The Applications and Limitations of Printable Batteries

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Matthew Delmanowski

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Abstract

This study focuses on the potential applications for printed batteries and how they could affect the printing industry. It also analyzes the main problems associated with manufacturing this technology and what needs to be done to overcome these issues. To find the answers to these questions, two methods of research were used. The first was through the elite and specialized interviewing of Dr. Scott Williams of Rochester Institute of Technology and Professor Nancy Cullins from Cal Poly. The second form of research was a common, yet useful, method called secondary research. This entailed looking at recent written research papers about printable batteries to help find information and interpretations in order to draw conclusions.

This study discovered some of the applications for printable batteries included advertising, disposable packaging, car batteries, and medical devices. The main issue that is delaying progress in this technology appears to be discrepancies in the ink formulation and setbacks in the materials. As for its impact on the printing industry, it was found that printable batteries probably wont have as much of a profound effect as previously thought. Though it will be a great product for the industry, it will most likely become a niche market for specialized printers.

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Chapter I – Introduction

Change is something that the printing industry has become quite accustomed to in recent decades. The methods used to manage print-related tasks have been adapted over time to meet modern needs, and the technologies used to produce printed materials are constantly being upgraded and enhanced. Examples of some of the major changes printers have weathered can be seen in the shift from lead type to phototypesetting in the 1960s, the desktop publishing revolution of the 1980s, and the dawn of the Internet in the 1990s. All these events have significantly affected those involved in printing and are a strong reminder of how one new idea can change entire industries. In 2010, the paradigms of the print industry continue to shift and expand in new directions, especially with the advent of newer technologies such as digital printing, variable-data printing, and carbon nanotechnology.

Perhaps one of the most important of these changes will come from the advances in the area of printable electronics. This is the ability to print electronic components and circuits using conductive and dielectric inks that are applied directly onto a flexible substrate such as paper or plastic film. If this process is perfected, applications such as paper video displays, printable memory devices, and much more will become highly plausible. What might have once been only thought of as an idea out of a science fiction novel is now starting to become reality, and has a strong potential to cause another major revolution within the printing industry. As technology improves, these concepts of

printable electronics are becoming ever more feasible. However, at the moment this field is still in its infancy with many discrepancies that will need to be solved.

One of the primary constraints of printable electronics is the trouble with relatively large and inefficient power sources. Existing batteries used to power basic displays and electronics are still encased in metal canisters and are bulky in comparison to flat printed circuits. This significantly hinders the possibilities of flexible products, and requires the battery to be external with connecting wires. To advance forward with viable printed electronics, it is clear that a new smaller power source is needed to make these products compact. Similar to the idea of printing circuits, researchers are developing an idea that would enable the ability to make a battery out of paper. It would be flat, flexible, and ideally environmentally friendly, which is a large problem with current batteries. As time progresses it seems that there is more of a demand for smaller products, but in many electronics the battery is still the largest component. A smaller battery would, thus, make smaller products possible. The applications for a printed battery could potentially expand outside the realm of printed electronics, as it could be used for powering a wide range of gadgets from hand-held electronics to small medical devices and maybe to even power cars. The possibilities are endless.

There is still much work to be done before these ideas can be readily available to the public. This study addresses important questions for the developers of printed batteries to keep in mind: What are the current limitations of printable batteries and what are the problems associated with manufacturing these products on a mass-produced scale? This study finds that there are some serious problems that need to be fixed to advance forward with this concept, such as setbacks with materials and ink consistencies.

It looks into the research that is being done in the area of printable batteries with the intent of discovering the answers to these questions, and to reveal what needs to be done to overcome these obstacles in order to make them commercially available in a mainstream market. This study speculates that some of the main problems are limitations of the materials used to make the batteries, printing issues such as pinholes and ink film thickness, and limitations of the battery itself. The central purpose and focus of this study is to establish the minimum requirements needed for a printed product to be considered a battery, and to uncover what are the basic problems associated with manufacturing these types of small power storage systems.

