Design of a Novel Mobile Solar-PV Energy System for an Average House in the Texas Panhandle

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Abstract

This paper aims at evaluating and presenting a solar-PV energy system offering a secondary, affordable, mobile, and reliable renewable source of electricity made from two Sun- tracking, 300-Watt solar panels along with the electrical hardware necessary to optimize electricity harnessed and stored. The proposed system will establish deeper understanding of the optimal performance of mobile solar energy systems under normal conditions and during emergencies. A prototype of this system was built at WTAMU thanks to funding obtained from an internal grant as well as capstone senior design funding that allowed undergraduate senior students to build the prototype over a full academic year. This project will open a gate to undergraduate research on solar energy in the Texas Panhandle, which is a region rich in solar energy resources. This paper will describe the prototype, and experimental results will show daily electricity harnessed from the system in an average house in Amarillo, TX. The proposed system will not only advance the understanding of mobile solar energy but also provide a green, environmentally friendly energy source helping with typical daily electricity needs as well during catastrophes. The research leading up to this system aligns with the federal goal of achieving higher percentage of renewable energy per state. This system provides between 8% to 63% of the daily electricity demand for an average household during normal times and can act as a standalone emergency source of electricity during natural disasters that result in long-lasting power outages.

Introduction

In mid-February 2021, an unprecedented snow storm hit most of the state of Texas resulting in massive power outages due to historically low temperatures [1]. The electricity demand skyrocketed, and the state's capacity to generate electricity could not match the sudden electricity demand. This resulted in wide spread outages that ranged from a few hours to a few days depending on the damage sustained in every local area. This research aims at evaluating and providing a solution to such incidents by offering a secondary, affordable, and reliable renewable source of electricity made from two 300-Watt solar panels tracking the sun along with the electrical hardware necessary to optimize electricity harnessed and stored. This system provides between 10 to 50% of the electricity demand for an average household during normal times, and can act as a standalone emergency source of electricity during natural disasters that result in long-lasting power outages. The proposed research will establish deeper understanding of the optimal performance of mobile solar energy systems under normal conditions and during emergencies. This research has started thanks to an internal research grant from WTAMU in 2021. Preliminary results describe the built prototype and show data presenting daily electricity harnessed from the system in an average house in Amarillo, TX. The proposed research will not only advance the understanding of mobile solar energy but also provide a green, environmentally friendly energy source helping with typical daily electricity needs as well during catastrophes.

The majority of the Texas Panhandle receives the third highest amount of solar energy in the nation as shown in figure 1 where the US map provided by NREL shows solar energy irradiance distribution in the nation. To put this in perspective, Randall County receives an average of more than 5 $kWh/m^2/day$. This amount of energy per unit area per day is about half of the average daily electrical energy consumed in a 1405-ft^2 house located in this county in Amarillo, TX. A prototype of a standalone solar-powered power system that provides electrical power to a house has been built at WTAMU. The advantage of this system is its ability to be affordable and mobile.

