Table of Contents

Volume XXXVII, Number 2, Fall 2011

Printing Processes Used to Manufacture Photovoltaic Solar Cells

Tina E. Rardin and Renmei Xu

Abstract

There is a growing need for renewable energy sources, and solar power is a good option in many instances. Photovoltaic solar panels are now being manufactured via various methods, and different printing processes are being incorporated into the manufacturing process. Screen printing has been used most prevalently in the printing process to make solar cells, but some companies have used the offset web press type methods to put material onto foil; they also have created solar cells with inkjet printing. The printing of solar cells has helped to reduce manufacturing costs in most cases, and it also has increased the various applications in which solar power both is and can be used. Many more options for photovoltaic solar panels are available, and not simply the traditional ones that are often placed on rooftops. Such a variety of solar panels are partially to the result of the implementation of suitable printing processes during the production of these cells.

Introduction

With ever-increasing political and economic oil conflicts as well as climate change, a growing need for renewable energy that comes from natural resources, such as sunlight, wind, rain, tides, and geothermal heat, is warranted. Wars have been caused in part to protect oil supplies, and millions of tons of pollutants and greenhouse gases are emitted into the atmosphere every year due to the burning of fossil fuels to create energy. There is no other area of technology than renewable energy technologies that can both "meet the challenges of climate change and secure an energy supply in an intelligent manner" (Wengenmayr & Bührke, 2008, p. 1). A number of options for new technologies of renewable energy exist, that is, from geothermal to wind to hydrogen fuel cells to hydropower; however, one of the most accessible and widely used technologies is solar energy. Solar power does not create any noise when it is working, "is non-polluting, does not generate greenhouse gases, and creates no waste products," (Brenner, 2010, p. 27), which is also why it is an increasingly preferred renewable energy. Additionally, the potential for solar power is immense. The energy from the sunlight that strikes the earth for only forty minutes is equal to the global energy consumption for an entire year (Zweibel, Mason, & Vasilis, 2008). All of that energy is of no use, unless it can be captured. A good method to harness this immense amount of energy and thus to eventually use it as electricity is through the use of photovoltaic (PV) energy systems.

Photovoltaic Power

According to the U.S. Department of Energy (2010, p. 1), "the diversity, adaptability, and modularity of PV technology make it distinct from other renewable resources." Solar photovoltaic power is extremely useful because it can be produced in a number of ways from a variety of materials, and it can be used for numerous applications. Photovoltaic cells can be used for anything (e.g., from a small strip that powers a simple calculator to personal panels on homes to larger commercial settings and solar farms spread out over vast areas of land). Photovoltaic modules are also useful since they have minimal maintenance costs and are extremely long lasting; some manufacturers offer up to 25-year warrantees (Brenner, 2010). In 2008, photovoltaic systems were the largest producer of electricity directly from solar energy in the world, in terms of kWh produced per year (Vanek & Albright, 2008).

The photovoltaic or PV cell is a type of technology that uses semiconducting materials to convert the energy in sunlight into usable electricity. Derived from Greek, the term *photovoltaic* can be translated as "electrical energy from light" (Wengenmayr & Bührke, 2008, p. 42). The cells transfer the energy of the photons penetrating the solar panels to electrons that are "channeled into an external circuit for powering an electrical load" (Vanek & Albright, 2008, p. 249). A PV panel is made up of multiple photovoltaic cells, anywhere from 50 to 120, which are connected together in an electrical circuit that can then be connected to an exterior circuit at a single point. An entire PV system often is comprised of a number of panels, so that a greater, more desirable amount of voltage is produced. These PV cells take on many forms and are produced in a number of different ways, often including various printing processes.

Printing Solar Cells

In order to make the use of solar power a likely alternative to fossil fuels, it needs to be economically comparable to conventional energy sources like coal, natural gas, and oil. This matter of cost is the largest issue facing the success of photovoltaic solar panel use. Efficiency of solar cells is the percentage that they are efficient at "converting the radiation from the sun into electricity for the area of the active part of the module" (Brenner, 2010, p. 29). Efficiency is possibly the most important factor when determining the overall use and quality of a solar cell, and it can play a large role in reducing overall costs. The two main strategies to reduce the cost of power production in photovoltaic devices are to increase efficiency and to lower production costs of the starting materials (Wengenmayr & Bührke, 2008). Implementing different printing processes throughout certain steps of manufacturing has recently helped to accomplish both efficiency and lower costs. Certain printing processes like screen printing, inkjet printing, and even web press offset printing lend themselves to being just what is needed to make various types of solar cells. These processes are becoming a large part of solar-cell manufacturing for different kinds of photovoltaic solar energy, each with its own benefits and drawbacks. It is important to understand the different types of solar cells and materials that are used to make them in order to understand where these printing processes can fit in.

Traditional PV Material

Conventional solar cells are made from silicon, are flat plated and rigid, and generally have the highest efficiencies. Crystalline silicon (c-Si) is the most widely used and most efficient material expended in the production of photovoltaic solar cells, with commercial efficiencies sometimes reaching 20%. It is estimated that about 80% of all photovoltaic solar panels are created with crystalline silicon, and this material is especially useful because it has shown both long-term performance and reliability (Applied Materials, 2010). Crystalline silicon cells are made from silicon wafers that can be either mono-crystalline or multi-crystalline structures, depending on what is available or what is needed for that particular process. All structures using pure silicon will face shortages, especially since the material is used in other semiconductor industries as well as in solar PV. Silicon is a plentiful element in the earth's crust, but most of it occurs in compounds that would be costly to extract the pure silicon from them (Vanek & Albright, 2008). Crystalline silicon has been the go-to material to make efficient solar panels; however, because of shortages and the general high costs of silicon, other options have been developed with other materials or smaller amounts of silicon.

Thin Film PV Materials

Thin film solar cells offer the best option in terms of producing solar cells. Thin film solar cells require less semiconductor material, so material costs are substantially reduced (Zoomer, 2010). The versatility of applications with thin film could also vastly increase the use of solar power. While numerous different materials have been used for thin film, the most widely used at present are amorphous silicon, organic polymers, and a combination of conductive metals including compounds of copper, indium, diselenide, and sometimes gallium.

In terms of the more conventional materials, amorphous silicon (a-Si) can be mass produced more easily than crystalline silicon, and it can be very thin, even to the point of being flexible, so much smaller amounts are required (Vanek & Albright, 2008). Since the atoms are not arranged in any particular order, like in a crystalline structure, there is more flexibility with what can be made with amorphous silicon. The material is full of defects naturally so impurities are not a problem, and it can be applied uniformly over very large surfaces, making it more usable than crystalline silicon. Amorphous silicon does not have the same quality of electrical properties as crystalline silicon, but the gap has been closed in recent years (Amorphous Semiconductors Research Group, 2010).

Several combinations of conductive and semiconductive metals and compounds can be used to create solar cells, but the most acclaimed and most common seems to be one consisting of copper indium diselenide, also known as CIS (Goetzberger, Knobloch, & Voss, 1998). As early as 1978, high efficiencies without degradation were observed, which made this a very important material in the thin film solar industry. Recently, a similar but even more productive combination of copper, indium, selenium, and gallium, also known as CIGS, has been used (Inslee & Hendricks, 2008). These materials help to make the mass production of solar cells more of a reality, and since CIGS can potentially have similar efficiencies to traditional cells, about 19.5% (Contreras, et al., 2005), this is one of the most promising new PV technologies.

A company called Konarka Technologies has developed thin film solar PV cells from organic polymers in the form of "Power Plastic." These organic photovoltaics are a third-generation type of solar power that uses a photo-reactive polymer that can be combined with several other very thin layers to be used in a number of products. The Power Plastic can be printed on large rolls of flexible substrates, is made from recyclable materials, and converts light to energy both outdoors from the sun and indoors from a light bulb (Konarka Technologies, 2010). Another application of organic polymers is seen when it is used as a dye that is a combination of nanoparticles that convert light to electricity (Fraunhofer-Gesellschaft, 2008). Both of these applications of organic polymers immensely help reduce the cost of manufacturing solar cells, but they are not as efficient as silicon-based cells, and the longevity is not known of these new cells.

Screen Printing

The basic principle of the process of screen printing is simply the use of a stencil to reproduce the same image over and over again. This is currently conventionally done with the use of a mesh screen coated with light-sensitive emulsion that is then exposed to light with the desired positive image blocked, and then washed out to create the mesh stencil. There are other ways to make the stencil, but the use of photographic emulsion is most common. Ink is then applied to the screen and pushed through with a squeegee to transfer the ink on the open image area to the desired substrate. This process can be repeated as many times as the screen materials will last. Screen printing is one of the most versatile printing processes because almost anything from glass to paper to fabric to plastic can be printed on, and a very thick amount of ink can be laid down, unlike in other printing processes. A number of factors should be considered when screen printing is used, depending on the type of materials and images that are being printed. Factors including mesh count, screen angle, emulsion-on-mesh thickness, stencil surface smoothness, ink type, how detailed the image is, how many impressions the screen can last, and squeegee pressure can all affect the overall quality of the product that is being printed. This screen-printing process has been used as part of the process to make conventional silicon solar cells due to its versatile nature.

According to Peter Brenner (2010), global marketing manager of photovoltaics for DuPont Microcircuit Materials, "Screen printing photovoltaic cells is the most reliable method and fastest growing application in industrial printing" (p. 26). Screen printing is also the most commonly and conventionally used printing process throughout the manufacture of photovoltaic solar cells. In fact, over 90% of all crystalline silicon modules are manufactured using screen printing, and about 60% of flexible thin film modules use screen printing in the manufacturing process (Brenner, 2010).

The way that screen printing is used in the process of making solar cells is that PV solar cells are often metalized through a screen-printing process. This is the application of three different types of metallization pastes onto the c-Si cell. The first paste is the front-side silver used on the side facing the sun; it makes up the collector gridlines and the silver bus bars, and the second is the rear-side tabbing silver or silver-aluminum, and the third is the rear-side aluminum paste that actually reacts with the silicon to create the back surface field (Brenner, 2010). The screen-printing process is especially useful in applying these pastes since consistency in each application as well as the ability to lay down different thicknesses for the different types of pastes are both very important. However, according to Brenner (2010), similar to screen printing any object, a number of variables involved in screen-printing photovoltaics must be monitored: ink composition (solid content, viscosity, rheology, evaporation rate, dispersion), press setup (squeegee durometer and shape, attack angle, squeegee pressure, print speed, snap off, registration control), screen/stencil (mesh count, wire diameter, percent of open area, emulsion thickness, mesh tension), and the environment (room temperature, humidity, air turbulence, cleanliness, substrate surface, shelf life of ink and screens). Each of these variables is generally something that should be considered in any type of screen printing, but it is especially important with printing PV modules due to the nature of the materials and the accuracy that is needed.

Another way that screen printing is utilized in the manufacture of solar panels is through the use of organic dye, a combination of nanoparticles, which serves as a semiconductor to convert sunlight to energy. The versatility of this dye allows for different colors and designs to be printed, making this an excellent option to be integrated into the façade of a building or to serve as a decorative element. These panels could be integrated into windows and not only convert sunlight to electricity but also serve as a sunshade to the interior of the building, saving additional energy. Even though screen-printing this dye onto glass makes it an excellent choice for building integration, the cells only have an efficiency of about 4%, so they are not yet competitive with conventional silicon panels. The longevity of this technology is yet to be determined, though it did seem to perform well in initial tests (Fraunhofer-Gesellschaft, 2008). Even with these drawbacks, this organic dye could be a very popular choice by consumers due to its more aesthetically pleasing qualities and consumers' options to have whatever design or color they desire.

Inkjet Printing

Inkjet printing is one of the newest and most experimental methods used to make solar cells, and it could potentially have a very big role in making solar panels accessible to everyone. The most common type of personal computer printers use inkjet technology, and it is also used widely in industrial applications such as the production of numerous microscopic items, the formation of conductive traces for circuits, and the manufacture of color filters in LCD and plasma displays (Clark, 2008). Inkjet printing is a non-impact printing that uses a number of nozzles to spray ink droplets directly onto the paper or substrate without touching it (Tyson, 2010). This basic principle makes inkjet printing very useful in that not only can it spray onto a number of different surfaces, but also it can spray onto a number of materials. It is not simply conventional printing ink that can be sprayed. Inkjet printing recently has been used in the production of both flexible thin film solar cells as well as more conventional rigid silicon cells.

Using inkjet printing to apply semiconductive material onto flexible substrates that could result in the formation of a thin film PV solar cell has the potential to become available to any person who has an inkjet printer. While this is not the case yet, many places are using inkjet printing to reduce manufacturing costs and trying to increase efficiencies of thin film solar cells. Konarka Technologies is using inkjet printing as part of the production process of their Power Plastic thin film solar cells, which are made of organic polymers. This material has been in production and development for a few years, and in 2008, inkjet printing was used, making the process much cheaper than it previously had been (Masamitsu, 2008). This paper-thin plastic has infinite possibilities and can be applied to any flexible surface such as tents, umbrellas, and handbags, but there are a few drawbacks. The efficiency of this inkjet printed material is only 3-5%, so to get anywhere near the amount of energy a conventional silicon solar cell can get, there would need to be a very large area available to lay down this Power Plastic. These cells also only last about a couple of years, as opposed to decades that conventional cells last (Bullis, 2008). These drawbacks currently limit the use of the product, but the benefits are still very great since potentially anyone could print these cells. That may be a few years away, but the versatility and massive amount of places this plastic could be used are not to be taken lightly. Inkjet printing has played an important role in helping to make this happen.

Inkjet printing is also now being used in place of screen printing to make electrical connections during the process of making more conventional crystalline silicon solar modules. The inkjet method can be more precise than previous methods, and since the print heads do not make contact with the silicon, a thinner, more fragile piece can be used. Conventional screen printing methods need to use silicon wafers that are at least 200 micrometers thick because any thinner wafer will likely break. It is estimated that 100 micrometers of silicon can be used with this inkjet process, and since silicon can account for 75% of the total cost of materials and production, this could greatly reduce overall costs (Bullis, 2009). The silver gridlines can be printed with inkjet printing and the ink used is more conductive than the silver paste in screen printing. Maikel van Hest, a scientist at the National Renewable Energy Laboratory, noted more precise lines of 35 to 40 micrometers wide, compared with 100 to 125 micrometers wide with screen printing can also be printed (Bullis, 2009). This ultimately means that not as much silver will need to be used, saving additional money and resources. The thinner lines also can block less of the solar collecting material, so that the sun's radiation can hit more of the surfaces that are actually collecting it, as opposed to bouncing off because of the thicker silver lines. These thinner lines make the cells more efficient, although at the moment the amount of increased efficiency is unknown.

No matter what application inkjet printing is being used in, the process is proving to be a very important part of making photovoltaic solar cells more economical and more accessible. While currently it is only used in mass production, the potential of being able to print on a personal printer is definitely a considerable advantage that this process has over any of the others. Not only is inkjet printing improving already-developed PV manufacturing processes, but it is also a key component to an entirely new type of thin film that could be used for any number of purposes. Inkjet printing is helping to reduce costs of manufacturing and increase the efficiency and availability of solar cells, which are currently vital goals of the photovoltaic solar industry.

Web Printing

Though not exactly using the principle of offset lithographic printing, there are companies using web press applications to coat semiconducting materials onto flexible substrates. The substrates that are currently being used are plastics and metal foils. Offset printing is a type of planography, because the plates used during printing are completely flat. The principle of offset lithography is that the oil-based ink only sticks to the hydrophobic image area on the plate, which is transferred to a blanket, and then transferred onto the substrate. Web offset printing is a continuous process that prints on rolls of substrates, though it is still an indirect process due to the nature of offset lithographic printing. Newspapers, for instance, are often printed by an offset web press and then cut down into the necessary sheets. With the manufacture of solar cells, certain principles of web offset printing are applied, and they are shown to greatly decrease costs and increase production capabilities.

Nanosolar is a company that prints the semiconductive compound of copper, indium, gallium, and selenium (CIGS) onto thin foil. The company uses a web press application and "can produce a hundred feet of continuously rolled solar cell per minute" (Inslee & Hendricks, 2008, p. 72). Their nanoparticle ink mixture, consisting of CIGS and the necessary components for proper dispersion, is coated onto "a specially-prepared proprietary alloy of metal foil using high-throughput coating/printing techniques" (Nanosolar, 2010, paragraph 4). This method of printing has replaced the conventional process of high-vacuum deposition, which is much more time consuming. Nanosolar has taken the economics and processes of printing and applied them to the formation of solar cells and seems to have done so very successfully. Their process should make this type of solar cell electricity as cheap as the current electricity taken off the grid (Inslee & Hendricks, 2008). The National Renewable Energies Laboratory certifies that their solar cells have up to a 15.3% efficiency (Nanosolar Communications, 2009), which is comparable to conventional crystalline silicon cells. The product itself is also thin and flexible, which could be useful in a number of applications. Nanosolar's thin film cells are much more economical than traditional silicon cells, and they can be mass-produced very quickly thanks to the use of a printing process.

Konarka's Power Plastic uses not only inkjet printing but also a web press application in some instances. They use a type of coating process that is continuously rolled to get the right substrate combination of usable photographic film and organic polymers (Bullis, 2008). Though not exactly a printing process, this application is most definitely inspired by traditional web printing, and this is an important part of the process of the manufacture of Power Plastic.

Web press applications are fairly new to the photovoltaic solar cell industry, but they are playing a very important role in the ability of this industry to use mass-production processes. This ultimately makes the cells more economical, and in the case of Nanosolar, the cells are fairly comparable in efficiency. The use of web printing is definitely a help for the solar-cell industry

Conclusions

In these times of uncertain energy sources and with the impacts that they are having on the atmosphere, clean, renewable solar energy is a good alternative. However, it is still more expensive than methods used currently by consumers, and in order to be a viable option, it has to be attainable and affordable. With the use of different materials and thin film technologies, the use of photovoltaic solar energy for the average person is becoming more of a reality.

Printing processes have helped the photovoltaic solar industry by providing useful solutions to decrease manufacturing costs and increase the availability of these technologies to consumers. Screen printing has been used for years as a good option for metallization when producing traditional crystalline silicon solar cells, and it has more recently been used as the means of applying organic semiconducting dye to make photovoltaic solar cells. Inkjet printing is useful in the production of solar cells as both a new replacement for the screen-printing metallization and in the manufacturing of thin film solar cells. Even web offset printing has inspired some of the processes used to make thin film solar cells, and it is a very effective way to mass-produce these cells quickly. Each of these processes has helped to make solar cells more affordable and attainable.

Thin film solar cells would not be as widely produced and researched if it were not for the printing processes that helped make them as useful as they currently have become. Conventional crystalline silicon solar cells are efficient and have great longevity, but they cannot be used everywhere since they are rigid; they also are very expensive and resource intensive to produce. Thin film seems to be the direction that the people who make solar cells are heading, and if they can get equal efficiencies then there is no reason why these cells should not be used as replacements for conventional energy methods. Thin film cells also can be used on roofs, but they can also be placed just about anywhere and are more aesthetically pleasing, which would make them more marketable than conventional solar panels. There are a number of new developments in the photovoltaic solar industry, and with the help of processes inspired by the printing industry, this industry will continue to develop, and eventually PV cells will be a highly sought-after energy source.

Tina Rardin is currently a Production Coordinator at Pratt Corporation in Indianapolis, Indiana.

Dr. Renmei Xu is an Assistant Professor in the Department of Technology at Ball State University, Muncie, IN.

References

Amorphous Semiconductors Research Group (2010). Amorphous silicon. Retrieved from http://www.ayil.hacettepe.edu.tr/pages/Amorphous/Amorphous%20silicon.html

Applied Materials (2010). The world's most efficient solar cells. Retrieved from http://www.applied-materials.com/technologies/solar/crystalline-silicon

Brenner, P. (2010). Printing photovoltaics. Industrial + Specialty Printing, 1(01), 26-33.

Bullis, K. (2008). Mass production of plastic solar cells. Technology Review. Retrieved from http://www.technologyreview.com/energy/21574/page1/

Bullis, K. (2009). Ink-jet printing for cheaper solar cells. Technology Review. Retrieved from http://www.technologyreview.com/energy/22599/page2/

Clark, E. (2008). Solar cells created with inkjet technology. Gizmag. Retrieved from http://www.gizmag.com/solar-cells-created-with-inkjet-technology/9094/

Contreras, M. A., Ramanathan, K., Abushama, J., Hasoon, F., Young, D. L., Egaas, B., & Noufi, R. (2005). Diode characteristics of state-of-the-art ZnO/CdS/Cu(In1-xGax)Se2 solar cells. Progress in Photovoltaics: Research and Applications, 13: 209.

Fraunhofer-Gesellschaft (2008, January 31). Screen-printed solar cells in many colors and designs, even used in windows. ScienceDaily. Retrieved from http://www.sciencedaily.com/releases/2008/01/080130194130.htm

Goetzberger, A., Knobloch, J., & Voss, B. (1998). Crystalline silicon solar cells. Weinheim: Wiley.

Inslee, J., & Hendricks, B. (2008). Apollo's fire: Igniting America's clean energy economy. Washington: Island Press.

Konarka Technologies (2010). Konarka's paradigm-shifting technology. Retrieved from http://www.konarka.com/index.php/technology/our-technology/

Masamitsu, E. (2008). Startup makes cheap solar film cells . . . with an inkjet printer. Popular Mechanics. Retrieved from http://www.popularmechanics.com/science/energy/solar-wind/4253464

Nanosolar (2010). Production process. Retrieved from http://www.nanosolar.com/technology/production-process

Nanosolar Communications (2009, January 9). NREL certifies 15.3% Nanosolar foil efficiency. Retrieved from http://www.nanosolar.com/company/blog#68

Tyson, J. (2010). How inkjet printers work. Retrieved from http://computer.howstuffworks.com/inkjet-printer.htm

U.S. Department of Energy (2010). Photovoltaics. Retrieved from www.eere.energy.gov/solar/pdfs/43684.pdf

Vanek, F. M., & Albright, L. D. (2008). Energy systems engineering: Evaluation & implementation. New York: McGraw Hill.

Wengenmayr, R., & Bührke, T. (Eds.) (2008). Renewable energy: Sustainable energy concepts for the future. Weinheim: Wiley-VCH.

Zoomer, W. (2010). Contemporary thin-film solar cells. Industrial + Specialty Printing, 1(03), 18-21.

Zweibel, K., Mason, J., & Vasilis, F. (2008, January). Solar grand plan. Scientific American. 64-73.

Sustainable Design: An Educational Imperative

David Klein and Ken Phillips

Abstract

This contribution presents a curriculum model and pedagogy for teaching sustainability concepts to industrial design students at the Metropolitan State College of Denver (MSCD). The curriculum provides students with instruction about low-impact material and process selection (renewable, toxic, embodied energy); energy efficiency (transportation, processing, use of product); quality and durability; design for reuse/recycling; and social relevancy/value, consumer value, responsible production/procurement (fair labor). Although the authors are aware of the interrelationship of these categories, they isolated each one to make them easier to teach, explain, and assess.

In our industrial design studio courses, sustainability and product life cycle assessment are established as design parameters for all projects throughout the curriculum. Sustainable principles are internalized as students devise practical design solutions. This pedagogy enables students to practice sustainability in relation to product design as they conduct product feasibility studies, design development, and production planning.

This article aims to advance design education by serving as an example of how sustainability may be taught and integrated into a curriculum and by providing case studies of completed student design projects.

Introduction

Design is concerned with the development of products, tools, machines, artifacts, and other devices produced on a massive scale, resulting in a profound and direct influence on ecology (Papanek, 2003). When design students are made aware of the context in which products are manufactured, they are more likely to consider barriers to sustainability outside of their usual parameters; increasingly resource-hungry technology, a culture that focuses on the short term, and pervasive advertising and marketing efforts aimed at increasing consumption. According to Orr (1994), “the truth is that without significant precautions, education can equip people merely to be more effective vandals of the Earth” (p. 5).

The traditional definition of sustainability calls for policies and strategies that meet society’s present needs without compromising the ability of future generations to meet their own needs. Industrial designers make their living developing designs that meet the needs of the present, but are not always bound to consider future generations. They are integral components of a manufacturing system that maintains product flow, and they make decisions concerning the production processes and materials that, in turn, have the most impact on whether or not a product is sustainable. It is particularly important that industrial designers be aware of—or even be—champions for sustainable practices. Principles of sustainability can stimulate technological innovation, advance competitiveness, and improve quality of life. Sustainable development reflects not only the trade-off between business and the environment but also the synergy between them.
A responsible design educational program should help students realize that environmental protection does not preclude economic development and economic development must be ecologically viable now and in the long run.

True sustainability involves a wider range of issues than the design, manufacture, and disposal of industrially produced products. The numerous factors that contribute to a culture of consumption and consumerism beg to be considered, “ . . . the urge to consume is merely symptomatic of a stimulus-hungry species dwelling in a homogenized and over-streamlined world where the prevailing mode of existence comes with the majority of problems already solved” (Chapman, 2005, p. 29). Designs embedded with meaning, those that stimulate consumers on a multitude of levels (functional, emotional, status reinforcement, etc.), are less likely to be victims of product replacement (Chapman, 2005). Notable exceptions to this concept are "technology" objects, like computers, whose existence relies on software and microchips that apparently require an update every two years, according to some.
Our Industrial Design program has developed a curriculum that addresses the following categories of sustainability concepts, listed in

no particular order of relevance.

1. Low-impact, renewable, nontoxic material selection, minimal embodied energy requirements

2. Efficiency in transportation, consumer use, and manufacturing of products

3. Life cycle assessment

4. Product design that considers reuse/ recycle

5. Social relevancy of concept/product.

This article presents the pedagogy and curriculum utilized in teaching these sustainability concepts to industrial design students at MSCD.

Sustainability Issues and Industrial Design

The sum total effect of factors contributing to ecological impact of a product, or a society, may be cumulatively referred to as the "ecological footprint" that is "occupied." Plato may have been the first to acknowledge an ecological footprint when he realized that adequate human support cannot be fixed without consideration of the land and surrounding resources. Modern ecological footprint analysis is an accounting tool that enables us to estimate the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area (Wackernagel & Rees, 1996).