Researchers are just beginning to examine the implications of current printable power sources, and there is still much work that needs to be done. Nonetheless, it is fully expected that there are many applications that have a great potential for changing the world once these problems are identified and corrected. It can be foreseen that printable power sources will have a major impact on the printing market and, along with printed electronics, it has the capability to cause another major paradigm shift. As previously noted, the printing industry has evolved many times and this study shows that printable battery technology is the next drastic step that will revolutionize the way printers are used. It is not a question of whether or not printable batteries can be created efficiently, it is a matter of when and how long until this technology is easily available.

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Chapter II – Literature Review

To comprehend the logistics of creating a printable power source, it is first vital to understand what exactly a battery is and the basic components and conditions needed for one to work. According to the American Chemical Society, a battery is defined as a container that stores chemical energy that is later converted into electrical energy used to power a device. For a battery to engage in this energy conversion process, it requires two electrodes (the negative one is called the cathode, and the positive one the anode) and an ion-conducting solution called the electrolyte.[1] "[Batteries] develop voltage from the chemical reaction produced when two unlike materials, such as the positive and negative plates, are immersed in the electrolyte, a solution of sulfuric acid and water."[2] Basically, the cathode—usually made of manganese dioxide—attracts electrons more easily than the zinc anode, with the electrolyte being the carrier solution. The greater the difference in this attraction between the anode and cathode, the higher the voltage of the battery will be. A simple example of a battery can be made with a lemon by inserting a copper coin and a zinc nail into it and wiring that to a light bulb. The nail would be the anode, the coin the cathode, and the lemon the electrolyte solution. This chemical reaction generates

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[1] http://acswebcontent.acs.org/landmarks/drycell/batteries.html

[2] http://www.batterycouncil.org/LeadAcidBatteries/HowaBatteryWorks/tabid/108/Default.aspx

a small amount of electricity to slightly power the light bulb.[3] It is possible to increase the total voltage output by aligning multiple batteries in a sequence, as is often done in electronics. All this is extremely important to the topic of printing batteries, because in order to manufacture a paper power source these principles must be kept in mind. A printed battery, like any other battery, still requires an anode, cathode, and electrolyte.[4]

The concept of batteries has been around for quite some time. The term "battery" was actually coined by the famous inventor Benjamin Franklin in 1752, referring to an array of charged glass plates. But it was not until 50 years later when Alassandro Volta created the first battery that offered a constant electric current. This apparatus was called the "Voltaic pile," which was made from pairs of zinc and silver discs (the anodes and cathodes) and was separated by cardboard soaked in an electrolyte solution. "Volta's pile was at first a technical curiosity but this electrochemical phenomenon very quickly opened the door to new branches of both physics and chemistry and a myriad of discoveries, inventions and applications. The electronics, computers and communications industries, power engineering and much of the chemical industry of today were founded on discoveries made possible by the battery."[5] With continued research of Volta's work by various other scientists and chemists over the next two centuries, it has now become possible to produce batteries of all different sizes that are capable of longer life spans, higher voltage outputs, and some that can even be recharged. Despite all these advances, the basic concept of cathodes, anodes, and electrolytic solutions still remains an important part of battery designs.[4]

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[3] http://www.zbattery.com/How-to-Make-a-Lemon-Battery
[4] http://www.explainthatstuff.com/batteries.html
[5] http://www.mpoweruk.com/history.htm#daniell

These innovations give an important supporting background to this study, as they have made possible the technologies that are needed for a printable battery. An analysis of this product by NanoMarkets has described the state of printable batteries as:

> Any battery that uses printing technology in its manufacturing. For example, many printed batteries today use printing only for the electrodes and then laminate the electrolyte in between these electrodes. These batteries typically involve liquid electrolytes, which so far have not provided an effective electrolyte layer via printing. There are several chemistries currently being used by companies that have developed printable battery technology, but they are usually zinc manganese dioxide or carbon zinc. These are relatively low-cost materials when compared with the various lithium chemistries used in many of the thin-film and conventional batteries. These materials can be formulated into inks, which are then printed via screen-printing onto a variety of substrates.[6]

NanoMarkets make a clear reference to one major problem with printing batteries, which is applying a viable electrolyte to the paper with a printing press. Another problem that can be called to attention is the relatively short lifespan of current printable batteries. An article from the Gizmag website states:

> Unfortunately, the two poles of the batteries tend to gradually dissipate during their life cycle, which makes them unsuitable for applications where reliability and a long, steady life cycle are essential. They would, on

[6] http://www.azom.com/details.asp?ArticleID=4951

the other hand, be excellent serving as a cheap power source for LEDs and other low-power devices.[7]

This will limit the amount of applications for flexible batteries, and will be an area for researchers to develop longer lasting, or even rechargeable paper batteries.

