Sustainable Low-Cost Household Energy Systems: Solar Photovoltaic and Shallow Geothermal Systems

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Abstract

An innovative research, service, and teaching initiative led by the Engineering for Development (E4D) program at Mercer University focuses on education, applied research, and service that aims to improve environmental practices at the household level in Macon, Georgia, USA (including water and energy efficiency; re-use and recycling; and use of renewable energy technologies). It focuses on cost-effective solutions that are 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 systems and shallow 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 initiative.

A low-cost 'Solar Self-Supply' starter solar photovoltaic kit was designed, constructed, and monitored over 4 years (2016-2020). 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.

The second form of low-cost renewable household energy studied is a shallow geothermal heating and cooling system, which utilizes manual well drilling to install a vertical loop, used in a split geothermal heat pump system. The largest cost component in shallow geothermal systems is the installation of the wells. Thus, using low-cost drilling options makes system installation more economically feasible for households. A preliminary design of the vertical loop was installed in a manually drilled well on Mercer University's Macon campus and monitored in Spring 2018.

Key technical, community development, and socio-economic aspects of the initiative have been incorporated into teaching in a senior and master's level Green Engineering course at Mercer University.

Keywords

renewable, sustainability, appropriate technology, community development, drilling, PV, heat pump, manually drilled well, social marketing

I. Introduction

The presented work is part of an education, applied research, and service initiative that aims to improve environmental practices at the household level in Macon, Georgia, USA, including: efficiency in energy and water use; re-use and recycling; and use of renewable energy technologies. The initiative is intended to improve the local environment while saving households money over the medium-term and long-term. Additionally, renewable energy system design processes and sustainable community development strategies are incorporated 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 messaging 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.

II. Background & Project Definition

Located just north of Macon, Georgia is Plant Scherer, which supplies electricity to the central Georgia area and is currently one of the largest coal-fired power plants in the nation. Plant Scherer is also one of the nation’s largest emitters of greenhouse gas emissions (EPA, 2018), which puts residents of central Georgia in a precarious situation, as they feel direct pressure to lower their energy consumption and move to cleaner energy sources. As the United States continues to shift from nonrenewable energy sources to more sustainable options, many lower- and middle-income households feel that significant home energy improvements are out of their reach. Largely this is because installation, house configuration, and material costs can cause renewable energy systems to be relatively expensive. There is currently also a medium- to long-term payback period, meaning homeowners won’t see a full financial return on their investment for many years. For these reasons, renewable and/or smart home energy system options are often viewed as economically unattractive or not feasible for lower- and middle-income homeowners.

The technical challenge that the project research addresses is to design options that can provide clean energy to the above-mentioned populations at affordable prices, with a complementary educational/social challenge to educate the public about home energy efficiency and energy conservation. Over the medium-term, the project aims to decrease overall dependence on coal-fired power through offering affordable energy conservation and clean-energy solutions to homeowners in central Georgia (and beyond).

The presented project takes a holistic approach to education and research design. Along with using technical engineering methods in system design, modeling, and assessment/testing, concepts from a range of disciplines are utilized in order to increase the likelihood of success of the project. A primary focus is behavior change, through the use of social marketing ('marketing behavior change for good') (Lee & Kotler, 2011). A social marketing framework is used to guide formative mixed-methods research (i.e. qualitative and quantitative research) that seeks to gain a deep understanding of homeowners' knowledge and perspectives on energy usage, production, and air quality. The framework is also being used in designing educational and promotional activities to inform homeowners of their options to make their homes more sustainable, their utility bills lower, and the air quality of the larger community better through energy efficiency and conservation as well as the use of clean energy technologies.

The project is collaborating with Macon Area Habitat for Humanity, to optimize green construction designs of their 'new-build' homes, which can typically range in size from 1,000 to 1,500 square feet, and to optimize solar photovoltaic (PV) system designs for new and existing homes of a similar size.

III. Research Description

As stated above, the project aims to decrease overall dependence on coal-fired power through offering affordable energy conservation and clean energy solutions to homeowners in central Georgia (and beyond). This is being done through a specific project objective, to design homes that are energy-efficient, optimized for the use of solar PV systems, and affordable for the average homeowner. The project objective includes five related project outputs: (1) energy-efficient new house design; (2) optimized solar PV system designs for new and existing homes; (3) optimized household component selection (lights, appliances, and other electric devices); (4) research of shallow geothermal energy options using manually drilled wells; and (5) energy conservation promotion planning. The objective and outputs 2, 4, and 5 (the foci of this paper) are described below.

