Improving Household Environmental Practices in Central Georgia: Low-Cost Renewable Energy Systems

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Abstract
An ongoing project of the Engineering for Development program at Mercer University focuses on applied research and education that aims to improve environmental practices at the household level in Macon, Georgia (including water and energy efficiency; re-use and recycling; and use of renewable energy technologies). It is intended to improve the local environment while saving households money over the medium- and long-term, with key aspects incorporated into Mercer University's environmental engineering curriculum. This paper focuses on sustainable design and implementation of low-cost renewable energy technologies (specifically low-cost solar photovoltaic and geothermal heat pump systems), and use of these technologies in academic teaching. Social Marketing ('marketing behavior change') is central to the design and implementation of the project. A low-cost 'Solar Self-Supply' starter solar photovoltaic kit was designed, constructed, and tested as part of a senior capstone engineering class. This affordable, expandable system encourages local households to take advantage of recent drops in prices in photovoltaic panels, as well as partial federal subsidies for the entire cost of solar household systems. System design, construction, and testing results are discussed, as are project implementation strategies. Also, initial plans to design low-cost household heating and cooling systems using a geothermal heat pump and manually drilled well(s) are discussed.

Keywords
Solar PV, geothermal, heat pump, manually drilled well, social marketing

I. Introduction
The presented work is part of an applied research and education project that aims to improve environmental practices at the household level in Macon, Georgia, including: water and energy efficiency; re-use and recycling; and use of renewable energy technologies. It is intended to improve the local environment while saving households money over the medium- and long-term. Additionally, the project is incorporating renewable energy system design processes and sustainable community development strategies into undergraduate engineering classes at Mercer University.

This paper focuses on sustainable design and implementation of low-cost renewable energy technologies, specifically low-cost solar PV (photovoltaic) and geothermal heat pump systems, and use of these technologies in academic teaching. Social Marketing ('marketing behavior change') is central to the design and implementation of the project, and a social marketing framework is used in the design of a project implementation plan.

A low-cost "Solar Self-Supply" starter solar PV kit was designed, constructed, and tested as part of a senior capstone engineering class. This affordable, expandable system encourages local households to take advantage of recent drops in prices in Solar PV panels, as well as partial federal subsidies for the entire cost of solar household systems. The system is designed to be connected to the utility power grid. System design, construction, and testing results are discussed, as are project implementation strategies.

Geothermal heat pump (GHP) systems make use of the near-constant temperature of the Earth's subsurface to help control the temperature of a building. While conventional GHP systems for households can be cost-effective over the medium- to long-term, their high initial cost may make them unaffordable to many households. This research discusses the potential applicability of manual drilling of wells for GHP systems, with an aim of significantly reducing the installed cost of household GHP systems.

Approach – Social Marketing

Social marketing can be defined in a simplified way as 'marketing behavior change'. Social Marketing combines marketing tools and formative research on behavior to bring positive social change[1]. While there are multiple ways to conduct a social marketing program, the model used for this project is known as the Community-Based Social Marketing model. Community-Based Social Marketing includes the following five steps:

1. Select the Behavior
2. Identify the Barriers and Benefits
3. Develop Solution Strategy
4. Pilot the Program
5. Implementation and Evaluation

Social Marketing places a heavy emphasis upon choosing the exact behavior the social marketer wants to change. Choosing a non-divisible, end-state behavior, meaning a behavior that cannot be broken down to achieve your end goal, is imperative to bring about change. After the behavior has been chosen, research must be done to understand why the target population does the current behavior, and what prevents the population from instead doing the desired behavior. Once this information is known, the researcher has the tools necessary to develop a social marketing plan[2].

Using research from the Solar PV Mercer Senior Design project, social marketing was utilized to create a plan of action to analyze behaviors and influence the citizens of Macon to purchase solar power systems. This plan of action took into account the target audience, potential barriers, proposed solutions, and areas where more research is needed to be completed before piloting a project. This plan directs us to find out the reasons why not every resident purchases solar PV systems, and what we can do to make them more attractive to our target population.