Today, there is an ever-increasing interest in the ability to print small, flexible batteries. With the popularity of smaller wireless hand-held devices and more mobile and interactive lifestyles, it is becoming more and more important to find power sources that are smaller in size, yet that are still able to hold a longer charge. "Thin-film and printed batteries with their customizable shapes, flexible form factors and ultra-low weight are enabling new functionality to be added to a broad range of electronic products, such as smartcards, radio frequency identification devices (RFID), and sensors both increasing their usefulness and the size of their addressable markets,"[8] says *Electronics Manufacturing Magazine*. Researchers from this publication also go on to predict that the printed battery industry will be worth upwards of $5.6 billion by the year 2015. Other experts from the *Science Daily* website recently wrote that, "for a long time, batteries were bulky and heavy. Now, a new cutting-edge battery is revolutionizing the field. It is thinner than a millimeter, lighter than a gram, and can be produced cost-effectively through a printing process."[9] It appears that there is a strong potential for printing batteries in the future, and it seems that many people within the industry are excited for the future capabilities of this area of printable electronics.

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[7] http://www.gizmag.com/inexpensive-thin-printable-batteries-fraunhofer/12156/
[8] http://www.emasiamag.com/article-2887-thinfilmprintablebatterymarketstoreach56billionby2015-Asia.html

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Chapter III – Research Methods and Procedures

In conducting this study, there needed to be clear and accurate methods for gathering the data required to make conclusions about the current state of printable batteries and the problems facing it. There are many ways to conduct research when studying a particular topic, however it is first important to identify and define those methods. The information used in this study was collected in two primary ways: elite and specialized interviewing, and historical research.

Perhaps the most beneficial method for this study was through elite and specialized interviews, a process developed by Lewis A. Dexter. He was an esteemed social scientist, and pioneered and perfected ideal ways to conduct interviews. Dexter describes elite and specialized interviewing as a way to extract information from professionals through "taking the form of a conversation. Hence, the interviewer's questions may be answered without a formal sequencing of questions." This allows those involved in the interview to essentially have a conversation regarding the subject. It gives the interviewee the ability to set up their own perspectives without restricting the information they give away.[10]

There are two professionals who agreed to lend their expertise to this study, both of whom were interviewed thoroughly. The first is Dr. Scott Williams. He is a scholar at the Rochester Institute of Technology in New York who is doing extensive research on printable battery capabilities, and is working on developing better materials and processes

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[9] http://www.sciencedaily.com/releases/2009/07/090702080358.htm

for it. He was very helpful and was able to answer many of the questions this study is addressing. He is very passionate about the advancement of this technology, and was eager to help clarify the challenges that are faced by printing a power source. Some examples of questions that were asked were:

- How do printed batteries differ from conventional batteries, and what are some of their advantages?
- What are some of the biggest issues/obstacles with making printable batteries?
- How long do you think it will be until printed batteries are widely used in a commercial market?

The second interviewee was Nancy Cullins. She is a professor at the Graphic Communication Department at California Polytechnic State University (Cal Poly) in San Luis Obispo, California. She is currently doing her masters thesis on the topic of printed electronics, and was able to provide some intelligent insights about the prospect of printed electronics, and how it might affect the printing industry and society. Below are a few of the topics discussed:

- What applications printable electronics could be used for.
- The sustainability of printed electronic products.
- How printable electronics might affect the printing industry.

Another method that helped to collect important information on the subject was through secondary research. According to DJS Research Ltd, an independent market research company, secondary research can be defined as "processing data that has already

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[10] Levinson, H. (2001). Some Ideas About Doing Research in Graphic Communication.

been collected by another party. With this form, researchers will consult previous studies and findings such as reports, press articles and previous research projects in order to come to a conclusion."[11] Basically, secondary research looks at past written works to help find information and interpretations. This is most commonly accomplished through finding information from past publications or anything that has already been written about the topic. Searching online and in libraries aided this study in finding useful publications that pertain to the area of printed battery production. A helpful example of this is an article entitled "Printable Battery Benefits,"[12] which was found from the Power Paper web site, one of the leading producers of printed batteries. Through these specialized interviews and secondary research, many important facts about printable batteries and the problems associated with manufacturing them were discovered.