It is especially important to recognize that economic and ecologic sustainability go hand in hand. There may, in fact, be capitalist motivations that spearhead efforts toward true long-term sustainability. Smart entrepreneurs, movers, and shakers invest their time and capital in endeavors that offer economic growth and prosperity, and long-term commercial success relies on acceptable environmental performance. Excessive resource depletion and pollution are disruptive and costly, and it can call into question the social responsibility of a company (Mackenzie, 1997). People are accustomed to thinking of industry and the environment as being at odds, because conventional methods of extraction, manufacture, and disposal have historically been destructive to the natural world. It is a condition that complicates efforts to achieve sustainability. "As natural as drawing breath, the urge to consume is merely symptomatic of a stimulus-hungry species dwelling in a homogenized world where the prevailing mode of existence comes with the majority of problems already solved" (Chapman, 2005, p. 29). But our environment is saturated with messages and images to remind us that we, indeed, need more. Studies have shown that the more people look outside of themselves as a way of satisfying needs (affluenza, peer approval, etc.), the less likely they are to have their actual needs met (Thorpe, 2007).
The "environmental crisis" is perhaps less an environmental and technical problem than it is a behavioral and social one (Wackernagel & Rees, 1996). But there is a need for playfulness and desire in our lives which consumer-led design helps to meet. It is the extent to which these products have become dominant that is troublesome. Papanek (1973) held that “in an age of mass-production when everything must be planned and designed, design has become the most powerful tool with which man shapes his tools and environment (and by extension, society and himself)” (p. 14).

Higher education has largely been shaped by the drive to extend human domination, to "manage" planet Earth to its fullest. Design competence requires the integration of first-hand experience and practical competence with theoretical knowledge (Orr, 1994).
Our leaders and technologists have been educated in a system that emphasizes theories instead of values, concepts rather then human beings, abstraction rather then consciousness, answers instead of questions, efficiency rather than conscience. This points to the fact that education itself is no guarantee of decency or wisdom. "It is not education, but that of a certain kind that will save us" (Orr, 1994, p. 8).
Designers have not been taught in consideration of the larger social context and ecological impact, so they assume that their area of responsibility is limited to functional and aesthetic experiences (Mackenzie, 1997).
The value of contributing to positive social change emphasized by Papanek (2003) and others has more recently been downplayed in favor of form giving and branding. “The action of the profession has been comparable to what would happen if all medical doctors were to forsake general practice and surgery and concentrate exclusively on plastic surgery and cosmetics” (Whiteley, 1993, p. 99). In the end

"the most important ability that a designer can bring to their work is the ability to recognize, isolate, define and solve problems" (Papanek, 1973, p. 160).

Design approaches that embrace the natural world are perhaps more inherently sustainable. The branch of industrial design known as biomimicry begins with an examination of natural systems, particularly the many biomechanical characteristics found in nature. The rationale for this approach is the ideas that appropriate solutions for a given natural life form may provide inspiration for "natural" solutions to man-made problems (Birkeland, 2002). It also reinforces respect for nature and serves as a reminder that we are "of " nature, and not simply existing within it. Biomimics explore what works, and what lasts, in the natural world.

Figures 1 and 2.

The more our world looks and functions like the natural world, the more likely we are to exist in harmony (Benyus, 2002). Natural forms and patterns famously inspired design styles like Art Nouveau, but there is more to learn by studying the deeper underlying principles found in nature. Examples of biomechanical principles applied to product design include pliers based on the mechanics of the human jaw, Velcro based on the Burdock plant cockleburs, ball-and-socket joints based on the human hip joint, tensile fibers inspired by spiderwebs, and a drinking fountain that mimics a leaf form (Klein, 2010, Figs. 1 & 2). Designers can benefit in many ways by being students of the natural world.

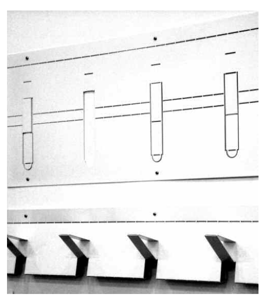
Case Studies

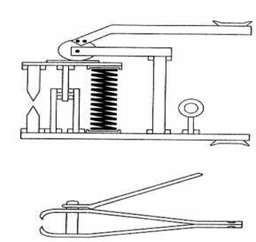
Designs that show particular sensitivity to each category of sustainability in our curriculum may provide further understanding of the underlying principles.

Wood-based materials utilized for extruded shapes (Guidot, 2006, p. 123, Fig. 3) are a

Figures 3, 4 and 5. *(clockwise from left)*

renewable material alternative to plastic and metal, while specifying aluminum alloys with low melting points (Rocky Mounts bike rack, photo by David Klein, 2010, Fig. 4. Reproduced with permission) reduces manufacturing energy in comparison to other metals. Using recycled aluminum reduces energy required in the bauxite mining process, although it also presents its own energy requirements. Industrial Designer Ali Tayar designed a chair that relies on a single extruded shape, placed in different positions in order to reduce the manufacturing and energy costs associated with multiple tooling dies (Terragni, 2002, p. 357, Fig. 5).





Figures 6–9. *(clockwise from left)*

Flat-pack designs conserve shipping space for improved efficiency in transportation. They often result in less material waste if cut shapes can be nestled (Coat rack by Blu Dot, www.bludot.com, Fig. 6. Reprinted with permission). The most effective steps toward efficient manufacturing are simplification of the design and reduction in the number of required components (Bralla, 1999). This idea is illustrated in a nail clipper design comparison by Professor Karl Ulrich, of the Wharton School (Bralla, 1999, p. 7.9, Fig. 7. Reprinted with permission). The recognizable design on the bottom is improved in respect to efficiency, functionality, and aesthetics.

The Heat Wave electric radiator for Droog by Joris Laarman, (Photographer: Robaard/Theuwkens, Styling by Marjo Kranenborg, CMK, Fig. 8. Reprinted with permission) offers increased surface for airflow opportunity so that more heat is obtained with less energy than the traditional design (public domain, Fig. 9). A more interesting aesthetic is also achieved, and less floor space is required.

Life cycle assessment of plastic cutlery reveals a life span that far exceeds functional requirements. Cutlery made from plant starch (www.ecoproducts.com, Fig. 10. Reprinted with permission) or semolina flour material (Designer unknown, Fig. 11) offers a sustainable alternative to petroleum-based plastic utensils and will decay in landfills more rapidly.

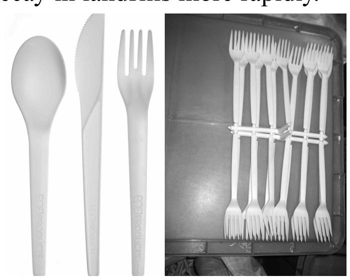


Figure 10.

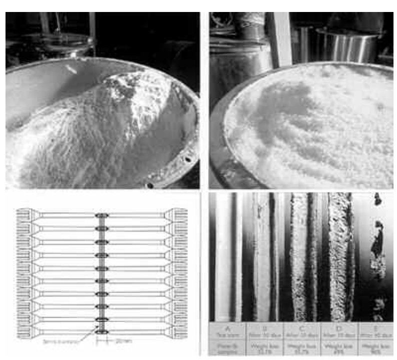


Figure 11.

The Heineken WOBO (short for WOrld BOttle) bottle never made it to the consumer market (Terragni, 2002, p. 418, Fig. 12). The concept of this bottle considered product reuse as a building "brick." The bottles were designed to fit modularly, with dimples on the flat surfaces to grip mortar.

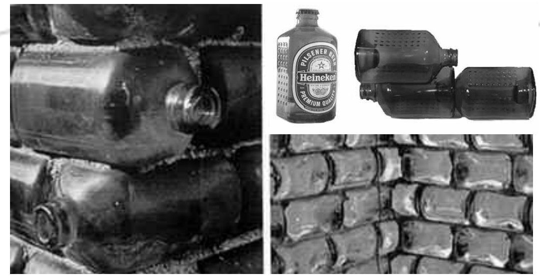


Figure 12.

The Hanger design offers an opportunity to reuse plastic bottles (Design by Xuan Yu , for the RE-think + Re-cycle competition at www.designboom.com, Fig. 13. Reprinted with permission). Even though such designs may not win wide public acceptance initially, it is more important that they provide inspiration for future designs that will.

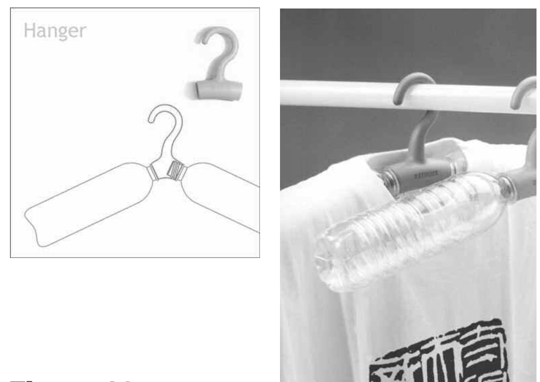


Figure 13.

The Mirra chair, produced by Herman Miller, represents an admirable model of sustainably produced furniture. The production line uses 100% green power (50% wind turbines, 50% captured off-gassing from landfills), and 96% of Mirra's content is specifically designed for recycle or reuse. The exceptions follow (courtesy of Herman Miller Inc., Fig. 14. Reprinted with permission).

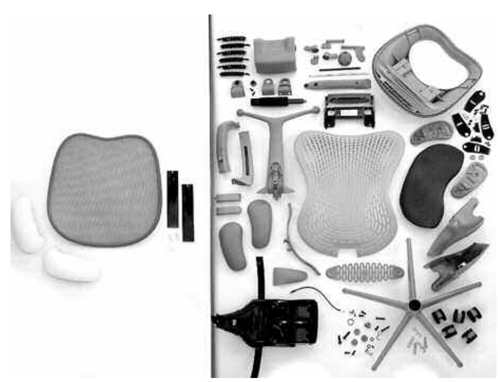


Figure 14.

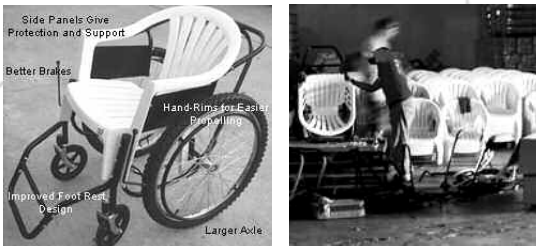


Figure 15.

The $50 wheelchair (actually $51.29) was designed by mechanical engineer Don Schoendorfer in 1999 and is distributed by his Free Wheelchair Mission (www.freewheelchairmission.org, Fig. 15). It utilizes many existing components in order to minimize tooling costs, and it helps to sustain the livelihood of people who otherwise would literally have to crawl from place to place.

The Tree bookshelf designed by Shawn Koh (www.designartist.co.kr, Fig. 16) reinforces the relationship between trees and books (paper comes from trees), encourages diverse reading through the use of diverse "shelf' shapes," and inspires by making it fun to interact with books. Each of these designs illustrates social relevancy that can be achieved in designed, manufactured products.

Pedagogy at MSCD

Figure 16.

Sustainability and product life cycle assessment are among the design parameters for studio design projects. The principles are internalized as students devise practical design solutions that draw from myriad sources. This pedagogy requires students to consider and employ sustainability concurrently with product design/development, as opposed to a curriculum in which sustainability is taught isolated, in lecture courses. But we do offer specific information in an instructional format to facilitate students developing a background in the application of sustainability principles. These techniques include lectures and presentations about contemporary and historical models of sustainable design thinking; the use of required readings in the content area; discussions; workshops and presentations by outside experts; and the application of this information.

The goal of this instructional program is to enable students to make informed design decisions regarding sustainability issues for their product designs. In addition to this comprehensive goal, the department faculty has developed specific learning objectives. Upon completion of the Industrial Design program, major students should be able to:

1. Recall, discuss, and apply information about low-impact materials—renewable materials, awareness of material toxicity, and the relative embodied energy of materials.

2. Evaluate and choose design solutions that provide increased energy efficiency in transportation, consumer use of products, and manufacturing processes.

3. Identify and discuss components of life cycle assessment techniques and select design solutions for maximal product quality and durability.

4. Design products that facilitate their reuse or recycling at the end of their lifecycle.

5. Select product designs, materials, and processes that have a positive social impact.

Assessment is an important element of any instructional program. The evaluation of students in regards to the objectives listed above occurs in several ways. There is an embedded component in the evaluation/critique of student designs by faculty and professionals that occurs in studio classes. Sustainability concepts tied to the instructional materials are part of the overall assessment of student designs. There are embedded elements of assessment for these objectives in quizzes and tests for some courses where the specific instruction occurs, and an overarching component to the assessment of these objectives. The capstone design studio course and the senior internship are evaluated for a number of student performance categories reflecting sustainability objectives and overall learning objectives for students so they will be able to perform the practice of industrial design. This assessment is administered both by faculty and practicing professionals, and it provides key data for the ongoing evaluation of the program. These results direct faculty so they can continue to improve both curriculum and instructional practices so they will reflect the assessment data. The faculty believe that evaluating department students' ability to utilize informed sustainable design decisions should be addressed at the more global outcome level; this would allow for an assessment of the integrated whole of the lower level courses and objectives regarding sustainable design. Program-level assessment data regarding sustainable design is discussed in a later section of this article.

The Curriculum Model

Although the authors are aware of the interrelationship of the categories represented in the learning objectives, their curriculum isolates each one to make them easier to teach, explain, and assess. Working definitions of the topics included in the categories follow.

1. Low-impact renewable, nontoxic material selection with minimal embodied energy requirements.

The working definition in the curriculum describes low-impact renewable materials as those that can be derived from agricultural crops (grown for nonfood uses) and from other plant or animal sources. They are renewable because they can be used and replaced without irreversibly depleting reserves; this property also makes them a valuable resource in combating climate change. Nontoxic material considerations delineated in coursework are based on the premise that "toxicity" refers to a material's ability to harm living things and at what level of exposure (White, St. Pierre, & Belletire, 2007, p. 17), Issues of concern for designers in relation to product consumer use addressed in the curriculum are: out-gassing issues, the use of carcinogens-materials considered capable of causing cancer, mutagens or materials that induce genetic changes in the DNA of chromosomes, and teratogens, a material or agent that causes physical defects in a developing embryo (www.epa.gov/enviro/html/emci/chemref). An awareness of research methods into material toxicity issues, the use of material safety data sheets, and material toxicity concerns in the manufacturing process are also addressed.

As presented in course lectures, embodied energy refers to the quantity of energy required to manufacture, and supply to the point of use, a product, material, or service. Embodied energy considers the energy requirements for materials from the raw material extraction, to transport, manufacturing, assembly, to produce a service or product, and finally to bring about its disassembly, deconstruction and/or decomposition. (White, St. Pierre, & Belletire, 2007).

2. Efficiency in transportation, consumer use, and manufacturing of products.

Transportation issues are discussed and emphasized, including the use of flat-pack designs and ready-to-assemble products. Packaging for shipping container efficiency, and product weight considerations are addressed. Energy considerations in regard to the consumer use of products are addressed in design discussions. Possible design solutions that utilize hand-power options, low-energy-consuming bulbs, auto shut-off features, and others are encouraged.

Manufacturing processes are important topics in the curriculum because they require so much energy, comprising as much as 80% of industrial energy use. Manufacturing plays a big role in U.S. energy use. Industry accounts for around 30% of the total, and manufacturing is responsible for around 80% of industrial use (Halber, 2006). The ability to research the energy requirements for different manufacturing processes is developed through the coursework.

3. Life-cycle assessment (LCA)

A critical challenge for designers is to embrace the "material trail" of their work. Awareness of the true amount, type, and source of materials behind their designs is a good step toward understanding the challenges of ecological sustainability (Thorpe, 2007). The question, "Paper or plastic?" posed by the grocery store clerk, actually opens up myriad questions and concerns that experts are continuing to debate over. In the end, it is best to bring a reusable bag, and answer "neither."

Because of the multiple factors and complexities in making decisions about design based on LCA, there are most often no clear "correct" answers. Challenges and opportunities may be realized in comprehensive product life-cycle assessments, but at the undergraduate level such complex assessments are difficult to construct and evaluate. It is the authors' aim to introduce the guiding concepts behind such detailed analysis and make students aware of the complexities that contribute to truly sustainable industrial design.

4. Product design that considers reuse/recycle

An assumption that guides the curriculum in this category is that a potential route to an environmentally friendly design solution is to extend product life through designs that allow repair and reuse. When the product is no longer usable, the materials and components can be recovered through recycling. Reuse is the recovery of materials and/or components for similar or alternate end use. Recycling turns materials that would otherwise become waste into resources for remanufacture in new products.

Authors of Cradle to Cradle (McDonough & Braungart, 2002) have referred to recycling as down cycling, as it reduces the quality of a material over time (and increasingly over multiple recycles). In some cases using materials that were never designed for their new application, reprocessing them into a new form, may require as much energy—and generate as much waste—as employing virgin materials, but without reliable, known characteristics (McDonough & Braungart, 2002). The trend in U.S. industry, and the U.S. EPA, is toward preventing wastes before they are created instead of treating, disposing, or reprocessing them later (Ciambrone, 1997). This is an indication that currently in industry many are realizing that the impact their products have on the environment is not limited to the manufacture of a product.

5. Social relevancy of concept/product

It is good for designs to be thematically pointed toward solutions that have positive impact on people and society. Designers must work to replace semantically loaded expressions as "beautiful," "ugly," "cool," "cute," and so on, with words like "meaningful" (Papanek, 1973, p. 25). It is important for ecologically intelligent products to be meaningful and to be at the forefront of human expression (McDonough & Braungart, 2002). Many examples of new technology and devices have languished because they were ahead of their time, including pneumatic tires, the laser, and fluorescent light bulbs (Volti, 2006). It is not enough for sustainable solutions to simply exist. There must be a desire for them. Their end should elegantly glorify their means.

Specific Curriculum

Currently, multiple courses deal with the topics regarding the above sustainable design considerations. In analyzing the instructional coverage of these topics the department has found it beneficial to chart the courses that address each topic, and to what extent. A matrix was developed that indicates where the topics are introduced (I), where they are reviewed and reinforced (R), and where the students demonstrate (D) application of the concepts. While the specific pedagogy may vary from faculty to faculty as course assignments change, the matrix representing these instructional steps remains in place. Assessment results may indicate the need for change over time, but Table 1 illustrates the current curricular plan.

Examples of how we address a specific sustainable design topic through the curriculum

Information about renewable materials and associated considerations are introduced initially in the materials courses. Students are made aware of the renewable nature of certain materials and are given information on available "green" materials. For example, in the

Table 1.

Sustainable Design Topics in Required Courses	Materials Classes	Manufacturing Materials and Processes Class	Beginning ID Studio	Intermediate ID Studio	Design for Production	Advanced ID Studio	Professional ID Studio	Concept and Portfolio Design	Professional Internship
Renewable materials	I	R	R	R	R	R	D		D
Material toxicity	I	R	R	R		R	D		D
Embodied energy	I	R	R	R		R	D		D
Transport efficiency			I	R		R	D		D
Consumer energy use			I	R		R	D		D
Efficient manufacturing processes		I	R	R	R	R	D		D
Life cycle assessment			I		R	R	D		D
Re-use/recycle	I	R	R	R	R	R	D		D
Positive social impact			I	R		R	D	R	D

I= Introduced
R= Reviewed and reinforced
D= Demonstrates application/integration in design solutions

department's Introductory Woodworking classes students are introduced to the industrial materials available for wood-based designs as well as how to price, specify, and order those materials. As a part of these presentations the use of green materials, such as FSC certified lumber and alternative quick growing resource sheet materials (bamboo and Kirei sorghum-based board), and sources for recycled lumber are relayed to the students. These considerations of renewable material use are reviewed and reinforced as they pertain to manufacturing processes in the department's manufacturing materials and process class. The same concepts are addressed with prompting from instructors as students address design problems in the lower level studio sequence classes and also the design for production class in regards to material selection. Students are expected to demonstrate an ability to apply renewable material considerations in the capstone studio class and during their internship placements.

Program Assessment of Sustainable Design

Our department believes that sustainable design should be assessed at the more global, program outcome level. Assessing them at the course level downplays the value of true integration of sustainability into the wider pedagogy and curriculum. We seek to integrate rather than separate this important subject matter. This section reports on the program assessment results regarding sustainable design. The Industrial Design program utilizes three different data-collection methods, which are tied directly to the program's student learning outcomes, and it provides evaluators with an opportunity to provide input on all of them. The data-collection instruments are utilized by internship supervisors, faculty, and professionals observing senior presentations; student interns use it for self-evaluations regarding how well the program has prepared them. The three instruments evaluate students at or near the end of the program and thus can assess the integrated nature of the sustainability outcome. Although there are seven overall program-level learning outcomes, the instruments expand those outcomes into 22 elements for an improved ability to address specifics. Sustainable design is one of the 22 elements that are assessed each year as part of the regular program assessment process.

The department has instituted a minimum target score of 80% (or 3.2 on the 4-point scale) on the evaluation instruments. This is consistent with faculty expectations of meeting standards to succeed in the profession and represents what the faculty believe is an appropriate expectation for student achievement. The current data-collection instruments have been in place for two years. Though this report will include comments comparing this year's scores to last year's data, it is probably premature to identify clear trends from this limited sample. Figure 17 shows the current level of achievement regarding student knowledge and application of sustainable design concepts. The data show a trend toward improved scores for student achievement, over the relatively short time span of two assessment cycles.

Conclusions

An academic institution's approach to teaching sustainability will vary widely depending on the clientele that it serves and the context in which the institution exists. Given our program's context and the nature of our student body, the most appropriate focus for our program is on the material, technical aspects of ecological solutions that may be readily applied. The department exhibits a commitment to the concept of sustainable design with ongoing work to educate students and encourage appropriate sustainable design solutions. The ongoing program assessment data will direct instructional and curricular adjustments to improve the current pedagogical strategies for this vital design imperative.

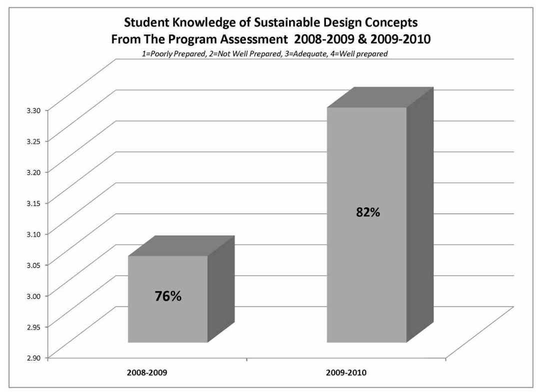


Figure 17.

*This article is based in part on a conference paper presented at the NCIIA 13th Annual Meeting on March 19-21, 2009. Washington DC.

Dr. David Klein is an Associate Professor of Industrial Design at Metropolitan State College of Denver, Colorado. He is a member of the Nu Field Chapter of Epsilon Phi Tau

Dr. Kenneth R. Phillips is the Department Chair for the Industrial Design Department at Metropolitan State College of Denver (MSCD).

References

Benyus, J. M. (2002). *Biomimicry: Innovation inspired by nature*. New York: Harper Perennial (reissue).

Birkeland, J. (2002). *Design for sustainability: A sourcebook of integrated, eco-logical solutions*. London: Earthscan Publications Ltd.

Bralla, J. G. (1999). *Design for manufacturability handbook*. New York: McGraw-Hill.

Chapman, J. (2005). *Emotionally durable design*. London: Earthscan.

Ciambrone, D. F. (1997). *Environmental life cycle analysis*. New York: Lewis Publishers. Retrieved from http://www.epa.gov/Sustainability/basicinfo.htm

Guidot, R. (2006). *Industrial design techniques and materials*. Milan: Flammarion.

Halber, D. (2006). *Engineer launches review of energy use in manufacturing*. Retrieved from http://web.mit.edu/newsoffice/2006/manufacturing-1101.html

Klein, D. W. (2010). Original photos of figure 1 (Rocky Mounts bike rack, www.yakima.com, reprinted with permission), and figure 2 (water fountain, designer unknown).

Mackenzie, D. (1997). *Green design: Design for the environment*. London: Laurence King.

McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. New York: North Point Press.

Orr, D. W. (1994). *Earth in mind: On education, environment, and the human prospect*. Washington: Island Press.

Papanek, V. (1973). *Design for the real world: Human ecology and social change*. Toronto: Bantam Books.

Papanek, V. (1995). *The green imperative: Ecology and ethics in design and architecture*. London: Thames & Hudson.

Thorpe, A. (2007). *The designer's atlas of sustainability: Charting the conceptual landscape through economy, ecology, and culture*. Washington: Island Press.

Terragni, E. (Ed.). (2002). *Spoon, 100 designers*. Phaidon Press Limited.

United States Environmental Protection Agency (EPDA). (2011). *What is sustainability?* Retrieved from http://www.epa.gov/sustainability/basicinfo.htm#sustainability

Volti, R. (2006). *Society and technological change* (5th ed.). New York: Worth Publishers.

Wackernagel, M., & Rees, W. (1996). *Our ecological footprint, reducing human impact on the earth*. Gabriola Island, BC: New Society Publishers.

White, P., St. Pierre, L., & Belletire, S. (2007). *Okala course guide*. Dulles, VA: IDSA.

Whiteley, N. (1993). *Design for society*. London: Reakton Books LTD.

Toward a Zero Energy Home: Applying Swiss Building Practices/Attitudes to U.S. Residential Construction

Daphene C. Koch, William J. Hutzel, Jason M. Kutch and Eric A. Holt

Abstract

This project evaluated typical U.S. and Swiss homes to identify construction practices that are most energy efficient and have economic payback. A net zero energy home (ZEH) produces as much energy as is consumed in it over time. Students in a College of Technology in a Midwest Indiana State University and a technical University in Switzerland resulted in developing models of homes that combined U.S. and Swiss standards. The project was completed in two phases: during the first phase of this project, construction costs, energy use, and economic payback was calculated for six homes that were designed using both Swiss and U.S. standards. During the second phase of the project, cultural norms that influence energy use were explored. A survey was used to compare U.S. and Swiss college students' lifestyles and energy habits. All homes had the same basic size and layout, but some used construction practices typical for the United States and others were designed according to Swiss guidelines for residential construction. The results of the study showed that a Swiss-style low-energy home is not cost effective for the Midwestern United States if energy costs remain low, but it could become attractive if energy rates escalate significantly. It was also recognized that technology by itself will not minimize energy consumption, a result of the second part of the project that explored cultural norms that influence energy use. From the survey of both U.S. and Swiss college students' lifestyles and energy habits, it was revealed with a high level of confidence that Swiss students are more energy conscious than their U.S. counterparts.

