Project Report
TIP-98

Smart PV Micro Grids for Cooking in Heavily Disadvantaged Communities: FY19 HP/ATC/HADR Technical Investment Program

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31 October 2019

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This material is based upon work supported by the United States Air Force under Air Force Contract No. FA8702-15-D-0001.

This report is the result of studies performed at Lincoln Laboratory, a federally funded research and development center operated by Massachusetts Institute of Technology. This material is based upon work supported by the United States Air Force under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Air Force.

Massachusetts Institute of Technology
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ACKNOWLEDGMENTS

The authors would like to thank Fulvio Fabrizi, Tom Reynolds, and Mark Worris of Group 43 for their work in solar irradiance forecasting for this effort, and Dave Kiser of FSD for his assistance in accessing data from the Lincoln Garage Photovoltaic Array.

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1. INTRODUCTION

1.1 BACKGROUND

It is well documented that biomass cooking has a severe detrimental impact on the health, environment, climate and economy of worldwide communities[1]. *Over four million people die each year* from illnesses caused by indoor air pollution from biomass cooking. Massive deforestation in countries like Uganda, Rwanda, and Kenya occur when 90% of the population, mostly women and children, search up to 6 hours per day for biomass fuel. There is no quick solution. Cookstove technology has dramatically improved over the last few years, but efficiency remains low, the stoves are expensive and special fuel is required for clean cooking. Other alternative clean burning fuels, such as LPG, have gained momentum but require a large distribution and maintenance infrastructure that many countries cannot afford at scale.

PV micro grid installations, however, can provide clean, low-cost electricity for cooking as well as establish a scalable power infrastructure for the community. Recent price reductions in PV hardware have greatly lowered installation costs, but these costs can be significantly further reduced, up to ~40%, by minimizing the need for battery storage[2]. This strategy however would require the community to cook a majority of their food (rice, beans, teas, and soups) during the day. A smart PV micro grid is needed to distribute power in an efficient, reliable and equitable fashion for electricity to be accepted by a community.

The primary issue for advancing any fuel technology is household adoption and continued use over long periods. Many factors enter into this equation including marketing strategies, business models, training, supply chain, and maintenance. In addition, customers need a reliable system and process for cooking or they will discontinue service causing utility operation costs to spiral and be unsustainable. Technology, too, plays an important role of breaking down barriers to adoption by providing tools that make using, in this case, electricity, extremely simple and safe to use. It also provides solutions that can streamline processes and increase efficiencies that reduce cost and strengthen customer loyalty. The overriding goal of this program was to develop, prototype, and test technical solutions that will compel successful and safe adoption of electricity for cooking.

1.2 SMART PV CONCEPT

The smart PV concept connects the micro-grid to a family's home where their daily meals are being prepared. Power, however, is not available on demand. It is distributed daily to connected families by the micro grid's smart scheduling and distribution system that matches real-time capacity with scheduled demand. The smart power controller uses algorithms to distribute power in a prioritized fashion during low capacity and to alert customers of power availability in times of higher capacity. Smart distribution boxes provide feedback on power utilization while smart outlets and appliances reduce the energy required for daily cooking (Figure 1).