[11] http://www.marketresearchworld.net
[12] http://www.powerpaper.com/?categoryId=33405

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Chapter IV – Results

The first person interviewed was Dr. Scott Williams of the Rochester Institute of Technology (RIT) in New York. He has his PhD in chemistry, and has worked for the past 20 years in the field of electrochemistry and batteries. After joining the staff at RIT in 2004 he began to look into the vast possibilities of printed batteries. Within the past year or two he, along with some of his graduate students, have begun doing research and testing with the hope of advancing printed battery technology. Below are some questions that were asked of him for the purpose of this study, and the information he gave in response:

- How do printed batteries differ from conventional batteries, and what are some of their advantages?

  First of all, since printable batteries are printed on paper or plastic film, the battery itself can be flexible along with the substrate. Since all conventional batteries right now have rigid metal containers, a bendable battery will allow for room to grow in a wide variety of products that require some degree of flexibility. Also, since paper batteries are inherently lightweight and require no metal containers, electronic devices that are normally weighed down by bulky batteries can be significantly slimmed down. Another important difference is the "green" factor. Regular batteries are very acidic and quite harmful to the environment, however the printed batteries that are in development are very environmentally friendly given that they are made mostly of paper and don not have as harsh of

chemicals in them. Although printed batteries are not quite as durable as their conventional counterparts at the moment, they can be mass-produced more quickly and for much cheaper.

• How long can these printed batteries hold a charge?

According to many tests, they have the same relative lifespan as a regular canister battery.

• How much voltage can a printed battery produce?

Also about the same as canister batteries, which are generally around 1.5 volts. However these can theoretically be printed contact-to-contact and rolled up for increased voltages, quite similar to how multiple canister batteries are loaded together in larger electronic products.

• What about durability? Can they withstand outside forces such as heat, cold, sunlight, vibrations, pressure, etc?

Testing has shown that excessive pressure and extreme temperatures can change the voltage and have adverse effects on the battery, although they are able to withstand considerable flexing and bending. But for the most part regular canister batteries are probably the more durable of the two.

• What types of materials are used in your research for the cathode? Anode? Electrolyte?

For the cathode a good material is manganese dioxide (MNO_2), while the anode is typically made of zinc. Potassium hydroxide (KOH) or lithium is typically used for the electrolyte. The electrodes also require a separate material, which is commonly made of conductive polymers.

• Which of these components do you find is the hardest to print?

The material for the anode is proving to be the most difficult to manufacture and print. Since it needs to be made of zinc metal, it makes it tough to devise an ink solution of metal particles. In addition to that, the zinc is also problematic in the sense that it easily oxidizes and corrodes. This means that the battery needs to be laminated in order to keep the anode from deteriorating.

• What printing processes could currently be used to manufacture batteries?

Since current ink mixtures for printed batteries use pigments and polymers that are about 100 microns thick, only screen printing or hybrid processes can be used to apply them to substrates because they can lay down such a thick ink film. Although slot coating is technically not a printing process, it may also be a possibility for laying down ink film. These particular ink mixtures are essentially more of a paste than a liquid ink formula, so screen-printing and slot coating are really the only viable processes available right now. It would be most desirable to be able to print using a roll-to-roll flexographic process, however the ink film thickness would have to be significantly smaller, down to about 10 microns to be able to do so. This would still require tipping in electrodes, as is presently being

done with screen processes and printing RFID tags. Printing batteries also requires a lamination for the electrolyte, otherwise it would dry out and stop working. To print a battery using current technology would require a specially rigged press, probably with 4-5 bays for the anode, cathode, electrolyte, tipping in electrodes, and lamination. Right now there is only one or two places in the world doing this, but still have only limited success.

- What are some of the biggest issues/obstacles with making printable batteries?