Introduction

This project evaluated typical U.S. and Swiss residential design to identify construction practices that are most energy efficient. The analysis reviewed current best practices in both countries along with an evaluation of attitudes toward energy use by individuals. In the United States an Energy Star system is being used to model homes. Energy Star is an umbrella of voluntary programs started in 1992, which ran as a joint program since 1996 with the U.S. Environmental Protection Agency (EPA) and the DOE to improve energy efficiency of homes (Banerjee & Solomon, 2003). The Swiss method of building a sustainable home is the Minergie System (Minergie, 2010). Zero Energy Homes (ZEH) have been built in Japan, Sweden, Germany, Norway, Austria, and the United States. Unfortunately, there is no real database to centralize information to globalize the adoption of successful homes worldwide (Charron & Athientitis, 2005). To add to the existing body of knowledge, this project reviewed the importance of moving toward ZEH homes, and the current practices and attitudes of the United States and Switzerland toward energy efficiency. The research modeled six variations of designs that incorporated the Energy Star and Minergie systems.

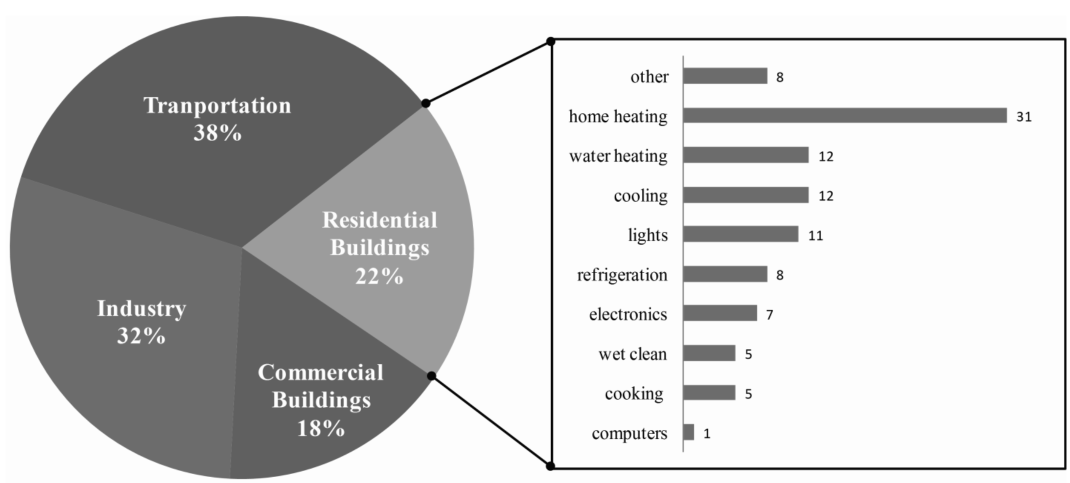


Figure 1. Energy Usage by Sector Including Detail for Residential (*Energy Star, 2010; Perez-Lombard, Ortiz, & Pout, 2008*)

Figure 2. Swiss Masonry Walls (left) and U.S. Wood-frame Walls (right) *(photos by authors)*

Significance of Energy Consumption

The International Energy Outlook (IEO) report projects that the world energy consumption is expected to expand by 50% in 2030 (Energy Star, 2010). Residential buildings account for 22% of the primary energy use according to the Energy Information Administration (EIA, 2008). Within residential buildings, space heating and water heating (both natural gas and electric) are the biggest opportunities for energy savings. Figure 1 details the exact usage of electricity in the home. It shows that most energy is used for heating (home and water), lighting, and cooling. These should be the initial targets to better design a home.

The Department of Energy (DOE) started a program, "Build America," with a goal of reducing whole-house energy use for new home by 50% by 2015 and 95% by 2025 (Anderson & Horowitz, 2006). The Build America initiative targets significant improvements to the building envelope (the makeup of the walls, roof, and floor) through better insulation and sealants, and major reductions in electricity through using highly efficient appliances, lighting, and mechanical systems. The remaining energy for achieving net-zero will be supplied by a renewable energy source, such as solar or wind.

Residential Construction Standards in the United States and Switzerland

A detailed inspection of the Swiss and U.S. homes showed fundamental differences in construction techniques. Figure 2 shows photos taken by the students to document the typical systems used in each country. The Swiss building standards are more similar to U.S. commercial standards of building with heavy use of a thick masonry brick-type component. This creates more thermal mass than the typical U.S.-style wood-frame home. Significant attention in optimizing the building envelope in terms of insulation, air sealant, and efficient windows is a component of the Swiss system. The highly efficient mechanical systems included air-to-air heat recovery, radiant slab heating and cooling, and solar domestic hot water in Swiss homes, which is currently utilized in more commercial applications in the United States.

Typical Swiss home are built using a masonry type of material, which does not exist in the United States. A Swiss home also typically costs more than $600,000 (U.S.) to purchase, and in Switzerland, most people do not own homes, but rather inherit them. The U.S. has produced affordable housing using wood-frame construction. This vast difference in materials used for homes resulted in the development of a typical midrange U.S. home layout that was developed to be used for modeling the standards of Minergie and Energy Star. Figure 3 shows the standard home layout

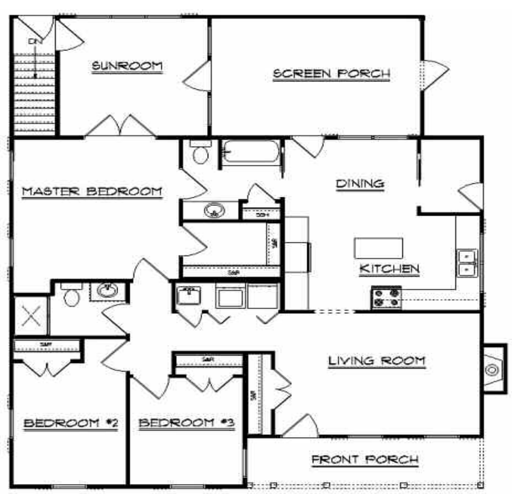


Figure 3. Floor Plan of Typical Midrange U.S. Home *(plan produced for research project)*

Table 1. Major Specifications for Six Residential Construction Models

Construction Category	Wall R-value (R_{SI})	Attic R-value (R_{SI})	Heating	Solar for Hot Water
Standard U.S.	11 (1.94)	30 (5.28)	Gas - 80% AFUE 80 MBtuh (23.4 kW)	No
Energy Star	19 (3.35)	50 (8.81)	Gas - 92% AFUE 80 MBtuh (23.4 kW)	No
Standard Swiss	19 (3.35)	38 (6.69)	GSHP - 5.0 COP 40 MBtuh (11.7 kW)	No
Minergie	30 (5.28)	50 (5.28)	GSHP - 5.0 COP 36 MBtuh (10.5 kW)	Yes
Hybrid Energy Star	19 (3.35)	50 (8.81)	GSHP - 5.0 COP 40 MBtuh (11.7 kW)	Yes
Hybrid Minergie	30 (5.28)	50 (8.81)	Gas – 92% AFUE 80 MBtuh (23.4 kW)	No

that was developed to standardize comparisons of different characteristics of homes.

A single-family home with one story and a conditioned unfinished basement was used because this type of construction is found in both countries. The floor plan included three bedrooms, two bathrooms, one walk-in closet, a living room, a dining room, a kitchen, a sunroom, a screened-in porch, and a front porch: it totaled 1,504 ft2 (139.7m2). Four exterior doors account for approximately 100 ft2 (9.3 m2) of surface area and the windows equaled approximately 237 ft2 (22 m2); the majority of the windows face south, which provides additional heating during the winter. The above-grade wall surface area is approximately 1400 ft2 (130 m2).

The basis of the project was to differentiate the Energy Star and Minergie building standards, but it was found that in the United States not all of the Swiss standards were realistically applied. Table 1 identifies six different combinations of residential construction identifying the wall and attic insulation, heating, and application of solar hot water heating. These are the major characteristics of the home that were modeled to evaluate using the standardized floor plan. The combinations range from the least energy efficient design, standard U.S. home, to the standard Minergie home of Switzerland.

The insulating value of the walls and attic in Table 1 is expressed in terms of an R-value. Two systems of units are shown. The U.S. customary R-value has units of ft2-°F-hr/Btu. The conversion to comparable SI units is 5.68 ft2-°F-hr/Btu equals 1.0 m2-°C/W. Table 1 shows the U.S. R-value first, with the SI version (labeled RSI) in parentheses. The exterior walls of the "Standard U.S." home have R-11 (1.94 RSI) insulation, whereas the attic has an R-30 (5.28 RSI). Heating is provided by a natural gas furnace rated at an annual fuel utilization efficiency (AFUE) of 80% with a capacity of 80 MBtuh (23.4 kW).

Modeling U.S. and Swiss Homes

A software tool, RemRate, was used to analyze energy use. RemRate is an easy-to-use computer program for residential construction that calculates heating, cooling, hot water, lighting, and appliance loads. Certified energy auditors use the program to determine whether a new home design meets the requirements for

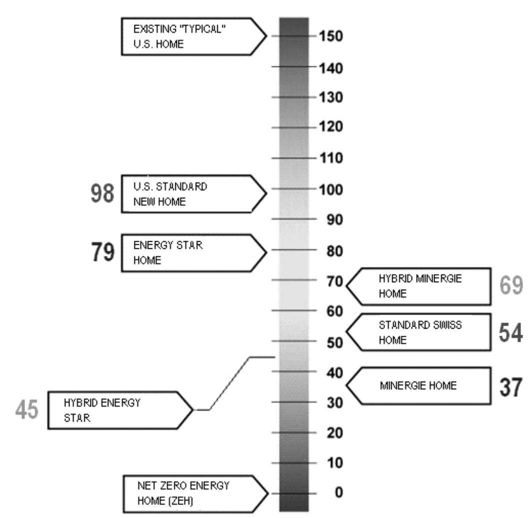


Figure 4. HERS Index Ratings for Research Model Homes ***(developed by researchers)***

Table 2. Construction and Utility Costs for Each Category

Construction Category	Construction Cost ($)	Annual Energy Cost ($)
Standard U.S.	141,546	$2,356
Energy Star	144,848	$2,088
Standard Swiss	161,932	$1,838
Minergie	164,013	$1,242
Hybrid Energy Star	152,148	$1,475
Hybrid Minergie	156,713	$2,095

U.S. Energy Star certification. RemRate includes climate data for cities and towns throughout North America. The analysis for this project was conducted in a Midwestern city, which is classified as a cold climate according to DOE's Building Technologies Program (Polly et al., 2011). The winter design temperature used was -5 °F (-20.6 °C) and a summer design temperature is 93 °F (-33.9 °C).

The RemRate software also predicts annual utility costs when rates are provided.
This project assumed utility rates that are typical for an area, but low compared to the rest of the United States. Electricity was $0.10 / kilowatt-hour (kWh). Natural gas was $1.50 / hundred cubic feet (CCF). During the economic analysis, an energy escalation rate of 3% annually and a discount rate of 1% were used as the baseline. These assumptions are significant because different locations in the U.S. have different energy rates, potentially affecting the economic analysis. This case study is valid for this location.

RemRate also provides a Home Energy Rating System (HERS) Index for a given home (Energy Star, 2009). Figure 4 shows the HERS scoring for the model homes in this project. HERS is a scoring system in which a home built to the specifications of the HERS Reference Home (based on the 2006 International Energy Conservation Code) scores a HERS Index of 100, while a net-zero energy home scores a HERS Index of 0 (Judkoff & Neymark, 1995). The lower a home's HERS Index, the more energy efficient it is in comparison to the HERS Reference Home. There are no units intrinsic to the HERS Index; it is a relative scale between 0 and 100.

The standard U.S. home scored 98 with an improved score of 79 for the Energy Star home. In contrast, the Standard Swiss home scored a 54, whereas the low-energy (Minergie) version scored a 37. The Hybrid Minergie and Hybrid Energy Star homes scored a 69 and a 45, respectively. These numbers indicate that the mechanical systems in the Minergie home played a major role in reducing overall energy consumption. The impact of the Swiss building envelope was less important.

Payback Analysis

Estimates of energy consumption do not provide a complete picture of overall performance. An energy efficient home is not a worthwhile investment unless the utility costs are reduced by a corresponding amount over the life of the home. To calculate actual life cost analysis, an estimate of the construction costs of the six home models was conducted. Table 2 summarizes the costs for both construction and annual energy costs. The land is not included because it would be the same for each home category. The standard U.S. home has the lowest cost at $141,546, but it also has the highest energy costs $2,356. The Swiss Minergie home

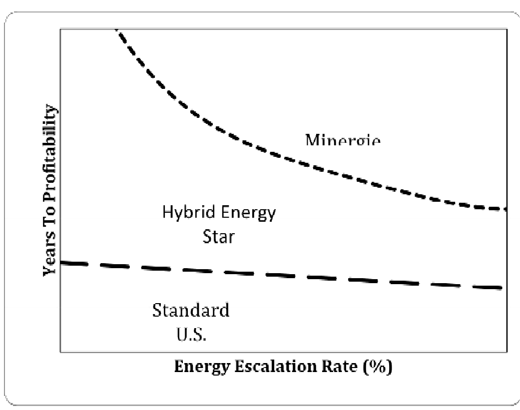


Figure 5. Economic Payback as a Function of Energy Escalation Rate

is more expensive ($164,013), but it would operate on an annual basis of only $1,242.

Figure 5 summarizes the results of a payback analysis that considered the costs for the various housing options as a function of energy escalation rate. The vertical axis of the graph is the time period in years where various housing options are most economical. A discount rate of 1% was assumed for all computations. Only three of the six possible housing options appear in Figure 5, because those are the ones that achieved the highest savings.

The Standard U.S. home would be the most cost effective option until year 13. The lower construction costs offset the larger energy expenditures for the first 13 years of home ownership. At that point, the Hybrid Energy Star would become cheaper and remain so until year 43. After year 43 the Minergie option would become the most cost-effective option. These examples show that more expensive and energy efficient housing options become attractive if energy rates increase sharply. As an extreme example, at a 10% annual energy escalation rate the more expensive Hybrid Energy Star home would become cost effective after 10 years. A Swiss-style Minergie home would be the best choice after 22 years.

Before the volatility of the real estate market began, people in the U.S tended to move frequently, so a home that is less expensive in terms of first cost is cost effective despite the higher energy costs. In contrast, a Swiss home is a once-in-a-lifetime investment, so it makes sense to invest in something that is cost effective over a much longer time period. It is also interesting that the Hybrid Energy Star option is cost effective between roughly 10 to 20 years of home ownership. This is the option that includes the building envelope of a U.S. Energy Star home with the mechanical systems of a Swiss Minergie home. This result shows that for this simplified analysis it was easier to justify the cost of improved mechanical systems as opposed to investing in a highly insulated building envelope.

Attitudes Toward Energy by Culture

Recognizing that technology by itself will not minimize energy consumption, a second part of the project explored cultural norms that influence energy use. A survey of U.S. and Swiss college students compared lifestyles and energy habits. Data was collected from students in comparable undergraduate thermodynamics classes at both a Midwestern U.S. university and a Swiss technical school. The survey included 58 U.S. students and 28 Swiss students. The difference in the size of the two student populations is directly related to the enrollment of the two academic programs.

The U.S. students were juniors; approximately 20 to 21 years of age, whereas the Swiss students were approximately 25 years old. The Swiss students were older because of a 4-year professional internship requirement before the formal academic training. This simple survey was not able to account for how differences in age and professional experience affect the results. One other potential flaw is that the survey was delivered in written English to both student populations. Although the Swiss students were generally fluent in both Swiss-German and English, there could be translation issues that the researchers were not aware of. The survey questions were kept simple, and visual cues were included on the survey form to make it easy to interpret. However, the survey did not specifically evaluate how proficiency in English affected the data.

Three broad areas were evaluated. One set of questions targeted basic expectations for housing in terms of size, style, cost, and so on. A second set of questions evaluated overall energy awareness and whether energy efficiency

Table 3. Sample Questions About Housing

Housing Options	Swiss		U.S.	
	Median	Mode	Median	Mode
What age (years) do you expect to be when buying your first	35	35	25	25
What is your expected price for your first home?	$600,000	$1,000,000	$150,000	$150,000

Table 4. Questions About Energy Awareness

Energy Awareness	Category 1	2	3	4	5
How important is it to shut off your computer at night before going to bed?	Not Important	Not Interested	Neutral	Interested	Very Important
How important is it to you to recycle (e.g., Glass, Paper, or Plastic)?	Not Important	Not Interested	Neutral	Interested	Very Important

is an integral part of a student's lifestyle. The third set of questions considered how energy awareness affected day-to-day decisions. The results of this brief survey revealed some substantial differences that begin to highlight how social norms can impact energy conservation.

The survey of Swiss and U.S. students included 21 questions. Many, but not all questions, were expressed as a 5-point Likert-type item. Table 4 is a sample of the survey results related to housing. These questions show how expectations for home ownership vary between Swiss and U.S. college students. The median age for achieving home ownership varied dramatically. Swiss students expected to buy their first home by age 35, whereas most U.S students expected to purchase their first home by age 25. Several Swiss students actually reported "never" in terms of home ownership, which supports the observation that long-term apartment living is relatively common in Switzerland.

Table 3 also shows that the student-reported median home price in Switzerland was $600,000, while the median was only $150,000 in the United States. As reported previously, the higher costs in Switzerland are driven by significantly different construction standards. A typical Swiss home is built for a design life of 100 years, much longer than one in the U.S. The striking cost difference is also in part because of the value of land in Lucerne, Switzerland, as compared to land in Midwestern United States. The Swiss culture dictates that a home is a significant once-in-a-lifetime investment, and homes are often passed down from one generation to the next. It makes good sense for the Swiss to wait until they are able to afford a substantial home purchase. In contrast, homes in the U.S. were a relatively short-term investment.

Table 4 is a sample of questions evaluating overall energy awareness. Students were queried about the importance of shutting off electrical appliances and recycling. For each question, students were asked to respond to a 5-point Likert-type item indexed from "not important" to "very important." The goal of these survey questions was to discern whether students have a personal commitment toward sustainability.

Table 5. Results Related to Energy Awareness

Energy Awareness	Swiss Median	Swiss Mode	U.S. Median	U.S. Mode
How important is it to shut off your computer at night before going to bed?	4	5	2.5	1
How important is it to you to recycle (e.g., Glass, Paper, or Plastic)?	4	4	3	4

Table 6. Sample Questions About Lifestyle Impacts

Lifestyle Impacts	Category 1	2	3	4	5
How willing would you be to walk 10 blocks during the winter or summer in order to save gasoline?					
How happy would you be to not have air conditioning at all in your residence during the summer?					

The results shown in Table 4 illustrate some of the reported behavior patterns. Swiss students ranked the importance of turning off a computer much higher than their U.S. counterparts. The median value for Swiss students was 4, and the median value for U.S. students was 2.5. The two student populations responded in a similar way to the survey question that dealt with recycling. The rankings by both Swiss and U.S. students suggest that this topic has become part of the student culture. It has been observed that most U.S. students have grown up with recycling programs in their homes and schools.

Table 6 is a sample of the survey questions that evaluated the lifestyle impacts of energy conservation. The goal was to discern whether students make a conscious effort to engage in activities or behaviors that conserve energy. Rather than a scale in written English, emoticons were used. The simple facial expressions used in the survey and shown in Table 6 convey the same categorical information while avoiding the subtleties of written English.

Table 7 shows some results from the part of the survey that targeted lifestyle impacts. The first lifestyle question showed that Swiss students were more amenable to the prospect of walking 10 blocks (on the order of one mile) to save gas. The median and mode responses were a 4 for Swiss students and a 3 for U.S. students.

The second lifestyle question explores the importance of air conditioning in the summer. Stark differences between Swiss and U.S. students were noted on this question. The median answer for Swiss students was a 4.5, which implies that summer air conditioning is not mandatory. The median response for their U.S. counterparts was a 2, meaning that summer air conditioning is an expectation for day-to-day living.

The air conditioning question reveals significant lifestyle differences. Many Swiss residences have a limited amount of air conditioning, due in part to a moderate climate noted in Table 1, but also because of differences in comfort expectations and regulations on residential electricity consumption. It is probably not a coincidence that many Swiss people take a month-long holiday in August, when apartment life without air conditioning could become very uncomfortable.

What is the overall message from this survey of Swiss and U.S. students? Is there an

Table 7. Results Related to Lifestyle Impacts

Lifestyle Impacts	Swiss Median	Swiss Mode	U.S. Median	U.S. Mode
How willingly would you be to walk 10 blocks during the winter or summer in order to save gasoline?	4	4	3	3
How happy would you be to not have air conditioning at all in your residence during the summer?	4.5	5	2	1

underlying theme that sheds light on differences in residential construction practices? An effort was made to consolidate the survey results by computing an "energy consciousness quotient." This is an informal term that combines the three major survey topics (housing options, energy awareness, and resulting lifestyle impacts) in order to directly compare Swiss and U.S. students in terms of lifestyle differences that impact energy use.

The results of selected survey questions were combined into a scale with a range from 0 to 100%. The mean value for this "energy consciousness quotient" for the Swiss students was 85.5%, with a standard deviation of 0.51. The mean for U.S. students was 71%, with a standard deviation of 0.83. Statistics were applied to see whether the difference between the two values was statistically significant. T-statistic calculations showed with 99.9 % confidence Swiss students have a higher "energy consciousness quotient" than their U.S. counterparts.

The "energy consciousness quotient" is an interesting parameter. Within the population surveyed it probably does a reasonable job of quantifying to what extent energy conservation has an impact on student lifestyles. It was encouraging to document that both student populations consider energy conservation as part of day-to-day living. It is not surprising that Swiss students rated higher in this regard, probably because of simple economics. Costs for fuel, electricity, and other energy resources are typically higher in Switzerland.

Conclusions

This research analyzed six different residential construction models using Swiss and U.S. metrics. It was found that a Swiss home built in Indiana would be more expensive, yet more energy efficient than the other homes in its neighborhood. Typical U.S. construction techniques are cost effective during the short term. However, Swiss low energy construction becomes a better investment after longer periods of home ownership. A brief survey of students noted cultural, lifestyle, and economic differences that might also help explain the differences in construction standards.

Changes in energy policy and technology could affect some of the trends noted in this article. In the United States, federal tax credits for investments in residential energy efficiency, such as windows or insulation, have been popular. Future research could be completed utilizing this as a method to review possible zero-energy and energy efficiency techniques. European countries have more historic data that could be applied to the research of energy efficiency in the United States in the future.

Dr. Daphene Cyr Koch is an Assistant Professor in Building Construction Management at Purdue University in West Lafayette, Indiana.

William J. Hutzel is an Associate Professor of Mechanical Engineering Technology at Purdue University in West Lafayette, Indiana.

Jason M. Kutch was a graduate student in Mechanical Engineering Technology at Purdue University in West Lafayette, Indiana. He now works in facilities services at the university where he applies the energy developed from his research.

Eric A. Holt is a PhD graduate student of Building Construction Management at Purdue University in West Lafayette, Indiana.

References

Anderson, R., Christensen, C., & Horowitz, S. (2006). Analysis of residential system strategies targeting least-cost solutions leading to net zero energy homes. *ASHRAE Transactions*, 112 (Part 2), 330–341.

Banerjee, A., & Solomon, B. (2003). Eco-labeling for energy efficiency and sustainability: A meta-evaluation of US programs. *Energy Policy*. 31(2003). 109-123.

Charron, R., & Athieneitis, A. (2005). *An international review of low and zero energy home initiatives*. Paper presented at the ISES Solar World Congress 2005, Orlando, FL.

Energy Information Administration (EIA) (2010). *International Energy Outlook 2010* (Report No. DOE/EIA-0484). Retrieved from http://www.eia.doe.gov/oiaf/ieo/

Energy Star (2009). *Energy Star Qualified New Homes*. Retrieved from http://www.energystar.gov/index.cfm?c=new_homes.hm_index

International Energy Agency (2008). Energy technologies perspectives: Scenarios and strategies to 2050, *OECD/IEA*, 2008, Paris.

Judkoff, R., & Neymark, J., (1995). Home energy rating system building energy simulation test (HERS BESTEST): Volume 1, Tier 1 and Tier 2 tests user's manual, Goldon, CO: National Renewable Energy Lab.

Minergie Homepage (2010). Retrieved from http://www.minergie.com

Polly, B., Gestwick, M., Bianchi, M., Anderson, R., Horowitz, S., Christensen, C., & Judkoff, R., (2011). A method of determining optimal residential energy efficiency retrofit packages. Goldon, CO: U.S. Department of Energy.

Perez-Lombard, L., Ortiz, J., & Pout, C., (2008). A review on buildings energy consumption information. *Energy and Building* 40(3) 394-398.

Design, Operation, and Analysis of a Floating Water Fountain System Using Renewable Energy Technology

Hans Chapman, Eduardo Gomez, Nilesh Joshi, and Sanjeev Adhikari

Abstract

Engineering and technological applications of renewable energy installations, such as photovoltaic (solar) energy, are making important contributions toward the development of environmentally friendly products and processes for a more sustainable future. This article presents the design, assembly, and operation of a solar powered floating fountain system for analysis of aeration in stagnant water. The goal was to increase the level of dissolved oxygen in a body of water by harnessing solar energy for submerged aeration. The system is composed of six solar panels, a kit of batteries, a linear current booster, pressurized water tank, two pumps, an air compressor, and a float. The design factors for dissolved oxygen (DO) measurements were determined from depth of water, time of the day, location of fountain, and status of fountain (on or off). A Split Plot design was used to investigate the performance of the fountain, based on the changes in levels of DO in the pond. Statistical analysis showed a 120% gain in DO concentration during a 20-day period with significant destratification of the pond. This applied research will be of interest to engineers and technologists in various areas, including environmental development, green construction, and aquatic and energy conservation.

Keywords: Renewable Energy Technology, Solar Powered Fountain, Aeration, Dissolved Oxygen.

Introduction

Photovoltaic (PV) renewable energy systems offer new alternatives for consumers and businesses as to how power can be provided. PV systems react to light by transforming part of the radiant energy into electricity. PV cells require no fuel to operate, produce no pollution, require little maintenance, and are modular. These attributes permit a wide range of solar - electric applications (Markvart, 1999; Marshall & Dimova-Malinovska, 2002; Dunlap, 2010). Other advantages of PV systems include: unlimited input solar energy, reliable power output, flexibility in assembly, and easy installation (Boyd, 1997; Butler & Sinton, 2004).