<u>Project Objective: To design homes that are energy-efficient, optimized for the use of solar PV systems, and affordable for the average homeowner</u>.

Most sustainable home energy systems are typically marketed to those with relatively high incomes, while disadvantaged households and communities fall by the wayside. This causes an even bigger gap between America's wealthy and working-class citizens, leaving a large portion of the population to rely on energy produced from coal-fired power plants and without sustainable home energy options. Much of the project area receives their electricity from the large Plant Scherer coal-burning, multi-pollutant emitting plant. The coal-burning process produces carbon dioxide (major greenhouse gas), sulfur dioxide and nitrogen oxides (contributing to respiratory illnesses and environmental issues), mercury and other heavy metals (linked to neurological and developmental damages in humans), and other pollutants (EIA, 2018). This project aims to lead to improvements in community air quality while empowering disadvantaged populations in the central Georgia area and beyond, by designing new houses that are energy-efficient and designing clean energy systems optimized for new and existing homes, that are affordable for the average homeowner. Installation costs will be significantly reduced by having system designs that can be easily installed by local technicians/builders or handy homeowners. By developing and marketing eco-friendly energy solutions appropriate for those at the base of the housing market rather than at the top, disadvantaged homeowners in particular can become empowered and this can help to stimulate the U.S. in moving more rapidly in the direction of what is needed for a sustainable future.

Project Output 2: Optimized solar PV system design for new and existing homes
Pilot design, installation, and testing of low-cost solar PV systems has been carried out. By combining energy optimizing methods with these solar PV systems on homes (research/pilot system installed on one house in 2016; an additional system is to be installed on a local Habitat for Humanity house in Spring 2020), the home's energy bills and use of electricity that is produced from burning of coal can be significantly less than that of homes that have not been constructed using these designs/systems. This research has shown that household solar PV systems can be designed to be easily installed by local technicians, and configured to make expansion of the system (e.g. from a 1-kilowatt system up to a several-kilowatt system) very straightforward. Example activities for output 2 have included: design/configuration of expandable solar PV systems to be installed on new-build homes (e.g. starting out at an estimated 2-kW size); and design/configuration of systems/kits that are initially of a smaller-size, yet still expandable (e.g. starting out at a 1-kW size), for existing homes.

Design and Testing of Expandable Solar PV System
The household solar self-supply system developed by a Mercer University Senior Engineering team and installed in 2016 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 options available to consumers, which can vary based on budget and energy needs. For the purpose of this project a system was designed that would be as simple as possible for the consumer and expandable. For these reasons the design utilized microinverter technology, which allowed for the most 'plug-and-play' design possible, which allows for homeowners to expand at any level whenever they have disposable income to invest in their solar PV system.

The pilot Solar PV 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.
The starting design chosen for the client's energy needs was a 1.1 kW system, consisting of four solar PV panels that are each approximately three feet by five feet in size. 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 allows for evaluation of the efficiency of the system against the National Renewable Energy Laboratory (NREL) model which

made an energy estimate of the system given the system size, 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 (NREL 2016).

Utilizing past energy usage data collected by the homeowner and the NREL model, projections were made on the efficacy of the current system in reducing electricity usage coming from coal. In Figure 1, the current 1.1 kW system is projected to cover approximately one-third of the energy needs in the spring and fall season, 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) would need to be added. 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 is needed on an instantaneous basis throughout the year, and over-sizing would ultimately increase the pay-off period for the system.