The social marketing framework is crucial to the success of this project as it outlines areas where more research is needed. Because the target population is so specific, primary research is limited and difficult to find. Without this information, the research team was required to look at all potential barriers, with each barrier consisting of multiple sub-parts to evaluate. In order to conduct this research, the team recommends a survey to find residents' attitudes to having solar PV systems on their house, as well as further researching the feasibility of solar panels on roofs in the city of Macon. This includes researching the bylaws of multiple homeowners' associations and the direct costs it would have on the consumers. Once this research is complete, the project will have a much better understanding of the issues, and can better design a program to promote change that has a positive effect on the local environment.

II. Background

As of 2015, roughly 67% of electricity in the United States was produced by fossil fuels, and of those fossil fuels coal was used to produce roughly 33% of the overall electricity in the country[3]. While regulations are stringent in coal-powered power plants, there are a large amount of pollutants that are associated with coal burning which negatively impact air quality. More importantly, large amounts of Carbon Dioxide are associated with the 904 metric tons of coal produced in the United States, so taking steps to reduce the energy demand causing this environmental crisis would be very useful to future public health[4].

Solar Photovoltaic

Due to recent cost reductions in solar PV panels, adopting solar PV systems at the household level is a feasible way that most people could be involved in decreasing their contribution to burning of coal to produce electricity. Through approaching solar energy in an incremental step-ladder approach, a low buy-in program could be developed to attract a large amount of people that would later have the option to continually expand their green energy producing capabilities. A 30% federal tax incentive, which has been extended to 2019, can be used to subsidize the costs of investing in solar energy.

Three main components of this household solar PV system are the solar panels, the microinverters, and the racking (Figure 1). The actual solar PV panels are responsible for producing an electrical current through the silicon portion of the panel. The solar PV panel is then connected to a microinverter which transforms the direct current produced by the panel into an alternating current that can be used by the house or uploaded to the electrical grid. The solar PV panels are attached to the roof via aluminum racking securing the panels, microinverters, and all general wiring to the roof. The system is wired to the main breaker panel of the house. The wiring is then run through the attic and the side of the house to connect to the microinverters (which are placed on the underside of the solar PV panels). The microinverters transform the current from the panels on the roof from DC (direct current) to AC (alternating current). The aluminum racking system use in this project was purchased from a local solar supply warehouse, and was installed over the course of two days by the student team in charge of the project. Excess energy created by the system and not being used by the house is uploaded to the local electrical grid.

