1964, Raytheon demonstrated a microwave-powered helicopter, one of the earliest successful experiments in wirelessly transmitting power; the theoretical work supporting the system showed a maximum efficiency of nearly 100% [74]. More recently, Raytheon filed a patent on a system related to generation, transmission, and reception of wirelessly-transmitted power, and more specifically, wireless power transmission systems capable of efficiently illuminating multiple dispersed wireless power receivers [75]. This system allows the transmission of wireless power to multiple receivers in an array with minimal loss of energy in the area between receiver beacons.

The National Aeronautics and Space Administration (NASA) is a government-funded organization that investigates aeronautical and aerospace engineering technologies to enhance mankind's understanding of the world. Since 1970, this organization has explored the applications of wireless charging in atmospheric and extraterrestrial laser transmission [76]. In 2008, NASA incorporated gallium-nitrogen based diodes, which are high-efficiency semi-conductors, into fuel cells to produce wireless mobile energy sources for underdeveloped regions of the world [76]. Further development by the organization used wireless resonant power systems within a vacuum to model energy supply mechanisms between orbiting satellites [77, 78]. NASA researchers are also investigating the behavior of laser energy transport in an extraterrestrial medium, considering potential sources of signal interference [79].

4.4 Conclusions

Several companies and government agencies have been investigating alternative forms of energy transmission while reducing the reliance on fossil fuels. Within the academic community, research has been conducted to characterize the efficiency and safety of newly developed wireless devices. This academic research has focused on demonstrating the practicality of a broad range of wireless charging systems while avoiding product specificity. The work conducted in commercial industries and academia together form a system that will lead to the improvement of wireless energy transmission methods in the near future.

Chapter 5

Making The Shift Toward Wireless Energy

One of the major goals of this report is to compare the desire for using wireless systems to the cost of implementing such systems. For the past hundred years, society has relied on wires and cables to transmit data and energy from one place to another. Over the past fifteen to twenty years, developments in technology have allowed for information transfer without a physical medium, creating the introduction of wireless devices and Internet.

There is a desire to convert to wireless energy since this would improve household cleanliness due to decreased amounts of excess wiring. For instance, with an induction system using resonance coupling, a user's device could be charged without operator input. Similarly, if radio wave transmission could be implemented on the global scale, devices could then be charged from any location. Before any type of implementation, certain risks and hazards have to be addressed. Health and environmental concerns are always a priority to address with any new technology to be used at this scale. These effects include changes to wildlife, weather, climate, as well as short and long-term exposure risks. If it can be proven that these risks will not become issues, widespread implementation of wireless charging technology will be feasible.

5.1 Desire Vs. Cost

With any type of new technology, there are many factors to consider before implementation. The first cost to look at is manufacturing costs of new cable, coil and control systems. The design portion could be funded by research grants and companies interested in this field. Another cost is the implementation of a system of transmitting and receiving coils. We also have considered the societal costs in terms of environmental and health effects as people will fear the increased exposure to radio waves. This fear can only be addressed over time by rigorous testing. In this section of the report, we will discuss several topics, including the cost of the raw materials, the ways to promote this type of technology to society, the implementation of the system and its cost of installation.

5.1.1 Cost of Copper

Copper is a naturally occurring metallic element distributed throughout the Earth's crust that has been used by humanity for many generations. Its properties include ductility, malleability, and conductivity. Some of copper's many applications in today's world besides wiring include kitchen utensils, pumps, piping, and transportation applications [80, 81]. Copper is a commodity mainly traded on the London Metal Exchange in the form of futures. These prices have been mostly steady for the past five years (See Figure 5.1), except when the housing bubble burst, creating a surplus on the market [82].

Market analysts claim that copper prices will be increasing in the future. Morgan Stanley is expecting a 7.6% jump in 2013 prices due to the increase in consumer buying power in China, U.S. and European countries. This price increase is also based on a current market deficit. Copper prices are then expected to drop between 2014 and 2015, as suppliers increase production. This price is expected to level around $3.50 a ton in 2015, but demand will still be increasing in the Chinese and other developing markets [83]. The price of copper has many fluctuating factors that make predicting future prices difficult, which creates doubt within corporations when conducting research [81].

Copper production begins with the mining of copper sulfide and copper oxide ores, which are then treated by either leaching-electrowinning or smelting-electrolytic refining to produce a copper solution. Starter poles are then inserted into the solution to electrolytically remove the pure copper for final processing [84]. Copper is formed into coils by being molded into sheets that are then spun into spiral columns, increasing surface area. The increased surface area allows for the creation of a larger magnetic field and in turn a greater magnetic field to electric field conversion.

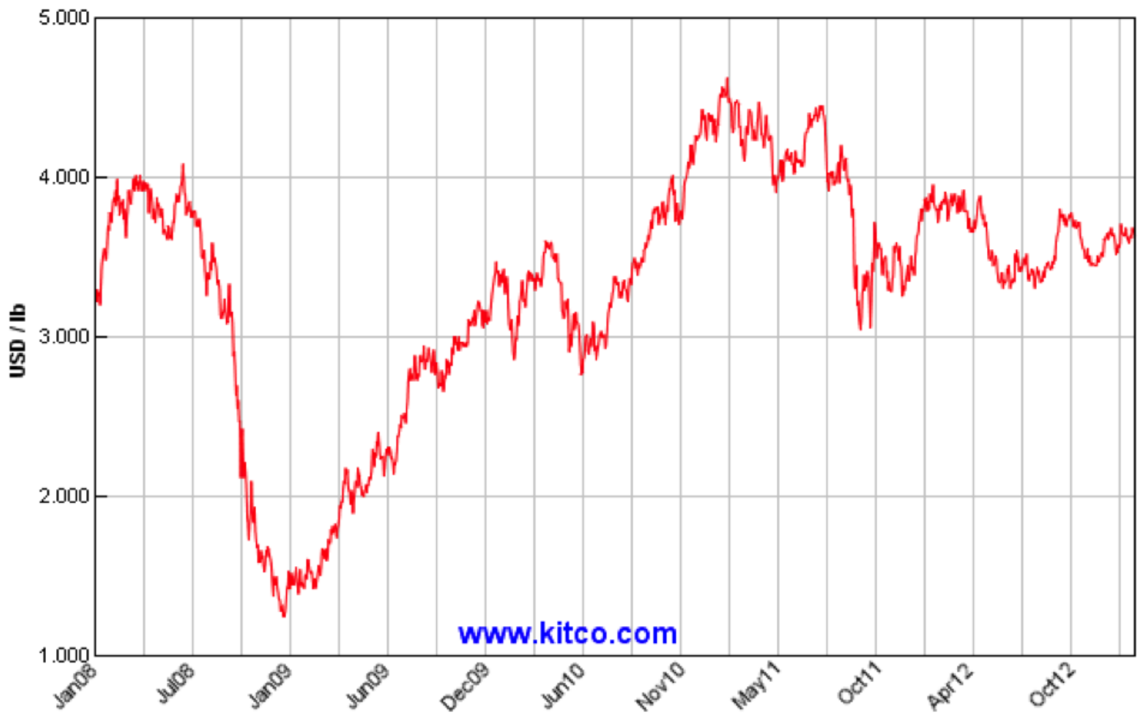

Figure 5.1: The price of copper between 2008 and 2012. Source: www.kitco.com

The cost of the production fluctuates depending on the purity levels of the copper mined and the mines' and plants' cost of operations. Average costs are about $30,000 per ton. This cost is based on a starting composition of .5% copper ore. The cost distribution is as follows: $10,000 for mining operations, $10,000 for the concentration process, $9,000 for the smelting process, and $1,000 for the electrolytic refiner. This gives the average cost of goods sold of $6 per kg of pure copper in 2011. The selling price of pure copper on the London Exchange was $9 per kg [85].

The cost of the copper coil needed for wireless energy transfer depends on the application of the device, production processes and tolerances. The type of the coil needed is dependent on the field needed, the location of strongest field flux, the radial size and orientation. These factors affect the average cost of the coil. A rough estimate shows finished coils to be between $5 and $12 for small coils, and roughly $600 or more for larger applications [86–88].

The future of magnetic coils seems to be favoring the use of superconductors. The superconducting coil would comprise of a liquid nitrogen or liquid helium system, where the coil is supercooled, allowing for near frictionless electron flow, creating a greater ratio between the magnetic field per unit area. The coils will also be made out of either a Niobium-Tin or Niobium-Titanium alloy; which are both better superconductors. This technology could enhance magnetic fields to allow for long distance wireless energy transmission to be feasible [89].

5.1.2 Rewiring Homes

There are various factors to consider when rewiring a home: the size, configuration, and purpose of the structure. In this section, we will discuss the price of rewiring the average American home and the cost of implementing charging stations.

Considering the orientation and arrangement of the coils in a typical house, any number of them could be placed within walls, ceilings, or floors; dependent on the use and the configuration of the room. As observed during the test conducted during the WiTricity interview, a coil with a diameter of 4 inches operates with maximum charging efficiency when charging only one device at a radius of 6 inches. In a larger living space, a larger diameter coil has the potential to transmit power throughout a room.