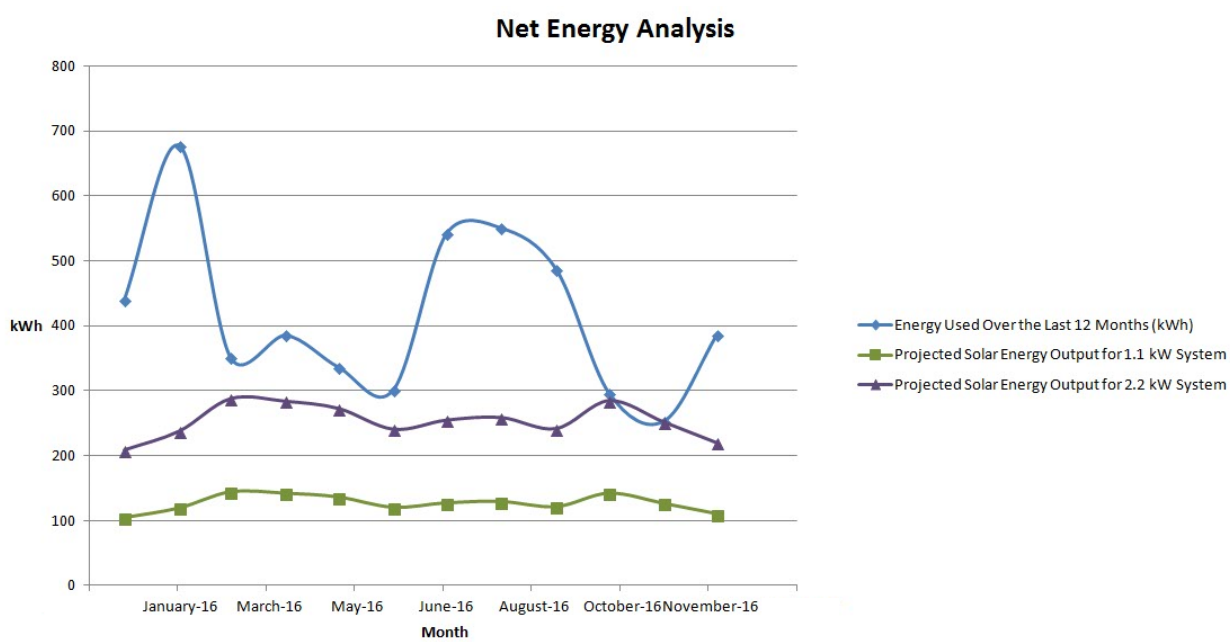

Figure 1: Energy Analysis Projections

The accuracy of the NREL PVWatts tool was tested, with monthly energy production totals being monitored over six months, as shown in Figure 2. While the model results were slightly higher than the system production, overall energy production over nearly 4 years (April 2016 – April 2020, as a lump sum, i.e. not monitored monthly) is more in line with the model. Thus the accuracy of the model would appear sufficiently accurate to justify the calculations made using the PVWatts tool.