  The most problematic issue hindering advancement in printed electronics technology is the materials. Even though there are many ideas and potential applications for printed batteries, none of it can really be manufactured or implemented until better ink formulas are designed. As stated earlier, current ink mixtures for battery components result in approximately a 100 micron thick ink film, but they need to be down to about 10 microns to be able to print on a standard roll-to-roll press. Another problem associated with the materials is that of the electrolyte. Most standard alkaline batteries use potassium hydroxide (KOH) for the electrolyte, however this is essentially the same fluid that is used in drain cleaner and is therefore highly corrosive. This will pose problems for the press itself, because a KOH-based ink could cause corrosion and degradation of the press parts, potentially ruining million-dollar pieces of equipment. An alternative could be to use lithium instead since it is not as corrosive, except it is a limited resource and is more expensive. The zinc anode also oxidizes when it comes in contact with air, so the whole battery will still need to be laminated.

Ideally, it would be best to find cheaper materials that have more durable qualities, similar to those used in RFID inks. In addition to ink formulation problems, there are always the press issues associated with printing any type of electronics, such as short-circuiting from printing on multiple layers, ink film thickness, surface uniformity, and registration tolerances.

• To your knowledge, are conventional battery manufacturers investing in this technology?

Duracell is supposedly doing a fair amount of research on printable batteries, but most other battery companies probably are too. Since this technology has the potential to be a huge money-maker, it is likely that many companies are just keeping their testing confidential as trade secrets to protect themselves from others infringing on their profits.

• How long do you think it will be until printed batteries are widely used in a commercial market?

Widespread use of printed electronics and batteries are still quite a ways off. An optimistic estimate would be around five to ten years, but probably longer because it seems like developers are always saying that the technology will be feasible in five years, and when that time comes they are still saying in five more years. Before any of this technology can be available commercially, there needs to be better ink formulas for the battery components to allow them to be printed on current existing presses. When this becomes possible, economies of scale (things

become cheaper when the are mass produced) would likely allow them to be accepted for use in a widespread market.

• How do you think printed batteries might affect the printing industry?

A good guess would be that it will probably have a similar impact to what RFID did for the industry—it gave normal printers a way of employing equipment that they used for standard printing jobs, and turning around to use them to make RFID tags without having to retrofit or make any major alterations to the press. The result was huge profit margins, since they did not have to make any large initial investments in terms of equipment or new processes. If batteries could be made in a similar fashion, the entry barriers could be low enough for many printers to make the switch from printing paper products to printing flexible power sources. In terms of the industry as a whole, it has been on the decline due to the fact that more and more paper products are going digital. The ability to print batteries would allow the industry to move into the manufacturing of goods, and could potentially reinvigorate the industry.

• What are some potential uses you foresee of printed batteries?

It is probably likely that printed batteries will be used to power other printed electronic components for the purposes of advertising and packaging. Presently, small screen-printed batteries are already being implemented in greeting cards to play sounds and songs. There are, however, more significant applications for printed batteries. Electronics that are currently bogged down by heavy battery

packs could be revolutionized by lightweight paper batteries. A good example might be with military radios, where most of their weight comes from the bulky batteries required to power them. On an even larger scale, it could be said that a roll of paper batteries that are printed contact-to-contact for higher voltages may one day replace car batteries. With a roll of paper being much lighter than today's lithium-ion battery packs, electric vehicles will be able to travel much farther and more efficiently. Printed batteries could also play an important role in terms of "green" products, since regular batteries pose a danger to the environment due to its caustic nature. An environmentally friendly printed battery could be used to make disposable products designed for one-time use.

• What do you consider to be the "Holy Grail" of printed batteries?

The most ideal situation would be to have roll-to-roll printing using existing presses and methods, where the entire component—in this case a battery's anode, cathode, electrolyte, and electrodes—are all printed in one continuous line. The same can be said for printed electronic products in general, where the graphics, electronics, and batteries are all produced in one continual process.

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Being that printed electronics will require a battery that also needs to be printed, it was considered beneficial to have the input of someone familiar with these printable electronics. Nancy Cullins, a professor in the Graphic Communications department at Cal Poly San Luis Obispo was the second person interviewed for this study. She is currently

doing her masters thesis on the subject of printed electronics, and was willing to share some of her findings and thoughts on the subject. Below are some of her insights.