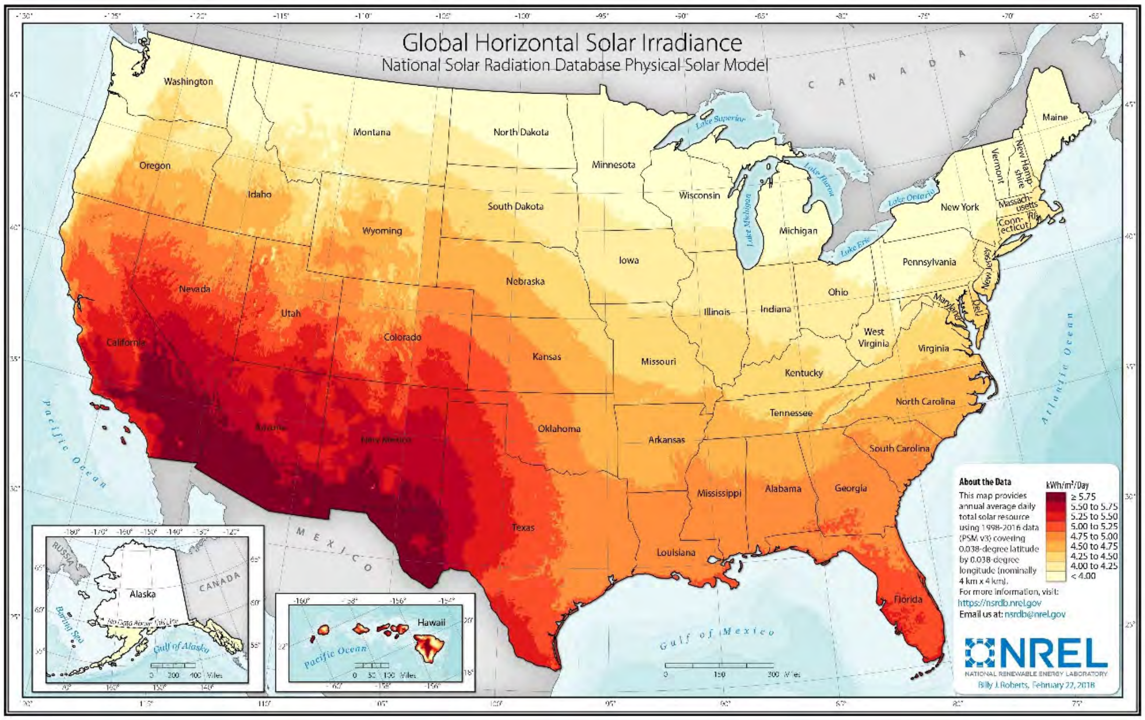

Figure 1. Solar Energy distribution in the United States [2]

The first milestone of this research is to build the solar system along with batteries, battery management system (BMS), and inverter allowing this solar generated power to be used with home appliances requiring AC 120 V. This milestone has already been partially achieved with an internal WTAMU grant. The data show that on any given day, the system can provide anywhere between 8% and 63% of the electrical demand for this particular house. The second milestone involves designing and building the mobile structure that holds the system components inside a trailer case allowing it to be mobile. The third milestone is to investigate the best method to design and build a solar tracking mechanism. The fourth milestone is to test its performance during emergencies such as inclement weather. The fifth milestone is to calculate the amount of greenhouse emissions that are cut as a result of integrating this system with the electric grid in the house. The sixth and last milestone is to investigate the commercial feasibility of this system as a standalone renewable energy producing system.

The Electric Reliability Council of Texas (ERCOT) is responsible for providing 90% of the state of Texas with electric power [3]. This means that 90% of the electric grid in the state is not connected to the major electric interconnections in the nation, i.e. the eastern interconnection and the western interconnection. This makes this research more relevant and important for the state of Texas if its electric grid continues to operate as an independent entity.

Novelty of the research in the context of the existing literature

When solar-PV is mentioned as a renewable source of electricity, the vast majority of this type of power comes from either solar-PV farms [4] or from solar panels mounted on house roof tops belonging to people who decide to get their electricity this way contributing to what is called distributed generation solar-PV [5]. The performance of a PV system is dependent to some extent on the climatic conditions relevant to the location where the system is installed. PV system performances in a tropical country such as Malaysia have been documented [6,7]. These studies have indicated the system's average productivity to be 2.4 kWh/kWp per day with an average performance factor of 75%. The unit kWh/kWp is referred to as the specific yield which is defined as the kWh produced by every kWp (kilowatt peak) of module capacity over a period of time. Performance factor is defined as the ratio of the measured output energy to the incident energy from solar irradiance. Grid-connected rooftop PV systems for small houses have also been analyzed in subtropical regions such as India [8]. Results show a daily average productivity of 4.2 kW h/kWp and a performance factor of 75% as well. In a hyper arid desert climate such as Kuwait, PV panel performance on school rooftops has yielded an average daily productivity of 4.5 kWh/kWp with a performance factor ranging between 74% and 85% [9], while in a maritime climate such as Norway, performance assessment of grid-connected rooftop PV system yielded an average daily productivity of 2.5 kWh/kWp with a performance factor of 83% [10].