There are many different costs that are incurred during the transition from physically-connected charging apparatus to a wireless system. The primary cost would be the necessity to remove any previously installed copper wiring from within the house. This process would be expensive, but depending on the age of the house and the quality of the previous wiring, it could be a relatively simple process for an experienced electrician. The work involved would include the removal of wiring for electrical sockets and the disposal of wiring from the remodeling site. This process costs between $70 and $120 per outlet, switch, and fixture, the raw material costing between $1000 and $3000, depending on the size of the building [90]. The removal of the old wiring will probably be discounted, since it can be sold to metal scrap yards for a profit [91].

Another cost incurred would be the conversion of devices to receive wireless energy. Many companies such as Duracell offer induction charging [49], while WiTricity and Qualcomm use magnetic charging systems [92]. The receiving device would contain a coil to accept the magnetic field, where it can be transferred to the proper circuits to generate power. This part of the transition will be relatively inexpensive in comparison to the conversion of the building.

The major costs of the conversion would be the installation of coils into the framework of the building. This involves removing sheetrock and running new, heavier gauge wire to handle the increased energy needed to create the magnetic and electric fields. Currently, the wiring would be comprised of copper, but in the future this could be superconductive wiring [89]. Depending on the design chosen for the room—one massive coil or many smaller coils—the building's framework may need adjustments to compensate for the size, weight, and spacing of the coil system. To remodel the framework, the sheetrock or the floor would have to be removed to install the coils. This will introduce an increase of between $50,000 and $150,000 in reconstruction, depending on location and current markets for materials and labor costs.

The conversion process is costly, however, government incentives could help encourage the process. If the technology were to become popular, the increase of economic flux in a local economy could be substantial, as there would be lower unemployment rates and a higher cash flow. If a nation's government realizes the potential of wireless energy, they could promote the idea and in turn, the economic wealth of their country [93].

Another factor to consider would be city regulations regarding reconstruction and replacement of wiring, which in most cities involves permits and inspections. Regulations on electrical code are different from location to location; city officials who are not informed about this technology may be apprehensive in approving permits for the installation of a wireless system due to health and safety concerns. A future legal consideration must be given to how laws should be developed and interpreted regarding this technology and cases of injury or damage [94].

With any growing field there are constant changes and developments in the implementation process. The creation of the printed circuit board (PCB), allows an electrical circuit to be printed onto a semi-conductor [95]. This type of system can be placed onto any surface as long as the printed coil is not so thin such that the coil would not be able to handle the energy passed through it [96]. With this technology, any arrangement of coils can be used in an area. Via testing, an optimal amount of coils per an unit area can be determined. Another system to consider, developed by eCoupled, allows the transformation of any surface into an inductive charging system. With this system, there will have to be a central control panel that will monitor and control electrical output to each coil and theoretically regulate power output based on the devices communicating with the coil [97]. The control module could also control device access to its field.

There are many different factors to consider when converting a building to wireless energy. While some have been addressed, new obstacles could arise. Many concerns come along with a conversion of such magnitude, as it is costly and time-consuming. The most effective and reasonable approach is to design the structure with wireless energy in mind so that there will be less waste both in time and resources.

5.1.3 Regulation of Wireless Technology

Following the implementation of these charging apparatuses, several regulations have been implemented to ensure continued safety and ease of maintenance. The regulations that determine the practicality of the charging systems are the International Electromagnetic Compatibility (EMC) Standards. These standards obligate developers of wireless technology to test the impact of wireless charging panels on other electronic devices. Diagnostic tests have shown that the wireless charging interfaces do not impact the use and functionality of telecommunication, medical, or industrial equipment, signifying that the wireless charging mechanisms are compatible with modern electrical systems [98].

5.1.4 Managing Which Devices Are Charged

The use of wireless power creates issues regarding proper energy distribution to devices. One of the issues is how to develop an efficient control process. Presently, control of a charging system is not an issue, since the major form of wireless technology uses inductive charging. This involves the receiving and transmitting coils being close to each other. A protocol for this charging system was established called Qi, developed by Professor Ron Hui and the Wireless Power Consortium [99, 100]. There are currently 135 corporations that follow Qi protocol and have products commercially available under the Qi symbol [100]. Qi defines the scale of the power production for a wireless charged device's transmitter and receiver. There are many approved types of charging receivers available, but only few types of transmitters. The Wireless Power Consortium is in the process of developing the second version of their wireless protocol called Qi 2.0, which will expand the line of approved transmitters and also increase the allowed power output. A protocol will be established for mid-size charging stations related to laptops and tablet devices. These protocols help standardize the induction charging market in terms of regulation and product differentiation, but do not control access to the wireless charging system.

Efficient induction charging is becoming a major factor in the biomedical field, as many implanted devices require a power source. A wireless rechargeable battery would be beneficial as it would prevent invasive battery replacement surgeries [101]. These devices operate using a closed loop system containing a power amplifier, which can be varied depending on distance between the transmitter and receiver as well as signals from the RFID [101]. This concept has led to the development of eCoupled technology by Fulton Innovations. This company is one of the founding members of Qi and has also implemented ideas for controlling power consumption of connected devices [102]. eCoupled has over 600 patents in the field of wireless energy transmission for circuitry designs and control systems that are in current use [103]. With their coil-controlling system, the surface can produce 1400 W of energy with transmission efficiency of 98%, which is comparable to conductive coupling, but is a vast improvement over inefficient radio wave transmission [104]. Creating an efficient system is the first challenge in controlling the usage of the coil's energy production. eCoupled has already addressed this issue, as their devices can only be used with a compatible eCoupled charging system. When near a charging system, the device communicates its power requirements to it, and if the transmitter does not detect a device, it will not produce any power [102, 104]. Using the enabled surface creates a uni-axial transmission direction, preventing unwanted energy siphoning [105]. The next issue is to develop a system that will allow for the owner to control transmission to eCoupled devices. This can be done using near-field communication to transmit a frequency that the eCoupled transmitter can recognize and authenticate. The authentication system could work similar to wireless internet security by either requiring a password for the transmitter or having the owner approve the device for charging, but these details are proprietary to eCoupled [104]. This issue will have to be considered thoroughly before companies continue to expand and implement this technology.

Proving that wireless energy transmission is more efficient and controllable will be one of the steps to achieving its acceptance within society. Addressing these issues will take research and investments from companies that promote wireless energy. The shift toward this technology will take time after research has been completed, but the transition time required will depend on societal reactions to the technology.

5.1.5 Benefits and Drawbacks of Wireless Technology

Wireless energy transmission presents a viable alternative source of power for various mobile devices. However, like other forms of power transmission and production, this new technology has both small and large-scale applications that may influence public perception about using wireless charging systems.

One of the major arguments that support the conversion to wireless charging technology is the reduction of wasteful hardware components, such as disposable batteries. Currently, several personal mobile devices rely on power derived from batteries to provide DC voltages for the operation of the overall system. The constant operation of the mobile device gradually degrades the battery's capacity. Disposable and rechargeable batteries are two common mechanisms for maintaining device functionality. Although rechargeable batteries minimize replacement costs for the consumer, the energy storage capacity of the battery diminishes over time due to repetitive charging.

A major shortcoming of present-day mobile internal charging systems is the necessity to carry accessories. These systems can only establish the physical charging connection in specific locations on the device. As presented in Forbes Magazine by Mr. David Ferris, the removal of a physical cord connection and the longevity of the wirelessly charged battery would motivate the research sector to further investigate device durability and protection [106].

The invention of the electric toothbrush serves as an example of why wireless charging presents safer alternatives to contact charging. The electric toothbrush charging apparatus is one of the first wireless charging devices that requires no metal-to-metal contact between the platform and toothbrush. Because the toothbrush is used in locations that involve water, a metallic connection between the toothbrush and charging station introduces the risk of water seeping into the connections, potentially generating a shock hazard [107].

Various innovations such as Tesla Motors's electric car and the Philips electric toothbrush show that the phenomenon of wireless charging has safe and economical applications. For example, modern electric car companies are beginning to develop widespread power grids that can support more charging stations for electric cars, reducing automotive emissions of greenhouse gases [108]. However, these state-of-the art solutions mean that the cost of each system is more expensive than its more abundant combustion-engine counterpart. For example, the cost of an average new car is about $30,000. In contrast, the cost of a Tesla electric sedan is at least $52,400, almost twice as much as the cost of the average gasoline powered sedan [109, 110]. Similarly, a reliable Oral-B brand electric toothbrush costs approximately $105, whereas a manual Oral-B toothbrush costs about $4 [111, 112]. These large price differences demonstrate that the new technology presents long-lasting and energy-efficient solutions, but the costs of components are much more expensive for the consumer [113].