Her first topic during the interview regarded the way printed electronics might be used in the coming years. She predicted that it is likely that many printed electronics applications will be used extensively for advertising purposes. Printed screens with video and sound units on point-of-purchase (POP) displays, movie posters, signage, and packaging are just a few examples of ways that printed electronics could be implemented for advertisements. Assuming that printed electronics will one day be able to be produced cheaply and effectively, advertising companies will probably be the first to adapt this technology for public use.

Another topic she went on to discuss was the need for developing environmentally acceptable products. "American consumerism generates an incredible amount of waste," she says, "this makes the concept of implementing truly sustainable printing extremely important. It is quite difficult to change the entire mind set of the American society, so a good place to start is by making the disposable goods they use more green." She emphasized that while some products may be advertised as sustainable, it might not be in the long run if one takes into account all the resources and energy required to manufacture the items and to process or recycle them. This applies directly to printed electronics, especially since there are many steps involved and a lot of different materials used. It is imperative that the electronic products developed in the printing industry are recyclable and environmentally friendly—especially since they are likely to be integrated in disposable packaging and temporary advertisements.

She also made an interesting point of challenging whether or not printable electronics would even be as applicable or necessary in the future. With portable technologies becoming more an essential part of people's lives, a lot of things will become digitized and could make many forms of physical media obsolete. An example could be with advertising. Since people are spending more time on portable devices and the Internet, it makes more sense for companies to advertise on those rather than with paper and external campaigns. Perhaps the development of printed electronics is investing tons of money and research into something that may not be needed in a world that relies less and less on physical media, especially since one of the main uses would be for advertising. Of course there should still be many other applications for printed electronics, however maybe not as much as people are currently anticipating.

When Professor Cullins was asked how printable electronics and batteries might change the printing industry and cause major paradigm shifts, her response was less grandiose than that of Dr. Williams. She explained that although printed electronics may be revolutionary and new, the methods used to produce these products would ideally be identical to the methods used today on regular printed material. It would not be the print industry itself that is changing, it is the customer base and the product produced that will be different. In reality the printer is just a middleman between the customer and the proposed product, and an upgrade in the manufactured product will have the most impact on the customer's market that is implementing the technology. It is very likely that printed electronics will become more of a niche market for the print industry rather than a commonality. Also, she reminded that it is important to keep in mind that printing could be cut out of the process of manufacturing these small flexible electronics. There is a

draw to “printed” electronics because it has the potential to be one of the best ways of making these devices quickly, cheaply, and on a large scale, however if electronics manufacturers develop their own comparative methods of producing these they probably would not want to outsource to printers in an unrelated field. They would probably stick with what they know and trust instead, and could possibly bypass the print industry.

Lastly, Cullins described some of the difficulties of making printed electronics and batteries. Ink film thickness seems to be one of the most important obstacles for printable electronics, because electrical components require very fine lines, yet still must be uniform and even throughout in order to conduct properly. This is remarkably difficult to do on press, especially since ink mixtures are still too thick. She recommended that developers worry about the materials aspect first. Once the inks can be formulated to allow for good printing, the printing process and capabilities will follow.

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Perhaps one of the most promising ways of overcoming the materials issues of printed electronics is through the use of nano-engineering and nanotechnologies. According to an article released by the Stanford News Service, the university is in the process of developing a battery that uses nanomaterials, such as carbon nanotubes, in an ink solution. These are microscopic cylinders only nanometers wide, which can conduct electrical charges. This nanotube-infused ink adheres very well when applied to paper, and is proving to be extremely durable. It can withstand crumpling, and even when soaked in acidic or basic solutions it proves to be unaffected. The researchers at Stanford have also applied the technology to supercapacitors, an important component of circuitry design. Though the paper batteries at Stanford are constructed in a lab by hand, not by a

full-scale printing press, the nanomaterials seem to be manufactured easily and have properties that could very likely be applied to a press one day. One of the researchers, Yi Cui, predicted that his paper batteries might be very significant for devices that require extremely large amounts of power storage, such as solar and wind farms. Also working on the project is Peidong Yang, professor of chemistry at the University of California-Berkeley who was cited in the article as saying, "This technology has potential to be commercialized within a short time…I don't think it will be limited to just energy storage devices. This is potentially a very nice, low-cost, flexible electrode for any electrical device."[13]