The objective of this research is to investigate facets of relying on the electricity provided by the electric grid established and maintained by local electric companies while at the same time producing a significant amount of electricity from an affordable standalone solar-PV electricity source with dual-axis tracking capability that can also be moved around to serve as an electricity source during camping trips instead of using a Diesel or gas generator. Solar tracking systems are divided into single-axis [11,12] and dual-axis systems [13-15] based on the number of directions of independent movements. In single-axis systems, the panel is rotated such that it tracks the sun azimuthal angle. The most ideal orientation is the one along the north meridian axis [11,12]. On the other hand, dual-axis systems involve two axes of rotation that are perpendicular to each other. Even though dual-axes systems have higher cost and maintenance issues associated with them, they are the preferred choice of solar tracking systems for this project due to their boost of the harvested energy. Sun et al. [16] shows a typical increase between 15% and 17% in the harvested energy when using a dual-axis solar tracker in comparison to a single-axis system. The proposed design will help reduce the electricity bill amount, limit greenhouse emissions, and provide necessary electricity when the grid is disconnected during emergencies. On a research level, this system will allow ad-ons and will serve as a test bed for technological advances that could appear in the future such as energy storage with larger capacity or solar panels at a higher power capability or higher efficiency. Current systems that exist in the market are provided by a single vendor. They lack the ability to be connected to the grid and are highly expensive ranging in price from $16,487 to $87,730 per system and ranging in power capacity from 530 Watts to 4800 Watts respectively

[17]. One of the objectives of this research is to make a mobile solar-PV system affordable to a wider range of households. The research in this project responds to the current need for experimental studies and improvements to achieve distributed generation of solar-PV energy as an alternative to fossil fuels contributing to climate change. It also helps achieve energy independence, a national security element. This research also aligns with the federal goal of achieving higher percentage of renewable energy per state. The experimental studies will lead to the development of a novel, optimal, mobile, solar PV, sun tracking, electricity generating system that provides tangible electricity during normal and abnormal times. Experiments will provide insight into the influence of various system parameters on the system performance, energy efficiency, energy contribution factor, and energy storage life span. In addition, the prototype will act as a test bed for state-of-the-art developments in solar PV technology keeping the door open for continuous engineering analysis and development. This will possibly lead to major enhancements in the design of solar PV energy. Tests performed on the proposed prototype will evaluate the feasibility of using the system on a commercial basis.

Description of Experimental Methods and Procedures

A. Designing the system structure and case allowing mobility

This step includes designing, building, and testing a mobile solar-PV system along with battery energy storage, battery management system with MPPT, an inverter, and trailer structure. The system has been fully electrically designed and partially structurally designed. This happened due to the limited internal funds available at the time. This still allows for the electrical performance to be comprehensively evaluated while improving the mechanical and structural design when external funds are available. Figure 2 shows a picture of the solar-PV prototype with dual axis tracking capability. Figure 3 shows the system prototype designed using CAD before it was built in the WTAMU machine shop. Figure 4 shows the electrical side of the system comprised of a Lead-Acid battery made up of two units each at 6V connected in series to reach 12V, a 2000-Watt inverter, a battery management system (BMS) with maximum power point tracking, and the electronics for the Sun-tracking system.