Pumps are useful devices for the operation of water fountains. Fountains are installed on water bodies, like ponds, streams, and lakes, to prevent destratification of the water (Michaud & Noel, 1991; Lynch & Commer, 1994). Water pumping is one of the most competitive areas for PV power. PV pumping systems pump most water during the sunniest, hottest days of summers. PV pumping systems have, as a minimum, a PV array, a motor, and a pump. In addition to water pumping, PV systems can also be useful for aeration of water bodies.

Natural stream purification processes require adequate dissolved oxygen levels in order to provide for aerobic life forms. When pollution enters a body of water, plant and algae die and sink to the bottom, resulting in an overload of organic sludge. A lower form of life in lakes and ponds die and this debris eventually rots. Oxygen solubility has been shown to increase with decreasing temperature, salinity and pressure (Wieland & Kühl, 2006). When dissolved oxygen (DO) is at saturation level, the number of oxygen molecules leaving the water surface equals the number entering (no net movement) (Michaud & Noel, 1991). Below DO saturation, there is a net movement of oxygen from atmosphere to water. The greater the difference between the oxygen pressures in the water and the atmosphere, the larger the movement of oxygen from the atmosphere to the water.

System Design

The solar powered water fountain (SPOWF) was designed to enhance dissolved oxygen levels in a test pond at Innovation Park, Tallahassee, Florida. The three primary components for producing electricity using solar power are: solar panels, a charge controller, and batteries. Solar panels charge the batteries, and the charge regulator or linear current booster (LCB) ensures proper charging of the battery. The system was designed in two main parts (the fountain and the aerator). The water fountain adds oxygen to the water body by exposing the water to the external air. The aerator provides air bubbles into the body of

Table 1. Loads and Their Electrical Ratings for the Fountain

Description	Volts	Amps	Watts	Amp –hour /day
Submersible pump	24	4	96	48
Surface pump	24	6	144	72

water by using an air supply line from an air compressor. A different electrical circuit was designed for each part. The required solar panels and batteries were placed onshore and the loads were located offshore. The loads of the fountain include a submersible pump, a surface pump, and the air compressor.

Design of the Fountain

The fountain design consists of (i) solar array, (ii) deep cycle batteries, (iii) pumps, and (iv) pressure tank. The loads for the fountain are shown in Table 1.

The number of solar modules in parallel required was 3. It was also determined that 2 modules in series were required for the 24 Volts battery, making a total of 6 batteries.

Deep-cycle Batteries

The capacity of the deep-cycle batteries used for a total of 432 Amp-hours (assuming 3 days in the week without sun and a correction factor of 1.2) was determined to be 4 batteries in series.

Pumps and Pressure Tank

Two pumps were chosen:

- A positive displacement 3-chamber diaphragm submersible pump with a total vertical lift of 70 meters, a flow rate of 8.6×10^{-4} m^3/s, and a maximum pressure of 6.9×10^5 N/m^2.
- A surface pump with a vertical lift of 9.1 meters, a flow rate of 3.3×10^{-5} m^3/s, and a maximum pressure of 3.1×10^5 N/m^2.

Figure 1 is a schematic diagram of the fountain showing how the panels, batteries, actuator, and pumps are connected. Considering the pressure and flow rate of the pumps, a 0.13 m3 tank was chosen. Additionally, a "cut-in 2.1×10^5 N/m^2 / cut-out 3.4×10^5 N/m^2" pressure switch and a pressure gauge were attached to the tank.

Design of the aerator

The aerator is comprised of one item each from the following: 7.2 Amps solar panel, 6- Amp air compressor, 6.1 m #12 AWG wire, 15 Amps charge regulator, 12 Volts battery, and a plastic case. A 0.13 m diameter, 1.68 m long PVC pipe was chosen, and a 90˚ elbow was glued at the top of the pipe to transport the air bubbles from the bottom to the surface of the lake. Four radial holes were drilled six inches from the end of the pipe to hold the air stones in place, using plastic fittings. The air stones were interconnected to a 9.5×10^{-3} m flexible hose. The hose was connected to the air compressor located on top of the fountain as shown in Figure 2. The PVC pipe was then strapped with two 0.91 m x 0.04 m aluminum flat bars. One side was welded to the SPOWF aluminum structure, and the other side bolted to the pipe as showed in Figure 2.

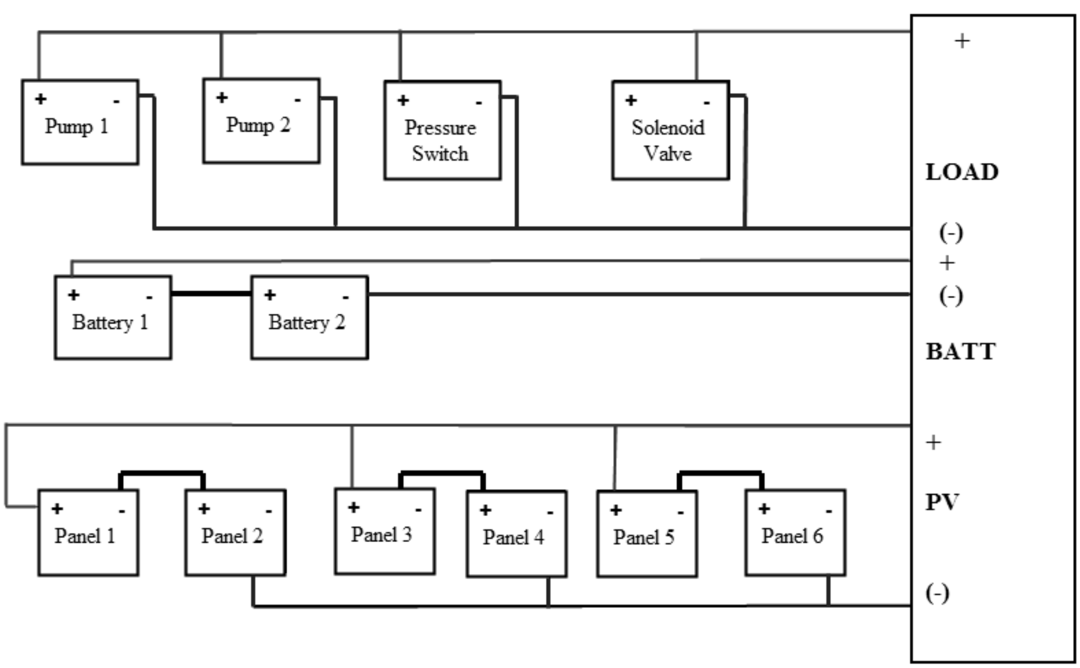


Figure 1. Schematic Diagram Showing the Arrangement of Pumps, Batteries, and Solar Panels in the Fountain Design

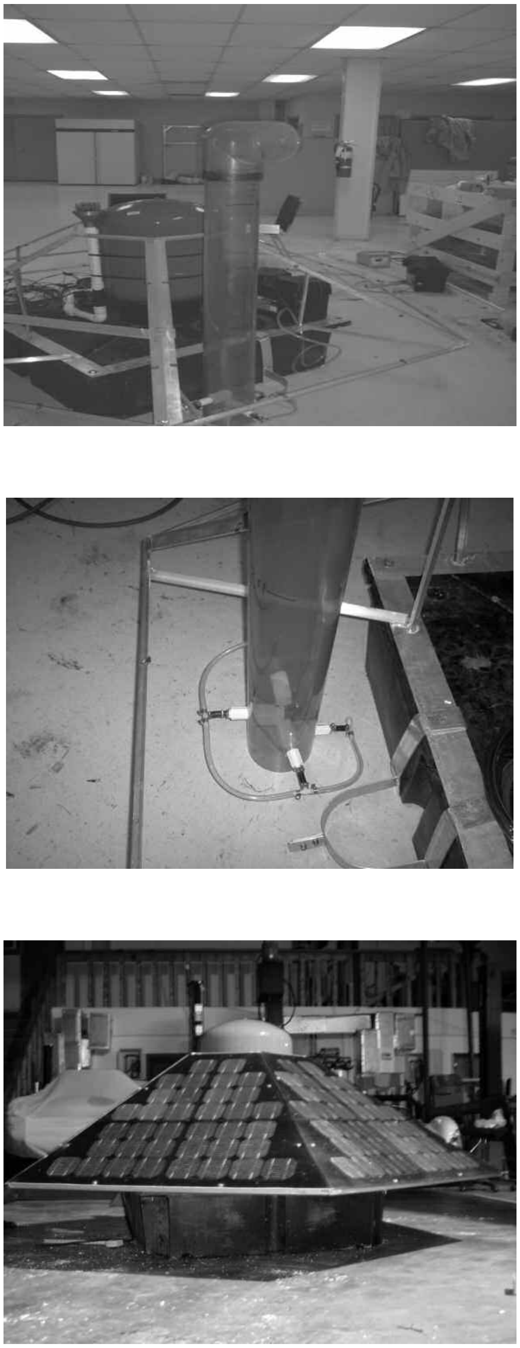


Figure 2. Photos of the Solar-powered Water Fountain (SPOWF) *[Top]: SPOWF unit under construction, showing the aeration system (vertical tube), blue water tank, aluminum frame, base float, and electrical wiring for connecting the panels, batteries, and actuator. [Middle]: Close-up view of the bottom part of the aerator, revealing arrangement of air stones. [Bottom]: Fully assembled SPOWF unit*

System Operation

When the SPOWF system is turned on, both pumps constantly pump water into the tank through the one-way valve. As the water flows into the tank, the pressure in the tank increases steadily to 3.44 x 10^5 N/m^2. At this critical pressure, water is jetted of the fountain through the nozzles. The flow stops when the pressure drops below 2.1 x 10^5 N/m^2, and the pressure switch shuts off to rebuild the pressure in the tank. This sequence is continued as long as there is enough current flow to power the loads (Braimah, 2004; Gomez, 2006).

The purpose of running both the fountain and aerator together was to maximize the daily water circulation. The voltage output of the PV panels is often too low to run the pumps under these conditions. To offset this limitation, it was necessary to operate an energy booster with the system. The linear current booster (LCB) works by enhancing the output current from two batteries, especially under low light conditions, cloudy days, and early morning or late evening.

System Analysis

Cause-and-effect diagram

A cause-and effect diagram was developed for the SPOWF system as shown in Figure 3. From this diagram, the factors were classified as design factors, factors held-constant, and nuisance factors. The design factors were: depth of the water, time of the day, location of the fountain, and the status of the fountain i.e., ON or OFF. The factors held-constant were variables that could modify the response, but for the purpose of this experiment, these factors were not of interest, so they were held at their specific level. Some of them were: filters, fountain, solar panels, and pumps. Nuisance factors, on the other hand may have a large effect that must be accounted for. The nuisance factors considered in this experiment were: barometric pressure, temperature of the water, cloudiness, and air temperature.

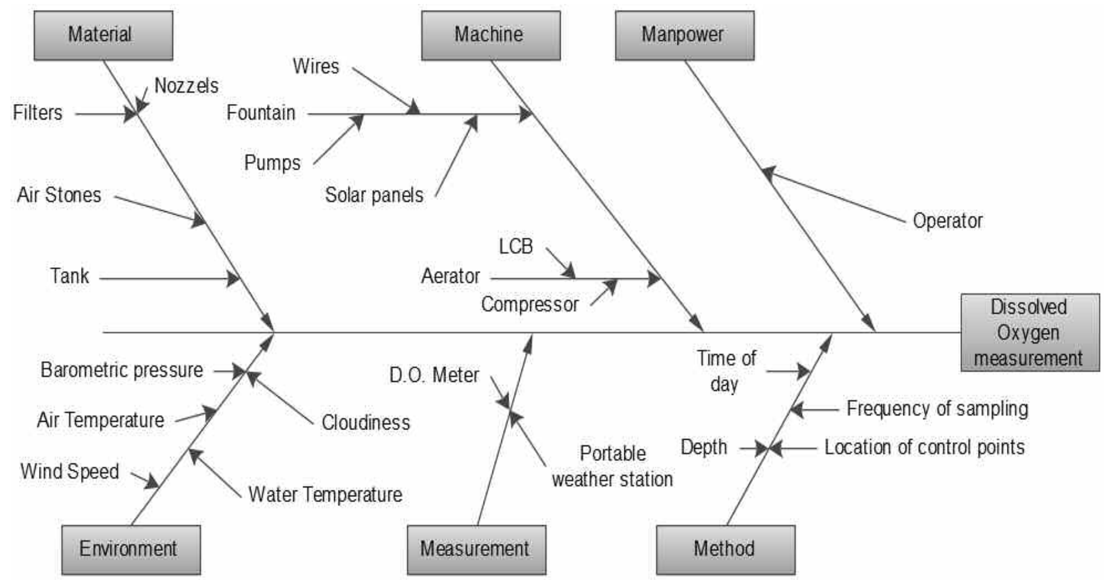
Dissolved oxygen measurement

The dissolved oxygen meter provided the reading of the concentration of dissolved oxygen as well as the depth and temperature of the water. Measurements were done every day at 7:00 AM and 1:00 PM during 20 consecutive days in October and November. Table 2 shows the data set after measurements were taken.

Estimated general linear relation for final model

The final estimated model equation in terms of coded units with all the statistically significant terms was determined for two scenarios, i.e., "Fountain Off" and "Fountain On" as indicated below:

Figure 3. Cause-and-effect Diagram for the Solar-powered Floating Fountain



Fountain OFF

DO = 4.63 **-** 0.5244 (Location) + 0.3569 (time of day) (7)

Fountain ON

DO = 6.0455 – 1.0238 (Location) + 0.7138 (time of day) (8)

Interactions between "fountain with location" and "fountain with time of day" are evident in the differing coefficient estimates for location and time of day for "fountain off" vs. "fountain on", respectively. A response surface analysis (Simpson, Kowalsky, & Landman, 2004) was performed and the results are shown in Figure 4.

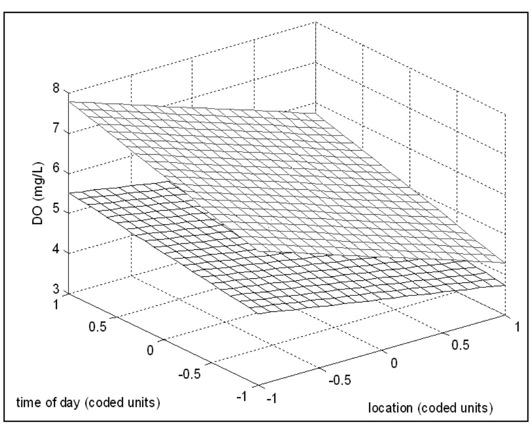


Figure 4. Response Surface for Dissolved Oxygen (DO) as a Function of Location and Time of Day, When Fountain is ON (top) and Fountain is OFF (bottom)

In order to accurately predict DO as a function of location and time of day, a transformation from natural to coded units (Myers & Montgomery, 2002; Montgomery, 2005) should be made prior to applying the model as shown in Eqs. 7 and 8, respectively.

In general,

$$\text{Coded units} = \frac{NU - [Min + Max]/2}{[Max - Min]/2} \quad (9)$$

Where, *NU* is the value in natural units

Min is the (-1) value of the factor in natural units

Max is the (+1) value of the factor in natural units.

Table 3 shows an example for calculating DO at a location, 3.7 m away from the fountain at 9:00 AM.

Final model charts

The first datum for the fourth subplot was collected again, after 12 days, with the fountain in the OFF status. It was observed that the aeration effect due to the floating fountain had disappeared. Consequently, the measured DO levels were at the original values as shown in Figure 5. This new information is valuable because it can be inferred that the experiment was time independent.

Table 2. Data Set Collected Indicating Factors and Response (*dissolved oxygen measurement*)

Day	Depth of water (meters)	Time of day (hours)	Location (meters)	Status of Fountain (On / Off)	Air Temp (°K)	Water Temp (°K)	Cloudiness (0 or 1)	Wind speed (m/s)	DO (mg/L)
1	0.3	13	1.52	Off	291	293	0	2.24	4.5
2	1.52	13	7.62	Off	291	291	1	0.45	4.7
3	0.3	7	7.62	Off	280	293	1	0	4.8
4	0.91	10	4.57	Off	291	292	0	1.34	4.6
5	1.52	7	1.52	Off	279	291	0	0.89	4.5
6	1.52	7	1.52	On	279	291	0	0.45	6.4
7	0.3	7	7.62	On	282	291	1	1.34	7.1
8	0.3	13	1.52	On	301	298	0	0.89	6.1
9	0.91	10	4.57	On	292	295	0	1.34	9.8
10	1.52	13	7.62	On	295	291	0	0.89	7.6
11	1.52	13	7.62	On	297	292	1	0.45	10
12	1.52	7	1.52	On	283	294	1	1.34	6.4
13	0.91	10	4.57	On	295	295	0	0.89	6.3
14	0.3	13	1.52	On	299	296	1	0.45	7.1
15	0.3	7	7.62	On	284	299	0	0.45	7.8
16	0.3	13	1.52	Off	300	302	1	1.34	4.6
17	0.91	10	4.57	Off	295	299	0	1.34	4.7
18	0.3	7	7.62	Off	285	299	1	1.79	4.6
19	1.52	7	1.52	Off	282	293	1	2.24	4.8
20	1.52	13	7.62	Off	295	296	1	2.24	4.5

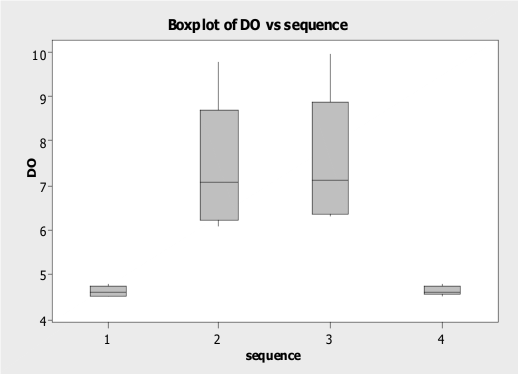


Figure 5. Box Plot of DO Concentration Showing Time Independent Effect

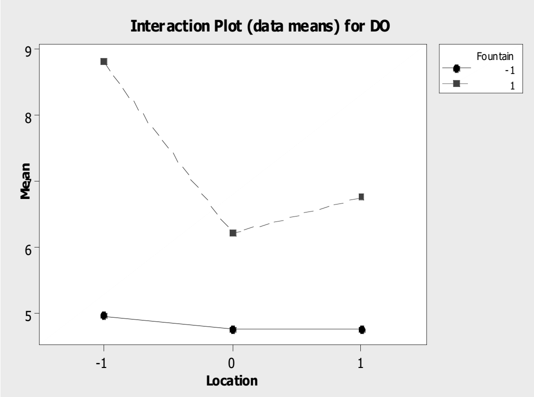


Figure 6. Interaction Between Fountain and Location Set Up at Two Levels

Table 3. Natural to Coded Units Transformation for Dissolved Oxygen Measurement, 3.7 m Away from the Fountain at 9.00 AM

Natural Units		Coded Units		DO (mg / L)	
Location	Time of Day	Location	Time of Day	ON	OFF
3.7 m	9:00 AM	-0.30	-0.33	6.1147	4.66

The interaction between the fountain and its location is shown in Figure 6. When the aeration system was in the OFF status, the DO concentration was observed to be 4.95 mg / L at 5 feet away from the fountain. At the same location when the aeration system was in the ON status, the value for DO was 8.8 mg / L. At the high level of location (7.6 m away from the fountain), the results were similar. When the fountain was OFF, the DO was 4.75 mg/ L and when the fountain was ON, the DO reached 6.75 mg/L. Note that there was a difference for the center point between fountain OFF and ON. The DO changed from 4.75 to 6.2 mg /L respectively.

Figure 7 shows the interaction between fountain and time of day. There was an increase in DO at different times of day whether the fountain was ON or OFF. However, the magnitude of the increase depended on the fountain status. When the fountain was ON, the DO value increased from 7.06 mg /L at 7:00 am to 8.49 mg / L at 1:00 pm. When the fountain was OFF, the DO value changed from 4.75 mg / L to 4.85 mg / L. As with the interaction between fountain status and location, the center point responded differently when the fountain was ON compared to OFF mode. The accepted minimum level of dissolved oxygen required for aquatic species is 6 mg/L (Hondzo & Steinberger, 2002). Results indicated that the floating fountain achieved the minimum desired level of dissolved oxygen.

Cost Analysis of the Floating Fountain

Table 4 lists the materials, labor and maintenance cost for the floating water fountain system. All cost items have been rounded to the nearest $50. Small-scale solar PV installations require minimum yearly maintenance, if any. Thus, a lifetime maintenance cost of $1,000 is included.

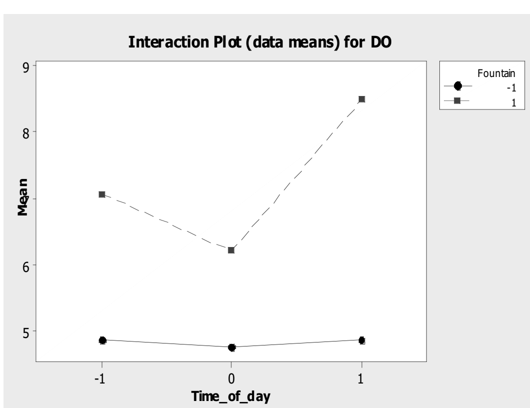


Figure 7. Interaction Between DO and Time of Day When the Fountain is ON and OFF

Total Cost = Materials Cost + Labor Cost + Maintenance Cost
= $6,600.00 (4)

On the other hand, assuming that the fountain is powered entirely by utility grid electricity, the total estimated amount of Kw used during operation of the Floating Fountain is as follows:

Fountain:
(24 V x 8.4 Amp) x 24 hours = 4.8 kw-hr/day (5)

Aerator:
(12 V x 6.4 Amp) x 24 hours = 1.8 kw-hr/day (6)

The Total usage is 6.4 kw-hr/day.

Thus, the estimated annual output in kw-hr/year is equivalent to 2340 kw-hr/year

If the cost of electricity (utility)
= $ 0.2175 / kw-hr (for Tallahassee, FL)
= approximately $500 / year

(*assuming no inflation and no increase in electricity tariffs*)

The use of grid electricity will require all the materials listed in Table 4, with the exception of the PV modules and batteries.

Table 4. Materials, Labor and Maintenance Cost of the Floating Fountain

Description	Cost ($)	Subtotal ($)
Materials		**5,000.00**
Modules	3,000.00	
Pumps	300.00	
Structure	500.00	
Tank	300.00	
Plumbing	100.00	
Compressor	200.00	
Batteries	200.00	
Hoses and fittings	150.00	
Linear current booster	150.00	
Wiring	100.00	
Labor	600.00	**600.00**
Maintenance	1,000.00	**1,000.00**
Total		**6,600.00**

Since the cost of solar PV modules and batteries is $3,200, the above analysis yields a payback period of 3,200 / 500 = 6.4 years, which is economically profitable, considering that the useful life of photovoltaic modules is 20 – 30 years. There is also the added environmental benefit of using solar energy.

Conclusion

Solar-powered appliances present unique advantages over traditional devices. The Solar-Powered Water Fountain (SPOWF) system manufactured and tested in this work achieved its main function, i.e., aeration of a selected water body with the aid of the aerator and fountain. Consequently, the dissolved oxygen (DO) concentration was increased significantly from a low level of 4.5 mg/L to a high of 9.95 mg/L, an increase of about 120%. Statistical analysis of the data (DO measurements) was conducted using a Split Plot Design. This mathematical model described a linear relationship between the primary operating factors, location of the aerator and time of the day, and the output, DO.

Economic analysis conducted using a payback period approach, by comparing the solar generated power with the utility grid electricity, yielded a payback period of 6.4 years. Considering that photovoltaic systems have a useful life of between 20 to 30 years, this payback period is profitable both economically and environmentally, considering the enormous benefits of the aerator / fountain unit to aquatic life.

The SPOWF system has immense potential commercialization opportunities. Possible consumer markets include environmental, building and construction, parks and gardens, private homes, estate developers, aquatic, and energy conservation.

Acknowledgement

This research was made possible with funding support provided by the US Department of Education Title III Grant Programs for Minority Students. Special thanks go to Dr. Yaw A. Owusu, Director of the Research for Center for Cutting-Edge Technologies and Professor of Industrial and Manufacturing Engineering at the FAMU - FSU College of Engineering, Tallahassee, Florida, for his guidance during this work. Our gratitude also goes to Dr. Ibrahim Braimah, also of the Research Center for Cutting-Edge Technologies, for the initiative he took in the design and assembly of the solar-powered floating fountain.

Dr. Hans Chapman is an Assistant Professor at the Department of Applied Engineering and Technology, Morehead State University, Kentucky. He is a member of the Gamma Mu Chapter of Epsilon Pi Tau.

Mr. Eduardo Gomez obtained his MS in Industrial Engineering from Florida State University, Tallahassee, Florida.

Dr. Nilesh N. Joshi is an Assistant Professor at the Department of Applied Engineering and Technology, Morehead State University, Kentucky.

Dr. Sanjeev Adhikari is an Assistant Professor of Civil Engineering and Construction Management at the Department of Applied Engineering and Engineering Technology, Morehead State University, Kentucky.

References

Boyd, C. E. (1997). *Advances in pond aeration technology and practices*. INFOFISH Int., 2/97, pp. 24–28.

Braimah, I. (2004). *Design and manufacture of affordable floating solar-powered water fountain* (published master's thesis). Department of Industrial and Manufacturing Engineering, Florida Agricultural and Mechanical University.

Butler, R. & Sinton, W. (2004). *Solar-powered water pumping system in New York State*. New York State Energy Research and Development Authority.

Dunlap, J. (2010). *Water pumping applications*. Photovoltaic Systems, American Technical Publishers, Orlando Park, IL, pp. 10-11.

Gomez, E. (2006). *Performance and cost analysis of solar–powered water fountain* (SPOWF) using a scaled model (published master's thesis). Department of Industrial and Manufacturing Engineering, Florida Agricultural and Mechanical University.

Hondzo, M. & Steinberger, N. (2002). *A semi-analytical model for dissolved oxygen mass transfer coefficient at the sediment–water interface*. Hydrobiologia, 479 (1-3), pp. 63–68.

Lynch, J. & Commer, W. (1994). *Understanding pond stratification*. Ohio State University Extension Fact Sheet (OSUEFS), A-7-10-03. Retrieved from http://ohioline.osu.edu/a-fact/0007.html

Markvart, T. (1999). *Solar electricity*. New York: John Wiley & Sons.

Marshall, J. M. & Dimova-Malinovska, D. (2002). *Photovoltaic materials–properties, technology and applications*. NATO Science Series II: Mathematics, Physics and Chemistry, (80), pp.15-18.