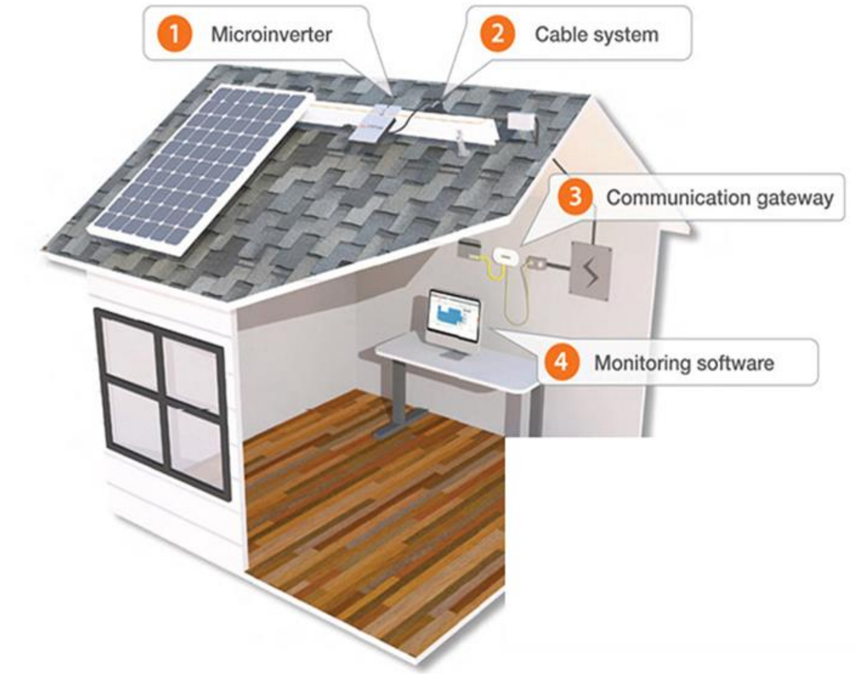

Figure 1: Example of Solar PV System, showing main components

Shallow Geothermal

Fundamental laws of thermodynamics state that heat flows from warm areas to cold areas. GHPs use an electrically driven heat exchanger (compressor-evaporator-ventilator) setup to transfer and supplement low-grade heat from a warmer area to a colder area[4]. During cooler periods GHPs use the earth's subsurface as a heat source, and during warmer periods GHPs use the earth's subsurface as a heat sink. In heating mode, heat is extracted from the ground through a liquid and pumped to the interior of a house, where it undergoes heat transfer and supplementation through the heat exchanger setup. In cooling mode the process is reversed with heat being extracted from the house and transferred to the ground. GHPs differ from traditional, air source heat pumps as the ground temperature is much closer to the desired temperature in a home than is the outside air temperature (at times of the year that active heating or cooling is required). GHPs recycle heat to and from the ground and are a sustainable solution to heating and cooling buildings, minimizing the additional energy needed to run the system (compared to air source heat pumps)[5].

There are two types of GHP systems: open loop and closed loop. Open loop systems circulate water, from a nearby pond or underground water source, directly from the source to the home. The water passes through a pressure tank, increasing the temperature, and then the heat pump, undergoing heat transfer with air in the home. In order to remain environmentally safe, the discharged water must be passed through a water filter to ensure contaminant removal. Open loop GHPs are most efficient since water conducts heat more easily than soil. A closed loop GHP system has pipes buried in wells in the ground. The pipes contain an antifreeze solution, which is pumped through the system to circulate heat. The pipes can be buried various ways, such as horizontally, coiled, or vertically. Horizontal GHPs require large areas of land but are less expensive to install; pipes are buried to a depth of 1.8 to 2.5 meters in the ground. Coiled pipes are buried to the same depth of 1.8 to 2.5 meters, but require less land area than horizontal pipes. When land area is limited, vertical loops are employed. The "u-shaped" pipes in vertical loops are commonly installed in drilled wells from 55-110 meters depth, depending on the attached system's heating and cooling capacity. Since the pipes are buried deeper in the ground, the ground temperature fluctuates less and provides more stability[5].

Macon is located on the fall line in Georgia, so the depth of bedrock varies greatly. Until reaching bedrock, the soil is a sand, clay, and gravel mixture. The bedrock in northern Macon can begin anywhere from 15-30 meters depth; however, in southern Macon, the bedrock starts at 30-46 meters. Since manual drilling techniques cannot be used in bedrock, the study area in south Macon is most suitable to test manual drilling. For two wells installed on Mercer's campus in Macon, with conventional machine drilling, bedrock was recorded at 50 and 46 meters depth.

Manual drilling techniques use human energy as the main source of drilling power. The most common techniques of manual drilling are hand augering, sludging, jetting, and manual percussion[6]. Hand augering and manual percussion of wells is generally not done much beyond depths of 25 meters, which is not a sufficient depth for vertical loop GHP systems. Sludging and jetting are used for depths of 35-45 meters. Sludging is more diverse in application as it can be used in sand, silt, clay, and stiff or weathered laterite; whereas jetting can only be used in sand and soft clay. Sludging circulates water to bring cuttings to the surface as the drill pipes are moved up and down. As the drill bit goes down and makes impact, it breaks up the ground, with the soil cuttings then being brought to the surface through water inside the drilling pipe (which will contain some form of one-way valve. The water flows into a pit next to the well, and the sediment settles out before the water recirculates into the well.

The most successful application sites for GHPs in the U.S. have been in the south due to warmer ground temperatures, making Macon a promising candidate for GHP applications. Macon soil is semi-permeable and ideal for the manual sludging technique[6]. Sludging is also an appropriate method since the wells can be drilled to 35-45 meters, which requires less wells to incorporate an average household GHP system. Below 2 meters, the seasonal cycle affects the soil temperature insignificantly, which means that the efficiency will be relatively stable year round.