Another article entitled "Carbon Nanotubes Turn Office Paper Into Batteries" from the *Scientific American* website also elaborates on the work of Yi Cui and the Stanford team. Here it outlines the fundamental materials they used and the processes they devised for making these paper batteries:

> "Positive and negative electrodes—cathodes and anodes—were applied as slurries dried on the nanotube-impregnated paper. (The cathodes were made from lithium manganese oxide nanorods, and the anodes made either from nanopowders of lithium titanium oxide or nanowires with cores of carbon covered with shells of silicon.) The batteries were then dipped in

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[13] Weaver, J. (2009, December 7). "At Stanford, Nanotubes + Ink + Paper = Instant Battery." Stanford Report, Retrieved on May 1, 2010 from http://news.stanford.edu/news/2009/december7/nanotubes-ink-paper-120709.html

an electrolyte of lithium hexafluorophosphate solution to connect the electrodes and sealed in a pouch. In this setup the nanotubes collected current from each electrode."[14]

The paper also goes on to recognize that Robert Linhardt, a biopolymer scientist from Renesselaer Polytechnic Institute in New York, designed a battery using paper coated with carbon nanotubes as the cathode, lithium film for the anode, and blood or sweat as the electrolyte. With the use of these bionic materials, there are hints that it might be possible for printed batteries to be safely implanted in the human body to power certain medical devices that would normally require bulky external battery packs.

There are, however, a few concerns associated with the carbon nanotube research. The first is that the electrical resistance of the nanotube sheets is about ten times more than that of conventional batteries. Infusing tiny nanowires into the sheets may be a way to fix this problem though, says Cui. The other trouble with using carbon nanotubes is the relatively high price of making them. It is likely that prices may drop as it becomes more popular, and there is the possibility of substituting the carbon nanotubes with cheaper nanomaterials like graphene.

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[14] Choi, C.Q. (2009, December 7). Carbon Nanotubes Turn Office Paper Into Batteries. Scientific American, Retrieved on April 24, 2010 from http://www.scientificamerican.com/article.cfm?id=carbon-nanotubes-turn-off

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Chapter V – Conclusions

Batteries are everywhere in today's society and there's no doubt that a smaller, flexible, and more efficient battery will lead to some amazing new forms of technology. It is remarkable all the applications and ideas that are awaiting the printed battery. Printed power sources have a huge potential for changing common products in need of smaller, lighter batteries, and will play an integral part in the development of printable flexible electronics. This study discovered that some of the applications for it included advertising, disposable packaging, car batteries, and medical devices. For the most part, anything that uses a battery could be enhanced by these printed power storage systems. Right now printed batteries may be somewhat limited by their decreased durability, but they still have many advantages over their rigid counterparts and should prove to be very useful.

Before any of these concepts can be applied there are still many design issues with the technology that need to be resolved. Based on the results from the interviews and articles, it is safe to say that there is still a lot of work that needs to be done before printed batteries can be used on a mass produced scale. This study originally suspected that press issues such as pinholes and uneven surface uniformities would pose some of the biggest limitations with printing batteries, however most of the sources tended to agree that the most imperative obstacle in achieving success is the problems with the materials. Discrepancies in the ink formulation and thickness are the main things holding back

progress in printed battery technology, and although press issues will still remain a problem, it does not make much difference until the materials can be engineered to work on a standard press first. Fortunately, it seems that advancements in nanotechnology and the engineering of carbon nanotubes may be the best option for solving these issues.

It was also expected that printable batteries would have a major impact on the printing industry and cause a significant shift towards the manufacturing of goods with a press, but based on the interviews of Dr. Scott Williams and Professor Nancy Cullins it appears that a printing revolution caused by printed batteries may be somewhat of an overstatement. The ability to print power sources will no doubt have many positive effects on the industry, just not as drastic as previously noted. The methods used for printing may remain the same and printing batteries and electronics will probably become more of a new, but niche, market for specialized printers. Nonetheless, many people in the industry are looking forward to these products and are supportive of the effect it will have on the printing market. Though there are barriers that are making the development of these batteries difficult, it is likely that many people could see these become a common product well within their lifetimes. The prospects of printable batteries are very interesting and exciting and will surely revolutionize many products once the materials and printing issues are resolved. Only time will reveal the full impact and potential for this wonderful technology.

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