Michaud, J. P. & Noel, S. (1991). *A citizen's guide to understanding and monitoring lakes and streams*. Envirovision Environmental Consulting Service, Olympia, WA, 8-56.

Montgomery, D. C. (2005). *Design and analysis of experiments*. New York: John Wiley & Sons.

Myers, R. & Montgomery, D. C. (2002). *Response surface methodology: process and product optimization using designed experiments* (2nd ed.). New York: John Wiley & Sons.

Simpson, J. R., Kowalsky, S. M. & Landman, D. (2004). *Experimentation with randomization restrictions: targeting practical implementation*. Quality and Reliability Engineering International, 20 (5), pp. 481-495.

Wieland, A., & Kühl, M. (2006). *Regulation of photosynthesis and oxygen consumption in a hypersaline cyanobacterial mat (Camargue, France) by irradiance, temperature and salinity*. Journal of Microbiology and Ecology, 55 (2), pp. 195–210.

Innovative Rotary Displacer Stirling Engine: Sustainable Power Generation for Private and Fleet Vehicle Applications

Phillip R. Foster

Abstract

The Stirling cycle and related terminology is defined. Selected contemporary research involving the cycle in environmentally friendly applications is cited. Three conventional engine configurations that utilize a reciprocating power piston and crank shaft (the Alpha, Beta, and Gamma) are characterized, in terms of minimum number of components, advantages, and disadvantages. A new type of Stirling engine that employs a segmented rotary displacer and other related design improvements is presented along with preliminary findings from engine test runs.

Keywords: Stirling engine, electric power generation, renewable energy

Robert Stirling, in 1816, developed and patented the air engine that bears his name. The steam engines of the early 19th century had a reputation for unreliability, particularly regarding boiler explosion, and the Stirling cycle engine was thought by some as a possible substitute. Fascination regarding the potential for the Stirling cycle can be seen in the prolific development of Stirling cycle engines. Although this cycle provides several distinct advantages over other engine cycles currently in widespread use, there are some noteworthy disadvantages that technology has been hard pressed to eliminate. Thus, most innovation in Stirling engine design has not been adopted. Despite its shortcomings, the Stirling cycle engine is once again under study, but for entirely different reasons.

Worldwide concern over global warming and depletion of nonrenewable energy sources has renewed interest in the Stirling cycle being used for generating green or sustainable energy. Hsu, Lin, and Chiou (2003) reported on what is believed to be the first study of the Stirling cycle, fueled by waste energy, to generate electricity. The heat source was an incinerator. Experimental hardware included a free-piston Stirling engine coupled to a linear alternator. The researchers selected the free-piston Stirling because crank-driven Stirling engines "… presented some challenging design problems, including power modulation, leakage of working fluid, isolation of lubricants, etc." (Hsu et al., p. 61). Their findings demonstrated the difficulty in simulating actual engine performance, but on a larger scale, these authors pointed the way for other researchers to pursue the topic. In 2008, Snyman, Harms, and Strauss investigated applying the Stirling engine to energy generation through waste heat recovery. Their work focused on the utilization of three design analysis methods for simulating the optimization of a Beta configuration Stirling engine utilizing waste heat. Also included in their research was an experimental setup, using an instrumented Beta Stirling, which was powered by exhaust gases from the combustion of propane. The experimental setup replicated the simulation conditions. The authors' findings indicated that actual engine performance could be predicted by the simulation analysis. Chang and Ko (2009) also studied waste heat recovery for electricity generation utilizing the Stirling cycle. The renewable heat source used in their research originated from a waste incinerator. Leu (2010) studied the viability of biomass as a heat source for small-scale electrical generation using the Stirling engine. In this application, solid biomass fueled a fixed-bed gasifier with a combustor. Flue gas from the combustor provided the energy input for the Stirling engine-generator set.

The Stirling Cycle and Related Terminology

Stirling Cycle

All modern engines encountered in day-to-day use operate on a well-known cycle characteristic of their operation. For example, four-stroke reciprocating internal combustion engines utilize spark ignition. These function according to the Otto cycle. Engines that utilize compression ignition adhere to the Diesel cycle. These are mechanical cycles in which the working fluid, a fuel-air mixture, does not undergo a thermodynamic cycle involving cooling to the initial state. They are not reversible. Rather, after combustion imparts work to the mechanism, the remains of the working fluid are expelled from the engine and replaced with fresh mixture. A complete cycle may require one or two 360° revolutions (Cengel & Boles, 1998; Howell & Buckius, 1992; Wood, 1991).

The Stirling cycle is a reversible thermodynamic cycle consisting of four phases: heat addition (isovolumetric heating), expansion (isothermal expansion), heat rejection (isovolumetric cooling), and compression (isothermal compression). The four phases, which constitute one complete cycle, are completed in a single 360° revolution. A displacer alternately shuttles the working fluid from the cold to the hot workspaces of the engine in synchronization with the power piston. When in the hot workspace, the working fluid is heated, its pressure increases and it expands, thus moving a power piston and doing work. When the displacer shuttles the working fluid into the cold workspace, it is cooled, its pressure is reduced, and the power piston compresses the working fluid back to its original volume (Beale, 1984; Biwa, Tashiro, & Yazaki, 2008; Gras, 2011; Woodbank Communications, Ltd., 2011).

The positive attributes of the cycle have been well known since its inception. They include quiet operation, high thermal efficiency, safe operation, ease of operation, and the ability to function on any form of thermal energy (including both traditional combustion and non-polluting sources, such as biomass, solar energy, and geothermal energy). Shortcomings of the Stirling cycle have hindered its wider application in competition with steam, electric, and internal combustion. These shortcomings include the complexity of design and a relatively low power output per size and weight (Beale, 1984; Der Minassians & Sanders, 2009; Karabulut, Yucesu, & Koca, 2000; Snyman et al., 2008).

Selected Stirling Engine Terminology

A basic knowledge of selected Stirling engine terminology will help the reader understand the narrative pertaining to contemporary engine configurations. Further, it is essential to an understanding of the major objectives of this article, that is, the discussion of an innovative rotary displacer Stirling engine. The following terms are defined: phase angle, dead space, regenerator, working fluid, workspace, displacer, and volume compression ratio.

Phase angle (α). The displacer piston always moves in advance of the power piston. Both pistons are mechanically connected to a common flywheel and crankshaft. Typically, the phase angle is 90° (Senft, 2002; Snyman et al., 2008).

Dead space (dead volume). Conduits, passageways, internal heat exchangers, and similar features for conveying the working fluid that is not directly shuttled by the displacer make up the dead space. Some dead space is inevitable, but it must be minimized because it is detrimental to the indicated work of the cycle (Senft, 2002).

Regenerator. A feature consisting of layers or coils of heat-absorbent material located on the internal surfaces of working fluid conduits or passageways. This feature is used to increase the efficiency of the cycle by (a) accumulating excess heat from the expanding working fluid, which can then be transferred to the fluid during subsequent cycles, and (b) reducing the amount of heat that must be accommodated by the external heat sink through the cold workspace (Snyman et al., 2008).

Working fluid (working gas). The design of Stirling engines is such that the internal spaces contain a gas that is alternately heated and cooled during the cycle but is unable to escape from the mechanism. This gas, referred to as the working fluid or working gas, is commonly air. However, gases with lighter molecular weight (i.e., helium or hydrogen) provide thermodynamic advantages over air. The working fluid is not consumed in the cycle (Snyman et al., 2008).

Workspace. The interior volume of the displacer housing, excluding the displacer itself and any engine dead space, constitutes the workspace. This area contains the bulk of the working fluid and has provisions for the addition and rejection of heat. These provisions subdivide the workspace into the hot workspace and the cold workspace, areas that are thermally insulated from each other.

Displacer. The displacer is a reciprocating piston that moves along the axis of the displacer housing, thus alternately communicating the working fluid to the hot and cold workspaces of the engine (Beale, 1984; Der Minassians & Sanders, 2009).

Volume compression ratio. Any given engine has a maximum volume and a minimum volume. The former is the sum of the displacer volume plus the power piston cylinder volume. The latter is the displacer volume alone. The ratio of the maximum engine volume to the minimum engine volume is referred to as the volume compression ratio (Senft, 2007).

Conventional Commercial Stirling Engine Configurations

Three related engine configurations have persisted over the years and these are most commonly used in contemporary commercial applications: the Alpha, the Beta, and the Gamma. All of these configurations utilize the conventional piston, crankshaft, and cylinder arrangement, but two of the three (i.e., Beta and Gamma) use them in conjunction with a uniquely Stirling cycle addition, the displacer. The following sections characterize the three prevalent reciprocating piston-type Stirling cycle engines. Descriptions and figures are generic interpretations of these configurations. No attempt has been made to describe or render the complexities associated with actual working engines.

Characteristics of the Alpha Stirling Engine

The Alpha Stirling engine consists of two power pistons, each with a separate cylinder and connecting rod. One power piston and cylinder represents hot workspace, the other cold workspace. The connecting rods join a common journal on a single flywheel/crankshaft. This arrangement is shown in Figure 1. As the figure depicts, the hot and cold workspaces are physically separated from each other. This feature provides excellent thermal isolation for the two workspaces. The conduit that joins the two workspaces, however, adds to the dead space associated with this design.

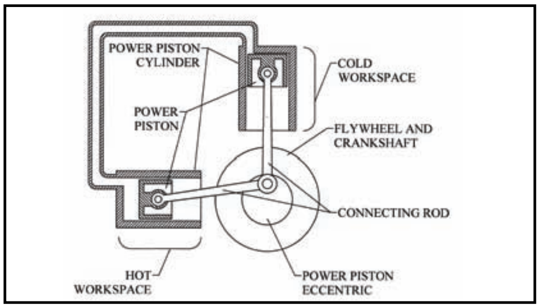


Figure 1: Alpha Configuration of Stirling Engine

The Alpha then, in its simplest form, utilizes four reciprocating parts and one rotary part. This configuration requires a close tolerance fit between each power piston and its respective cylinder. This is not an issue for those components operating within the cold workspace. The hot workspace piston and cylinder do represent a problem with regard to maintaining a reliable seal in an environment with high heat coupled with sliding friction. Seals on this piston can be subject to early failure due to these operating conditions. Techniques that alleviate piston seal failure may also increase engine dead space. The Alpha is known for its high power-to-volume ratio.

Characteristics of the Beta Stirling Engine

The Beta Stirling engine included design features that eliminated the hot seal failure issues of the Alpha. The engine utilizes a power piston with a connecting rod, similar to the "cold" power piston of the Alpha, but the "hot" power piston is replaced by a displacer with a connecting rod. The displacer represents a major improvement. The power piston and the displacer both share a common cylinder and a common flywheel/crankshaft. This arrangement is shown in Figure 2. Unlike a piston, the displacer does not require a tight tolerance seal along its surfaces. Its function is to simply shuttle working fluid within the hot and cold workspaces. This insulates the power piston from the high temperatures that exist in the hot workspace. Also, dead space is minimal.

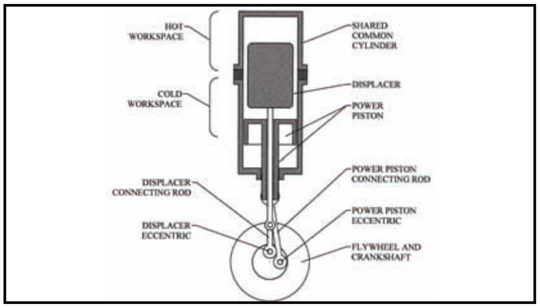


Figure 2: Beta Configuration of Stirling Engine

A design in which there is sharing of a common cylinder presents thermal conduction issues not encountered in the Alpha. The junction of Beta hot and cold workspaces must include an additional thermal barrier to reduce conduction and maintain efficiency. The Beta, in its simplest form, consists of four reciprocating parts and one rotary part.

Characteristics of the Gamma Stirling Engine

The Gamma Stirling engine is similar to the Beta it that it utilizes the same type of moving parts. It has one major difference. The Gamma power piston does not share a common cylinder with the displacer. Its design employs two distinct cylinders, a feature evident in Figure 3. However, the hot and cold workspaces of the displacer cylinder require the addition of a thermal barrier. Therefore, in its simplest form, the

Gamma configuration also consists of four reciprocating parts and one rotary part. The Gamma shares the same advantages as the Beta and also holds the potential for being mechanically simpler. Gammas are particularly suited to multicylinder applications.

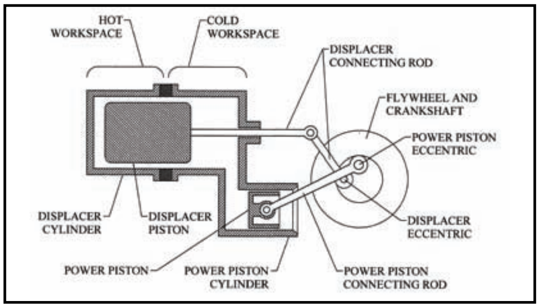


Figure 3: Gamma Configuration of Stirling Engine

In the preceding explanation, the reciprocating and rotating part count was always prefaced by the phrase "in simplest form." The reality of conventional commercial Stirling design seldom if ever adheres to the simplest form. Contemporary engines display a range of mechanisms, some fairly complex, to change linear motion into rotary.

Summary of Conventional Stirling Configurations

Certain generalizations can be made from the preceding sections. There is a renewed interest in the Stirling cycle for sustainable and/or environmentally friendly electrical generation. Reciprocating piston-type Stirling engines, particularly the Alpha, the Beta, and the Gamma, have been harnessed in these applications and have been reported to be effective. These engine configurations, in their simplest form, utilize four reciprocating parts and one rotary part (per power cylinder). Actual commercial engines are typically more complex (i.e., have more moving parts per power cylinder).

Genesis of the Stirling With Attitude (SWATT) Engine

The author was convinced that the cycle could be effectively achieved with fewer than five moving parts per power cylinder. A reduction in parts, particularly reciprocating parts, would contribute to mechanism longevity while reducing complexity. It was proposed that the cycle be represented by three moving parts, two reciprocating and one rotary. The reciprocating parts included the power piston and connecting rod assembly. The rotary part was the displacer. Integrated into the displacer were the crankshaft/flywheel and a valve mechanism. The crankshaft/flywheel also incorporated provisions for teaming engines to provide greatly simplified, multipower cylinder configurations.

The following parameters were selected as a starting point for initial engine design: liquid cooling, power cylinder bore and stroke = 1.000" X .625" (volume = .491 in3), phase angle 90°, and volume compression ratio 1.244. The power cylinder specifications and the volume compression ratio established the volume of the rotary displacer at 2.009 in3. Materials selected included stainless steel for all major structural components, graphite for the piston, titanium for the connecting rod assembly, and polymer for the rotary displacer. The following sections address design features of major components, specifically, the individual displacer segments, the rotary displacer assembly, the displacer housing, and a rotary valve mechanism.

Individual Displacer Segments

The displacer of the subject engine is not of one-piece construction. Rather, it is made up of 16 polymer segments, 14 of which are virtually identical. Individually balanced, each has a stepped profile along about 180° of the outer circumference (see Figure 4), which is evident along the lower half of the segment in the figure. The same profile is mirror imaged in the internal surfaces of the two-piece stainless steel displacer housing. This design feature increases the surface area of the hot and cold workspace, enabling a more rapid isovolumetric heating (expansion) and cooling (compression) of a larger volume of working fluid. The six holes adjacent to the stepped area balance the segment by removing a mass equivalent to that removed in the creation of the stepped profile.

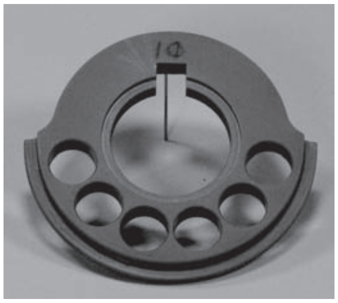


Figure 4: Typical Rotary Displacer Segment

The balancing holes, in the fully assembled displacer, are filled with an expanded foam insert that has a very low mass coupled with a high temperature resistance. If left unfilled, balancing holes would add substantially to the engine's dead space. The axial hole with keyway locates the segment along the assembled displacer's long axis while preventing rotation about it. Individual segments are kept in position through two retaining rings, one on either side of each segment. One of these rings is shown in Figure 5.

Using a segmented displacer that had a stepped profile that could enhance the heat transfer area was possible because the displacer was rotary. This permitted the use of one of several relatively new engineered polymers. PolyEtherEtherKetone (PEEK) has mechanical and thermal properties that make it ideal for this application. These include: tensile strength of 16 ksi, compressive strength of 20 ksi, maximum operating temperature of 480°F, thermal conductivity of 1.75 BTU-in./ft.2-hr.-°F, and a coefficient of thermal expansion, 2.6 X 10-5in./in./°F (Boedeker Plastics, Inc., 2011, pp. 2-3). Thus, PEEK is a very good insulator that will neither absorb nor transmit too much thermal energy. It is also strong for a polymer and has a high operating temperature ceiling. Like most polymers, however, it "grows" when heated, and this growth is more than that encountered with most metallics. The type of stainless steel used in the water-cooled displacer housing is AISI 304, which has a much lower coefficient of thermal expansion, 9.6 μ in./in..-°F (Oberg, Jones, Horton, & Ryffel 2004, p. 472). Because the displacer segments are individually located along the axis of the housing using retaining rings, their relatively large coefficient of expansion is of consequence for a relatively short lateral dimension, their individual thickness. This expansion is easily accommodated in the sizing of the corresponding workspace for a given segment, even though the stainless "grows" very little by comparison.

The Rotary Displacer Assembly

Adoption of a rotary displacer over a reciprocating one provided two significant advantages. These are reduced cycle power needs and increased design flexibility. Each will be briefly discussed.

Reduced cycle power needs. Reciprocating displacers waste energy. In the 360° rotation representing one complete cycle, the displacer changes direction twice. The displacer is accelerated from rest at 0°. It achieves maximum velocity at 90°, followed by deceleration and rest again at 180°. It is again accelerated achieving maximum velocity at 270°, followed by deceleration as it approaches 360° in its return to starting point. Energy is consumed in both acceleration and deceleration. A rotary displacer, however, never changes direction. Therefore, no engine energy is consumed in the constant acceleration-deceleration associated with the reciprocating arrangement. Further, its mass contributes to that required by the flywheel/crankshaft assembly that is essential to the Stirling cycle.

Increased design flexibility. Reciprocating displacers limit the design options available for optimizing engine operation. This is because minimizing reciprocating mass must take precedence over other factors. Minimizing mass influences material selection, which can result in compromises in thermal and mechanical properties. For example, high stiffness, low weight, low thermal conductivity, and high thermal resistance are also very desirable displacer material characteristics. Unfortunately, it is difficult to identify a cost-effective material selection that offers such diverse characteristics and is, at the same time, low mass. Also affected are the physical design, the axial orientation (vertical vs. horizontal), and displacer surface topology (i.e., its axial cross-section). Surface topology includes design features intended to increase the displacer surface area that is available for heat transfer. Minimal surface area for effective heat transfer has been cited as an issue. Senft (2007, p. 64) wrote "[i]n many real engines the expansion and compression processes for the most part occur in engine spaces that have relatively little heat transfer area." Mechanism wear must be controlled to maintain an adequate service life. For the same reasons that they waste energy, reciprocating displacers load other components (e.g., bearings and linkages), requiring more robust design of these components.

A rotary displacer, at operational speed, exerts radial and thrust loads only. These are the normal loads placed on bearings, and they do not adversely influence engine design in other areas. A rotary displacer also opens up design options in other ways. Because mass is not an issue, there are novel design opportunities for the displacer. The rotary displacer can be long, can incorporate features for increased surface area, and can still function from ambient to operating temperature within the close confines of the stainless housing.

Figure 5 shows the fully assembled, segmented rotary displacer. The top surface of the displacer creates the hot and cold workspaces of the engine; this is in concert with the hot and cold sections of the displacer housing. The lines appearing along the circumference, indicating the sides of each segment, also represent the physical space between segments. This space allows for the thermal "growth" that is

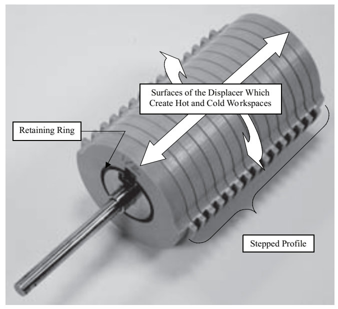


Figure 5: Complete Segmented Rotary Displacer

inevitable as the segment warms from close proximity with the hot workspace. Each segment is restricted in its lateral movement associated with this "growth," by two retaining rings. The maximum extent of this movement, either left or right, always coincides with the width of the corresponding radial groove in the housing.

The Displacer Housing

The displacer housing consists of four major components, all of type 304 stainless steel. The hot and cold workspaces are achieved through two partial cylinders that are joined along their edges to form a complete cylinder. A PEEK seal is located along their linear joints to prevent thermal conduction between the hot and cold workspaces. Their internal configuration, as previously noted, is a mirror image of the rotary displacer. The ends of the housing contain the bearings and provisions for liquid cooling. Additionally, the right-hand end contains features that contribute to the rotary valve mechanism as well as the means for the hot and cold workspaces to communicate with the power piston. The internal ends of the housing are faced with PEEK seals to prevent thermal conduction. Clearances between the rotary displacer and the housing are tight to minimize dead space but sufficient to ensure no contact. Figure 6 shows a single displacer segment in a partial assembly with half of the displacer housing. In this figure, the housing shown is that of the cold workspace (note the coolant manifold connections at the lower left). A single displacer segment is shown here to clarify the internal configuration of the housing, the cold workspace. One segment retaining ring also appears clearly.

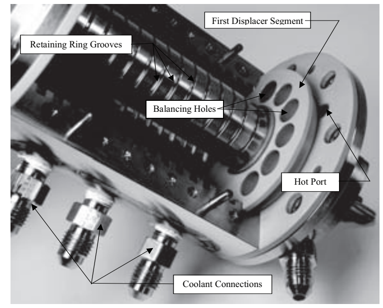


Figure 6: Open Displacer Housing Showing Cold Workspace and Partially Assembled Rotary Displacer

Each of the radial grooves along the inner surface of the cold workspace corresponds to one of the 15 segments not yet in the displacer assembly. The internal configuration of the hot side of the displacer housing is identical to that of the cold side.

Rotary Valve Mechanism

Another design feature that is possible because of the rotary displacer is a rotary valve integral with the first displacer segment and the adjacent portion of the housing. This arrangement does not add additional moving parts, but it effectively directs the working fluid in the following way. The power cylinder has two ports, one in communication with the hot workspace through the hot port (see Figure 6) and one in communication with the cold workspace through the cold port. The cold port is not visible in Figure 6; it is obscured by the segment. Regardless, it is situated 180° from the hot port and lies on the same circular centerline in the side of the displacer housing. These ports are positioned immediately adjacent to the stepped profile groove occupied by the first displacer segment. Recall that the stepped profile of the segments exists for about 180° only (see Figure 3). Hot and cold ports connect to the power cylinder through passageways. The cold port and its passageway represent a heat sink in that they are kept cold by the engine's liquid cooling system. These areas are also insulated from the hot workspace. The hot port and its passageway represent thermal energy input, being in communication with the hot workspace. When the displacer rotates through its cycle, it alternately blocks and opens the hot and cold ports. During isovolumetric heating (expansion), therefore, the hot working fluid is inhibited from moving through the cold passageway, even though pressure throughout the engine is the same. Similarly, during isovolumetric cooling (compression), the cold working fluid is inhibited from moving through the hot passageway.

Preliminary Findings From Initial Running of SWATT Engine

This engine has been under development for approximately 10 years, and much of this time has been spent on design and fabrication. Figure 7 shows the assembled engine from the perspective of the cold workspace. Major subassemblies have been identified.

In order to run the engine, various auxiliary units must be connected. These include a propane gas burner, connections for the liquid cooling, and various instrumentation components. To facilitate collection of engine performance data, a test bed was constructed to hold the engine and auxiliary units. The complete setup has been operable for about two years and has accrued data from about 120 hours of run time. It is instrumented with five externally mounted surface contact type K thermocouple probes. These are located at various positions to collect temperature distribution data. Two probes monitor hot workspace (thermocouple locations 1 and 3), two monitor cold workspace, and one monitors power cylinder temperature, also representing cold workspace (thermocouple locations 2, 4 and 5, respectively). Thermocouple probes are connected to two Fluke 52 II and one Fluke 51 II digital thermometers. This instrumentation displays data that provides the mean hot workspace temperature, the mean cold workspace temperature, and the resulting difference in temperature (ΔT). A noncontact laser photo tachometer, an Extech Model 1PX61, is also mounted on the test bed. This instrument displays the engine's RPM. Because there is a patent pending on the engine, it is now possible to release some design and performance information.

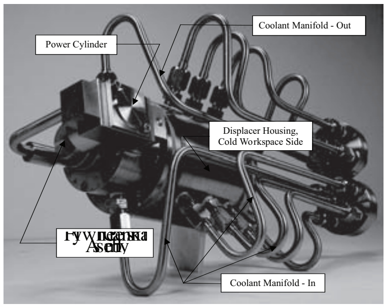


Figure 7: Assembled SWATT Engine

Although its appearance is radically different from Alpha, Beta, or Gamma Stirling engines, the SWATT engine definitely functions on the Stirling cycle (i.e., the nonconsumed working fluid is alternately heated and cooled but always returns to its initial state with each revolution). Although work on the design parameters it still under way, some unexpected findings regarding one, the phase angle, have come to light. The ideal phase angle was found to be remarkably different from that typically attributed to either Beta or Gamma engines, which operate with a phase angle of approximately 90°. As previously noted, the SWATT engine was initially designed and built with this angle. Initial engine runs, however, indicated ceiling RPM of about 400, which was less than anticipated. By varying the phase angle on the flywheel/crankshaft assembly, it was possible to experimentally determine an ideal phase angle through observation of tachometer readings.

Determination of the Ideal Phase Angle

Eccentrics

The flywheel/crankshaft assembly consists of several components, one of which serves as an eccentric. A cylindrical piece, the eccentric is bored through its longitudinal centerline to connect to the rotary displacer axle. When assembled, only one orientation is possible. A crank pin, which engages the power piston connecting rod, screws into the eccentric. The distance from the eccentric centerline to that of the crank pin establishes the stroke of the engine. The radial displacement of the crank pin, in relation to that of the rotary displacer, establishes the phase angle. Eccentrics were constructed to enable engine operation with phase angles of 75, 80, 85, 115, 120, 125, 130, and 135 degrees. Phase angles on either side of 90° were selected because it was not known whether an ideal angle was less than or greater than 90°.