Figure 2. Solar PV prototype with dual axis Sun tracking capability

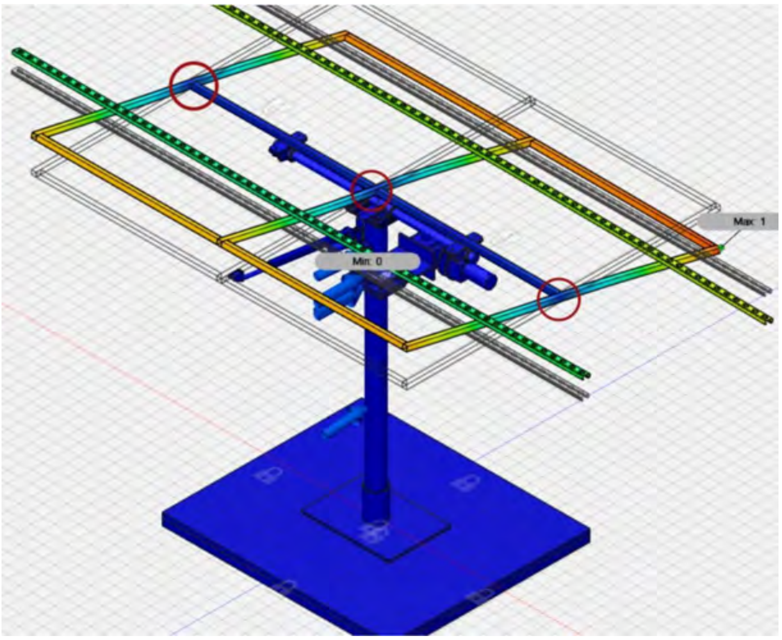

Figure 3. CAD picture of the system during design phase

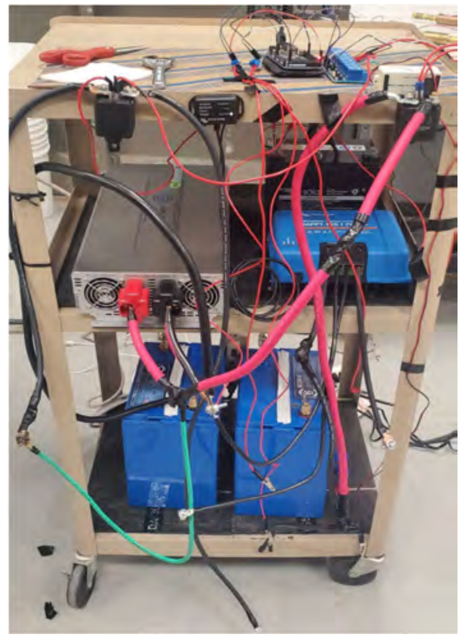

Figure 4. Electrical components of the system

B. Observing amount of energy collected in the span of two years

This step involves observing the amount of electricity consumed from the local electric company as well as the electricity produced by the solar-PV system each day in order to investigate the percentage of the solar energy collected and consumed in a house located in Amarillo. This step has already started in April 2022 and is a continuous effort that will span a few years. Figure 5 shows the electricity generated each day during the 30-day period spanning February of 2022. Figure 6 shows the same for the month of August 2022. One observation that can be made is that cooler months generate more electricity via solar-PV due to the negative high temperature effect on solar panel output power. It has been observed that an excellent day for solar-PV panels would be a sunny cool day. The longer days during the spring and summer seasons make up for the degradation caused by high heat.