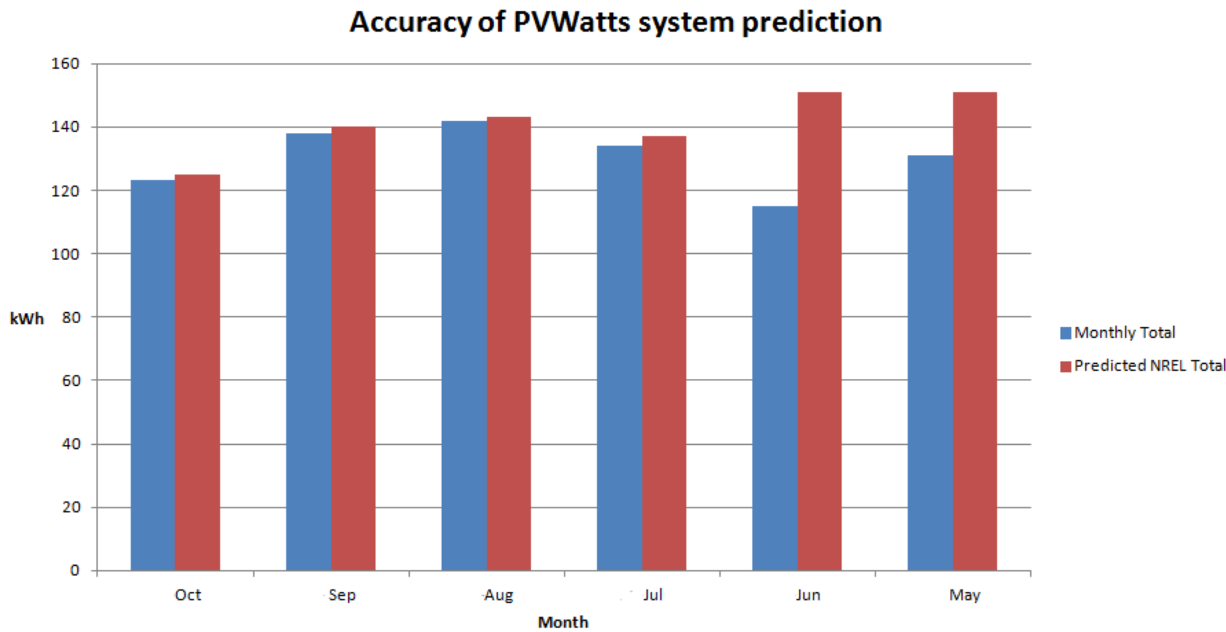

Figure 2: Graphical Comparison of NREL Model to 2016 System Data

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 in this case was roughly $2,500 after the federal tax credit, leaving a pay-off time of 14 years with a system that should last at least 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 installed systems could be up to 14 times this cost (2016 estimate). 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.

<u>Project Output 3: Manually drilled wells for shallow geothermal systems</u>

Environmentally friendly heating and cooling solutions are more available than ever; however, high initial costs for hardware and installation often dissuade low- and medium-income families from pursuing these sustainable, cost-effective options. It is thus valuable to design systems that efficiently heat and cool homes with manageable installation costs. Geothermal heat pumps (GHP) take advantage of near-constant ground temperatures at relatively shallow depths to transfer heat to cool or heat the interior of houses. GHP wells can be effectively installed using manual drilling practices that are innovative to the industry and that can significantly reduce total system costs to the owner. The aim of this project output is to design, build, and test an environmentally friendly, household shallow geothermal heating and cooling system that employs low-cost manually drilled wells. The new system considers fundamental laws of thermodynamics, local climatic patterns, and local geology and has been tested in a senior design course. These shallow geothermal technologies and manual drilling techniques are key areas in Mercer University's environmental engineering curriculum and this project has been used as a valuable teaching example in a Green Engineering course.

As a start to determining the feasibility of using manual drilling for GHP wells, a 2017-2018 Senior Design team was tasked with designing a single vertical loop system, manually drilling a well, then installing and testing the vertical loop system. The project site was at the Mercer University campus in Macon. The installed ground loop was tested by using a thermal conductivity testing (TCT) rig, which included a generator, pump, and heating element. To drill the borehole, the team used a manual drilling technique commonly called 'Baptist drilling', which is a hybrid technique that combines percussion and sludging into a single system. The team completed the manual drilling of the borehole over the course of three weeks and approximately 50 hours. Once the borehole drilling was completed, the team began pipe installation. The team installed a 1.25" HDPE pipe loop in the hole, working with the assistance of a local expert driller to get the HDPE to a depth of 33 feet; however, the pipe would not move farther into the borehole, so the team decided to decrease the initial 40 feet borehole design to 33 feet. The team then grouted the borehole with a geothermal grout to ensure maximum heat transfer and to prevent groundwater contamination. After grouting was complete, the team cut the remaining HDPE pipe above ground, leaving approximately ten feet for testing purposes. To prevent above-ground heat transfer, the team insulated the HDPE pipe.

The TCT rig holds 3 main components: the pump, the generator, and the heater. The generator provides power to the pump and the heater. The pump circulates fluid throughout the ground loop, and the heater increases the circulation fluid up to a desired temperature. Onboard temperature sensors and computer system collects temperature data from the inlet and outlet pipes of the system. To check this data, additional IcePick temperature sensors were attached at the inlet and outlet pipes as a way to verify the onboard temperature sensors. After testing for approximately 41 hours, the team retrieved data collected by the IcePick temperature probes and the TCT rig Geocube. The team saw an average decrease of temperature of one to two degrees Fahrenheit. The flow rate fluctuated between 10 and 11.5 GPM, and the pressure remained static at -50 PSI.

Testing of the installed GHP well showed the installation to have been done effectively. Additionally, manually drilling of the well was done successfully. However, well cleanout and installation of the vertical loop proved to be much more difficult than envisioned, and necessitated the use of heavier equipment that the drilling process did. Lessons learned from the pilot project are being considered in the design of a next phase of this research. Students in Mercer University's Spring 2018 Green Engineering course participated in the well drilling/installation, and students in the course in subsequent years have completed a geothermal module that includes exploring this case study.