Engine Performance Log

An engine performance log was developed to standardize data collection during phase angle testing. The log provided for manual recording of the time of an observation, the temperatures at the five thermocouples, and the RPM. Also recorded were the mean hot workspace temperature, the mean cold workspace temperature, and the temperature difference (ΔT) between each. The last three quantities are calculated and recorded post test. A representation of this form is depicted in Table 1. This contains test data for the 90° phase angle.

Table 1 90° Phase Angle Performance Log Showing RPM and Temperature in °F

	Thermocouple Locations (1-5) and Recorded Temperatures (°F)					Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
Time (h:m)	T_1	T_2	T_3	T_4	T_5				
4:00	77	77	77	77	75	N/A	N/A	N/A	N/A
4:05	182	80	181	79	76	182	78	104	576
4:07	197	81	185	80	77	191	79	112	577
4:09	197	82	169	81	78	183	80	103	420
4:11	198	82	169	81	79	184	81	103	484
4:13	198	82	168	81	79	183	81	102	428
4:15	190	82	156	81	80	173	81	92	368
4:17	198	82	174	81	80	186	81	105	511
4:19	204	82	179	81	81	192	81	111	407
4:21	198	83	164	81	81	181	82	99	382
4:23	193	83	158	81	81	176	82	94	364
4:25	193	82	159	81	81	176	81	95	392
4:27	194	83	159	81	82	177	82	95	408
4:29	194	82	160	81	82	177	82	95	418
4:31	194	82	161	81	82	178	82	96	426
μ	195	82	167	81	80	181	81	100	440

Note that the first data row, highlighted in red, shows only time and thermocouple temperatures at the start of the test. Calculation of mean hot and cold workspace temperatures as well as the engine workspace temperature difference (ΔT) are irrelevant at this point. At the bottom of the table, means are provided for temperatures taken at all thermocouple locations, grand means for the hot and cold workspaces, mean temperature difference, and mean RPM for the duration of the test run.

Phase Angle Testing Procedure

Experience running the engine has demonstrated that it needs approximately 20-23 minutes of initial run time to stabilize operation. The term stabilize implies that engine RPM is at or very near maximum, and minimal burner adjustment is necessary to maintain that RPM. This condition is termed steady state, and once achieved, heat input and RPM output remain relatively consistent over the duration of the engine test run.

During the initial 20 minutes of operation, however, constant adjustment of the burner is required. Thus, temperature and RPM data collected during this time display fluctuations that necessarily differ from test run to test run. This is evident in first 11 rows of temperature data for thermocouples monitoring hot workspace (T1 and T3) and the respective RPM figures shown in Table 1. The magnitude of fluctuations is dependent on how aggressively heat is applied. Both excessive heat and insufficient heat are detrimental to maximal RPM. Though high temperatures and RPMs can occur during this time, they do not characterize sustainable operation. These initial temperature and RPM figures are useful, even essential, in stabilizing operation, but that is the extent of their utility. For this reason, it was decided that all test runs in the phase angle study would be 31 minutes in duration with a 23-minute stabilization period, during which collected data would not be utilized to assess the effectiveness of a given angle. Only the last 8 minutes of the test would be used to collect data representing the performance of a given phase angle. The temperature and RPM sampling interval for a complete test run was set at 2 minutes with the exception of the initial reading, which was 5 minutes from the commencement of the test (the engine requires an approximate 3-minute warm up prior to running). All temperatures were recorded in degrees Fahrenheit (°F). Temperatures and RPMs were recorded to the nearest integer and standard rounding practice was used.

Findings: Phase Angles 75°, 80°, and 85°

The 75° phase angle was tested first. It was not possible to start the engine. The same results occurred with the 80° phase angle. At the 85° phase angle, the engine started, but it proved very difficult to stabilize, and the test run was aborted. Therefore, there is no performance data for the first three tests. Lack of run data, however, did provide valuable insight. Because the initial engine configuration successfully employed a 90° phase angle, the difficulties encountered with angles of 75°, 80°, and 85° demonstrated that if there were potential for improved engine RPM performance through phase angle manipulation, that manipulation would involve phase angles of 90° or more.

Findings: Phase Angle 90°

An eccentric having the 90° phase angle suggested by the literature was initially built with the engine. It was effective when the engine was first run, but empirical evidence characterizing the extent of its effectiveness had yet to be collected. Therefore, the fourth phase angle test was based on 90°, and, as previously noted, findings are shown in Table 1. This table, however, can be condensed through the elimination of the run data accrued during the 23-minute stabilization period. This reformatting (see Table 2), which will be used in the discussion of remaining phase angles as well, makes it possible to compile means for temperatures and RPMs that are not influenced by startup fluctuations.

Table 2 90° Phase Angle Performance Log Showing RPM and Temperature in °F after Engine Stabilization

Time (Minutes into Run)	Thermocouple Locations (1-5) and Recorded Temperatures (°F): T_1	T_2	T_3	T_4	T_5	Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
25	193	82	159	81	81	176	81	95	392
27	194	83	159	81	82	177	82	95	408
29	194	82	160	81	82	177	82	95	418
31	194	82	161	81	82	178	82	96	426
μ	194	82	160	81	82	177	82	95	411

Table 3 115° Phase Angle Performance Log Showing RPM and Temperature in °F after Engine Stabilization

Time (Minutes into Run)	Thermocouple Locations (1-5) and Recorded Temperatures (°F): T_1	T_2	T_3	T_4	T_5	Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
25	194	80	163	77	81	179	79	100	713
27	196	80	164	78	82	180	80	100	709
29	197	80	163	78	82	180	80	100	696
31	197	80	162	78	82	180	80	100	685
μ	196	80	163	78	82	180	80	100	701

Findings indicate a high level of consistency for virtually all temperature readings. The consistency of cold workspace temperatures (taken from locations T2, T4, and T5,) indicates sustainable, effective cooling (grand mean of 82°F). This is characteristic of steady state operation. A similar statement can be said of hot workspace temperatures taken from locations T1 and T3 (grand mean of 177°F). The 90° phase angle also rendered a mean ΔT of 95°F and an RPM of 411.

Findings: Phase Angle 115°

Contained in Table 3 are findings from the 115° phase angle test. Again, temperatures display consistency. Cold workspace temperatures had a grand mean of 80° F, whereas hot workspace temperatures indicate a grand mean of 180°F. This, in conjunction with consistency in RPM, indicates the engine is functioning near steady state. The mean ΔT was 100°F and the mean RPM was 701. The RPM statistic represents a major improvement over that obtained with the 90° angle suggested by the literature.

Findings: Phase Angle 120°

Table 4 contains the findings for the 120° phase angle test. Temperatures remained consistent at a given thermocouple over time. Cold workspace temperatures had a grand mean of 82° F, whereas hot workspace temperatures indicate a grand mean of 179°F. These values are similar to those derived from the 115° phase angle data. The ΔT, at 97°F, dropped slightly from that encountered with the previous phase angle, but the average RPM recorded during the test increased to 712.

Findings: Phase Angle 125°

Table 5 contains the findings for the 125° phase angle test. Individual hot workspace thermocouples (T1 and T3) indicated temperatures that remained consistent, but to a somewhat lesser degree than the previous test. Individual cold workspace temperatures, as measured by thermocouples at locations T2, T4, and T5, displayed the same high level of consistency as seen in previous tests.

Table 4 120° Phase Angle Performance Log Showing RPM and Temperature in °F after Engine Stabilization

Time (Minutes into Run)	Thermocouple Locations (1-5) and Recorded Temperatures (°F)					Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
	T_1	T_2	T_3	T_4	T_5				
25	194	82	163	81	82	179	82	97	729
27	195	83	163	81	82	179	82	97	720
29	195	83	162	81	82	179	82	97	708
31	195	83	162	81	82	179	82	97	691
μ	195	83	163	81	82	179	82	97	712

Table 5 125° Phase Angle Performance Log Showing RPM and Temperature in °F after Engine Stabilization

Time (Minutes into Run)	Thermocouple Locations (1-5) and Recorded Temperatures (°F)					Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
	T_1	T_2	T_3	T_4	T_5				
25	194	75	160	71	81	177	76	101	776
27	192	74	157	71	81	175	75	100	800
29	191	74	156	71	81	174	75	99	798
31	191	74	157	71	81	174	75	99	782
μ	192	74	158	71	81	175	75	100	789

Cold workspace temperatures had a grand mean of 75° F, whereas hot workspace temperatures indicate a grand mean of 175°F. The average ΔT returned to 100°F. The average RPM recorded during the test increased to 789, the highest yet obtained.

Findings: Phase Angle 130°

Contained in Table 6 are findings from the 130° phase angle test. Again, temperatures remained consistent. The mean ΔT was 100°F, but the RPM dropped to 738.

RPM dropped to 700 (see Table 7). This is the second consecutive drop in RPM, and it represents a substantial loss from the peak RPM value obtained with a 125° phase angle.

Summary of Findings Regarding the Ideal Phase Angle

The SWATT engine is a Stirling, however, it functions best with a phase angle that is significantly different from other Stirling engine configurations. It is not possible, at this time, to speculate as to why. What can be said is the ideal phase angle for SWATT is near 125°.

Table 6 130° Phase Angle Performance Log Showing RPM and Temperature in °F after Engine Stabilization

	Thermocouple Locations (1-5) and Recorded Temperatures (°F)					Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
Time (Minutes into Run)	T_1	T_2	T_3	T_4	T_5				
25	193	81	163	79	80	178	80	98	794
27	193	81	164	79	80	179	80	99	795
29	194	81	165	79	81	180	80	100	751
31	195	81	166	79	81	181	80	101	610
μ	194	81	165	79	81	180	80	100	738

Findings: Phase Angle 135°

This was the last phase angle tested. Findings indicate consistency in all cold workspace temperature readings (grand mean of 82°F). Data from thermocouples monitoring hot workspace temperature (T1 and T3), however, display some variability that was not evident in previous tests. The hot workspace temperatures indicate a grand mean of 176°F. The average ΔT was 94°F, and the

The mean ΔT has been reported in the discussions of phase angle tests. This has been provided for information purposes only. Although it seems to cluster around or at 100°F, it is not speculated that this has any relationship whatsoever to a maximized RPM for a given phase angle. Had the test procedure specified temperature measurements in °C, the derived values for mean ΔT would not have appeared so “calculated.”

Table 7 135° Phase Angle Performance Log Showing RPM and Temperature in °F after Engine Stabilization

	Thermocouple Locations (1-5) and Recorded Temperatures (°F)					Mean Hot: $(T_1 + T_3) \div 2$ (°F)	Mean Cold: $(T_2 + T_4 + T_5) \div 3$ (°F)	ΔT: (Mean Hot – Mean Cold) (°F)	RPM
Time (Minutes into Run)	T_1	T_2	T_3	T_4	T_5				
25	192	83	159	81	82	176	82	94	704
27	187	83	154	81	82	171	82	89	700
29	191	83	161	81	82	176	82	94	739
31	193	83	164	81	82	179	82	97	658
μ	191	83	160	81	82	176	82	94	700

Contained in Table 8 is a brief summary of findings that support a phase angle of 125°. Other performance characteristics have been observed during the initial running of the engine. The mean ΔT from ambient at which initial running occurs is 70°F with a corresponding RPM of about 550. From this point, the engine gradually heats to a mean ΔT of 99°F and the sustained 800-850 RPM. This represents steady state and the performance remains basically unchanged for the length of an individual test run (maximum to date of about six hours). This performance is based on the previous indicated parameters while using air as the working fluid, atmospheric buffering from below, and no regenerator. The mean ΔT at initial start is noteworthy. It has been documented on all engine tests utilizing the 125° phase angle.

Table 8 Summary of Phase Angle Study Findings

Phase Angle	ΔT (°F)	RPM
90°	95	411
115°	100	701
120°	97	712
125°	100	789
130°	100	738
135°	94	700

The Direction of Future Research Regarding this Engine

Commercial Stirling engines utilize noble gasses, such as hydrogen or helium, as the working fluid. These have superior thermodynamic properties. The SWATT engine was also designed for pressurized helium, which requires a gas-tight enclosure surrounding the flywheel/crankshaft and power piston/cylinder assemblies. The fabrication of this enclosure is incomplete at this writing. Once the enclosure is complete, the research will commence with optimization of selected traditional Stirling design parameters (e.g., volume compression ratio). The really significant optimization, however, will focus on the configuration of the rotary displacer itself. This is believed to be the key feature in terms of simplicity, reliability, and, hopefully, increased power output. Of particular consequence is the configuration of the first displacer segment. This controls the opening and closing of the hot and cold ports and also the duration of same as well as any overlap, during which times both ports are simultaneously open.

Implications of this Technology for an Energy Conscious World

The idea of using the Stirling cycle in hybrid electric applications is not new. Recent research provides ample evidence. Obtaining reliable, sustained engine operation coupled with reasonable power output, however, constitutes the real problem. When this becomes reality, there will be myriad applications.

The initial application of this technology, as far as the author was concerned, was in association with the small electric-powered vehicles that were recharged from the grid during non-operational periods. The storage batteries used by these vehicles provided sufficient charge for intra-city commuting for up to four hours, after which recharging was necessary. The vehicles could operate somewhat longer, however, failure to recharge at this point would shortly cause a condition known as deep discharge. Deep discharge always required excessive grid time recharging and could also be potentially damaging to the batteries. An on-board Stirling engine, operating on environmentally friendly fuels, could act as an auxiliary recharger in the field, thus extending the vehicle's range and lessening required charging time on the grid.

A similar concept involves fleet use. In this application, a larger Stirling-powered generator in a stationary configuration, would be harnessed to recharge batteries of small, electric-operated fleet vehicles. This would eliminate the added cost of individual on-board Stirling engines and would enable the use of exclusively electric propulsion without extra demands on the power grid.

On a broader scope, this engine could find application in electric generation through waste heat recovery. Early research in this area, as cited in the introductory sections of this paper, indicates a potential contribution.

Dr. Phillip R. Foster is an Associate Professor in the Department of Engineering Technology in the College of Engineering at the University of North Texas. He is a Member-at-large of Epsilon Pi Tau.

References

Aremco Products, Inc. (2011). Machinable & dense ceramics technical bulletin A1. Retrieved from http://www.aremco.com/products/machinable-dense-ceramics/.htm

Beale, W. (1984). Understanding Stirling engines. Retrieved from http://sleekfreak.ath.cx:81/3wdev/VITAHTML/SUBLEV/EN1/STIRLING.HTM

Biwa, T., Tashiro, Y., & Yazaki, T. (2008). How does Stirling engine work? J*ournal of Power and Energy Systems, 2(5)*, 1254-1260.

Boedeker Plastics, Inc. (2011). PEEK (PolyEtherEtherKetone) Specifications. Retrieved from http://www.boedeker.com/peek_p.htm

Cengel, Y. A., & Boles, M.A. (1998). *Thermodynamics: An engineering approach (3rd ed.).* Boston: WCB/McGraw-Hill.

Chang, T. B., & Ko, M. S. (2009). Optimizing the power generation of a radiation driven Stirling engine used in the combustion chamber of an incinerator. *Journal of the Chinese Institute of Engineers, 32(1),* 141-147.

Crane, H. R. (Ed.). (1990). The Stirling engine – 173 years old and running. *The Physics Teacher, 28*(4), 252-253.

Der Minassians, A., & Sanders, S. R. (2009). Multiphase Stirling engines. *Journal of Solar Energy Engineering, 131*, 021013-1-021013-11.

Gras, P. (2011). Operating principles of Stirling engine. Retrieved from http://www.robertstirlingengine.com/principles.php

Howell, J. R., & Buckius, R. O. (1992). *Fundamentals of engineering thermodynamics (2nd ed.).* NY: McGraw-Hill.

Hsu, S. T., Lin, F. Y., & Chiou, J. S. (2003). Heat-transfer aspects of Stirling power generation using incinerator waste energy. *Renewable Energy, 28*(1), 59-69.

Karabulut, H., Yucesu, H. S., & Koca, A. (2000). Manufacturing and testing of a v-type Stirling engine. *Turkish Journal of Engineering and Environmental Sciences, 24(2)*, 71-80.

Leu, J. H. (2010). Biomas power generation through direct integration of updraft gasifier and Stirling engine combustion system. *Advances in Mechanical Engineering*, 2010, 1-7.

Oberg, E., Jones, F. D., Horton, H. L., & Ryffel, H. R. (2004). *Machinery's handbook* (27th ed.). New York: Industrial Press.

Senft, J. R. (2002). Optimum Stirling engine geometry. I*nternational Journal of Energy Research, 26(12)*, 1087-1101.

Senft, J. R. (2007). *Mechanical efficiency of heat engines.* New York: Cambridge University Press.

Snyman, H., Harms, T. M., & Strauss, J. M. (2008). Design analysis methods for Stirling engines. *Journal of Energy in Southern Africa, 19(3),* 4-19.

Strong, A. B. (2006). *Plastics: Materials and processing* (3rd ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Wood, B. D. (1991). *Applications of thermodynamics (2nd ed.)*. Prospect Heights, IL: Waveland Press, Inc.

Woodbank Communications, Ltd. (2011). Electropaedia battery and engine technologies: Energy conversion and heat engines (with a little bit of thermodynamics). Retrieved from http://www.mpoweruk.com/heat_engines.htm

Impact of Climate and Geographic Location on Moisture Transport in Wood Construction Walls and Implications for Selecting Vapor Retarders

Kennard G. Larson

Abstract

This research effort studied two similarly built homes in two different geographic locations in an attempt to demonstrate the affect that climatic conditions have on the selection and installation of appropriate vapor diffusion retarders to control moisture transport in wood-framed structures. Much misinformation and suppositions exist regarding which vapor diffusion retarder to use, where to place it within the structure, and whether it is even necessary. As a result, uncontrolled moisture transport is often a significant factor in the premature degradation of a structure; this also adds to poor indoor air quality resulting from the growth of mold and mildew. Nine climatic values of temperature, humidity, and air pressure were recorded at 20-30 minute intervals at various locations within the wall cavities and the outside of both test structures, for a 12-week period from January to March. These data allowed the researchers to perform calculations to predict the potential for growth of mold or mildew within the structure. Ultimately, these data were further compared for moisture transport behavior with the simulation software WUFI ("Wärme und Feuchtigkeit Instationären), a PC program developed by the Institute for Building Physics in Germany and the Oak Ridge National Laboratories in Tennessee for calculating coupled heat and moisture transfer in building components.
Keywords: wood-framed house, sheathing, fiberglass insulation, moisture barriers, vapor barriers, intelligent vapor diffusion retarders, vapor diffusion retarders, moisture-thermal properties

Introduction

Moisture in buildings in the United States is considered one of the single, largest factors limiting the service life of a building (Lstiburek, 1991). In addition to the obvious liquid water, or rain, that can permeate the building envelope, the infusion of water vapor is of equal or greater concern because it is not visible or readily recognized. Water vapor can be controlled by placing the proper vapor diffusion retarder at proper locations within the wall components. A vapor diffusion retarder is typically, and less accurately, referenced in most literature as a "vapor barrier." However, a vapor retarder does not prevent all moisture from passing through as does a barrier (U.S. DOE, 2011).

Problem Statement

Incorrect use of vapor diffusion retarders ranks high on the list or controversial techniques and incorrect applications in construction (Laliberte, 2008). Much misinformation exists about which kind of vapor diffusion retarder to use, where it should be located, and if it is necessary. Illustrating this point, an Internet search at a do-it-yourself construction website revealed the following post: "Everything I've read says to put up a vapor barrier between the insulation and the drywall. They mention plastic sheeting, but nothing tells what (thickness) to use." The answers varied from: "Any plastic sheeting will provide a substantial barrier. The cheaper the better," to more accurate, scientific solutions (Tribe, 2007). Not only must vapor diffusion retarders limit moisture from getting into the construction, they also must let moisture out if indeed it does permeate the construction (Lstiburek, 2011). As such, the "plastic sheeting" mentioned in the blog as a solution, is not suitable in many climates. The goals of this research effort were to determine (a) the moisture transport activity in exterior walls of wood-framed construction, (b) the extent that geographical elevation above sea level affects the climatic and moisture transport behavior in similarly designed and constructed buildings, (c) if there is a preferred position/location for various types of vapor retarders (i.e., on the interior or exterior surface of the wood frame), and (d) which of the tested vapor retarder materials, if any, provides an adequate level of moisture control to inhibit the development of mold or fungus.

The test structures for this research were residential, single-family homes typical to the Midwest region in the United States. The Energy Efficient Building Association (EEBA) classifies this region as a "Heating Climate" region (Lstiburek, 2011) and recommends different moisture control methods for specific regions. Figure 1 shows Test Structure 1, later referenced as the Kearney Project, located in Kearney, Nebraska, with latitude 40° 44' N, elevation 652 meters above sea level. Figure 2 shows Test Structure 2, later referenced as the Laramie Project, located in Laramie, Wyoming, with a latitude 41° 3' N, elevation 2193 meters above sea level. Because the EEBA does not differentiate for elevation values above sea level, it was of interest to see if elevation and the impact of atmospheric air pressure may be a factor in potential for mold growth.

Figure 1. Kearney Test Project

Figure 2. Laramie Test Project

Wall Construction and Material Combinations

As is typical in most North American wood-frame construction (ICC 2006), the material assemblies of the exterior wall frames of both structures were constructed according to Table 1. The types of construction materials that comprise the wall assemblies are listed from exterior to interior, and the thicknesses (t) of various building components is listed in millimeters. In both test structures, the walls that were tested faced north. All measurements referenced in this paper are listed in metric equivalent values. The materials used in the construction of the walls of both test structures were identical with the exception of a kraftpaper vapor retarder and hardboard siding in the Kearney project versus a nonpermeable polyethylene vapor barrier and fiber cement siding in the Laramie project. Because the influence that climate had on mold development was the variable in question, these material differences were insignificant. Figure 3 and Figure 4 illustrate the different vapor retarders at the location of the measurements.

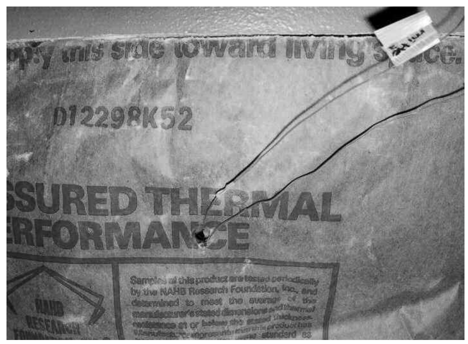


Figure 3. Kraftpaper Vapor Retarder, Kearney

Research Methodology

Data were collected using a "data logger" capable of capturing and storing nine measurement values every 20 to 30 seconds in the computer memory. All data were recorded in metric units, and this collection continued for at least three months at each location. Data were downloaded to a spreadsheet to generate graphic

Table 1. Sizes and Material Types of Wall Layer Components of the Test Structures

Layer		Kearney		Laramie
	t [mm]	material	t [mm]	material
Exterior paint		prepainted		1 coat latex primer 2 coats latex topcoat
Siding	10	"lapped" hardboard "Masonite Colorlok"	10	"lapped" fiber cement "Hardiboard"
Wind and water retarder		"Tyvek" (58 Perm)		"Tyvek" (58 Perm)
External sheathing	13	OSB	13	OSB
Insulation	89	R-11 Fibre glass batt	135	R-19 Fibre glass batt
Vapor retarder		kraftpaper	0,15	PE-foil (6 mil)
Internal sheathing	13	gypsum board (drywall)	13	gypsum board (drywall)
Interior paint		1 coat latex primer 1 coat latex topcoat		none

Figure 4. Polyethylene Vapor Retarder, Laramie

Figure 5. Data Logger and Interior Climate Sensors, Kearney

impressions of what was occurring within the walls regarding the development of moisture and the consequential potential for mold growth. Ultimately, anticipating the relative humidity (RH) on the inside surface of the oriented strand board (OSB) exterior sheathing was of interest due to the potential for mold growth at levels

Figure 6. In-Wall Temperature and Humidity Measurement Devices, Laramie

above 60% RH. For the Kearney project, the climatic data were collected for 12 weeks during winter 2006. For the Laramie project, the climatic data were collected for 12 weeks during fall 2004. For consistency, the measuring instruments were arranged in identical fashion in both structures, as illustrated in Figures 5 and 6. Care was taken to ensure that the same distances from reference surfaces were maintained.

Figures 7 and 8 illustrate location details and various positions of the sensors relative to the interior cavity of the wall and exterior atmosphere of the structure. The exterior temperature/moisture sensor is visible in Figure 7, while the Ahlborn data-logger, interior temperature/moisture sensor, and air pressure sensor are visible in Figure 8.

Table 2. Figure Code, Channels, Sensors, Values, Units, and Location of Sensors

Figure Code	Measure Channel	Sensor Type Temp	RH	Measured Values	Units	Location
i	M04	PT 100	Cond.	temperature and rel. humidity	°C %	air interior
i1	M00	Coup.		temperature	°C	air interior
i/e 0,0	M01	Coup.		temperature	°C	inner surface of drywall
i/e 0,5	M02	Coup.		temperature	°C	in insulation at 60 / 80 % away from ext. sheathing
i/e 0,8	M03	Coup.		temperature	°C	in insulation 40 / 50 % away from ext. sheathing
i/e 1,0/150	M05	PT 100	Cond.	temperature and rel. humidity	°C %	inside of the ext. sheathing and 150mm from ceiling
i/e 1,0/ 350	M06	PT 100	Cond.	temperature and rel. humidity	°C %	inside of the ext. sheathing and 350mm from ceiling
e	M07	PT 100	Cond.	temperature and rel. humidity	°C %	air exterior
pA	M08			air pressure	haPa	interior of room

Figure 7. Location of Exterior Climate Sensor

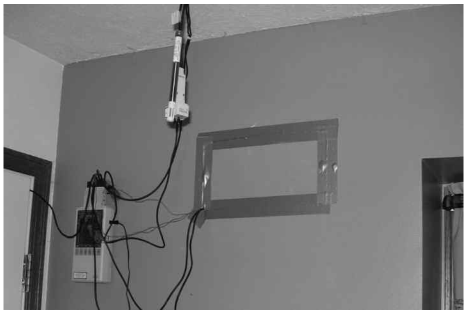


Figure 8. Room Climate Sensors and Sealed Cavity with Interior Sensors

Figure. 9 Ahlborn Data-Logger

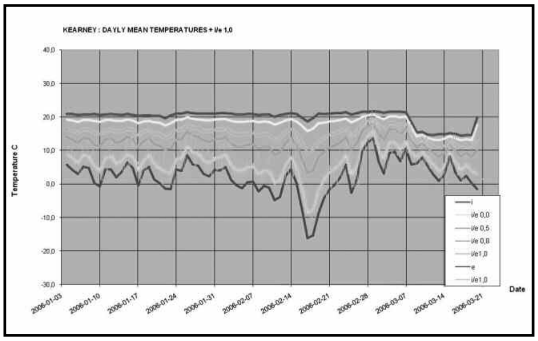


Figure 10. Temperature (C) from Interior to Exterior, Kearney

Recording and Measuring Equipment

An Ahlborn data-logger, model 2590-9 recording instrument, allows logging of up to nine data inputs on channels 00 through 08. The data-logger was calibrated to record at 20-minute intervals for the Kearney project and 30-minute intervals for the Laramie project. The shorter interval was used to improve the accuracy of the measurements taken at Kearney in order to determine if the output graphic data might be easier to view. However, there appeared to be no significant difference. A typical display of the data-logger is observed in Figure 9. The nine channels recorded temperature, air pressure, and relative humidity at various locations on the structure.