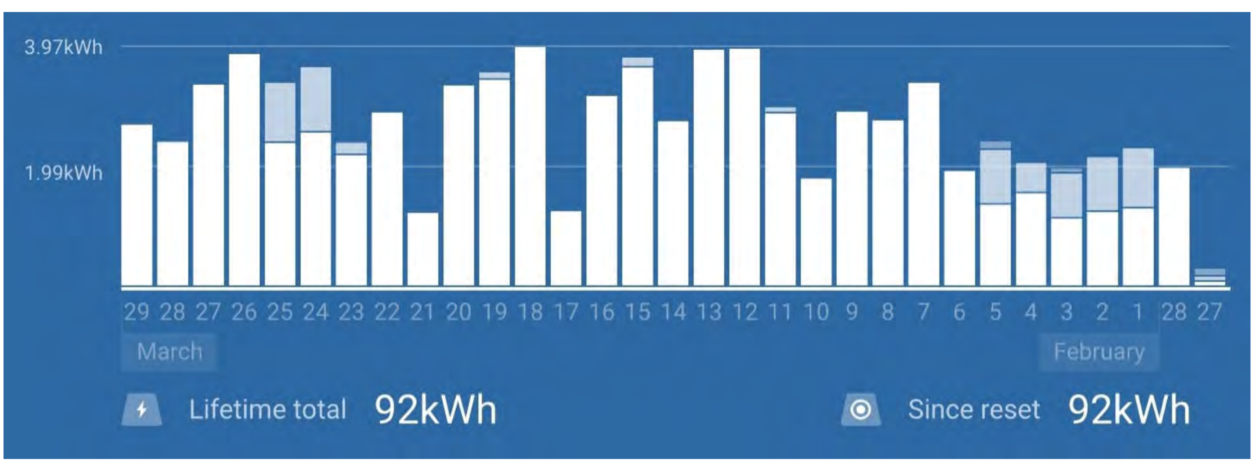

Figure 5. Electricity generated in kWhrs per day during the month of February 2022

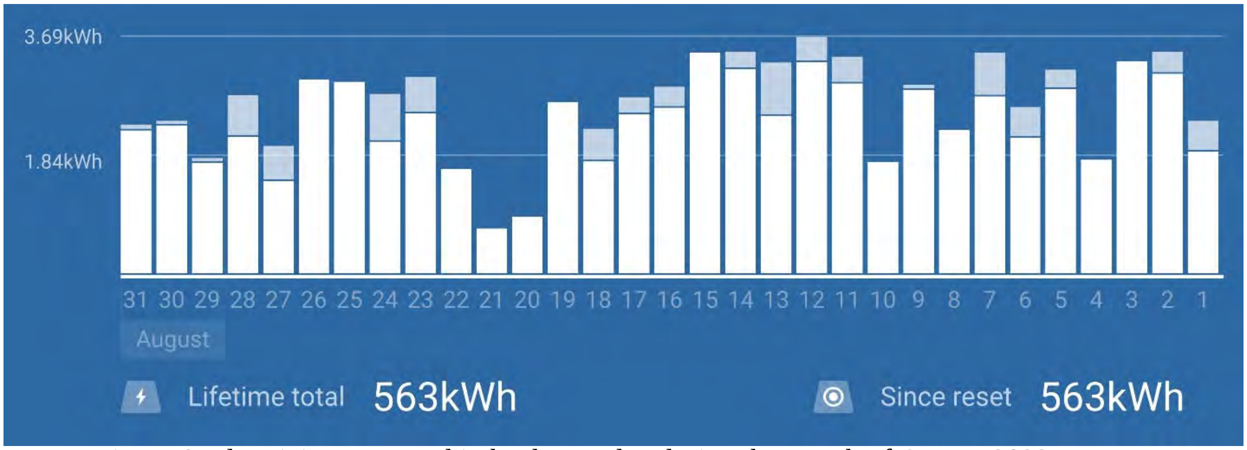

Figure 6. Electricity generated in kWhr per day during the month of August 2022

Figures 5 and 6 were generated by a mobile app that comes with the BMS/MPPT device. Some bars in these two figures show solid white color while others show light blue portion along the white part. The white portion indicates Bulk charging status, while the light blue portion indicates Absorption status. Absorption happens when the lead acid battery becomes 80% charged. There is also dark blue that indicated Float status, which happens when the battery gets fully charged and can no longer safely accept energy. This case happens very rarely and can be observed on February 27 and March 5th in Figure 5.

C. Observing the effect of solar tracking versus stationary panels

This step involves building a stationary system with no sun tracking. The goal is to investigate the benefit of tracking the sun on energy yield versus having a stationary system, with no moving parts, facing south at a tilt angle equal to the latitude of the location where the system would be installed. The idea here is to compare and contrast the two systems to explore the various design options that could minimize the cost and maximize the energy yield in order to reach an optimal set of design parameters. The internal WTAMU grant was only sufficient to build one prototype with a dual-axis tracking system. This prototype has been installed in the backyard of a house in Amarillo where it provides electricity on a daily basis since February 2022. Figure 7 shows the electricity consumption of this house for the past 18 months since October 2020. There is clear evidence up to this point that the system reduced the total electricity consumed from the power company. This can be observed by looking at the months of February through September with the only exception of July 2022 where the temperature was at a record high causing the AC to be turned on for the whole month during 2022, which was not the case in 2021.

