Haiti RELAY: A Cost-Effective and Portable Solar Home System for Rural Haitian Regions

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***Abstract*—Haiti is a Caribbean country located next to the Dominican Republic on the island of Hispaniola. Currently the poorest country in the Western Hemisphere, Haiti suffers from a lack of energy infrastructure leaving over 7.4 million people without power. The electrification rates are the worst in the rural, mountainous regions of Haiti where in 2013 only 15% of residents had access to electricity. The Georgia Institute of Technology's Haiti RELAY team was created in 2015 to help spark the growth of electrification rates in these regions through the development of a simple, cost-effective, and portable solar home system called the "Haiti RELAY". This fully-integrated solar charge controller device was designed through a data-driven approach to provide a consistent means for house lighting and phone charging. In May 2018, the Haiti RELAY team travelled to enact the Haiti RELAY pilot program in the mountains of Thoman, Haiti. As a part of this program, 25 families acquired a RELAY and agreed to provide feedback to help the team understand the efficacy of the design and the necessary improvements for moving the product towards full-scale production. This paper details the energy situation in Haiti, construction and functionality of the Haiti RELAY, and the results of the 2018 mission to Thoman.**

I. Introduction

Limited by the harsh environmental conditions and inadequate infrastructure, the construction of traditional electric power grids in remote regions of countries like Haiti faces serious technical and financial challenges. Considering the fact that only 38% of the population in Haiti has access to electricity (15% in rural areas) [1], distributed power generation systems, especially those based on solar energy that is readily available in low-latitude tropical islands, are proposed as a viable solution for these places. Solar power has become an even more promising and affordable way to electrify Haiti given the steadily dropping price of solar cells.

Based on this idea, many solar projects have been developed in remote areas of Haiti in the past few years [2]- [3]. But God Ministries (BGM), an American non-profit organization devoted to building sustainable communities, started their construction of health centers in Haiti in May 2011 [2]. One of these health centers, called "The Hope Center", is located in Thoman, Haiti, a mountainous village located 25 miles east of Port-au-Prince, Haiti's capital. In 2016, the Georgia Tech Haiti Solar Project equipped the Hope Center in Thoman with a 7 kW off-grid solar generation system, which provides sufficient electricity to the onsite clinic and living facilities for mission teams. However, limited by the requirement of large initial investment and high complexity of operation, such microgrid systems are not suitable for the houses of local villagers outside the Hope Center. To solve this problem, a team of Georgia Tech students travelled to this village in May 2016 and deployed two pilot solar charging systems in the local village homes [3]. Equipped with an 80W solar panel, these devices were used to power an LED light, and a cell phone charging port. Despite the successful installation in local communities, this system suffered from the following problems: 1) the 80 W solar panel was over-rated for the existing electronic loads, resulting in an efficiency as low as 20%; 2) the 80 W panel was too heavy and required a tedious and difficult installation step onto already unstable rooftops 3) the functionality of this system was limited by the lack of a dedicated energy storage device, which made it less useful at night and during the rainy season; 4) the charge controller was not designed with protection circuits to prevent the system from over-current, over-voltage, and over-charge conditions; 5) the PCB and enclosure were not sturdy and robust enough for prolonged daily usage; 6) mounted on the village homes, the system was stationary and vulnerable to extreme weather as well as theft; and 7) the cost of the system was not optimized to make it affordable for the local people. These problems greatly reduced the lifespan and efficacy of this product, and consequently, the systems stopped functioning after approximately one month of use.

To resolve these problems and enable a larger deployment of solar energy in rural Haitian regions, the Haiti RELAY, a newly designed solar home system is proposed in this paper. Featured with a smaller solar panel rated at 15 W, the system integrates both the battery and charge controller circuitry into a single enclosure to maximize portability and versatility. Following a data-driven approach, components in the system were carefully rated based on statistics of local surveys. The energy storage device was sized optimally based on complete hourly solar resource data from National Solar Radiation Database (NSRDB) [4]. The optimization of the

This work is supported by the IEEE Power and Energy Society (PES), Georgia Tech Student Foundation (GTSF), Georgia Tech ECE Opportunity Research Scholar (ORS) program, the Center for Distributed Energy (CDE) at Georgia Tech, and the Electric Power Research Institute (EPRI). Their support is greatly appreciated.

component sizes allowed for the unit cost to be greatly reduced from the 2016 system to a price range affordable to most rural Haitian villagers. The reliability and robustness of the system is greatly improved with the integration of the circuitry and battery charging protection. The Haiti RELAY team travelled to Haiti in May 2018 and successfully installed 25 RELAYs in the village of Thoman, Haiti. Performance of these devices has been verified through both simulation and field testing. The operational status of these devices will be continuously monitored through a feedback program in the following three months. A larger scale installation of the improved version of the RELAY is also scheduled in the future business plan by the end of 2018.