III. Design and Testing of expandable Solar PV system

The household solar self-supply system developed by the Mercer University Senior Engineering team was designed to produce roughly one-third of the energy needs of the client and be expandable to cover the client's entire energy needs (and provide a surplus if desired). In the solar PV market there are many design options available to consumers, which can vary based on budget and energy needs. For the purpose of this project a design was chosen that would be as simple as possible for the consumer and completely customizable. For these reasons a design was chosen that utilized microinverter technology, which allowed for the most plug-and-play design possible which would allow for homeowners to expand at any level whenever they have disposable income to invest in expanding their solar PV system.

This project came about through the Senior Design course at Mercer University, and was completed by four senior engineering students. Spanning two semesters (Fall 2015 and Spring 2016), this course was split into a design focused semester and a construction/testing semester;

both ending with Design and Review reports. Much of the background research required to complete the project was carried out in Summer 2015. Part of the design and research that went into this project looked at what was being done at the commercial and residential level locally, and why or why not those systems or programs were doing well. The senior design course itself had weekly meetings with lectures that provided a framework for the design process, and also included lectures on various subjects (e.g. patent law, engineering ethics). While the actual installation of the system was not completed until later in the second semester, much of the designated testing period was spent planning the installation process, contacting the proper officials for inspections, and ensuring the legality of residential solar PV systems with the local housing authority.

In the summer prior to the Senior Design course (Summer 2015), a design decision had to be made in order to meet funding deadlines through the university’s Quality Enhancement Program. Through some initial market research the common technologies being used in residential solar PV systems were isolated and evaluated. With this analysis three viable technologies were found, each with certain advantages that could help the future marketability of this project. One of the more traditional designs was a solar PV system that used a single string inverter for the panels in this project. The main benefit for this design choice is that it would be oversized for our current system, so that another inverter would not need to be purchased if the system was expanded. The next design was functionally the same, except the panels would be modified with power optimizers that would basically get rid of shading problems affecting the panels. Specifically, if a portion of any solar PV panel is subject to less light then the rest of the panel, the energy production from that panel is reduced, and the presence of power optimizers would reduce the effect of this. Lastly, microinverter technology was considered, which would transform the DC current produced from each panel at the source. This fairly simple change in design significantly changed the economics of the design by offering a lower initial cost to the homeowner, and also offering much more customization to the consumer. While using microinverter technology had the risk of costing the consumer more money if the system is later expanded, the lower initial cost and monitoring technology available for microinverters made it the more appealing option for this project.

The starting design chosen for the client’s energy needs was a 1.1 kW system, consisting of four solar panels that are each approximately five feet by four feet in area. Based on the portion of the roof available, the system could be expanded to four times its current size, which would leave a surplus of energy during roughly half of the year. Additionally, a wireless monitoring system was purchased to evaluate the efficiency of the system against the National Renewable Energy Laboratory (NREL) model which made an energy estimate of the system given the angle of the roof and local weather patterns. The NREL modeling tool, PVWatts Calculator, is a free program that allows homeowners and installers to estimate the costs and monthly energy outputs of potential solar PV systems[7].