5.1.6 Induction Transmission Vs. Radio Wave Transmission

Comparing both induction and radio wave transmission systems in terms of efficiency, implementation, cost, available technology, and societal impact shows that the efficiency of induction is much better than radio wave transmission; almost all of the energy transmitted in inductive systems can be received in near-field applications. The radio wave system needs more energy to transmit the field than to operate the device, but it increases mobility. Implementation of radio wave transmission is simpler; towers need to be constructed in fewer locations, leaving just the receiving coils to be attached to the devices. Inductive charging system will need both transmission and receiving coils, but the transmission apparatus could be smaller. However, to achieve the same coverage as the tower, more inductive coils would be needed.

The cost of the radio wave towers would be initial an expensive investment, but following construction, the upkeep costs would be minimal and only include yearly inspections and painting every five to eight years [114]. The only other cost incurred would be that of the receiving coils within the devices. The high quantities of induction coils needed could increase the cost of installation. Inductive technology is attracting investments, as companies can practically and profitably control the system. Public acceptance will depend on cost, health effects, and safety concerns. Inductive charging has been proven to meet health and safety requirements, while research into radio transmission is inconclusive [115]. Comparing between the two systems, induction transmission is more practical, but with future developments, radio transmission may become more feasible.

5.1.7 Environmental Effects

Several studies have been conducted to investigate the interaction between electromagnetic fields and the environment. Environmental research has shown that the propagation of seismo-electromagnetic waves generated within the Earth's core emanate into the atmosphere. The behavior and modulation of artificial electromagnetic waves that propagate through various media and materials can be modeled by this natural seismic wave propagation. Hayakawa [116] measured the fluctuations of light, pressure, and electrical waves in the atmosphere surrounding potential earthquake locations to demonstrate that the lithospheric vibrations produce acoustic and atmospheric gravity waves, which cause periodic vibrational disturbances in the ionosphere. The behaviors of artificial and seismic electromagnetic waves within ionospheric and atmospheric media consequently cause energy absorption within vapor and gases [116].

In 2010, Okamura and Ocuchi [117] investigated electromagnetic wave energy absorption within raindrops. The gain and subsequent loss of energy within the raindrops cause molecular scattering from polarization and subsequent depolarization. While falling through the atmosphere and being subjected to the magnetic field, the trajectories of the raindrops are altered, potentially causing more frequent intermolecular collisions between molecules. As depolarization restores the water to a more stable state, the nearby water vapor molecules form new, larger macroscopic droplets by restoration of hydrogen bonds. This study observed water drop size after exposure to electromagnetic waves, generating a directly proportional relationship between increasing droplet diameter and increasing electromagnetic wave frequency [117].

The effects of low-frequency electromagnetic waves on ionospheric and tropospheric composition have been investigated by various meteorological scientists [118]. The ability of electromagnetic waves to polarize atmospheric and ionospheric water molecules can change the properties of the troposphere in which thunderstorms are formed. If ionospheric water vapor is not affected by significant polarizing factors and lightning passes from the troposphere to the ground, the water is polarized, and quantities of the vapor are transported to the troposphere as high-energy gases. In the troposphere, the water vapor behaves as a greenhouse gas, preventing solar energy from exiting the earth through the ionosphere. However, when an extremely powerful magnetic field is polarizing the atmospheric water vapor during a thunderstorm, the slightly polarized water is transported by the storm to the troposphere in much larger concentrations, consequently increasing the greenhouse effect [118].

Electromagnetic wave propagation has a potentially significant effect on the surrounding ionospheric, and tropospheric environments. The interaction between the waves and water vapor can produce a substantial polarization effect if a strong enough electromagnetic field is generated. Changes in the tropospheric vapor concentrations can intensify the greenhouse gas effect and possibly change thunderstorm patterns. Conversely, the presence of water vapor in the vicinity of a magnetic field causes a gradual dissipation of transmitted energy over extended distances. Electromagnetic fields cannot propagate as far through atmospheric gases if there is not sufficient emitted energy to cause atmospheric ionization [118].

5.1.8 Interference

One of the obstacles associated with wireless energy transmission is interference from transmission through a structure. One form is caused by overlapping usage of electromagnetic frequencies. Examples of this include wireless internet routers, cell phones, remote control, and other devices that transmit information wirelessly. These devices use specific frequencies on the electromagnetic spectrum that can potentially overlap with energy and data transmission frequencies. Another type of interference occurs when the field encounters wiring within the building. Electrical wiring causes two main issues; parasitic induction and interference from external electromagnetic fields. Parasitic induction is the loss of inductive power to nearby metallic objects. The external electromagnetic fields disrupt the transmission field and diminish its effective range. Parasitic induction can occur with the building's plumbing system. The water supply system is made up of copper tubing, which is susceptible to parasitic induction, but the waste water plumbing system is mostly made up of polyvinyl chloride (PVC), which is a non-magnetic and non-conductive polymer. The material flowing through the plumbing is made up of anions and cations, which are easily affected by magnetic fields. This interaction would cause long-term issues that affect the flow and durability of the copper pipes. Many different structural components can interfere with a magnetic field and in the following we discuss these in more detail.

Overlapping Frequencies and Bandwidth

There are many devices that use electromagnetic fields during their operation, which can cause unwanted interactions with wireless charging systems. A likely interaction with wireless charging systems is the field from a wireless Internet router. In 1985, the Federal Communications Commission (FCC) designated specific frequencies for router transmission: 5.8 MHz for medical purposes, 928 MHz for industrial use, and 2.4 GHz for scientific work. Unlicensed transmission on these frequencies is allowed if the transmission power is less than 1 W [119]. Most routers operate on frequency bands at 2.4 GHz and 5 GHz. A router can either output a 2.4 GHz frequency, a single band router, or output on both the 2.4 GHz and 5 GHz frequencies, a dual band router [120]. In the past, the only commercially available routers were single band, but they were shown to interfere with cordless phones and other devices. 5 GHz is the newest frequency used for wireless Internet and has been commercially implemented over the past five years. This frequency is more powerful than its predecessor and does not interfere with as many wireless devices [120]. These interference issues can occur with both inductive and radio wave apparatus.

Another concern comes from radio station transmissions, as they transmit information using parts of the electromagnetic spectrum. Radio stations transmit on the 535 to 1700 KHz frequency range for AM transmission and 88 to 108 MHz for FM transmission [121]. Interference could occur between data and energy transmission, as both systems would likely use similar transmission frequencies.

Bandwidth interference can also arise from signals generated within an electronic device [122]. Some devices create signals using circuitry that involves transducers, which are components that transmit and convert energy into waveforms. These waveforms are received and used by filters and amplifiers, and the majority are contained within the device [123]. This will likely not have significant impact on the charging system, however, depending on the frequency, the charging system could cause the transducers to malfunction.

Although companies avoid bandwidth interference, it is not possible to account for all scenarios. Because induction charging has a smaller field, the probability of interference is less than radio wave transmission.

Other Wiring

Other wiring systems within a structure, such as electrical, phone, cable, etc. could interfere with a wireless charging system in various ways. Each of these wiring systems transports information and/or energy by a different mean. Basic household electrical wiring only transports energy (unless attached to data transmission devices), while phone wiring transports energy and information, and cable and Internet wiring both just transport information.

An electrical wiring system connects an outside source of electricity to an electric/electronic device. The transmission of electricity creates a small magnetic field around the wire in the plane perpendicular to the direction of current. This field could interfere with the transmission field. Parasitic coupling could also occur, causing a change in current flow within the wire [13]. This issue can be avoided by either properly insulating or removing any extra wiring.

Telephones wires consist of two singular strands: one that conducts current and the other that transmits the frequency and information. Wired phones operate by converting and transmitting a frequency, which is then decoded by the speaker at the receiver [124]. There are some similarities between the interference caused by electrical and phone wiring [125]. An issue that can develop is that information could be distorted due to fluctuations in the magnetic field around the wire. This can cause changes in the transmitted frequency, which can cause miscommunications during phone conversions. These cables are also used for basic Internet connections (DSL), which operate using similar principle to telephones, and therefore, similar distortions can also occur with the Internet. This can be avoided by the use of proper insulation or using an Internet service provider that uses coaxial cables.

Coaxial cable is used in the transmission of cable television and high speed Internet. Both signals are transmitted through the same line, which is then attached to a splitter. The splitter receives, decodes, and transmits the proper information to the correct device [126, 127]. Similar issues to that of telephone wire can develop. However, electromagnetic interference has a low probability of occurring in a coaxial cable due to the high amounts of insulation and its physical properties.

Plumbing, Heat and Ventilation

Another type of interference that can occur in a building is between the electromagnetic field and existing plumbing structures. There are many different types of plumbing within a building, including water, sewer, heat, ventilation, and natural gas. The piping for each of these is made from a different material, with different properties related to a magnetic field. The material transported within these systems can also interact with the magnetic field.

The first part plumbing system to consider relates to water. Water is transported to many different locations within a house, including sinks, bathrooms, appliances, water heaters, and other heating systems.