The remainder of this paper is organized as follows. Section II describes the current energy crisis in rural Haitian regions based on field research. Section III presents the proposed Haiti RELAY system in detail. Section IV introduces the feedback program and future business plans. Section V concludes this paper.

II. Energy Situation in Rural Haiti

A. Overview of Haiti Energy Situation

Haiti is home to almost 11 million people, of which 62% (around 7 million) have no access to electricity. The majority of those with electricity live in proximity to the power generation plants in major cities such as Port-au-Prince (capital) and Cap-Hatien. The electrification rate plummets as distance from these plants increase due to the high losses in energy transmission from grid inefficiencies. Over 85% of rural Haitians have no access to electricity due to these issues. The electricity market in Haiti fluctuates greatly and is very dependent on location. Since Thoman is a mountainous village, 25 miles east of Port-au-Prince, prices are higher than average and hard to track. Through interviews on the 2018 mission, the team was able to secure information about the current state of the electricity market in Thoman. The electrification rates vary greatly from village to village. In Thoman, 6 out of 25 residents who received a RELAY already had some form of access to electricity from a single wire earth return (SWER) distribution line. These lines are very unreliable and are often not energized. In the neighboring village of Mathias, residents had no access to electricity. Those who do not have access to electricity use kerosene lamps for lighting their homes. These lamps do not provide much light, are inconvenient to turn on for each use, produce toxic fumes, and have a much higher potential to burn down homes. Throughout the mission, the team heard numerous stories of houses that burned down due to flame-based light sources. The price of kerosene used in these lamps fluctuates. If the resident is able to buy from a gas station (far away from Thoman), it might cost 150 Gourdes ($2.3 USD) a month. If the resident buys from the local roadside stands, it will cost about 250 Gourdes ($3.83 USD) a month.

The majority of community members who have access to electricity did so through personally connecting small wires to secondary power lines and bringing them into their homes. Creating these connections is dangerous and only gives them very limited access to a very unreliable grid. In the cities, the price of electricity is extremely high at $0.35 USD per kWh which is about three times the average rate in America. Power to these lines is often unreliable so even the residents with electricity are interested in the RELAY as a back-up means for lighting and phone charging.

B. Typical Electrical Use in Rural Haiti

Fig. 1: Photo of kerosene lamp used by local villagers.

During the 2018 mission, the RELAY team was able to determine the typical load usage of the villagers. The electricity was mainly used for phone charging and lighting. If the house had electricity tapped from the transformer, there would typically be one or two fluorescent light bulbs throughout the home. A small number of the homes used the electricity to power a large refrigerator. However, these worked inconsistently, most likely due to a large voltage drop along the cable. For those without electricity, kerosene lamps shown in Fig. 1 were used for lighting. These lamps do not supply ample lighting and are tedious to light for each use. For the majority of the homes, a 5 W LED bulb connected via USB was sufficient for lighting. From field surveys, most of the villagers would only use the lights after dark from about 7:00pm-11:00pm. Given the fact that the 7 Ah battery in the Haiti RELAY provides more than 15 hours of lighting, the RELAY can far exceed this time frame.

III. Proposed Haiti RELAY System

A. Overview of Haiti RELAY System

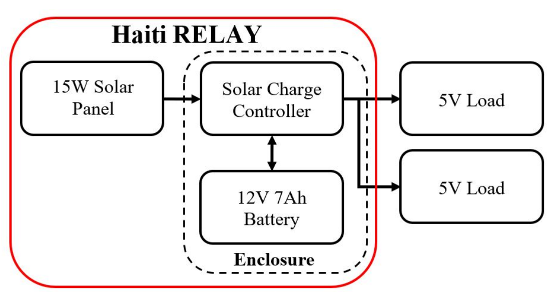


Fig. 2: Haiti RELAY system overview.