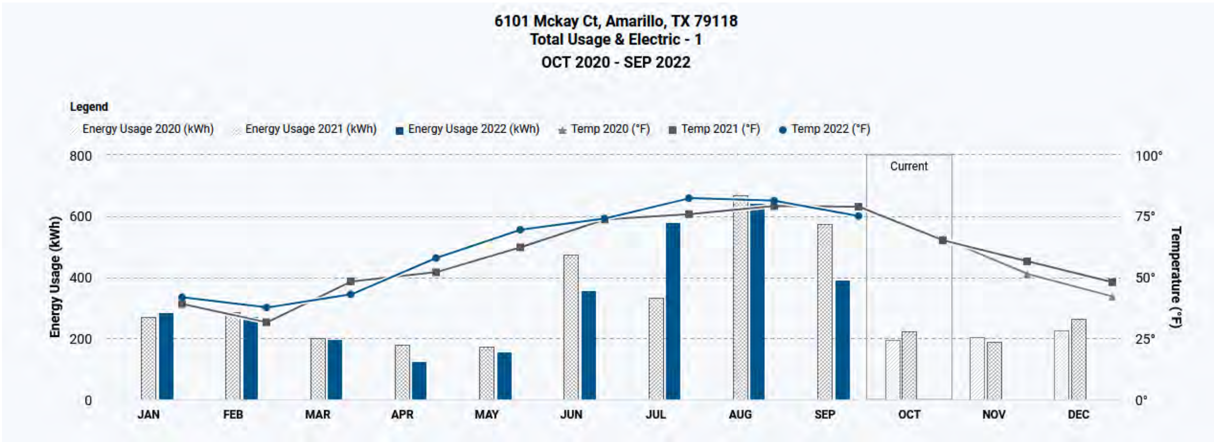

Figure 7. Electricity consumption per month at the house where the research is conducted

Mechanism for Assessing Success

Success in this research will be assessed by investigating the following:

1. The ratio of the electricity generated by the solar-PV system versus utility electricity
2. The ability of the system to provide enough electricity for basic needs during emergencies
3. The ability of the system to function for a long period of time without major maintenance requirements (longevity)
4. The overall cost of the system once it reaches a high level of maturity
5. The feasibility of commercializing the system after making it a product

Table 1 shows the average percentage of electricity that the existing prototype has provided since it was installed in February 2022. The data so far show promising results.

Table 1. Average percentage of electricity produced each month from the solar-PV prototype installed in a house in Amarillo, TX.

Month (2022)	System energy contribution percentage
April	44.0%
May	36.5%
June	21.0%
July	13.0%
August	14.75%
September	24.45%
October	35.6%
November	25.3%

One observation from Table 1 is that even though the month of July 2022 was one of the hottest months in 2022 requiring continuous air conditioning while reducing the solar panels output power capacity down to 60% of their nominal capacity, the system was still able to provide 13% of the electrical energy needs of the household in Amarillo, TX. This empirical result was higher than expected. Table 1 will be expanded to cover the entire period of the two years plus the months presented so far. This table helps with assessing success (criterion 1 of the success criteria listed on page 6).

Broader Impact

Impact on Texas, the Nation, and the World

On top of having a direct impact on the environment, the Texas Panhandle electric grid capacity, and national security relevant to energy in the US, this research has further goals contributing to broader impact on the lives of people within and outside the US. Specifically, this research could contribute to improve conditions in less fortunate countries where having access to constant electric power is not possible. This research has a global impact element taking into account global energy needs where electricity is not readily or easily available from electric grids. This last impact element is attainable when the research reaches a commercial level, which is going to be investigated as part of the research.