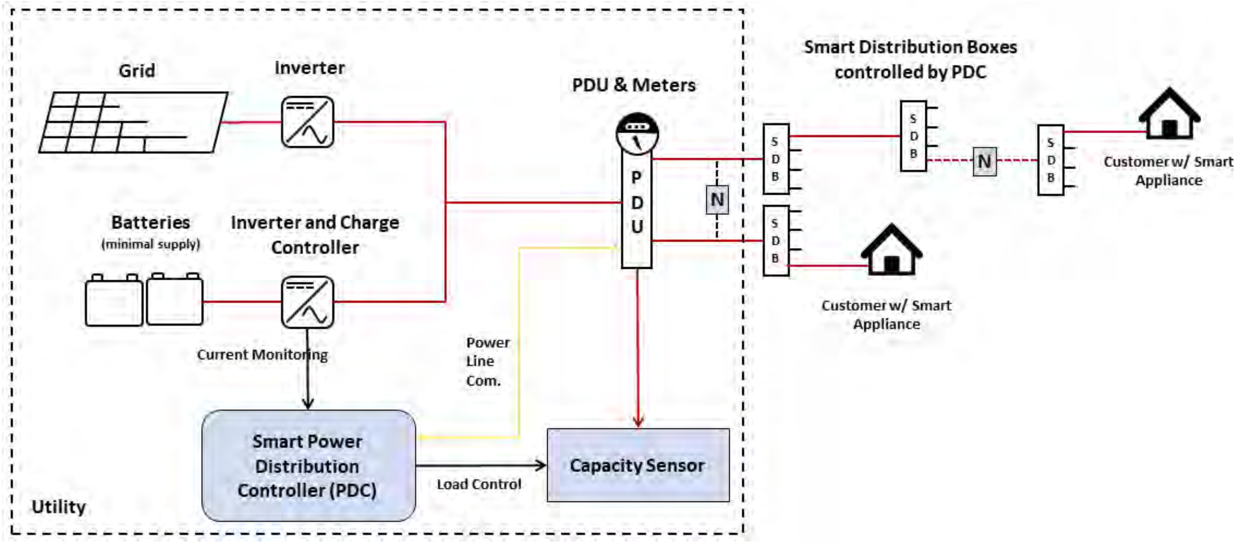


Figure 1. Smart PV grid architecture.

Although cooking has been the primary focus for the Lincoln Laboratory team, it is important to note that the technology being developed for smart PV micro grids can scale vertically with utility expansion as well as laterally for a variety of service use cases. For instance, the technology scales vertically since the algorithms for smart power distribution, scheduling, and billing can accommodate and service an ever-growing customer list. Should the utility decide to add storage for nighttime service, it can still utilize the same smart control algorithms and scheduling software to efficiently meet real-time capacity with customer demand without disrupting the community experience.

The smart technology scales laterally as well where applications for real-time power distribution can aid organizations serving disadvantaged communities. Columbia University uses a micro grid without storage to power irrigation pumps in Senegal while the International Organization for Migration (IOM) uses the same method to lift water to distribution tanks in refugee camps. Often, the micro grids are capable of producing more capacity than the operations use, but the organizations have no method of efficiently, and cost effectively distributing power to the community or other services in real time. The excess capacity could be used for cell phone charging, cooking, and water filtration. Also, prioritized scheduling can help organizations route power to specific resources in times of lower capacity. For instance, hospitals using PV as an additional power source can prioritize devices or facilities (medical refrigerators, etc.) to always receive power while scheduling and prioritizing other resources to receive power at certain dates and times (operating facilities, etc.).

2. SMART PV DEVELOPED TECHNOLOGIES

2.1 OVERVIEW

As mentioned, the goal of the smart PV system is to employ technologies that would compel household adoption of electricity for cooking in disadvantaged communities. Technology areas for a smart PV micro grid can be broken down into the three sectors shown in (Figure 2) which includes energy generation, power distribution, and endpoint utilization.

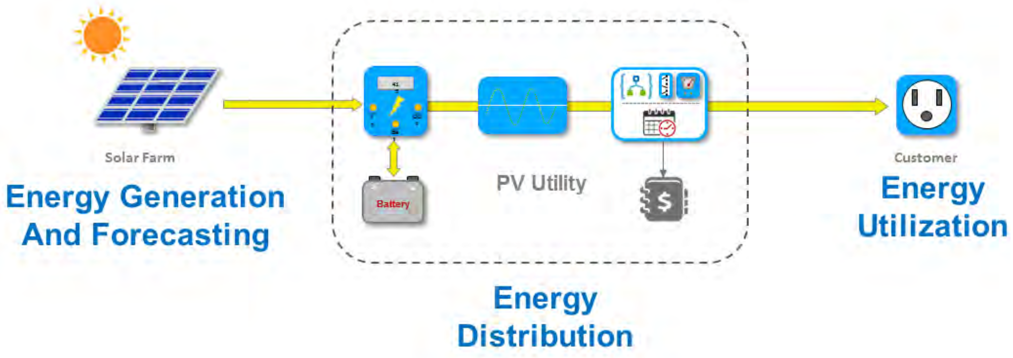


Figure 2. Technology Areas for Smart PV Development.

Phase I effort primarily focused on technology for enhanced energy distribution and utilization. Program goals centered around reducing upfront installation and operational costs of the utility, increasing operating efficiency, and developing simple and safe cooking methods for customers using electricity for the first time[3]. Several subsystems of the smart PV micro grid were successfully prototyped and tested by the team including a smart power distribution controller with scheduling and billing, a smart distribution box, and a smart endpoint-cooking controller.

Phase II efforts for smart PV grids focused on technology that would enable continued adoption of electricity for cooking by tackling important system level issues influencing customer experience. Reliability, consistency, and simplicity are critical factors for continued adoption by new customers especially when old methods are so readily available. This is particularly true for biomass cooking where nearly 100% community adoption is required to reduce the detrimental effects to family health and local climate.