Project Output 5: Energy conservation promotion planning

Energy conservation promotion planning. In order to engage the target audience, this project utilizes a message map, which is a tool commonly used in social marketing to develop 'key messages' along with 'supporting facts' to deliver to the population. A typical message map will include a few key messages along with supporting facts for each message. They are meant to clearly provide important messages to the target audience, and designed to assist the educators/trainers. Figure 3 is an example message map that the project team has developed to further the adoption of energy-saving options in middle- to low-income communities. Example activities for project output 5 (ongoing as of Spring 2020) include: implementing formative research study activities, including interviews and survey(s); development of message maps for specific target audiences (e.g. homeowners, small contractors, etc.); and development of social marketing promotional materials. Students in Mercer University's Green Engineering course are introduced to social marketing and messaging maps, studying numerous case studies related to the environment, and participating in the development of this project output.

Key Message 1	***Key Message 2***	***Key Message 3***
Installing a Solar PV system can reduce your energy bill	***Installing a Solar PV system is good for the environment***	***You can maximize your purchase by being as energy efficient as possible***
Supporting Fact 1-1	*Supporting Fact 2-1*	*Supporting Fact 3-1*
A 1 kW system can provide 10-30% of your energy needs.	*Coal fired power plants have a harmful effect on the environment.*	*Homes with better insulation will use less energy.*
Supporting Fact 1-2	*Supporting Fact 2-2*	*Supporting Fact 3-2*
If selling power back to the grid, it is possible to make a profit (with an expanded system)	*Solar panels produce clean energy.*	*Energy saving appliances will make the solar panels have a greater impact.*
Supporting Fact 1-3	*Supporting Fact 2-3*	*Supporting Fact 3-3*
The system will pay itself off in 14 years (after 30% Federal Tax Incentive) (Expanded system 11 yrs)	*The energy you use that is created by PV panels means that the same amount of energy will not be produced by fossil fuels/nuclear.*	*Energy efficient practices will add to the impact of the system.*

Figure 3: an example Message Map developed to promote household energy efficiency and low-cost solar PV systems on recently built homes in Macon, Georgia

IV. Educational and Interdisciplinary Aspects

This project is unique in that one of the key components of the project uses social marketing to educate the local community about sustainable home energy solutions. By utilizing the social marketing plan and interacting with homeowners, Habitat for Humanity, and local technicians, citizens gain knowledge about their energy consumption, its impact on the environment, and how they can reduce it.

Numerous student specialties/disciplines have been represented on the project team, consisting of environmental engineering and mechanical engineering majors with engineering for development minors, and an industrial design and management major. This range of subject areas has allowed for the team's improved environmental practices approach to be studied through various different lenses. This initiative's approach is currently taught in Mercer University's Green Engineering course, which covers topics such as energy efficiency, renewable energy technologies, green building, and engineering in disadvantaged communities (both in the U.S. and internationally). It's feasible that Mercer's business school could adopt project ideas relating to the local economy into its curriculum, as this project helps those in low-income communities save money and climb the socioeconomic ladder, and would also increase market demand for solar and smart home technology providers and installers. These concepts can also be added to the curriculum taught in public and global health classes, with the focus being on how clean-energy systems decrease environmental pollution and improve community health. Mercer University's Quality Enhancement Plan (QEP, running from 2015-2020) focuses on combining research with service (with a tagline of "Research that Reaches Out"), with a dedicated, staffed office. This project is coordinating with Mercer's QEP to advance integration of the initiative approach across the university.

Feedback from students in Mercer University's Green Engineering course has shown that they find the household level examples used to teach about energy efficiency and conservation to be beneficial and memorable, the study of small-scale solar PV and shallow geothermal systems to be a good way of teaching system design that is even relevant/similar at larger scales, and the behavior change aspect (taught using social marketing) to be a valuable to engineers (particularly environmental engineers).

References

EIA. Coal Explained: Coal and the environment, accessed on December 3, 2018 from https://www.eia.gov/energyexplained/index.php?page=coal_environment

EPA. Location and emissions for each reporting facility in the power plant sector, published online August 2018, accessed on December 3, 2018 from https://www.epa.gov/ghgreporting/ghgrp-power-plants#map-facilities

Lee, Nancy R., and Philip Kotler. Social marketing: Influencing behaviors for good. 4th Edition. SAGE publications, 2011.

NREL. National Renewable Energy Laboratory. PVWatts Calculator (version 5) [Interactive Web Application], 2016.