The Haiti REALY system is designed to be a robust and portable charging system that implements three main components: 1) the solar panel, 2) the battery, and 3) the solar charge controller. The system diagram is provided in Fig. 2. The solar panel is externally connected to the Haiti relay device using a DC barrel jack connector. The enclosure contains the solar charge controller and a 12 V, 7 Ah battery. In addition to the barrel jack connector input on the side of the Haiti RELAY, there are two USB output ports. These outputs are rated for 5 V at 3 A with the intention to power LED lights and charge cell phones.

The system works by providing power to the load using a solar panel and a 12 V battery. The solar panel converts energy from the sun into DC power, which is transferred to the solar charge controller through a DC barrel jack interface. The 12 V battery is also internally connected to the charge controller. With the input power from the solar panel, the solar charge controller will allow the panel to charge the battery and provide power to the output. When the battery is fully charged, the panel is internally disconnected within the solar charge controller, and the battery will provide power to the output. When the battery and the solar panel are unable to provide power, the solar charge controller will disconnect the output from the battery and from the panel until the battery charge reaches a suitable level of charge again.

B. Data-driven Design Approach

The capacity rating of the battery and power rating of the solar panel should be carefully determined to achieve maximum utilization of available resources while keeping the cost low. This optimized design is completed through a data-driven approach where the local historical solar radiation data and load profile data are used.

The capacity rating of the energy storage device, i.e., battery, is crucially important with respect to the functionality and portability of the system. Considering the typical load profile of local families and the daily available solar energy in the area, this battery should be rated at a balanced capacity. This capacity should be high enough to supply sufficient amount of load while low enough to prevent wasting of the energy and make the system more affordable. Meanwhile, the battery contributes to the majority of weight and size of the REALY. To keep the system portable, this battery should not be oversized.

The power of the solar panel is rated based on the load profile data collected from the community in Thoman. Considering the majority of electric load is cell phone charging and lighting, a 15 W panel is adopted in the RELAY.

The half-hourly values of solar radiation data in Thoman, Haiti is available through the Physical Solar Model (PSM3) of NSRDB [4]. Specifically, Direct Normal Irradiance (DNI), one of the most common solar radiation measurements, is used as the major metric in this study. DNI quantifies the amount of solar energy received per unit area by the surface that is always held perpendicular to the sunlight. The DNI data of Thoman in year 2015 is plotted in Fig. 3(a). The solar radiation during

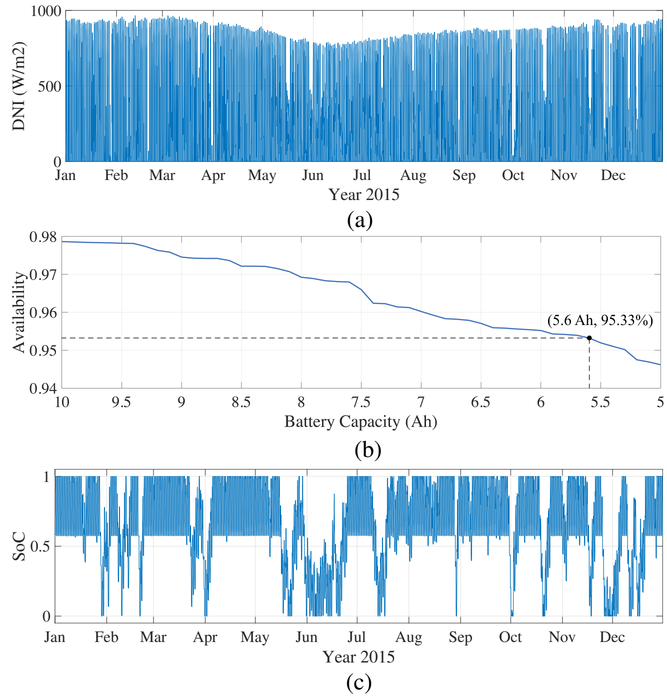


Fig. 3: Simulation results determining the state of charge (SoC) of various size batteries over the course of a year.

the summer is less due to the rain session. The daily maximum radiation, however, does not vary much throughout the whole year. Based on the DNI, the panel output current, $I_{\text{pv}}(t)$, is estimated through curve fitting of the panel characteristic data.

$$I_{\text{pv}}(t) = 0.0009115 \times \text{DNI}(t) - 0.005. \quad (1)$$

The output power from the panel is thus approximated as

$$P_{\text{pv}}(t) = I_{\text{pv}}(t) V_{\text{bat}}, \quad (2)$$

where V_{bat} is the nominal voltage of the battery.