Water supply pipes in most houses are made out copper, but older houses may have galvanized pipes. PVC piping is not recommended for most water supply applications due to the fear of leaching of toxic materials from the plastics and its brittleness [128]. This system is used to carry water from supply sources to a structure for daily use. Water supplied from a city reservoir has been previously treated with many chemicals to eliminate contaminants that include: bacteria, pollutants, and hazardous chemicals, while well water is treated with filtration systems included within the piping and pump system. Copper is a diamagnetic material, meaning that it will interact with a magnetic field. Copper will be repelled by the magnetic field, which can lead to increased strain and changes in flow rates over time [129]. There are many different salts contained within water for treatment purposes, which dissolve in water to form anions and cations. These ions could potentially interact with the magnetic field, eventually leading to changes in flow rate due to developing salt deposits on the pipe's interior walls [130]. This interaction could also lead to changes in the pipe's atomic structure due to substitution of atoms between the solution and the copper wall. This may result in weakened pipes and water contamination. Parasitic coupling can also occur with the pipe, causing a safety hazard.

The second system that is considered is the sewer or waste water system. This system uses PVC piping to remove waste water and refuse from the establishment [128]. It is under a decreased pressure and any leaching from the plastic into the waste water is not considered an issue. The plastic pipe will not react with a magnetic field since it is made out of hydrocarbons [131]. The solution inside the pipe could still interact with the electromagnetic field, which could affect flow rates. The concept of deposits forming on the pipe walls also has to be considered, but due to the inactivity of the PVC, atomic bonding would be diminished [132].

The heating systems being considered here operate using steam or blown hot air. The most common material used in a steam system is steel, which provides good thermal conductivity. Other metals can also be used, but less common [131]. The water inside this system is the same as the supply water and will experience similar effects. Depending on the steel alloy composition, the pipe could be structurally affected by the magnetic field, but the steel's strength can compensate for this effect [80]. Parasitic coupling could also occur with the steel, but it is dependent on the alloy's magnetic properties. A blown air system is usually made from aluminum ductwork so that it is lightweight and able to move high quantities of air [130]. The air in the ductwork has a very low concentration of impurities and the components of air are non-metals, which will not interact with a magnetic field in most cases [133].

Ventilation systems in most buildings are designed to remove impure air and consist of aluminum or plastic components [134]. Since this system uses similar materials and similar gases are transported through the system to blow hot air, it can be assumed that similar interactions would occur between the magnetic field and the ventilation systems [130].

Many new structures use petroleum-based heating systems. The plumbing needed for natural gas and liquid propane systems are similar. These systems transport materials comprised of hydrocarbons, which do not interact with magnetic fields [135]. A natural gas system can be designed using stainless steel, aluminum or copper tubing, depending on the application and applied pressures in the system. All materials associated with this system have already been discussed and determined not to interfere with electromagentic fields [135].

Based on this analysis of various plumbing systems, the water supply plumbing has the highest potential to interfere with a transmitted magnetic field. The other plumbing systems interact with the magnetic field only during extraneous conditions. The copper piping can be affected by the attraction and repulsion forces that the magnetic field applies, and the interaction of the ions flowing through pipe's solutions.

5.2 Health Effects

5.2.1 Studies at the Cellular Level

In recent years, several studies have been conducted to determine the effect of electromagnetic (EM) waves at a cellular level. These studies have tested a variety of tissues extracted from rats and humans to measure changes in cellular organelle functions during exposure to electromagnetic fields.

In 2010, Rajkovic et al. [136] determined the impact of low-frequency (50 Hz) electromagnetic fields on parafollicular (PF) cells in the thyroid glands of rats. Isolated in a laboratory, these living rats were subjected to fields of intensities ranging from 50 to 500 T for seven hours a day, five days a week, for three months. The morphological function of the thyroid cells of the exposed rats was then compared to those of unexposed rats. Following the 3-month exposure period, the rates were killed, and *ex vivo* testing showed that there were no statistically significant changes in thyroid cell function. However, in previous studies conducted by this group, results showed that exposure to electromagnetic fields during early postnatal life in Wistar rats caused the adaptation of PF cells to the surrounding conditions, and the continued cellular metabolic function [136].

Other studies have investigated the impact of electromagnetic wave exposure on the overall function of animal or human body [137]. Commonly used electromagnetic emitting devices such as cell phones and televisions have been used to determine relations between increased electromagnetic field exposure and hindrances of cariovascular function, but no statistically definite correlations have been established [138]. During some clinical interviews [139], patients have claimed that after using cell phones and watching television, they were not physically harmed but became more sensitive to their environments. These symptoms alone cannot directly relate heightened immune and nervous system sensitivities to electromagnetic field exposure because of patients' variable circumstances, such as distances from the devices and medical histories. Tests on the effects of electromagnetic waves on living systems, therefore, must be conducted in an isolated system to eliminate various environmental factors [139].

Another study investigated the interaction between cells in spheroidal clusters, simulating the behavior of individual biological tissues. Daus et al. [140] cultured cardiac cells from chickens and dissociated the collected tissues with trypsin, an agent that prevents cellular adhesion in culture. These cells were then centrifuged, and the trypsin solution was extracted. Cells pelleted were placed in culture flasks to allow growth and re-attachment to the surfaces. The natural aggregation of these cells in a shaking apparatus resulted in the formation of several spheroidal clusters. These cultures were then seeded onto microelectrode arrays (MEAs) and incubated at 37 degrees Celsius to measure non-thermal magnetic field effects at static temperatures. During experimentation, the electrical activity of the spheroids was measured by the MEAs before and after exposure to pulsed high-frequency (between 900 MHz and 3 GHz) electromagnetic waves. Analysis of the experimental results showed no significant changes in neuronal and cardiac cellular electrical activity as a result of high-frequency magnetic waves. The ability of these cells to maintain a steady propagation of action potentials during exposure resembles the unaffected bioelectric behavior of cardiac tissue in the human body near high-frequency waves [140]. Although this *in vitro* experiment suggests a negligible impact of magnetic waves on biological tissues, the isolation of this experimental system does not match the complexity of the human body [140].

Other studies have tested the impact of low-frequency electromagnetic fields on cultured PC12 rat neurons during differentiation. An experiment conducted by Caterina Morabito et al. [141] subjected neuron cultures to 50 Hz electromagnetic waves of intensities between 1 μT and 1 mT. These cultures were placed in a solenoid that produced a pulsed magnetic field for seven days. As a result, there were no significant morphological changes between the exposed and unexposed cultures. After measurement of intracellular calcium and reactive oxygen species (ROS) levels, only the concentrations of ROS (characterized by fluorescence microscopy) increased after exposure to magnetic fields. The change in oxygen concentrations after exposure to magnetic fields indicates an increase in cellular metabolic function (which is linked to the mitochondrion) during exposure. However, the lack of change in intracellular ion concentrations shows that low-frequency electromagnetic exposure has no impact on electrical activity during cellular differentiation in these cell types [141].

5.2.2 Direct Exposure to Wireless Devices

In 1753, Georg Richmann, while attempting to trap lightning, suffered the first recorded death from experimentation with electricity [142]. In the intervening time, death from electrocution has been a risk for not only those experimenting with electricity, but also consumers attempting to make use of the benefits of electrical power. In the United States, an average of 60 people die from consumer product electrocution each year [143]. In 2001, a total of 411 electrocution deaths were reported [144]. Common devices can cause such hazardous situations, emphasizing the need to assess the risks associated with new and developing technologies. However, the wireless energy poses minimal potential risks of electrocution. Resonant systems contain sensors that detect parasitic coupling (magnetic field interaction with an unauthorized object) and deactivate the charging mechanism; if a human body were at risk of acting as part of a coupled circuit, the charging system would immediately disengage . This security feature suggests that the only risk of electrocution arises from possible physical contact with internal components, such as the power cords entering the wireless system, the wires in the coils, or the power cords exiting the wireless system.

Resonant coils, such as the car charging system designed by WiTricity, operate in the KHz and MHz ranges [145]. At frequencies greater than 10 MHz, electricity in the human body is significantly subject to the skin effect, such that the flow of electricity remains at the surface of the body [146]. When a person comes into contact with alternating current at or above this frequency, the electrical current, remaining at the surface of the body, may cause severe burns depending on the current strength. Additionally, high current amplitudes cause significant cardiac malfunctions. However, alternating current at lower frequencies is capable of penetrating deeper into the body. In either case, direct contact with the resonant coils and the consequent transmission of current through the body result in severe electric shock and possible electrocution; the lethality of exposure to alternating current depends on the duration of exposure, the frequency of the current, and the magnitude of the current [147]. To prevent electric shock, precautions must be enacted to prevent any direct contact with current-carrying components of the coupled circuit.

5.2.3 Medical Devices and Implants

Medical implants have become a common solution to numerous medical ailments since the advent of the implantable pacemaker in 1959 [148]. However, this presents a potential complication; electrical technology is highly susceptible to interference from electromagnetic fields, an inherent aspect of wireless energy transfer. The failure of medical devices, both implanted and externally utilized technologies, due to radio frequency interference (RFI) has been well documented since 1998. Observed RFI-sensitive technologies from this period include powered wheelchairs, which, upon malfunction, would sometimes forcibly eject passengers or drive directly into traffic. Additionally, approximately sixty infants died in the mid-1980's after RFI-sensitive monitors were used to detect any discontinuance in breathing [149]. Externally utilized medical technology, while not as inherently dangerous upon malfunction as implanted technology, evidently presents a non-trivial health risk due to malfunction.