The data sensors located throughout the construction included four PT100/condensator combination sensors to measure temperature and relative humidity, four thermocouple (Coup.) bimetallic temperature sensors, and one atmospheric pressure sensor. Table 2 describes which sensors were connected to respective channels, the variable that the sensor measured, the units of measurement, and the location of the sensors. The "Figure Code" column identified in Table 2 is for the purpose of viewing the "daily mean" values, relative to their location in the structure, in Figures 10 through 13. Rows of data in Table 2 are listed beginning with interior room measurement locations, moving throughout the wall, and ultimately to the exterior of the structure. The figure code column correlates to the "Location" column to observe where the sensors were placed in the assembly. For example, the sensor "i" was located in the interior of the room and measured temperature (degrees Celsius) and relative humidity (percentage) on channel M04 with a PT100 condensator instrument. In contrast, sensor "i/e 0, 05" was in the insulation but closer to the interior wall surface and only measured temperature (degrees Celsius) with a thermocouple on channel M02.

Measurement Results

After the data were collected, they were downloaded from the logger to a spreadsheet to generate the following figures. Figure 10 illustrates the daily temperatures for the Kearney project. The red line is the room interior temperature; subsequent colors measured temperature at increasingly further distances from the interior, progressing to the blue line, which represents the exterior temperature. The interior room temperature remained relatively constant with the exception of an extremely cold period beginning on Feb. 17, shown by the dark blue line. In contrast, the drop in interior room temperature beginning on March 7, shown by the red line, is attributed to the owner setting back the thermostat 7 degrees C (12 degrees F) during a two-week spring break.

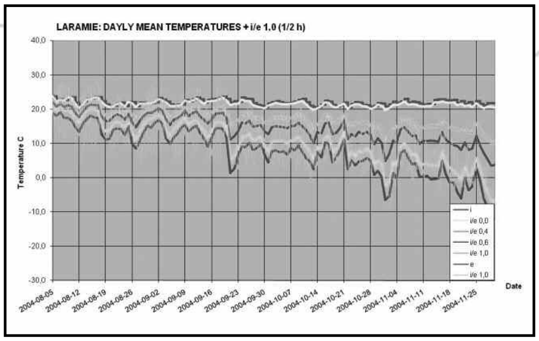


Figure 11. Temperature (C) from Interior to Exterior, Laramie

Figure 11 shows similar results with the exception of a somewhat higher and more variable indoor temperature. Possible explanations include perhaps the occasional use of an auxiliary heating device, such as a space heater or fireplace—they could also be the result of solar heat gain on sunny days.

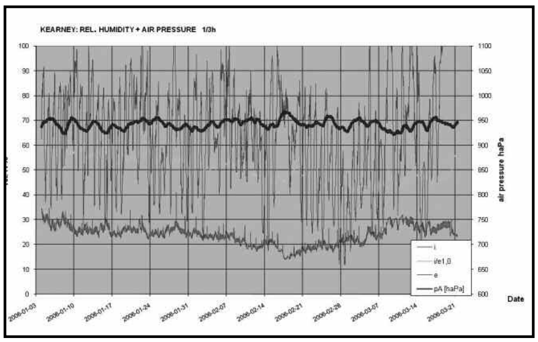


Figure 12. Relative Humidity and Atmospheric Pressure, Kearney

The critical consideration for mold potential is located at the interior surface of the OSB sheathing. Figure 12 graphs relative humidity (RH) levels at three locations: interior of room (red line), the interior surface of the OSB exterior sheathing (light blue line), and the exterior (dark blue line). In addition, atmospheric pressure (magenta line) was recorded in the interior of the room because of its influence on RH. Although the extremes in outdoor RH (dark blue) in the exterior atmosphere were great as noted by the wide range of readings, the RH within the wall construction (light blue), specifically on the inside surface of the OSB sheathing, was generally between 50% and 60%. At this low level of RH, no condensation would be expected, and therefore the development of mold would not be expected. A further observation is the relatively low RH within the living space of the room. It is likely that the lack of air tightness of the structure would explain this phenomenon by which moisture would escape via the high air exchange rate of the structure. Hagentoft (1996)

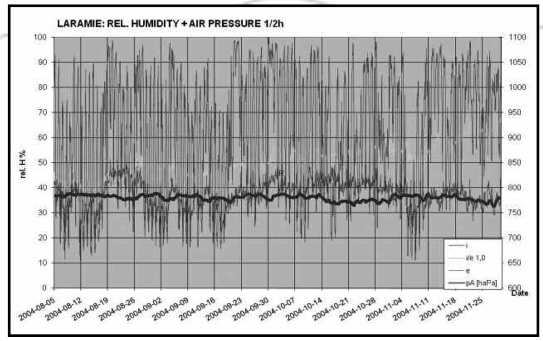


Figure 13. Relative Humidity and Atmospheric Pressure, Laramie

concluded similar results regarding air leakage carrying moist air into the construction that leads to unacceptably high values even for moderate indoor moisture levels.

Figure 13 demonstrates that low RH rates in the Laramie project at the interior surface of the OSB sheathing are attributed to the low air pressure (magenta line, ave. 750 haPa) at the relatively high elevation of 2193 meters above sea level. The low atmospheric pressure would lead to a high evaporation rate resulting in the low RH levels. Of special note is the increase of the RH from 40% in fall to 70 % at the beginning of winter. This would explain the appropriateness of using the nonpermeable PE vapor retarder at the much higher elevation without a concern for trapping moisture.

Simulation Models with WUFI

In an effort to determine if similar results could be attained through computer simulation, the researcher utilized the PC program WUFI ("Wärme und Feuchtigkeit Instationären Übertragung," loosely translated "Unsteady Heat and Moisture Transfer"). The program allows the selection of different types of vapor retarder materials, the location/position of the vapor retarder within the construction, warm or cold climate conditions, and geographic conditions including longitude, latitude, and elevation. The advantage of using such simulation is that it eliminates the need to physically install sensors within wall cavities, thus reducing corresponding damage to the wall surfaces. Simulation also allowed the researcher to conduct a full one-year calculation in a matter of minutes.

Tests were conducted using common types of vapor retarder scenarios, including no vapor retarder, kraftpaper, polyethylene film (PE), and "intelligent" film (PA) on the inside surface of the insulation. Tests were also done to determine if exterior air barriers, such as "Tyvek" or kraftpaper, would influence the results. Intelligent vapor retarders are made of polyacetate or nylon and have a variable permeability rate that allows moisture to pass through the film depending on temperature and moisture conditions. PA allows the material to keep most moisture vapor out, but it also allows moisture vapor to dry out if a high level does infiltrate the wall cavity. As would be expected in standard construction, the vapor retarders that were tested were located directly under the interior gypsum board and on the interior surface of the OSB sheathing. A cold Test Reference Year (TRY) was calculated for Laramie, but for Kearney both a cold TRY and a warm TRY were calculated because of the higher humidity and the concern for potential mold development in summer. A TRY represents a time period beginning January 1 and concluding December 31.

Though TRY climatic data for either Kearney or Laramie does not exist in the WUFI (North American version), climate data were available in the WUFI for Omaha, Nebraska, and Casper, Wyoming, respectively. These available climate data were deemed adequate because Omaha and Casper represent a more severe climate for potential mold growth than either Kearney or Laramie, respectively. The preferred indoor climate was designed at a temperature 20°C and a relative humidity of 30% and 50%.

Three typical examples of the 24 simulations are presented in Figures 14 through 16. These sample simulation graphs were selected because they represent the exact construction materials of the Kearney and Laramie projects assuming a cold climate, with the additional simulation for Kearney in a warm climate. Two monitor positions (measuring points) were installed to record the temperature and the relative humidity at the exterior (position 3: red) and interior (position 4: blue) sides of the insulation. In Figures 14 through16, the Y-axis represents the temperature C and RH% (Feuchte), while the X-axis represents time (Zeit) over one TRY or 1-365 days. In Figure 14, the crucial summer months from day 125 to day 250 show the RH values well below 50%, thus showing no risk of mold growth in Kearney. For a very short period beginning on day 92, the RH may increase up to 100% at the inside of the OSB, but this risk is minimal because the Kraftpaper is relatively vapor open.

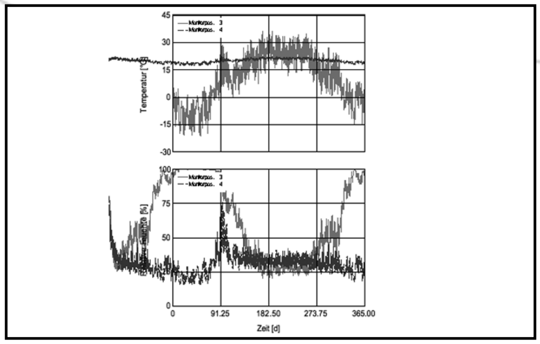


Figure 14. Kearney, Warm TRY with Kraftpaper Vapor Retarder and Indoor RH 30%

The simulation allowed the substitution of PE for kraftpaper in the Kearney project to see the how the results might vary. Thus, Figure 15 shows that even though PE foil would be an adequate vapor retarder in the winter (days 1-90 and days 275-365), during the summer the the PE foil would allow a higher RH of 50%-85% on both sides of the insulation, which would be a minor concern for mold damage. Therefore, kraftpaper is the recommended vapor diffusion retarder for the Kearney climate. It is relatively inexpensive and provides adequate potection without any risk of mold.

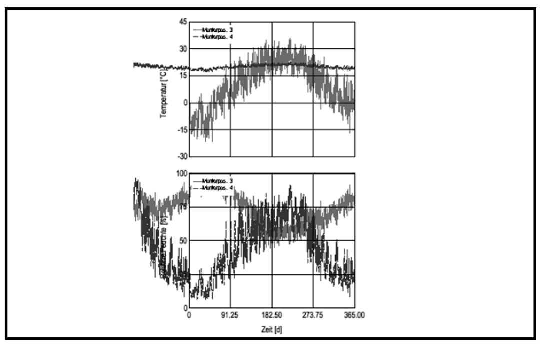


Figure 15. Kearney, Cold TRY with PE Foil Vapor Retarder and Indoor RH 50%

Figure 16 shows that PE foil is an acceptable vapor diffusion retarder for the Laramie climate, which has RH values below 50% in the

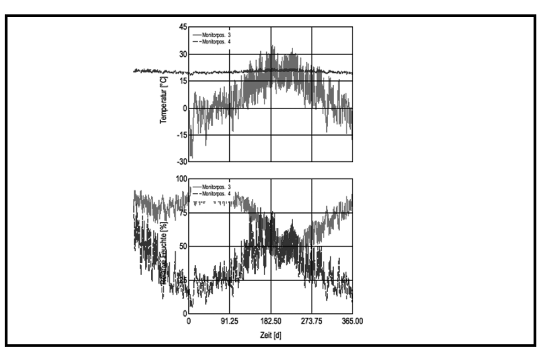


Figure 16. Laramie, Cold TRY with P.E. Foil Vapor Retarder and Indoor RH 50%

winter. Though in the summer the interior RH values can be above 50%, the high elevation and the associated low atmospheric pressure promotes rapid evaporation/drying and thus there is little concern for mold. This appears to be compatible with Lstiburek's recommendations (1991) for a maximum 35% indoor RH at 70 degrees F (20 C) during heating periods and when using PE foil as a vapor retarder.

The results of the WUFI simulations studies are shown in Table 3. It represents the results of the 24 simulations adjusted for the variables selected for the study. Data in the table are indicative of water per square meter (units in kilograms) (kg/m2) that could be expected on the interior surface of the OSB sheathing, depending on the type of vapor retarder. An assumption is made that values of less than 1 kg/m2 would be of little concern regarding mold development or condensed water. Values with an underscore are greater than 1kg/m2 ; they indicate that a particular vapor retarder would not be acceptable. Values in bold indicate the maximum result recorded for that test. Table 3 also illustrates that either in Laramie or Casper, there is little chance for mold to develop, regardless of the type of vapor retarder or whether a vapor retarder is even used. In contrast, it is apparent that while the type of vapor retarder used either in the Kearney or Omaha climate is of little consequence, not using a vapor retarder would be a genuine risk for mold. Regardless of the location of the vapor retarder or whether the climate data used was cold or warm, when using some type of vapor retarder, values were well within the acceptable limit of 1 kg/m2. Similarly, Levin and Gudmundsson (1999) concluded that when moisture loads are low, perhaps a vapor retarder is not necessary. However, indoor moisture conditions that exceed 2 kg/m3 will cause condensation on the inside of the external sheathing and high relative humidity in the insulation. This poses a significant potential for mold growth, structural damage, or both resulting from the degradation of the materials. Elevations above sea level are indicated in meters for all four cities. The data suggests that if an exterior air and moisture barrier, such as Tyvek or kraftpaper, was not used, then perhaps a vapor diffuser would not be necessary, explaining why many older homes without exterior air barriers do not have mold problems. Yet it is important to note that the advantage of exterior air and moisture barriers in reducing energy costs and preventing the exterior sheathing from becoming wet cannot be ignored.

Conclusions

The issue of mold growth and the consequential negative effect it has on structural damage to homes (e.g., wood members) as well as the impact mold can have on indoor air quality has become an increasing concern to builders and homeowners alike. This research concludes that the selection of proper vapor retarders to minimize the extent of damage is dependent on

Table 3: Need for Vapor Diffusion Retarders in Kearney and Laramie

Mineral Wool Insulation		Values		**Omaha**	Kearney	Insulation		**Casper**	Laramie	Insulation	
Water content				298 m El.	652 m El.	8,9 mm		1612 m El.	2293 m El.	12,5 mm	
[kg/m_]		**maximum**	start calc.:	0.16				0.24			
		interior VaporRetarder		none	kraft p.	PE	PA	none	kraft p.	PE	PA
Test Reference Year	warm	exterior Air Bar.	none	0.18	0.17	0.04	0.05	0.62	0.5	0.06	0.06
			(Tyvek)	**<u>1.63</u>**	**0.96**	**0.16**	**0.16**	**0.79**	**0.6**	**0.24**	**0.24**
	cold	exterior Air Bar.	none	0.19	0.17	0.04	0.03	0.53	0.43	0.05	0.06
			(Tyvek)	**<u>1.96</u>**	**0.96**	**0.16**	**0.16**	**1.1**	**0.78**	**0.24**	**0.24**
			none	0.19	0.17	0.04	0.05	0.53	0.43	0.05	0.06
			kraftp.	**<u>1.96</u>**	**0.97**	**0.16**	**0.16**	**1.1**	**0.78**	**0.24**	**0.24**

geographic location, elevation, and the choice of appropriate vapor retarders. It appears that the risk of mold is minimal at high elevations (such as Laramie) because of the rapid evaporation of moisture as a result of low atmospheric air pressure. It is apparent that a kraftpaper vapor retarder is adequate to control condensation within the walls of structures in geographic locations similar to Kearney; this can be accomplished with a minimal financial investment. In contrast, not to include a vapor retarder would pose a significant potential for mold growth in the Kearney climate. In any case, a vapor retarder at the inside surface of the insulation using foils that are open to vapor diffusion (e.g., kraftpaper or PA) is recommended. To conclude, during the winter, the temperatures in the Midwest United States are similar to those in Scandinavia. In contrast, during the summer, the United States has a tropical climate, very much unlike Scandinavia. Thus, the question of the location of the vapor retarder could not be directly correlated to previous studies from Scandinavia, some of which are cited in this article.

Dr. Kennard G. Larson is a Professor in the Department of Industrial Technology at the University of Nebraska, Kearney. He is a Member-at-large of Epsilon Pi Tau and received his Distinguished Service Award in 2005.

References

Ahlborn. (2003), Version 5-Handbuch: Mess- und Regelungstechnik GmbH (4th ed.). Holzkirchen, Germany:

Hagentoft, C.-E. (1996). Moisture conditions in a north facing wall with cellulose loose fill insulation: Constructions with and without vapor retarder and air leakage. Journal of Thermal Envelope and Building Science, 19, 228-243

International Code Council (ICC) (2006). International residential code for one- and two-family dwellings.

Levin, P., & Gudmundsson, K. (1999-2000). Moisture in constructions with loose-fill insulation and no vapour barrier. Nordic Journal of Building Physics, 2.

Laliberte, M. (2008). Retrieved from http://www.ecohomemagazine.com/building-science/understanding-vapor-barriers.aspx

Lstiburek, J. (1991). Moisture control handbook: New, low-rise residential construction. Washington, DC: U.S. Department of Commerce.

Lstiburek, J. (2011). Understanding vapor barriers. Building Science Digest, 106.

Tribe (2007). Retrieved from http://do-it-yourself.tribe.net/thread/0d6bf92e-6bd6-4622-b8e1-bb17c1d0e9c2

U.S. Department of Energy (DOE) (2011). Retrieved from http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11910

WUFI (Version 4.0) (2005). [Computer software]. Used for calculation of transient heat and moisture transport.Holzkirchen, Germany: Fraunhofer Institut für Bauphysik.

Acknowledgment of Additional Contributors

Note: This article is based in part on a peer reviewed oral presentation given at the Nordic Building Symposium in Copenhagen, Denmark.

Technical Assistance on Data Interpretation and Collection

Dr. Georg-Wilhelm Mainka
Universität Rostock, Germany

Data Collection in Wyoming

Dr. Katrin Riesner
R & M Shiptechnologies GmbH, Rostock, Germany

Provider of Test Structure in Wyoming

Dr. Robert Erikson
University of Wyoming, Laramie, USA

Leveraging Green Computing for Increased Viability and Sustainability

Dominick Fazarro and Rochell McWhorter

Abstract

Greening of computing processes is an environmental strategy gaining momentum in the 21st century as evidenced by increased virtual communications. Because of the rising cost of fuel to travel to meetings and conferences, corporations are adopting sophisticated technologies that provide a "personal" experience for geographically disbursed colleagues to interact in real time. This article highlights several companies and academic professional organizations that utilize video conferencing, virtual classrooms, and virtual worlds to create digital spaces for collaboration. The article compares the impact of face-to-face collaboration that includes business travel expenses to the impact of the same activity in a virtual space. The human side of technology is also examined through virtual human resource development that increases employees' learning capacity and performance improvement. As advances in technology continue, it is expected that meetings will become more lifelike with the improvement of holographics. Corporations must continue to integrate green strategies to satisfy both environmental concerns and financial viability.

Keywords: green communication, virtual communication, virtual human resource development, sustainability

Leveraging Green Computing for Increased Viability and Sustainability

Introduction

Economic recession and soaring fossil fuel prices have affected the *viability* of many privately held companies and public and nonprofit organizations. To remain competitive and achieve their goals, organizations are increasingly leveraging sophisticated communication technologies so that individuals and workgroups at a distance can collaborate (Bingham & Connor, 2010).

Concomitantly, there is a movement toward more environmentally friendly *"green"* products and processes to increase *sustainability* (Witkin, 2011). According to Hasbrouck and Woodruff (2008), the importance of environmental issues has trickled down the supply chain and "permeated the awareness of consumers, regulatory bodies, OEMs, and others over the past few years" (p. 39), bringing with it new ways of conducting business. Further, in a 2008 survey, more than 80% of polled U.S. workers agreed that it was important to work for a company or organization that makes the environment a top priority (Kauffeld, Malhotra, & Higgins, 2009).

The purpose of this article is to highlight current trends that organizations use for collaboration and organizational learning that increase their viability and digital footprint. This article will also seek to demonstrate that these virtual communications are a *green computing* initiative for the sustainability of the environment.

The term *green computing* refers to the "study and practice of using computing resources efficiently" (Childs, 2008, p. 1); it is comprised of many facets, including the design, manufacture, use, and disposal of computer hardware and software (Lo & Qian, 2010). For this article, the authors will focus on the efficient use of computing resources for collaboration that reduces travel time and cost, increases organizational efficiency, and addresses environmental concerns.

Virtuality as Green Strategy

Technology is permeating both professional and personal lives as never before (McWhorter, 2010). Hopper and Rice (2008) discussed the benefit of "digital alternatives to physical activities" (para.7) as a way to reduce the impact of travel and the use of fossil fuels. They offered examples, such as electronic versions of newspapers, music downloads from the Internet, and online shopping. Likewise, collaboration with colleagues can be conducted via digital space.

The history of the Internet depicts users who have *connected to, through*, and *within* technology (Kapp & O'Driscoll, 2010; McWhorter, 2010). Figure 1 depicts these three distinct phases of the evolution of information and communication technology that are conducive for the greening of technology. In the 1990s, PCs became popular and employees and learners began *connecting to* technology to access useful data. In sharp contrast to earlier generations, the advent of new technologies, such as Web 2.0 tools, moved the user to the next step, *connecting through* technology to collaborate with others. The technology has now evolved so that it enables users to *connect within* the technology in immersive meeting spaces. Such environments allow for advanced collaboration and co-creation of user-made organizational content (Gronstedt, 2008) where users establish a virtual co-presence (the feeling of being present in the same digital space).

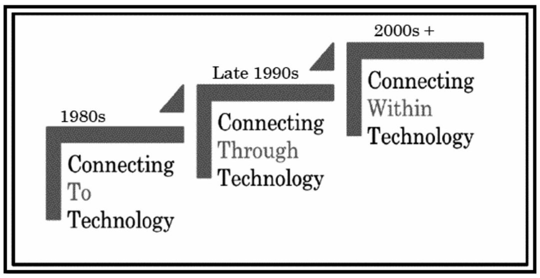


Figure 1. Evolution of Enabling Technologies for Green Computing (Source: McWhorter, 2011; adapted from Kapp & O'Driscoll, 2010)

Ted Nelson coined the term *virtuality* to describe the conceptual nature of an object (see Xanadu.com). Here the term *virtuality* is used to encompass synchronous (in real time) collaboration of learners and workers at a distance facilitated by integrated computing technologies. These synchronous collaborative "meetups" utilize integrated technologies, such as video conferencing, virtual classrooms, and virtual world platforms, so that colleagues can collaborate with each other although in geographically dispersed locations. In the context of green computing, each of these technologies will be discussed followed by the best practices of virtual collaboration for green computing.

Video Conferencing as Collaborative Green Spaces

The U.S. Travel Association reported that 31% of business travelers used videoconferencing in 2008 to replace at least one business trip (Bell, 2011). Video conferencing utilizes synchronous desktop media, such Skype™, Facetime™, or Yahoo Messenger™, to collaborate via text chat, voice, and video (through built-in or external webcam and microphone). According to Aamoth (2011), Skype™ was recently acquired by Microsoft, which opens the door to embedding it within Microsoft's many software applications.

For higher end video conferencing, companies can invest in a life-sized high-definition (HD) system, such as Cisco's TelePresence™, to conduct business with others at a distance (Kozubek, 2010) for truly "you are there" (p. 36) *telepresence* (technologies that make individuals feel they are meeting in the same space). This technology can connect team members face to face in virtual meetings transmitting full HD video to up to 48 locations globally. Viewing participants in HD appears to break down cultural barriers because participants can view common material on their computer screens and can see facial expressions and gestures.

Green computing also encompasses new trends in video conferencing, such as increased integration and portability. Smaller devices, such as smartphones (e.g., the iPhone™ and Blackberry Storm™) and digital tablets (e.g., the iPad ™ and HP TouchPad™) (Hiner, 2011) can be loaded with video conferencing software that requires smaller electrical loads. Such portable devices with video conferencing capabilities facilitate student learning, employee training, project management, and the broadcasting of organizational events (Toperczer, 2011).

Virtual Classrooms as Collaborative Green Spaces

A useful virtual classroom environment is formed by integrating voice over Internet Protocol (VoIP), a webcam, text chat capability, and the ability to share applications, such as a virtual whiteboard. In this digital space, users

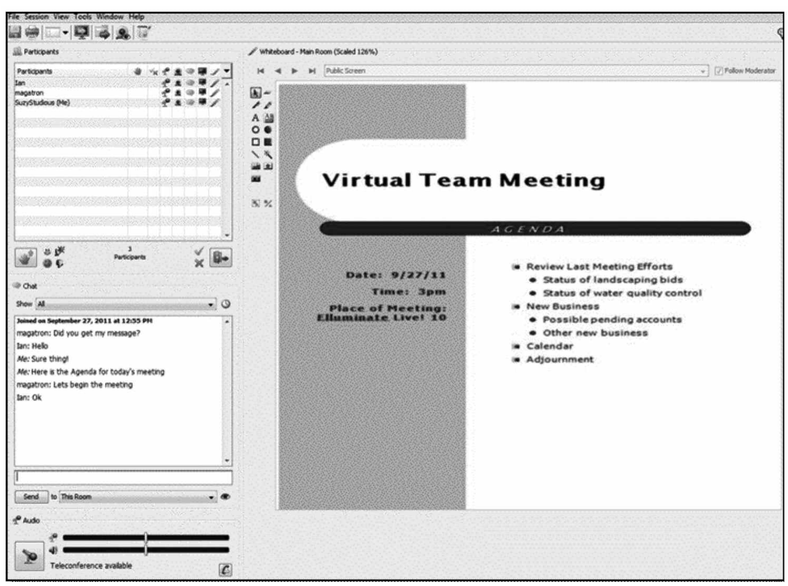


Figure 2. Screenshot of a Virtual Team Meeting using Elluminate Live! 10® (Top Left: List of Participants, bottom left: Instant Text Messenger, Right: Meeting Agenda)

can collaborate in real time through Internet technologies. An example of a virtual classroom environment is the Elluminate Live! 10 platform® that can be either a stand-alone product or one embedded into an organization’s learning management system. This platform combines an interactive whiteboard, breakout rooms, two-way audio, multipoint video, desktop and application sharing, rich media, and session recording capabilities (Elluminate.com, 2011). See Figure 2 for a screenshot illustrating a virtual team meeting among three geographically disbursed colleagues.