A 12.5 W load is assumed to be connected to the REALY for six hours a day (13:00-15:00 and 20:00-24:00). Therefore, the state of charge (SoC) of the battery can be simulated and updated based on the follow rule in (3) at every time step.

$$\text{SoC}(t_{k+1}) = \frac{1}{E_{\text{bat}}}[E_{\text{bat}} \cdot \text{SoC}(t_k) + (P_{\text{pv}}(t_k) - P_{\text{l}}(t_k)) \cdot \Delta t], \quad (3)$$

where E_{bat} is the total energy in the battery with the unit of watt hour. The amp hour battery capacity can be calculated as $E_{\text{b}}/V_{\text{b}}$. t_k and t_{k+1} are the current and next time step, respectively. Δt is 0.5 h.

The battery is not charged or discharged when the SoC hits 1 or 0 at any certain time step, respectively. To quantify the duration of the time when the power from RELAY is available to the user, a new metric, availability, is defined as

$$\text{Availability} = \frac{\sum_{k=1}^{k_{\text{total}}} \text{sgn}(\text{SoC}(t_k))}{k_{\text{total}}}, \quad (4)$$

where $k_{\text{total}} = 24 \times 2 \times 365$ is the total number of time steps throughout a year and $\text{sgn}(\cdot)$ is the sign function that gives 1 and 0 for positive and zero SoC, respectively.

The availability is plotted in Fig. 3(b) with respect to different battery capacity ranging from $5\,\mathrm{Ah}$ to $10\,\mathrm{Ah}$. The solar charge controller in the Haiti RELAY allows for a single stage of charging, bulk charging. While other commercial solar charge controllers include multiple stages of charging including PWM charging and trickle charging, the team concluded that bulk charging would suffice for the functionality needed in Haiti. Using a bulk charge method, 80% of the battery can be safely recharged. Considering the fact that Sealed Lead Acid (SLA) batteries are rated discretely at a step of $0.5\,\mathrm{Ah}$ for low power applications, to achieve 95% availability, a $7\,\mathrm{Ah}$ ($5.6\,\mathrm{Ah}$ when 80% rechargeable capacity is assumed) battery should be used. The simulated SoC of a $7\,\mathrm{Ah}$ battery is provided in Fig. 3(c). Using only one stage of charging allows for greater simplicity and lower cost. Thus, the Haiti RELAY risks fewer problems and becomes a more viable option cost-wise in a region such as Haiti.

C. Design of Solar Charge Controller and Simulation Results

The solar charge controller was designed by the team to help reduce the cost of the system and ensure the Haiti RELAY system functioned as expected. Within the design, the solar charge controller includes voltage and current protection as well as power electronics circuitry.

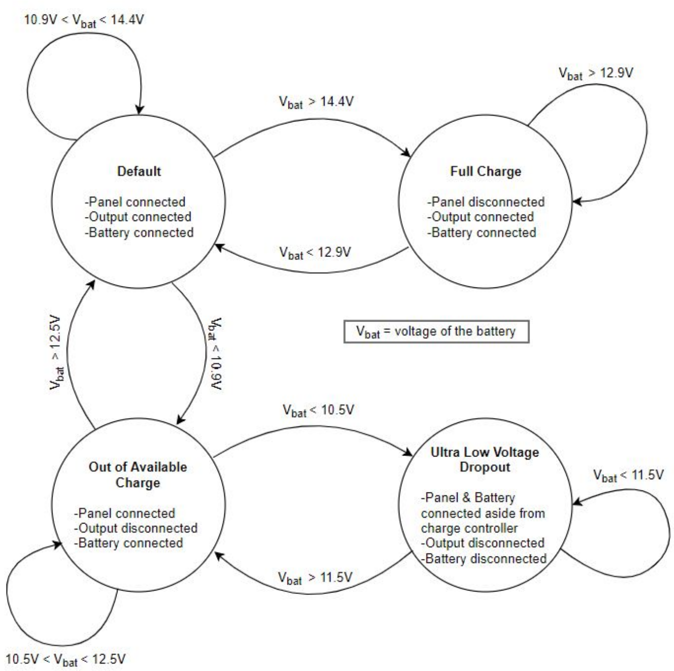


Fig. 4: State diagram of Haiti RELAY displaying the various states of connections between the battery, solar panel, and output port with the solar charge controller.