Of greater concern are internal medical devices; RFI between a transmission source and an internal pacemaker or defibrillator could cause lethal cardiac arrest or fibrillation. In a study, results showed that pacemakers in the vicinity of cellular phones delivered irregular stimuli or revert to a preprogrammed, unadaptive rate. Observing the hindered performance of implantable pacemakers, the scientists performing the study concluded that the health risk posed by the interactions between RFI and cellular phones could be best addressed with precautionary recommendations for individuals possessing implanted devices, but was not of concern to the rest of the population [149]. However, this specific research was performed in 1995, and since then, biomedical implants and RFI sources have become more complex, varied, and common [150]. Given both the evidence of the study and the rapid growth in technological proliferation, RFI must be considered a continuing concern and must be treated as such. In response to the increase in RFI, medical devices have been designed with protection against electric field up 3 V/m (the field acting on an object one meter from a cell phone) [150]. With wireless communications technology creating sufficient RFI to cause malfunctions, wireless power transfer, intended to broadcast significantly higher power, merits much greater concern. However, the 3 V/m industry standard for minimum field tolerance applies only to electric fields; the coupled charger developed by WiTricity uses magnetically resonant fields to broadcast power without risk of RFI causing malfunctions in nearby technologies [145]. Additionally, the field strength of inductive coupling decreases proportionally to the inverse square of the distance [151]. As such, while inductive coupling technology can potentially interfere with other electronics, the rapidly decreasing field strength limits its area of effect; by shielding the inductive coils, the field strength can be further diminished to reach a safe level.

5.2.4 Short and Long Term Exposure

Further considerations of potential health effects involve the possibility of nonlethal interactions between electromagnetic fields and the human body. A common concern regarding Magnetic Resonance Imaging (MRI) scans is that individuals with metallic, subdermal ink tattoos can receive severe burns. A justification for this concern is the potential for interactions between metallic elements in the ink and the powerful magnetic field generated by the MRI. Research has shown that there have been few documented cases, but nevertheless it is indeed possible for an MRI machine operating at a field strength of 1.5T to induce burns in patients with tattoos [152]. In contrast, the magnetic field of a resonant coil is significantly weaker than that in an MRI machine. Moreover, metals are not allowed near an MRI machine due to the strength of its field, whereas the resonant coils developed and demonstrated by WiTricity had no effect on nearby metals [153]. This clearly demonstrates that the field from the coils, even when transmitting at their maximum strength, is of lesser magnitude and poses no risk towards tattoo recipients.

Another concern related to the dissemination of wireless power is the possibility of damage to reproductive organs. Human infertility is often considered a hazard during evaluations of any technology that emits an electromagnetic fields. For example, a report prepared by Jean and Alasdair Phillips states that electromagnetic fields generated by cell phones skewed birth ratios (towards higher female numbers) and decreased sperm count [154]. Additionally, both low-frequency electromagnetic fields and weak magnetic fields lead to decreased sperm function [154]. In light of this correlation, it can be posited that the more powerful high-frequency fields of wireless power coils may have a similarly significant effect and merit further research, although as of now, to the best of our knowledge, no direct research has been done.

The condition with the most evidence associating it with electromagnetic field exposure is childhood leukemia. A couple of analyses have "demonstrated a consistent pattern of a two-fold increase in childhood leukemia", after observing patients who were exposed to an average residential electromagnetic field of at least 0.3 to 0.4 μT [155].

In 2002, the International Agency for Research on Cancer (IARC) referred to extremely low frequency (ELF) electromagnetic fields as "possibly carcinogenic to humans" [155]. However, the evidence provided by the study is weakened by methodological problems, such as test subject selection bias. Also, there is no currently known biological mechanisms that exposure to electromagnetic fields could affect [155].

5.3 Conclusions

The future development of wireless energy depends on many different factors. The desire of wireless energy compared to the cost of implementation has to be examined to allow for the public to make an informed decision about using this technology. The cost of copper is examined to determine the price to produce a copper coil. Wireless technology has to be regulated so that public will be able to control their power systems. The cost of reconstructing the infrastructure needs to be examined to determine the economic impact of this energy system. The benefits and drawbacks of the wireless energy system are compared to traditional physical connections. Wireless energy comes in two major forms, induction and radio waves, which are compared to determine which is more feasible at the present time. The environmental effects of electromagnetic waves are not fully understood and would have to be examined in terms of effects on climate and wildlife. The public will want assurance that wireless energy is safe for people to have short and long term exposure to constant electromagnetic energy.

Chapter 6

Survey

6.1 Design and Preparation of the Survey

One of our goals in this project was to collect data on the public perception of wireless energy transmission. To this end, we prepared a short survey, which consisted of seventeen questions relevant to our project (see Appendix). A total of 461 respondents completed the survey (February 3rd, 2013 and February 4th, 2013). The subjects of these questions ranged from Nikola Tesla's innovations in communication to the survey takers' speculations about future wireless technology. The survey was distributed via various media, including the student mailing lists at WPI and social media networks such as Facebook and Tumblr. Responses to the survey were stored anonymously in a Google spreadsheet.

6.2 Results

The first five questions of the survey were used to determine subject demographics, such as age and gender. These questions were optional and were not answered by all the respondents. The first question asked for the age range of each respondent. The distribution of survey-takers/ answers demonstrated that 92% of the respondents were between the ages of 17 and 24; this age group encompassed 425 of the respondents (see Figure 6.1).

The second demographic question asked about the subject's gender. There were 444 responses to this question, and the data (given in Figure 6.2) shows a gender distribution of 54% male and 46% female.

Based on the responses to the third question, most of the respondents identified themselves as Cau-

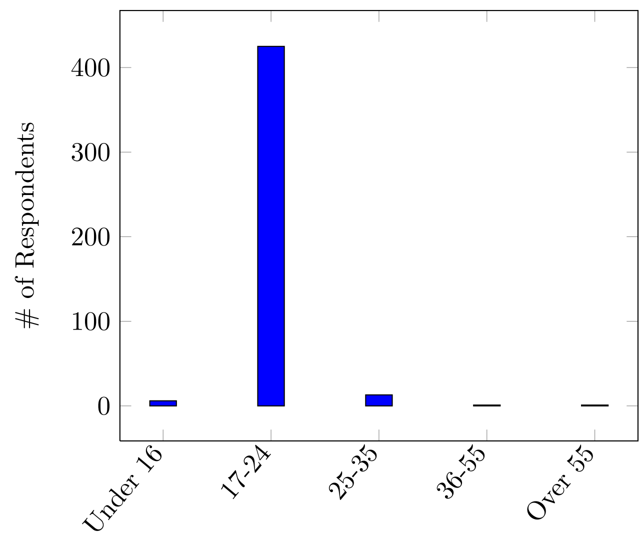

Figure 6.1: Age distribution of respondents.

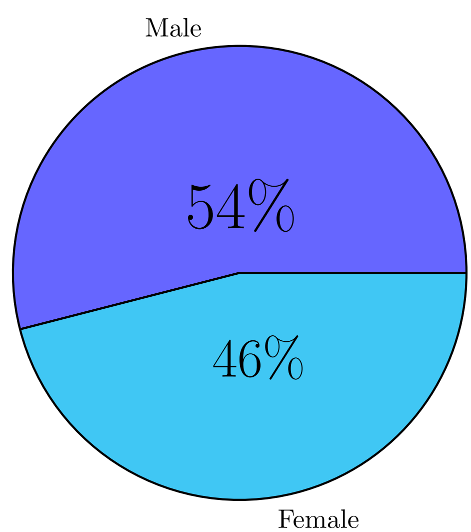

Figure 6.2: Gender distribution of respondents. Here the standard deviation is 10.51.

casians or Asians. The complete distribution is shown in Figure 6.3.

The next demographic question addressed the average income range of each respondent. A majority of the subjects described their annual income as under $20,000 mainly because the survey was distributed among the undergraduate students at WPI or other schools. Figure 6.4 shows the complete income distribution of the respondents.

The fifth demographic question asked each respondent about his or her occupation. The majority of

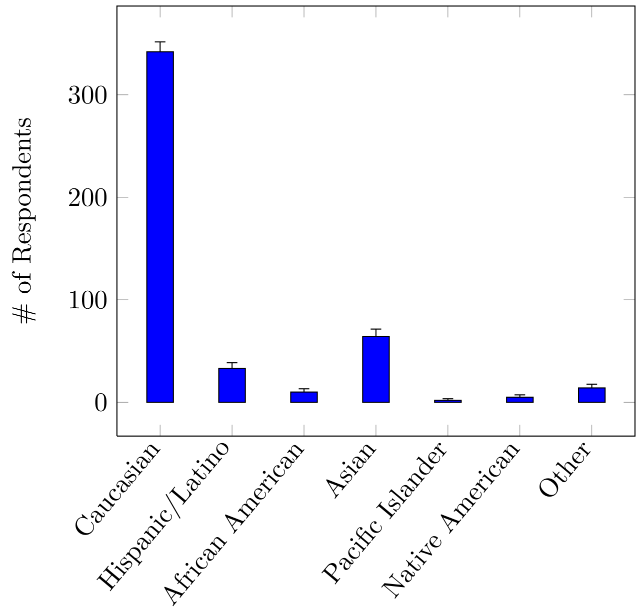

Figure 6.3: Racial distribution of the respondents. The error bars are calculated assuming a multinomial distribution.