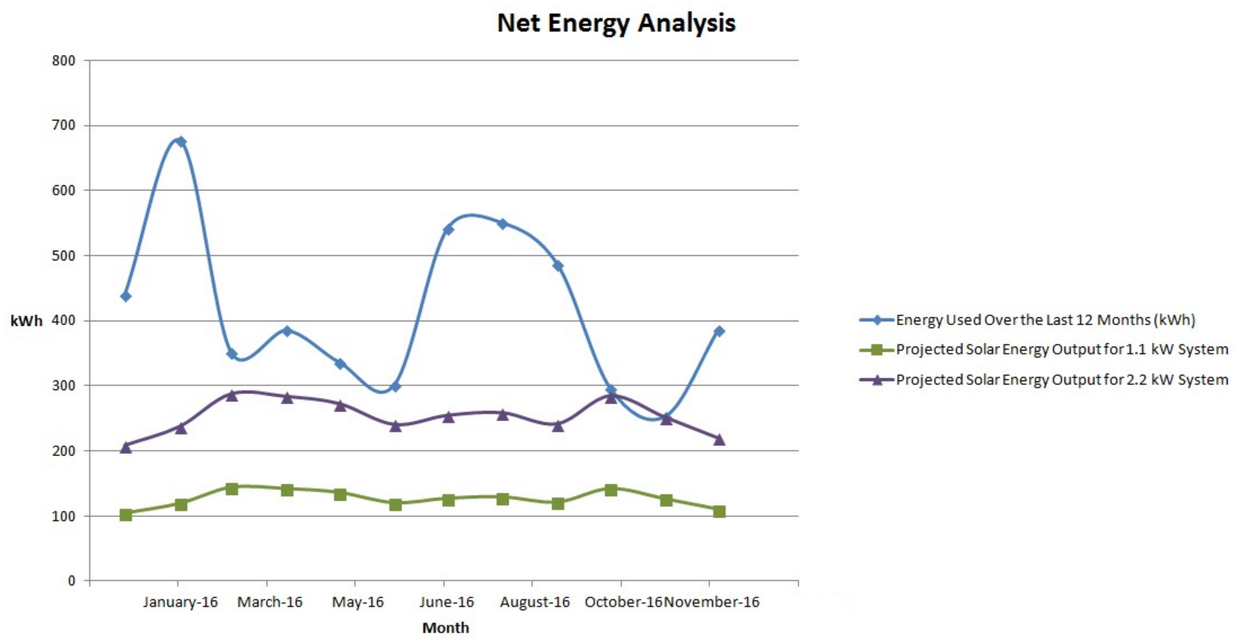

Figure 2: Energy Analysis Projections

Utilizing past energy usage data collected by the homeowner and the NREL model, projections were made on the efficacy of the current system to reduce electricity usage coming from coal. In Figure 2, the current 1.1 kW system is projected to cover approximately one-third of the energy needs in the Spring and Fall, and one-fifth of the energy needs in the Summer and Winter. Also shown is the potential energy production if the current system was doubled from its current size. Any level of expansion would ultimately be easier than the initial installation, since all of the system wiring to the house has been completed, so only new hardware (racking, microinvertors, and PV panels) is being added to the roof. This modeled expansion would be closer to an optimal size since the new projected outputs would be able to cover most of the energy needs throughout the year. Currently over-sizing the system would not be ideal, considering that the current energy buyback program with the client's energy company does not financially favor producing more energy than needed throughout the year, and over-sizing would ultimately increase the pay-off period for the system.