For protection of the battery, the solar charge controller prevents over-voltage and under-voltage of the battery using a voltage monitoring system. Initially, the Haiti RELAY starts in the "Default" stage, as shown in Fig. 4. Within this stage, the battery has sufficient charge to power a load, but also can charge further using the solar panel. When the voltage of the battery reaches $14.4\,\mathrm{V}$, the solar charge controller transitions from the "Default" state to the "Full Charge" state. In the "Full Charge" state, the solar charge controller disconnects the solar panel from the battery preventing the solar panel from charging the battery further. Since the battery voltage drops to a "resting voltage" after being disconnected from a charging source, it is important to implement a hysteresis method of control. This method allows the charge controller to disconnect the panel from the battery at $14.4\,\mathrm{V}$ but then keep the panel disconnected from the battery until the battery voltage drops below $12.9\,\mathrm{V}$. If the battery voltage drops below $12.9\,\mathrm{V}$, the solar charge controller will transition back into the default state. In addition to over-voltage protection, the charge controller detects when the battery voltage drops below $10.9\,\mathrm{V}$ and disconnects the battery from the output to prevent the battery from being further depleted by a connected load. When the battery is disconnected from the load, the solar charge controller transitions into "Out of Available Charge" state. Once in "Out of Available Charge" state, the battery will remain disconnected from the load until the battery reaches $12.5\,\mathrm{V}$ or greater. If the battery is not recharged and further depletes to $10.5\,\mathrm{V}$, the ultra-low voltage dropout feature will shut off the solar charge controller until the battery recharges back to $11.5\,\mathrm{V}$. The Haiti RELAY also provides $3\,\mathrm{A}$ current protection. This safety feature is achieved using $3\,\mathrm{A}$ fuses on the input battery line, solar panel line, and the $5\,\mathrm{V}$ output side of the solar charge controller. Along with protection circuitry, the solar charge controller implements a buck converter to convert $12\,\mathrm{V}$ DC to $5\,\mathrm{V}$ DC for the output.

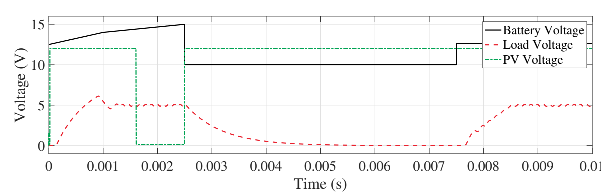


Fig. 5: Simulation results of battery, load, and PV voltages.

Proper operation of the over-voltage and under-voltage protection circuits is verified in the simulation waveforms of Fig. 5. The battery, load, and PV voltages are tracked by the protection circuitry. When the PV voltage is high, the RELAY is closed, allowing the solar panel to charge the battery. When it is low, the RELAY is open and charging stops. From these waveforms it is clear that while the battery voltage is below $14.4\,\mathrm{V}$, the solar panel is connected to the battery. As the battery charges past the $14.4\,\mathrm{V}$ threshold, the RELAY line drops low and thus disconnects the panel from the battery. Since the battery voltage is above the $10.9\,\mathrm{V}$ load cutoff voltage, the load voltage remains steady at $5\,\mathrm{V}$. This verifies proper operation of the over-voltage protection circuit. At $t = 2.5\,\mathrm{ms}$, the battery voltage drops to $10\,\mathrm{V}$. At this point, the load buck converter turns off and the panel reconnects to the battery. This shows proper operation of the under-voltage circuitry.

After simulation results confirmed functionality, the printed

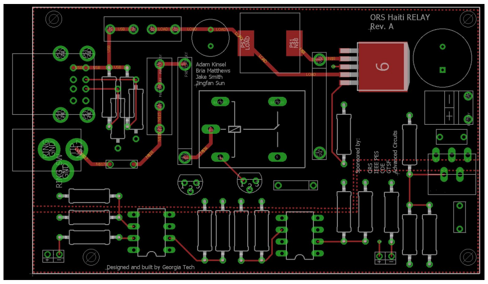
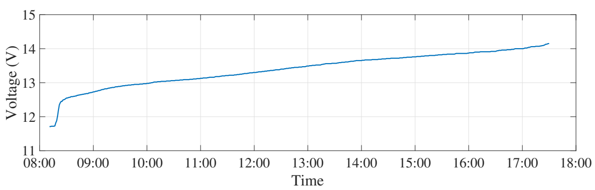