Virtual Worlds as Collaborative Green Spaces

A virtual world has been defined as “a synchronous, persistent network of people, represented as avatars, facilitated by networked computers” (Bell, 2008, p. 2). According to KZero Worldwide (2011), approximately 42 million registered users (aged 25 and up) take part in various virtual worlds. These 3D virtual worlds are used for both entertainment and professional activities, including training and development (Chapman & Stone, 2010).

A recent study into the media-rich interactive environment of Second Life™ found it conducive for adult learning endeavors (Mancuso, Chlup, & McWhorter, 2010). Highly effective for simulations and collaboration, these green virtual spaces provide real-time opportunities for virtual teams and events (Bingham & Conner, 2010; Raisor & McWhorter, 2011). As a case study, Fazarro, McWhorter, and Lawrence (2011) described how nanotechnology safety training could be taught effectively in such an environment. Through avatars (graphic representations), users can interact with one another using local text chat, voice chat, and instant messaging via user-user or user-groups. Figure 3 depicts collaboration between two colleagues as they examine a 3D model of a Sulfuric Acid Plant; this exemplifies the *meeting within* (McWhorter, 2010) context of technology, and it saves organizations time and money and is beneficial to the environment because fossil fuels are not expended for unnecessary travel.

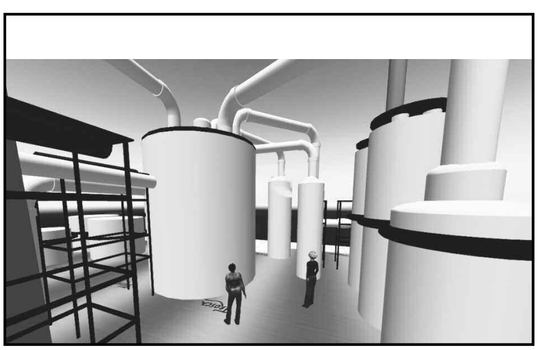


Figure 3. Virtual World Collaboration at a Sulfuric Acid Plant Source: Photo Courtesy of KR Virtual Designs

Greening of Professional Conferences: Adding the Virtual Component

A relatively new trend that buttresses the green computing concept is the addition of a virtual component to professional conferences. A number of professional organizations are now adding this option for members who cannot travel because of time or financial constraints. For a reduced conference cost, members can view the Keynote Address, a number of top presentations, and more. One example of a conference with a virtual component is the IEEE Nano Council’s *Nano 2011* Conference in Portland, Oregon. If unable to attend, a member could participate in the post conference, including the conference program, full proceedings on a USB flash drive, and online access to narrated slides, which the organization noted would be “saving travel, hotel and meal expenses” (IEEE Nano 2011 ¶3). A sample of other national conferences that offer a virtual or online component includes The Society for Human Resource Management, the American Society for Training and Development, the American Library Association, and the National Board for Professional Teaching Standards. Figure 4 depicts a virtual meeting area where attendees can examine an online exhibitor hall that includes information about various products and services.

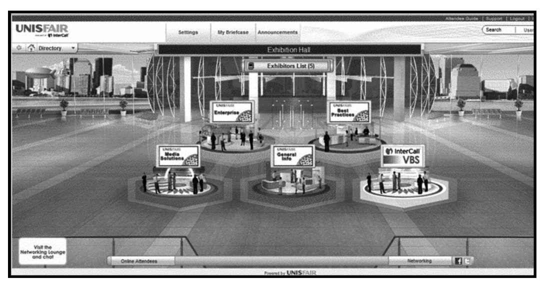


Figure 4. Exhibit Hall at a Virtual Conference
Source: http://events.unisfair.com

According to Bell (2011), virtual conferences are becoming more numerous. Some organizations offer a virtual conference component to their face-to-face (F2F) annual or semi-annual conference; however, some organizations are opting for the virtual-only conference, a true green computing initiative that benefits the environment and increases their viability.

Data has not been collected on either the number of individuals who attend virtual conferences or their feedback on the experience. However, a clue to market growth can be seen in the number of companies who offer support and services for virtual conferences. For instance, a recent search for virtual conference vendors revealed 40 companies that offered these services to organizations (Bell, 2011).

When contemplating a virtual conference as a hybrid component to a F2F conference or as a stand-alone event, organizations must consider the advantages and disadvantages afforded by each venue. Table 1 examines several dimensions, such as cost, convenience, and participation when comparing a F2F conference to a virtual conference.

Best Practices of Virtual Collaboration for Green Computing

Trevarthen (2008) and Räsänen, Moberg, Picha, and Borggren, (2010) provided the following best practices for using virtual communication within organizations:

1. Be mindful of the appropriateness of using virtual communications instead of F2F (need to know when and how to use it).

2. Determine the extent of executive and managerial buy-in using virtual technologies.

3. Establish goals and outcomes for using virtual communication.

4. Establish rules of engagement (protocols) with stakeholders.

In addition, Soule and Applegate (2009) established best practices for successful virtual project teams through virtual communications that included leaders adapting to technology. This is particularly important when organizations move from F2F meetings to virtual technologies.

Also, it is imperative that organizations spend adequate time and resources before they expect that members or employees will be

Table 1. Comparison of Face-to-Face Conferences to Virtual Conferences

Dimension	Face-to-Face (F2F) Conference	Virtual Conference
Cost to Attend	Conference Registration and Travel Expenses	Normally free or reduced conference registration; no travel fees required, but must have connectivity to access
Cost for Hosting	Typically very costly due to meeting spaces and food costs	Typically more cost-effective by paying a virtual conference vendor rather than F2F hotel venue
Convenience	Typical time required for travel and conference attendance	Can connect to virtual conference via desktop, laptop, or mobile device (contingent on chosen platform)
Global Participation	Attendees must spend greater travel costs and time expenditures to participate internationally	Although time zones are an issue, technology allows global real-time participation online
Networking	Connecting with colleagues and networking typically easier in F2F environment	Real-time collaboration is becoming available through integrated technologies such as virtual chatting, social media connections
Technology Integration	WiFi often unavailable to attendees in conference meeting rooms	Participation relatively easy with a reliable internet connection
Immersion	Easier to remove distractions and focus on the conference experience	More likely to be distracted by other tasks and daily routines
Post-Conference Experience	Follow-up normally done by organization in written format such as conference proceedings, newsletter and website reporting	Virtual conference can be fully archived through multimedia for asynchronous online access at attendee convenience

Adapted from: Bell (2011); Roberts and McWhorter (2011 effective with the new technology. Along with the greening of their collaborative efforts, organizations must enact virtual human resource development (VHRD) efforts to develop individuals' virtual technology literacy. VHRD is "the process of utilizing technologically integrative environments for increasing learning capacity and optimizing individual, group, community, work process, and organizational system performance" (McWhorter, 2011, p. 3).

These identified best practices are a sample of those that contribute to effective virtual communication. As technology improves, people must adapt and effectively use various technology-enabled collaborative techniques to maintain viability in the global marketplace and sustainability for the environment. The financial and environmental impact of using green computing will be discussed next.

What is the Impact?

According to LaBrosse, (2010): "The explosion of concern about the environment and the emerging business imperative for companies of all sizes to become sustainable presents a challenge for all managers" (p. 87). When introducing green computing within organizations, managers/leaders must first examine the cost benefits of the technology over the long term.

The impact of face-to-face collaboration involving geographically disbursed individuals and groups is costly from both the financial and environmental standpoints. For example, conventional travel to conferences requires using ground transportation, aircraft, or both, and these involve expensive fossil fuels and provide a massive output of CO2 (thought by a number of researchers in the scientific community to be very dangerous for the environment, and its impact is being investigated in many studies).

It is estimated that the average passenger automobile, for example, produces 8.8 kg of CO2 per gallon of gasoline with an average fuel efficacy of 20.3 miles per gallon (Environmental Protection Agency, 2005). Aircraft CO2 production varies by flight distance, and it is between .279 kg of CO2 per mile to .187 kg of CO2 per mile, depending on the length of the flight (Environmental Protection Agency, 2008). By comparison, videoconferencing makes use of equipment already available in the office, with the possible addition of a webcam. The savings made by decreasing travel for meetings that can be reasonably accommodated through modern technology have benefits that far outweigh any possible increase in energy used during videoconferencing.

In the 21st century, videoconferencing is an important activity of many businesses and organizations. One example of cost savings through videoconferencing follows. Ira Wainstein, partner and senior analyst of Wainhouse Research, focused on quality and speed of decision making and the development of more effective work teams and lower operation costs (Kozubek, 2011). Verizon Business™ (2011) designs videoconferencing technology to enhance the productivity of business meetings. Illustrated in Table 2, Verizon Business developed a cost comparison of four people attending a business meeting versus this meeting held via videoconferencing.

Corporations are facing uncertainty about the economy and the environment; however, companies are creating out-of-the-box approaches for viability and sustainability. Corporations that practice continuous improvement will provide new and innovative ways for cost and environmental savings both now and in the future (De Geus, 2002). Thus, ideas about the future of green computing will be discussed next.

Table 2. Cost Comparison with Videoconferencing Versus Business Travel for Four Employees

	Mode of Conference	
	Business Travel*	Videoconferencing*
Round Trip Flight, Transportation, Food, & Hotel Costs	$3,963.96	$1,320.00
Personnel Costs (i.e. meeting participants)	$1,233.54	$ 380.69
Total Time Spent for Conference	53.24 hours	16.29 hours
Total Costs	$5,197.50	$1,700.69
Money Saved		**$3,496.31**

*_Note:_ total costs. Adapted from Verizon Business (2011)

What does the Future Hold?

It can be speculated that in the year 2020, through the advancement of nanotechnology, processing speeds for computers will be tenfold compared to speeds in 2012. Also, the commitment to green communication will likely be commonplace for corporations that conduct business globally. In the future, advanced technology for conducting meetings may consist of full-scale virtual people to assist virtual communications. Figure 5 illustrates graphical interfaces for such collaboration in real time during the next decade.

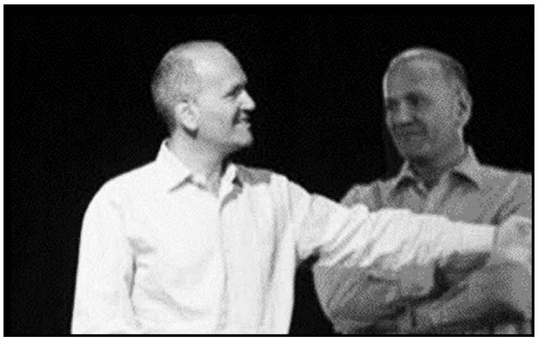


Figure 5 Real and Holographic Image Source: Barras (2009)

In fact, this depiction may be the optimal approach for virtual communication. For example, a CEO or an executive can conduct formal meetings using 3D high-definition holographic/virtual-world technology that projects an image of a person from any place on the planet to a place at the table. Furthermore, with sensors embedded in the holographic image, the image will have the tactile abilities that allow colleagues to shake the holographic hand of the person at the other worksite or event. For example, a full-scale *holodeck* might be used for a person to travel to London to attend a meeting without leaving the office. This technology has been researched for years with the concept derived from the science fiction show, *Star Trek: The Next Generation* (Grover, 2006).

This depiction may seem like science fiction, but with greater flexibility and capabilities formed through technology, virtual communications will likely become the main mode of conducting business. It is expected that the way people conduct business will likely be radically different during the next decade as they use increasingly sophisticated technologies.

Conclusion

The green technology movement is burgeoning as organizations are taking responsibility for the environment and embracing more efficient technology-enabled resources (Williams, 2007). This article has highlighted examples of cost savings and increased efficiency through the utilization of videoconferencing, virtual classrooms, virtual worlds, and virtual professional conferences. In addition, best practices for using sophisticated virtual technologies and future trends have been offered. These virtual initiatives provide a context for saving organizations time and money; they also benefit the environment by discontinuing unnecessary travel.

Organizations need to be cognizant of ways to achieve optimal savings regarding both financial and environmental impact and become savvy as they leverage technology in meaningful ways. Organizations should consider additional outcomes, such as recruiting new members through virtual conferences as these provide increased access to a global market.

Green computing allows for greater connectivity and customer service through efficiency of use. In the current lean status of organizations, technology should be considered for increasing membership, forming collaborative partnerships to share resources, and offering professional development. In addition, organizations should help their leaders and members to become more technologically astute.

Acknowledgment

The authors wish to acknowledge Curtis Felder for his research assistance during the development of this article.

Dr. Dominick Fazarro is an Associate Professor of Industrial Technology and Industrial Management at The University of Texas at Tyler. He is a Member-at-large of Epsilon Pi Tau.

Dr. Rochell McWhorter is an Assistant Professor of Human Resource Development at The University of Texas at Tyler, and is a member of the Delta Gamma Chapter of Epsilon Pi Tau.

References

Aamoth, D. (May 10, 2011). A brief history of Skype. Time.com. Retrieved from http://techland.time.com/2011/05/10/a-brief-history-of-skype/2/

Barras, C. (2009). Holographic' videoconferencing moves near the market. *New Scientist*. Retrieved from: http://www. newscientist.com /article/dn18169-holographic-videoconferencing-moves-nearer-to-market.html

Bell, M. W. (2008). Toward a definition of "virtual worlds." *Journal of Virtual Worlds Research*. Retrieved from journals.tdl.org/jvwr/article/download/283/237

Bell, S. (2011). A conference wherever you are. *Library Journal*. Retrieved from http://www.libraryjournal.com/lj/ljinprint/currentissue/891899-403/a_conference_wherever_you_are.html.csp

Bingham, T., & Conner, M. (2010). *The new social learning: A guide to transforming organizations through social media.* Alexandria, VA: ASTD Press.

Chapman, D. D., & Stone, S. J. (2010). Measurement of outcomes in virtual environments. *Advances in Developing Human Resources,* 12(6), 665-680. doi:10.1177/15233422310394792

Childs, S. (2008). Editorial: Green computing. *Health Information on the Internet, 62*(1), 1-2.

De Geus, A. (2002). *The living company: Habits for survival in a turbulent business environment.* Boston, MA: Harvard Business School Publishing.

Elluminate.com (2011). Transform the teaching and learning experience. Retrieved from http://www.elluminate.com/Services/Training/Elluminate_Live!/?id=418

Environmental Protection Agency. (2005). Emission facts: Greenhouse gas emissions from a typical passenger vehicle. In *Transportation and Climate.* Retrieved from http://www.epa.gov/otaq/climate/420f05004.htm

Environmental Protection Agency. (2008). *Optional emission from commuting, business travel and product transportation* (EPA Publication No. 430-R-08-006). Retrieved from http://www.epa.gov/climateleaders/documents/resources/commute_travel_product.pdf

Fazarro, D. E., McWhorter, R. R., & Lawrence, H. (2011). Going virtual: Delivering nanotechnology safety education on the web. *Journal of sTEm Teacher Education, 48*(2).

Gronstedt, A. (2008). Training in virtual worlds. *Infoline, 25*(803), 1-16.

Grover, S. (2006). Holding class on the holodeck: experimental learning through technology. *Perspective, 6* (2), 40-51.

Hasbrouck, J., & Woodruff, A. (2008). Green homeowners as lead adopters: Sustainable living and green computing. *Intel Technology Journal, 12*(1), 39-48.

Hiner, J. (2011). Top 10 tablets of 2011, the new leaderboard. ZDNet. Retrieved from http://www.zdnet.com/blog/btl/top-10-tablets-of-2011-the-new-leaderboard/48214

Hopper, A., & Rice, A. (2008). Computing for the future of the planet. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 388*(1881), 3685-3697. doi:10.1098/rsta.2008.0124

IEEE Nano 2011. (2011). Virtual conference attendance. Retrieved from http://ieeenano2011.org/

Kapp, K. M., & O'Driscoll, T. (2010). *Learning in 3D: Adding a new dimension to enterprise learning and collaboration.* San Francisco, CA: Pfieffer.

Kauffeld, R., Malhorta, A., & Higgins, S. (2009, December 21). Green is strategy: Five steps to "differentiated" sustainability for a full embrace of environmentalism. [Online forum content]. Retrieved from http://www.strategy-business.com/article/00013?gko=e5d36

Kozubek, M. (2011). Making connections: Videoconferencing helps companies save money and go green while breaking down cultural barriers. *Inside Counsel*. Retrieved from insidecounsel.com

KZero Worldwide (2011). Q2 2011 VW cumulative registered accounts reaches 1.4 billion. Retrieved from http://www.kzero.co.uk/blog/q2-2011-vw-cumulative-registered-accounts-reaches-1-4-billion/

LaBrosse, M. (2010). Incorporating green in project management. *Employment Relations Today, 37*(3), 85-90. doi: 10.1002/ert.20313

Lo, C. D., & Qian, K. (2010). Green computing methodology for next generation computing scientists. *34th Annual IEEE Computer Software and Applications Conference*, 250-251. doi:10.1109/COMPSAC.2010.31

Mancuso, D. S., Chlup, D. T., & McWhorter, R. R. (2010). A study of adult learning in a virtual environment. *Advances in Developing Human Resource Development, 12*(6), 691-699.

McWhorter, R. R. (2010). Exploring the emergence of virtual human resource development. *Advances in Developing Human Resources, 12*(6), 623-631. doi:10.1177/1523422310395367

McWhorter, R. R. (2011). *Scenario planning as the development of leadership capability and capacity; and virtual human resource development* (Doctoral dissertation). College Station, TX: Texas A&M University.

Raisor, C., & McWhorter, R. (2011). Using virtual world technology to facilitate technical communication instruction. *Innovative Research in Virtual Worlds 2011 Conference*, Coventry University, Puma Way, Coventry, UK.

Räsänen, M., Moberg ,_, Picha, M., & Borggren, C. (2010). Meeting at a distance: Experiences of media companies in Sweden. T*echnology in Society, 32*, 264-273.

Roberts, P. R., & McWhorter, R. R. (2011). V*irtual conferences as virtual human resource development.* Unpublished manuscript.

Soule, D. L., & Applegate, L. M. (2009). Virtual team learning: Reflecting and acting, alone or with others. *Harvard Business School*. Retrieved from http://www.hbs.edu/research/pdf/09-084.pdf

Toperczer, T. (2011). Video conferencing 2.0. *Credit union management*. Retrieved from http://pubs.royle.com/publication/?i=73978&p=12

Trevarthen, E. (2008). F. Virtual communications. *NASA*. Retrieved from http://www.time-management-guide.com/virtual-team.htmlhttp://blogs.nasa.gov/cm/wiki/?id=2741

Verizon Business (2011). A study of trends, costs, and attitudes toward business travel, and their impact on productivity [Online forum comment]. Retrieved from http:

https://e-meetings.verizonbusiness.com/global/en/meetingsinamerica/uswhitepaper.php

Williams, A. (2007, July 1). Buying into the green movement [Online forum comment]. Retrieved from http://www.nytimes.com/2007/07/01/ fashion/01green. html? pagewanted=all

Witkin, J. (August 25, 2011). Business studies become environmentally friendly. *The New York Times.* Retrieved from http://green.blogs.nytimes.com/2011/08/25/business- studies-become-environmentally-friendly/?scp=4&sq=sustainability&st=cse

The 2010 Paul T. Hiser Exemplary Publication Award Recipient

P. John Williams

"Technology Education to Engineering: A Good Move?"

The Board of Editors of The Journal of Technology Studies and the Board of Directors are pleased to announce the recipient of the Paul T. Hiser Exemplary Publication Award for Volume XXXVI, 2010.

The Board of Directors established this award for deserving scholars. In recognition for his exemplary service to the profession and to the honorary as a Trustee and Director, the award bears Dr. Hiser's name. It is given to the author or authors of articles judged to be the best of those published each year in this journal.

Selection Process

Each member of the Editorial Board recommends the manuscript that he or she considers the best of those reviewed during the year. The board nominates articles based on their evaluation against specific criteria. A majority vote of the editors is required for the award to be made. The honor society's Board of Directors renders final approval of the process and the award.

Criteria

1. The subject matter of the manuscript must be clearly in the domain of one or more of the professions in technology.

2. The article should be exemplary in one or more of the following ways:
    - Ground-breaking philosophical thought.
    - Historical consequence in that it contains significant lessons for the present and the future.
    - Innovative research methodology and design.
    - Trends or issues that currently influence the field or are likely to affect it.
    - Unique yet probable solutions to current or future problems.

A $300 award recognizes the recipient(s) for the year and is presented during an Epsilon Pi Tau program at an annual professional association conference.

GUIDELINES FOR The Journal of Technology Studies

A refereed publication of Epsilon Pi Tau the international honor society for professions in technology.

The Journal of Technology Studies (JOTS) is the flagship, peer-reviewed journal of Epsilon Pi Tau, an international honor society for technology professions. One printed volume per year is mailed to all active members of the society as well as to subscribing academic and general libraries around the globe. All issues (begining wih 1995 to the current year), both print and those published in electronic format, are available online at scholar.lib.vt.edu/ejournals/jots.

The journal is indexed in Current Index to Journals of Education, the International Bibliography of the Social Sciences, and by VOCED, the UNESCO/NCVER research database for technical and vocational education and training maintained by NCVER in Adelaide, Australia (www.voced.edu.au).

SUBJECT FOCUS

The JOTS welcomes *original* manuscripts from scholars worldwide focused on the depth and breadth of technology as practiced and understood past, present, and future. Epsilon Pi Tau, as perhaps the most comprehensive honor society among technology professions, seeks to provide up-to-date and insightful information to its increasingly diverse membership as well as the broader public. Authors need not be members of the society in order to submit manuscripts for consideration. Contributions from academe, government and the private sector are equally welcome.

An overview of the breadth of topics of potential interest to our readers can be gained from the 17 subclasses within the "Technology" category in the Library of Congress classification scheme (<lcweb.loc.gov.catdir/cpso/lcco/lcco_t. pdf>). Authors are strongly urged to peruse this list as they consider developing articles for journal consideration. In addition, JOTS is interested in manuscripts that provide:

- brief biographical portraits of leaders in technology that highlight the individuals' contributions made in dis tinct fields of technology or its wider appreciation within society,
- thoughtful reflections about technology practice,
- insights about personal transitions in technology from formal education to the work environment or vice versa, • anthropology, economics, history, philosophy, and sociology of technology,
- technology within society and its relationship to other disciplines, • technology policy at local, national, and international levels,
- comparative studies of technology development, implementation, and/or education,
- industrial research and development,or
- new and emerging technologies and technology's role in shaping the future.

The immense diversity of technology, along with its applications and import, requires that authors communicate clearly, concisely, and only semi-technically to readers from a diverse set of backgrounds. Authors may assume some technical background on the part of the reader but not in-depth knowledge of the particular technology that is the focus of the article. Highly technical articles on any field of technology are not within the purview of the journal.

Articles whose focus has been extensively explored in prior issues of the Journal are of potential interest only if they (a) open up entirely new vistas on the topic, (b) provide significant new information or data that overturn or modify prior conceptions; or (c) engage substantially one or more previously published articles in a debate that is likely to interest and inform readers. Syntheses of developments within a given field of technology are welcome as are metanalyses of research regarding a particular technology, its applications, or the process of technical education and/or skill acquisition. Research studies should employ methodological procedures appropriate to the problem being addressed and must evince suitable design, execution, analysis, and conclusions. Surveys, for example, that exhibit any or all of the following characteristics are of no interest to the journal: (a) insufficient awareness of prior research on this topic, (b) insufficient sample size, (c) improper survey design, (d) inappropriate survey administration, (e) high mortality, (f) inadequate statistical analysis, and/or (g) conclusions not supported by either the data or the research design employed. The JOTS is neutral in regards to qualitative, quantitative, or mixed method approaches to research but insists on research of high quality.

GUIDELINES FOR The Journal of Technology Studies (Continued)

GUIDELINES FOR SUBMISSION

Articles must conform to the current edition of the *Publication Manual of the American Psychological Association.* All articles must be original, represent work of the named authors, not be under consideration elsewhere, and not be published elsewhere in English or any other language. Electronic submissions in either rich-text format or Microsoft Word formats are required. E-mail submissions should be sent to the editor at jots@bgsu.edu.

Manuscripts should be no more that 25 double-spaced and unjustified pages, including references. Abstracts are required and should be no longer than 250 words. Also required is a list of keywords from your paper in your abstract. To do this, indent as you would if you were starting a new paragraph, type *keywords:* (italicized), and then list your keywords. Listing keywords will help researchers find your work in databases.

Typescript should be 12 point *Times New Roman* or a close approximation. Only manuscripts in English that conform to American usage will be accepted. Figures, tables, photographs, and artwork must be of good quality and conform to the *Publication Manual of the American Psychological Association, specifically complying with the rules of Style® for* form, citation style, and copyright. The Journal of Technology Studies seeks to maintain the highest standards of academic integrity and asks all contributors to apply proper due diligence in manuscript preparation.

REVIEW PROCESS

Articles deemed worthy for consideration by the editor undergo anonymous peer review by members of the JOTS editorial board. Authors who submit an article that does not merit review by the editorial board are informed within approximately three weeks of receipt of the article so they may explore other publishing venues. A rejection may be based solely on the content focus of the article and not its i ntrinsic merit, particularly where the topic has been extensively explored in prior JOTS articles. Articles that exhibit extensive problems in expression, grammar, spelling, and/ or APA format are summarily rejected. Authors of articles that have been peer-reviewed are informed within about two to three months from the date of submission. Anonymous comments of reviewers are provided to authors who are invited to submit a revised article for either publication or a second round of review. The editor does not automatically provide reviewer comments to authors whose articles have been rejected via the peer review process. However, such feedback may be provided if the editor determines that the feedback might prove helpful to authors as they pursue other publishing opportunities.

PUBLICATION

Accepted articles are published in the on-line version of the journal (http://scholar.lib.vt.edu/ejournals/JOTS/) as the manuscript exits the layout and proofing process. Currently, JOTS articles also appear in a print issue at the end of the calendar year. Authors co-retain rights to the published article along with Epsilon Pi Tau. When requested, the editor will supply information about an accepted article that has not yet appeared on-line or in print for faculty undergoing tenure review.