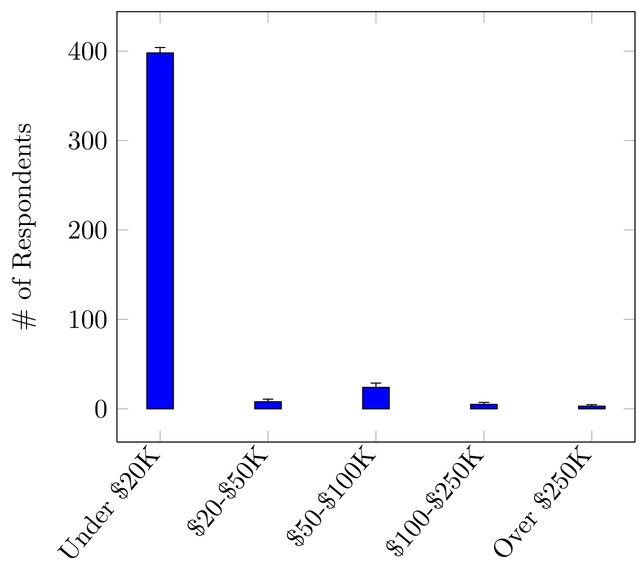

Figure 6.4: Income distribution of respondents. The error bars are calculated assuming a multinomial distribution.

the respondents identified themselves as students (see Figure 6.5).

The first required question of the survey asked the respondents to describe their knowledge about electricity. As shown in Figure 6.6, there were four different possible responses to this question: very basic,

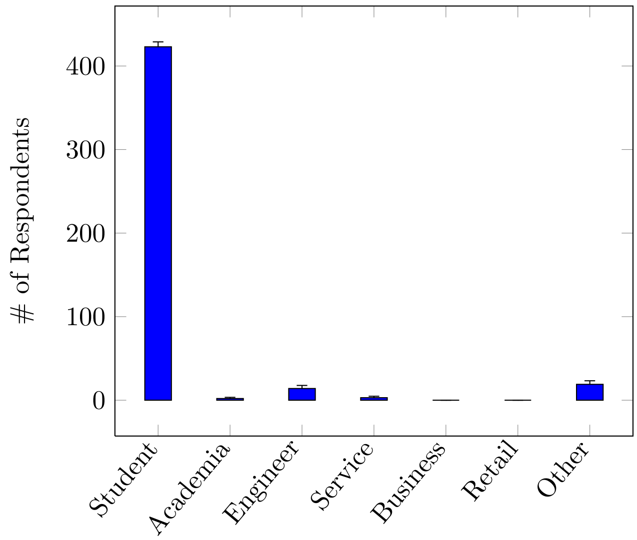

Figure 6.5: Profession distribution of respondents. The error bars are calculated assuming a multinomial distribution.

high-school, university, and expert. The next question asked if the respondents have heard of concepts

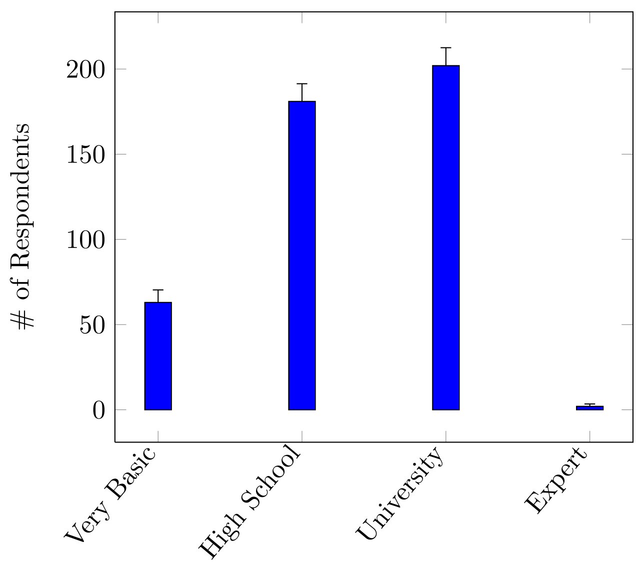

Figure 6.6: Distribution of the respondents' education level on electricity. The error bars are calculated assuming a multinomial distribution.

that Nikola Tesla created. This was a simple yes/no question. The data shows that about 66% of the respondents have heard of the ideas of Nikola Tesla (see Figure 6.7). This question was designed to relate knowledge of Nikola Tesla to awareness of wireless energy. The standard deviation of the data is 9.99. The next question asked the respondents if they felt that electrical transmission could be possible

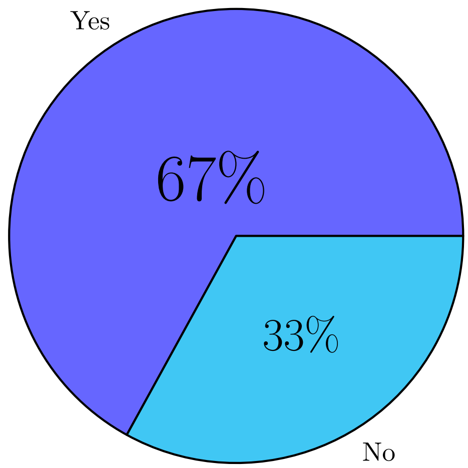

Figure 6.7: Percentage of respondents who had or did not have previous knowledge of Nikola Tesla's works. Here the standard deviation is 9.99.

without wires. This question was designed to determine whether the respondents had any prior knowledge or thoughts about wireless energy transmission. This question had three possible answers; based on the

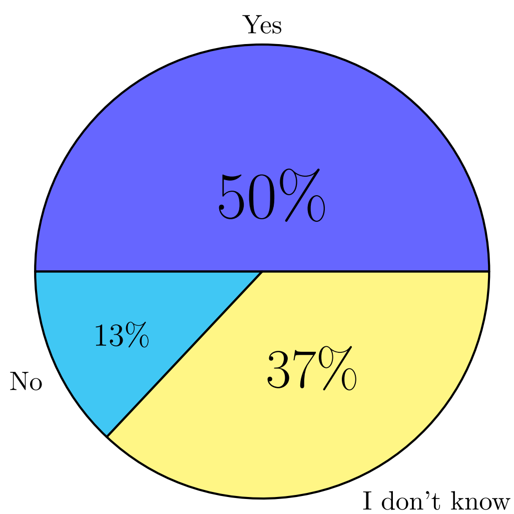

Figure 6.8: Answers to the question as to whether or not the survey takers think there are more efficient ways to transmit electricity besides using wires.

collected responses, about half of respondents believe in the existence of more efficient ways of transmitting electricity besides wires. The distribution of answers is shown in Figure 6.8.

The next question was a follow-up to the previous one, and it inquired about the respondents' prior knowledge of wireless energy transmission. There were 64% "yes" responses to this question (as shown in Figure 6.9), compared to 50% from the previous question. Comparing the "yes" responses between the two questions, 77% of the respondents feel that there are more efficient modes of energy transfer. The standard deviation in the responses is 10.16.

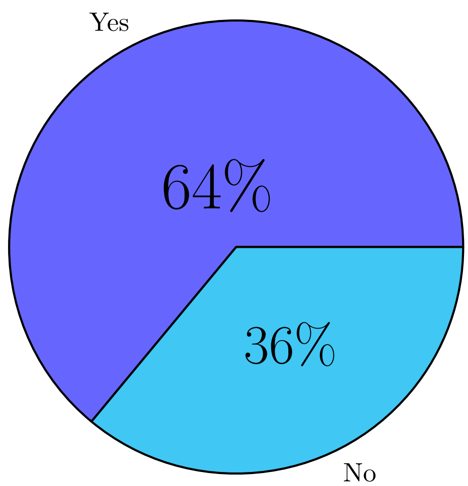

Figure 6.9: Responses to the inquiry about prior knowledge of wireless power transmission. Here the standard deviation is 10.16.

The next question asked the respondents whether or not they believed the possibility of transmitting energy through the air. The responses given in Figure 6.10 show that 90% people consider the transmission of power through the air as a possibility. The standard deviation for the data is 6.23.

The next question in the survey regarded knowledge of electromagnetic waves, which is the basis of inductive coupling and radio frequency transmission. The options for this question were: very basic, advanced, and expert. The answer "advanced" signifies that the responder has a basic working knowledge of the equations and fundamental concepts. The answer "expert" means that the respondent has advanced knowledge of the concepts that encompass electromagnetism. Whereas only a few respondents claiming to be experts, the remaining answers were nearly equally divided among basic and advanced knowledge of electromagnetic waves (see Figure 6.11).