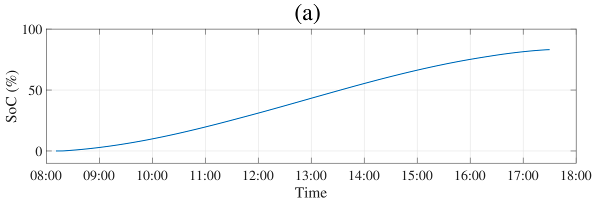
Fig. 6: PCB board of Haiti RELAY.

circuit board (PCB), as shown in Fig. 6, was designed. The PCB is manufactured from FR4 material. It is a two-layer $9.56 \times 5.72\,\mathrm{cm}$ board which contains 46 components. Due to the self-manufacturing of the first revision of the Haiti RELAY, the PCB contains mainly through hole components. In future revisions, many of these through hole components will be substituted for surface mount components.

D. Testing Results



(a)



(b)

Fig. 7: Plot of a) battery voltage during a full day test showing proper operation of the Haiti RELAY charge stage, and b) battery's SoC over a full day test showing 83% SoC.

The Haiti RELAY was subjected to multiple full-day charging and discharging tests to assure proper functionality of the system. The results of a single full-day test on a clear sunny day are shown in Fig. 7. First, the battery voltage presented in Fig. 7(a) shows that the battery was charged at a steady rate up until it reached $14.4\,\mathrm{V}$ in the late afternoon. The battery SoC is shown in Fig. 7(b). The goal for this test was to reach 80% SoC or $5.6\,\mathrm{Ah}$. In this test, the battery charge exceeded expectations and rose to 83% or $5.81\,\mathrm{Ah}$ thus verifying proper operation of the system during charging.

E. Enclosure Design

The RELAY requires a simple, durable, cost-effective design of its enclosure. The enclosure must withstand exposure to high temperatures as well as risks of mishandling. The current version of the RELAY makes use of a generic ABS project box modified to match the PCB board. The openings for the inputs, outputs, and ventilation (as shown in Fig. 8) were made using a Computer Numeric Control (CNC) mill allowing each unit to be precise and accurately fit all components.

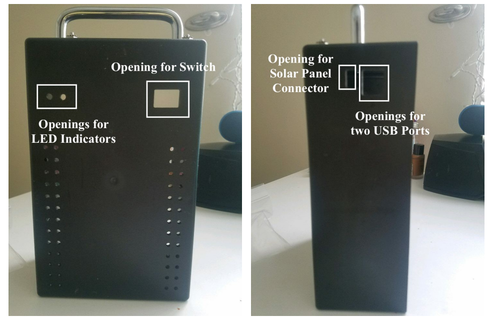


Fig. 8: ABS project box after modifications from CNC mill.

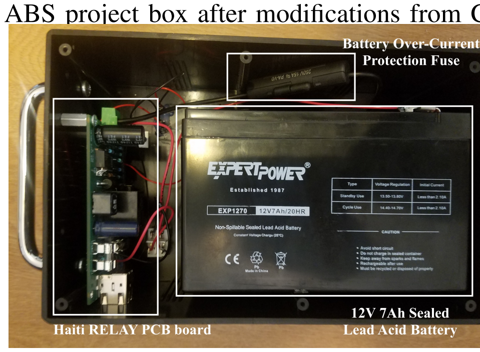


Fig. 9: Inside of the Haiti RELAY. The mounting positions of the PCB and battery are presented.

Using the metal standoffs, the PCB is mounted facing downwards at the top of the enclosure while the battery rests on the bottom as pictured in Fig. 9. The battery is secured using a heavy duty hook and loop strip to prevent it from hitting other components when the product is being moved. This design is favorable for small scale production because there is low start-up expense and the per unit cost is \$8.08 USD. However, this model also requires a significant amount of human labor to operate the CNC mill and assemble the parts, leaving room for human error as well as adding in labor costs, especially if this is produced on a larger scale as planned.

Fig. 10: SolidWorks model of the Haiti RELAY.