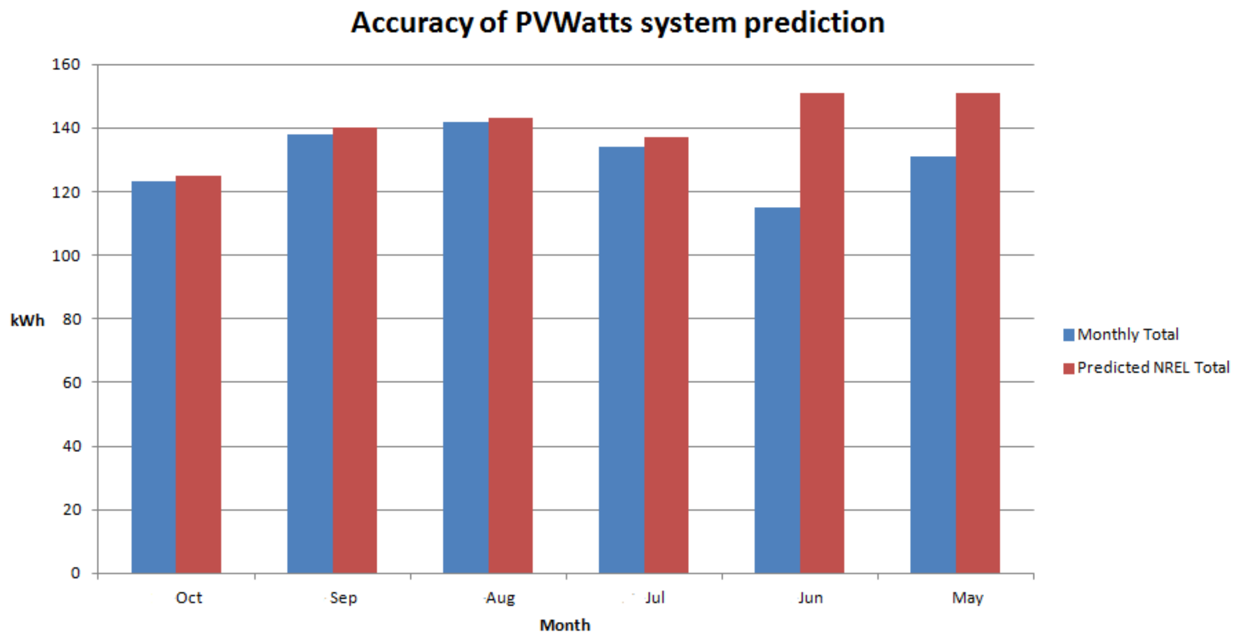

Figure 3: Graphical Comparison of NREL Model to 2016 System Data

The accuracy of the NREL PVWatts tool was tested, and while the model results were slightly higher than the system production, the current data set is limited as the system was only installed in May 2016, and a year's worth of testing would be ideal to fully measure the accuracy of the model. That being said, the accuracy of the model at this point would appear sufficiently accurate to justify the calculations made using the PVWatts tool.

The installation process of the system designed by the students is very simple and tested. Final connections and inspections required were done by a local qualified electrician, and no special training was required for the students to be able to complete the installation. After installation was successfully completed the students involved in the project documented their notes on the steps involved in the installation process in a technical manual. Ideally, any handy homeowner could pick up this technical manual and be able to make the appropriate purchases and have enough technical information to install such a system on their own.

A professional installer is not necessarily required for a homeowner to install a household solar self-supply system of their own; a main barrier is the cost of materials which after the federal tax was roughly $2,500 in this case, leaving a pay-off time of 14 years with a system that should last 20 years. The overall payback time for the system decreases as the system is expanded to meet the full energy needs of the household. The cost of the designed self-supply system is a relatively low initial cost, since average full scale systems can be up to 14 times this cost. In order to communicate this to the public, a social marketing plan was developed to change perceptions on the previously true barriers of solar technology that have recently been removed by cost reductions and improvements in the technology.

The main overall goal of the project is to spur environmentally friendly behaviors in homeowners in central Georgia. Having homeowners invest in green energy will make them more likely to look into other ways to improve their energy practices. In order to maximize their new solar investment, homeowners should also consider increasing the energy efficiency of their appliances, increasing their home insulation, using less energy in general, or further expanding their system in the future. In general, selecting solar as a form of household energy should become more feasible as the cost of solar continues to drop due to increasing efficiencies in the technology.

IV. Next steps

Following completion of further monitoring in 2017, it is expected that low-cost Solar Photovoltaic systems will be promoted/piloted in the neighborhoods near Mercer University, through a social marketing program that emphasizes cost-savings and environmental friendliness. Starting in Spring 2017 semester, a Mercer University engineering senior design team will continue work on the design of low-cost shallow geothermal systems using manually drilled wells. Low-cost renewable energy technologies, manual well drilling techniques, and social marketing, including lessons learned from this ongoing research, are being taught in senior undergraduate and Master's level courses in Green Engineering and Engineering for Development at Mercer University.

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References

1 Lefebvre, R. C. (2013). Social marketing and social change: Strategies and tools for health, well-being, and the environment. San Francisco, CA: Jossey-Bass. (Page 4)

2 McKenzie-Mohr, D. (2011). Fostering sustainable behavior: An introduction to community-based social marketing, 3rd ed. Gabriola Island, BC: New Society.(Page 8-15)

3 U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (n.d.). Retrieved October 26, 2016, from https://www.eia.gov/tools/faqs/faq.cfm?id=427

4 Phetteplace, G. (2007). Geothermal heat pumps. Journal of Energy Engineering, 133, 32-38. doi: 10.1061/(ASCE)0733-9402.

5 Lloyd, D.B. (2011). The smart guide to geothermal: How to harvest earth's free energy for heating & cooling. Masonville, CO: PixyJack Press, Inc.

6 Practica Foundation. (2010). *Understanding groundwater & wells in manual drilling* (2nd ed.). Papendrecht, Netherlands: Arjen van der Wal.

7 National Renewable Energy Laboratory. (2014). PVWatts Calculator (5.3) [Interactive Web Application].

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