Dissemination of the Results of the Research

The results of the research will be disseminated through undergraduate seminars held at WTAMU and conducted by PI and student collaborators. The students, along with the, will present their findings at national and regional conferences every year. The research findings will be presented at the WTAMU faculty annual poster presentations and WTAMU student annual research conferences. The results of the research will also be disseminated through the development of a special topics courses on Smart Grid and Renewable Energy (EENG 4392 and EENG 6307 respectively). The knowledge acquired from the research will be used to guide the coursework content.

Contribution to WTAMU Educational Goals

The PI has been actively involved in the initiation and development of the undergraduate engineering and the M.S. engineering programs at WTAMU. This project will enhance the infrastructure for research and education through an improved research facility. This research has an outreach component to incentivize undergraduate engineering students especially those coming from underrepresented minorities including women, Hispanics, African Americans, and students with disabilities. This research enhances the infrastructure for research and education through an improved research facility particularly in the renewable energy area. WTAMU is committed to serving as the principal academic, cultural, technical, service and research center of the multi-state region surrounding Canyon and Amarillo through the collective and individual efforts of the faculty, staff and students. Educationally, this research will create a link between the well-established mechanical, electrical, and engineering technology programs. At WTAMU, these programs have been and will continue to be successful in attracting both competitive and targeted investment in research capacity in the Texas Panhandle.

Criteria for Future Research

This research, when completed in a two-year period, would result in a prototype that meets or exceeds expectations providing a significant portion of the electricity demand in an average house in the Texas Panhandle. This would be a finished milestone that attains the level of a mature product; however, this is not to say that the research ends at that point. This project is the starting point for extended research relevant to the following aspects:

- Energy storage modeling, testing, and development
  The energy storage system currently selected for this project is a lead acid battery that is rated at 12V, 250 Ahr, and 3 kWhr. This can be easily replaced with another chemistry or entire technology for modeling verification, testing, and development aiming at reaching higher energy capacity and/or higher efficiency. The system in this case acts as a test bed for development from a storage standpoint.

- ***Solar-PV technology test bed***
  The project uses two solar panels each rated at 300 Watts (600 Watt total). The system will be designed to be able to handle 50% more power compatible with energy storage expansion, testing, and development.
- ***Electrical connection standardization***
  The system at this point will be designed to be standalone independent from the power grid. The door will be open to work on this aspect adding the possibility of connecting the system to the electric grid when the system is stationary for long periods of time. This adds the ability for the system to provide electricity to all existing outlets in a house as well as provide electricity to the electric grid during islanding events in a Smart Grid. This will be done in a way that gives the system owner the option to operate the system in stationary and mobile modes. When this aspect is past the research point, the electrical standards will have to be modified allowing a plug-and-play outlet connected to the breaker box to synchronize the AC power generated by the solar-PV system with the electric grid.
- ***Power electronics research***
  The system at this point uses a single device that manages the power flow as well as achieve maximum power point tracking. This is an area of research where the efficiency, reliability, and cost studies can be done allowing for extended research on power electronics devices.
- ***Undergraduate research opportunity***
  The system allows for research at the undergraduate level in electrical, mechanical, environmental, and possibly civil engineering. Students at the senior level working on their Capstone Senior design projects can do analysis and possibly contribute to the structural and electrical design aspects while environmental engineering students can study the environmental impact of such systems on the carbon footprint.

Summary and Conclusions

This paper presents preliminary results relevant to a solar-PV system that is designed to help provide tangible electricity to an average house on a regular basis and also during emergencies. A prototype of this mobile system has been built and tested over a period of several months to gauge the system capability of providing tangible electricity to an average house on a daily basis while also acting as an emergency source of electricity during inclement weather that cuts off the power grid. The results up to this point show a promising low-cost system that can be designed to be stationary and/or mobile adding to its overall value. The electricity percentage obtained from this system has been between 13% and 44% of the monthly electricity demand of a house in Amarillo, TX. This percentage changes based on the weather conditions such as solar irradiance, ambient temperature, shading by surrounding objects, and overall electricity demand. This project is ongoing and will engage undergraduate electrical and mechanical engineering students to do research on its upcoming milestones.

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