Therefore, another enclosure has been created for mass production. Designed using SolidWorks, this model perfectly fits the battery and PCB (Fig. 10). There is no need for hook and loop fasteners to keep the battery in place because the case matches the exact dimensions of the battery. The metal standoffs from the previous design are replaced by built in standoffs. Screws for PCB mounting and case closure are the only necessary outside materials. Although some assembly is still required, the process has been shortened, reducing the cost of human labor.

Fig. 11: First printed prototype of the Haiti RELAY.

This case was printed on a 3D printer to test its compatibility with the PCB, battery, and input/output interfaces. The prototype is shown in Fig. 11.

Initially, the plan was to print 25 units of the Haiti RELAY for product testing. However, the material costs of 3D printing were higher than expected at $125 USD per unit. Therefore, the ABS plastic box was chosen for small scale production. The next version of the RELAY will be mass produced through injection moulding which would require using this 3D model.

IV. Future Development

The Haiti RELAY team was able to successfully deploy 25 RELAYs to the Thoman community in May 2018. While these RELAYs are being used to provide electricity for these families, they are also being used to help the team assess the necessary changes to make the RELAY a commercial product. Each family who received a RELAY agreed to participate in the Haiti RELAY Pilot Program. This program consists of three feedback sessions, over the months of June, July, and August of 2018, where the RELAY recipients will provide status updates on how well the RELAY is functioning and give any suggestions for future improvements. This way, the team will have a full understanding on the steps required to make the RELAY a commercially available product.

In addition to this project, during this mission in 2018, students from the IEEE PES chapter of the Haiti Solar project conducted a business training seminar for 17 Haitian university students from around the country. This project was in conjunction with the B.E.L. initiative, a subsection of the Georgia Haitian-American Chamber of Commerce. These students participated in Georgia Tech student led classes which taught them skills in designing solar systems and running solar based businesses. The Haitian students showed great interest in the Haiti RELAY and the team is hoping that one or more of these students will take over the Haiti RELAY as a business in the future.

V. Reccommandations

For anyone wishing to replicate the Haiti RELAY in similar regions, take into account these suggestions:

1) Understand the electricity needs of the target area first, then design the system accordingly.
2) Ensure that there is a reliable point of contact in the region to provide feedback before and after the product has been distributed.
3) Improve and modify the design as needed based on the given feedback.
4) An in-depth understanding of the region's culture is of paramount importance. The priorities of the design and implementation strategy cannot be accurately planned without this step. Ample time must be spent getting to know the people the team will be working with.

The mediating organization, BGM, had major contributions to the success of the Haiti RELAY. BGM acted as the on-site liaison between the team and Thoman residents. The information regarding electricity usage of the community as well as feedback on the RELAY was sent through BGM. Not only has the organization facilitated communication, it has also prevented conflict. BGM provided connections with a revered pastor in the town who chose the recipients of the 25 RELAYs. His judgements were not questioned as the decisions of strangers would have been. These suggestions have the potential to reduce costs and increase worth to the community.

VI. Conclusion

This paper proposed the design and implementation of the Haiti RELAY, an affordable and portable solar home system designed for Haitians in the rural regions of the country. This system used bulk charging to achieve an 80% state of charge for the battery. The design included protections for over-voltage, under-voltage, and over-current events. In May 2018, Georgia Tech's Haiti RELAY team successfully implemented 25 RELAYs in the mountainous village of Thoman. The main goal of this installment was to assess the efficacy of the design in real-world conditions. The 25 families all agreed to provide feedback on the devices to help the team further improve the RELAY and move it closer to full-scale production. The overall goal of this project is to develop the RELAY to a point where local Haitians can use it to form their own businesses to spark economic growth in the region.

References

[1] Central Intelligence Agency (CIA). (2018, May) The world factbook 2018. CIA. Washington, DC. [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/ha.html

[2] But God Ministries. Our story. BGM. Ridgeland, MS. [Online]. Available: http://www.butgodministries.com/our-story/

[3] L. Wu, W. Kihinet, E. Robelo, E. Bezabih, K. Longwood, T. Tshimanga, M. Saeedifard, F. Lambert, and R. Harley, "Development of a solar-power-based nanogrid system for village huts in haiti mountain area," in *2016 North American Power Symposium (NAPS)*, Sep 2016.

[4] National Solar Radiation Database (NSRDB). National Renewable Energy Laboratory (NREL). Golden, CO. [Online]. Available: https://nsrdb.nrel.gov/