The next question had to do with the respondents' thoughts on the health risk of increased exposure to electromagnetic fields. This was a "yes" or "no" question. As shown in Figure 6.12, about 61%

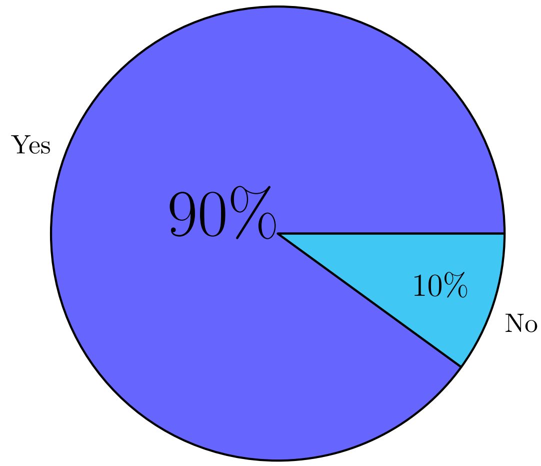

Figure 6.10: Responses to the question as to whether or not the survey takers believe that transmission of electricity through the air is possible. Here the standard deviation is 6.23.

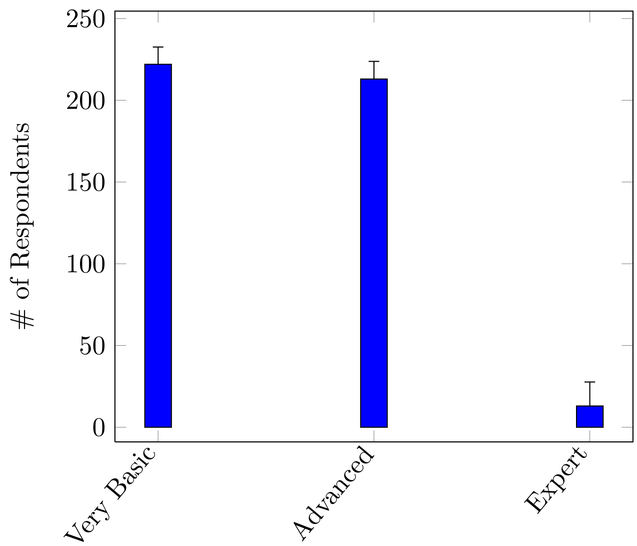

Figure 6.11: Responses to the question about the respondents' level of understanding of electromagnetic waves. The error bars are calculated assuming a multinomial distribution.

of the subjects answered "yes". This prompted us to investigate the health effects further, which is discussed in Section 5.2. It is important to note that about 3.7% of the survey takers thought this question was either poorly phrased or too vague. According to the comments, these respondents interpreted the question as either increasing the amount of electromagnetic field produced to illegal levels, or that the whole electromagnetic wave spectrum would be used for transmission. Answers to this question show that it is important to prove to the public that wireless technology can be considered safe, perhaps with fewer risks than today's forms of energy transmission.

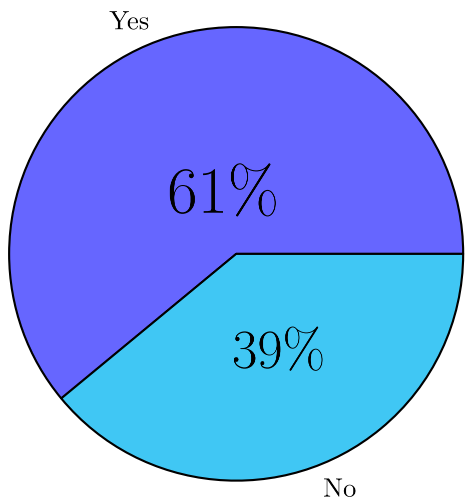

Figure 6.12: Responses to the question as to whether or not the survey takers feel that high amounts of exposure to electromagnetic waves creates a health risk. Here the standard deviation is 10.33.

The next two questions are coupled together because they inquire whether or not the responder would pay more for a wireless charging device, and if he or she would pay, how much he or she would be willing to spend. As shown in Figure 6.13, about 58% of the respondents stated that they would pay more for wireless energy, which shows that there is a marginally popular interest in the technology. This mixed reaction to the possibility of wireless charging technology also shows that some people are not interested in the technology at all, which could be caused by reasons that would need to be addressed for any type of implementation campaign to be effective.

Based on the answers to the next question (shown in Figure 6.14), only 3.1% of the respondents are willing to pay more than $500 for the technology, which is possibly due to the demographics of the participants—who are mostly students—of the survey.

The next question looks at where the removal of electrical lines would be the most helpful to society. There were five possible answers for this question based on the square footage that would have to be converted: room, house, town, state and country. Figure 6.15 shows the distribution of the answers. The most efficient way would be to remove power lines from all across the "country" and just have central charging towers. This was the historically unaccomplished purpose that Nikola Tesla had designed for WardenClyffe Tower. The respondents feel that the removal of power lines would be effective on either

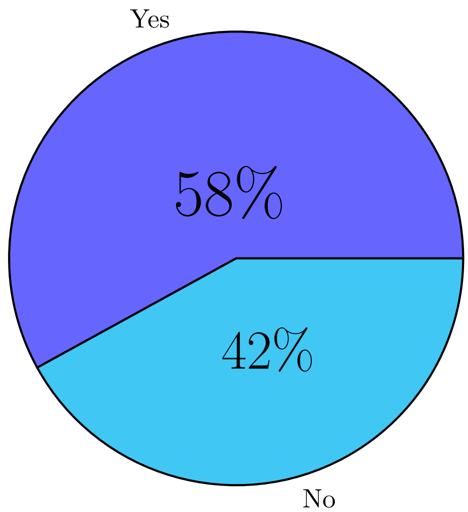

Figure 6.13: Responses to the question as to whether or not the respondents would be willing to pay more for a wireless charging device. Here the standard deviation is 10.46.

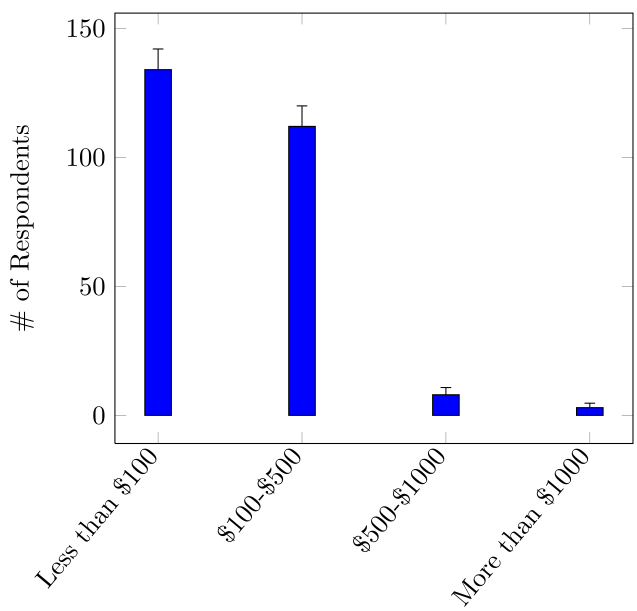

Figure 6.14: Distribution of the amounts respondents would feel comfortable to pay for wireless technology. The error bars are calculated assuming a multinomial distribution.

town or country level. The removal of wiring from houses was the third most popular response, whereas room and state were the least popular responses.

The next question looks at how long the respondents think a full-scale implementation of wireless

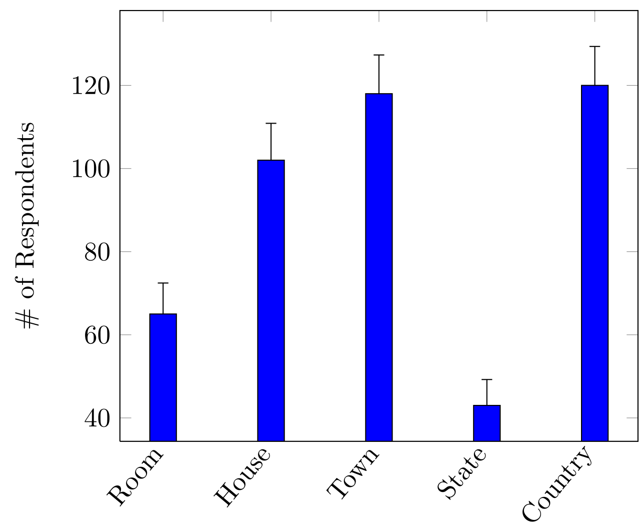

Figure 6.15: Responses to the question about where the survey takers think the elimination of power lines would be the most beneficial. The error bars are calculated assuming a multinomial distribution.

technology would take. There were five time ranges to choose from based in years. The resulting distribution is shown in Figure 6.16.

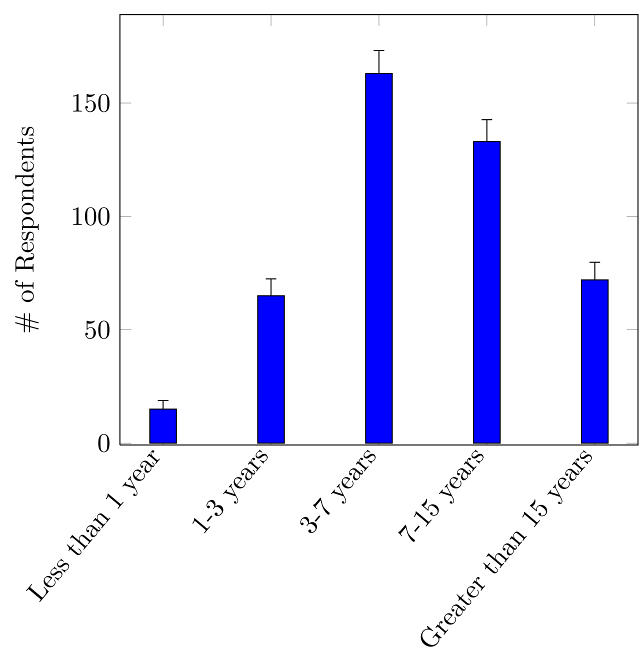

Figure 6.16: Distribution of the responses to the question as to in what time frame the respondents think a full-scale implementation of wireless technology would take place. The error bars are calculated assuming a multinomial distribution.

Figure 6.16 shows an interesting response pattern; a majority of the respondents selected the choice that indicated a predicted range of three to seven years. This response also makes the most logical sense based on technological advancements and developmental rates. The responses for “seven to fifteen years” and “greater than fifteen years” were more than “the less than one year” and “one to three years” responses.

The final question of the survey inquires about the industries that would benefit the most from the implementation of wireless power transmission. There are various fields to consider when thinking about who would benefit, and how they would benefit. Therefore, our group decided that the top six industries were: automotive, cellular, computer, video gaming, manufacturing, and electrical power production. There was also the choice of “all of the above”.

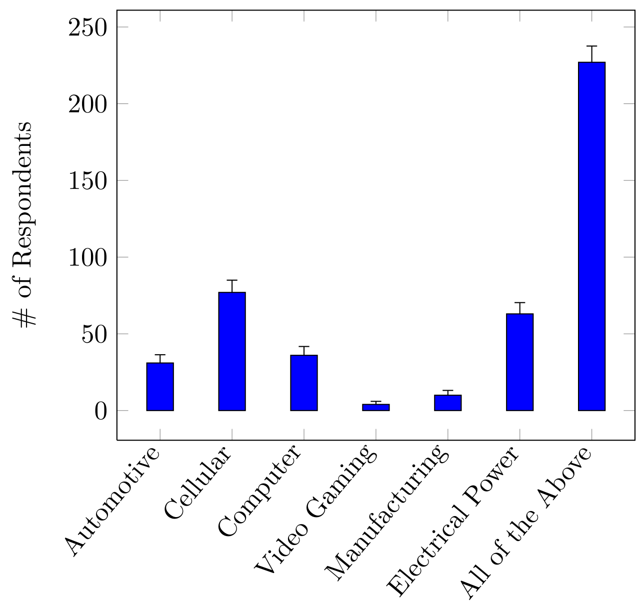

Figure 6.17: Responses to the question about which industry the survey takers think would benefit the most from wireless power transmission. The error bars are calculated assuming a multinomial distribution.

The data shows that about 50% of the respondents think that all six depicted industries would benefit from wireless power transmission, and the other 50% believe that only certain areas, like the cellular industry, could benefit the most.

6.3 Conclusions

This survey helped gather useful information on public perception of wireless power transmission. Our results argue that, in general, people would like to see this technology implemented within the next three to seven years. However, there seem to be major hesitations and uncertainties about the health risks of electromagnetic exposure, which could hinder implementation if safety concerns are not properly addressed.

Chapter 7

Conclusions

Based on the reviewed literature and collected data, our report suggests that wireless energy transmission could be feasible in the future using an inductive charging system. More research needs to be done in the area of radio wave transmission to develop more efficient, easily controllable systems.

Inductive charging seems feasible for many different reasons. Companies are already conducting research and manufacturing products that use this system. Moreover, The Wireless Energy Consortium is already in the process of developing regulations for induction charging systems, and many companies are joining this organization. With the regulation of this technology not only safe but approved devices would be sold. Inductive charging systems can also be implemented gradually, giving the public enough time to adjust to the presence of wireless charging. This slow transition would also give time to address testing issues. Companies are developing adaptations for existing devices to provide wireless charging capabilities. These charging surfaces incorporate safety and efficiency mechanisms to ensure consumer safety, which are safer than current wired charging systems. In addition, many of the respondents to our survey predicted that wireless charging would become more prominent in the society within the next three to seven years. Based on our interviews, companies also support this claim, saying widespread implementation of inductive charging systems will occur within ten years.

Radio wave transmission could be the system of the future, potentially ending the dependence on battery technology. However, since the deactivation of WardenClyffe Tower, there has not been major research on charging by radio wave transmission. Nikola Tesla's experimental system used large amounts of energy to generate a magnetic field in order to power devices located within an effective radius. The inability to control which devices are to be charged is a financial drawback for the industry: there is no feasible method, to this date, by which to accurately charge consumers for the amount of energy used by any one device. While this economic dilemma is one of the reasons behind the lack of funding for radio wave transmission of energy since the time of Tesla, it remains to be seen whether new technologies can be developed to overcome these obstacles.

Wireless energy transmission has been the subject of many studies in the past, and will continue to be so in the future. The challenge to design a more sophisticated, convenient, and efficient method of energy production presents applications in various technological disciplines. The modification of existing technologies with wireless charging apparatuses can contribute solutions to both small- and large-scale problems. Although the convenience and minimal impact to the environment might justify the implementation of wireless charging technologies, the need to guarantee widespread access to this energy, proper identification of potential health hazards, and the implementation of adequate regulations would affect the timeline of commercialization of this technology.

Appendix A

Survey Material

Worcester Polytechnic Institute IRB# 1
HHS IRB # 00007374

9 January 2013
File:12-213

Re: IRB Application for Exemption #12-213 "Wireless Energy IQP"

Dear Prof. Tuzel,

The WPI Institutional Review Committee (IRB) has reviewed the materials submitted in regards to the above mentioned study and has determined that this research is exempt from further IRB review and supervision under 45 CFR 46.101(b)(2):"Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation."

This exemption covers any research and data collected under your protocol from 9 January 2013 until 8 January 2014, unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific exemption must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue.

Please contact the undersigned if you have any questions about the terms of this exemption.

Thank you for your cooperation with the WPI IRB.

Sincerely,

Kent Rissmiller

Kent Rissmiller
WPI IRB Chair

Survey Questions

Demographic (optional)

1. What is your age?
    a. Under 16
    b. 17-24
    c. 25-35
    d. 36-55
    e. Over 55
2. With what gender do you identify?
    a. Male
    b. Female
3. How do you describe yourself?
    a. Caucasian
    b. Hispanic/Latino
    c. African/African American
    d. Asian
    e. Hawaiian/Pacific Islander
    f. Native Indian
    g. Other
4. What is your income level?
    a. Under $20,000
    b. $20,000-$49,999
    c. $50,000-$99,999
    d. $100,000-$249,999
    e. Over $250,000
5. What is your profession?
    a. Student
    b. Academia
    c. Engineer
    d. Service
    e. Business
    f. Retail
    g. Other

Wireless Energy Questions

6. Education level on electricity?
    a. Very Basic
    b. High school level
    c. University level
    d. Expert

7. Do you have previous knowledge of Nikola Tesla's works?
    a. Yes
    b. No
8. Do you think that there are more efficient ways to transmit electricity besides wire?
    a. Yes
    b. No
    c. I don't know
9. Have you heard of wireless power transmission?
    a. Yes
    b. No
10. Do you think that transmission of electricity through the air is possible?
    a. Yes
    b. No
11. What is your level of understanding of electromagnetic waves?
    a. Very basic
    b. Advanced (formulas, basic workings)
    c. Expert (advanced formulas, advanced theory work)
12. Do you feel that high amount of exposure to electromagnetic waves creates a health risks?
    a. Yes
    b. No
13. Would you be willing to pay more for wireless charging devices?
    a. Yes
    b. No

Cost of Wireless Energy

14. How much would you pay?
    a. Less than $99
    b. $100-$499
    c. $500-$999
    d. Greater than $1000

Future of Wireless Energy

15. Where do you see the elimination of power lines being the most beneficial?
    a. Room
    b. House
    c. Town
    d. State
    e. Country
16. In what time period do you think wireless energy transmission could be implemented?
    a. Less than 1 year
    b. 1-3 years

    c. 3-7 years
    d. 7-15 years
    e. Greater than 15 years
17. Which industry do you think would benefit the most from this technology?
    a. Automotive
    b. Cellular
    c. Computer
    d. Video Gaming
    e. Manufacturing
    f. Electric Power Industry
    g. All of the above
18. Any other comments or inputs?

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