During the Phase I hardware development, system process issues started to surface that dealt with operating a PV utility with minimal battery storage. Questions about scheduling, customer priority, and billing certainly came up, but solutions to these questions are mainly derived through community discussions with the utility and *facilitated* by technology (i.e., utility monitoring systems, mobile apps, accounting software). Questions did arise, however, where technology plays an important role in customer adoption by helping to provide simple, reliable electrical service. Chief among these questions that the Phase II effort tried to answer are:

- Can the utility predict if power will be available for a customer's time slot? How can customers be alerted if power will not be available? How far in advance can customers be alerted?
- Can the PV micro grid's capacity be determined in real time 1) to prevent overburdening of the grid? 2) to efficiently distribute excess power to the community? 3) for smart shedding of customers and community devices?
- What is the proper appliance for introducing electrical cooking into a community if cookware is vital for customer adoption?

In addition to identifying technology areas to aid adoption, the Phase II effort was focused on developing a Smart PV pilot to introduce electricity for cooking in highly disadvantaged Haitian communities. The pilot was to be a collaboration between MIT LL, Columbia University (CU), the Clean Cookstove Alliance (CCA), and a solar utility partner already established in Haiti. Apart from smart PV grids and electrical cooking, the pilot was also to investigate and document the process of introducing new technology into highly disadvantaged communities and factors that influence adoption. It was to be a case study that could be used by other organizations for introducing solutions into similar communities.

The following sections will detail the Phase II efforts to find and test solutions to these important questions as well as the efforts to pilot Smart PV in Haiti with our collaborating partners.

3. ENERGY FORECASTING

Adoption and continued use is one of the primary obstacles for implementing clean cooking technology into a community. Due to the widespread use of biomass fuel and the invasiveness of second-hand smoke, nearly 100% adoption is required for a community to realize the benefits of using alternative fuels. While providing more heat with less smoke, “clean” cookstove adoption has been limited due to difficulty obtaining fuels (i.e., wood pellets) and sufficient training for proper use. As stated earlier, reliability, consistency, and simplicity are critical elements for adoption of new technology. This applies to energy generation as well as end point cookware. Customers need to have confidence that if they are told they will have power to cook on a particular day with a scheduled time slot, that power will be provided. That confidence will lead to adoption.

How does the PV utility, which is greatly affected by weather for power generation, solve this problem? Possibly by using two different forecasting strategies. One strategy is to use prediction models that can be used to estimate energy availability several days in advance and alert the customer of the conditions. For instance, several days in advance of their time slot to cook, the customer may be alerted that there may not be available power. As the time slot draws closer, other alerts are issued refining the forecast. This simple and consistent process may ease adoption by giving the customer time to acquire other fuels or plan different methods of cooking for that day while giving them the confidence to use electricity when they know it will likely be available.

A second strategy for implementing energy forecasting is to continuously monitor local conditions at the utility, such as cloud cover, and give alerts as needed to customers up until their time slot for cooking. This strategy may resemble weather alerts people frequently receive from smart phone applications saying that a rain storm will hit their area in the next few minutes. A monitoring system capable of tracking local conditions would be installed at the utility and would alert customers as needed as conditions changed.

Team members from Group 43 pursued the strategy for long-term energy forecasting during this program. Their research, tests, and conclusions are compiled in a separate report entitled “Numerical Weather Prediction for Solar Irradiance Forecasting”[4]. The summary of the report is included for completeness:

> “We have made an initial study of solar irradiance forecast models applicable to remote locations. This work is in support of Project TI02-0135, Smart PV Micro Grids for Cooking in Disadvantaged Communities.
>
> We have surveyed the available academic and commercial models with coverage over the initial target area of Haiti. Of these, we selected the High-Resolution Rapid Refresh (HRRR) Model from NOAA, and compared it to irradiance data from the

Lincoln Laboratory Garage Photovoltaic Array. The results show that the model captures the coarse trends in irradiance from 2-18 hours, but not the fine details. The HRRR model largely over-predicts the observed irradiance. The nominal error, 200 W=m2, or about 60% of the average measured irradiance is comparable to errors reported against other models. From a model of electrical power, we estimated the error in forecasting the daily energy available at the Lincoln arrays using the HRRR to be about 60%-70%.

We expect some of this error could be reduced by correcting the model bias with archival irradiance measurements. Improvement at short time-scales would require additional forecast components such as those provided by local cloud cover measurement and tracking. Finally, extrapolating to a target system in a different region of the world requires more detailed study of a dedicated PV array design.”

4. ENERGY DISTRIBUTION – REAL-TIME GRID CAPACITY SENSOR

The expected behavior of the U.S. bulk power grid is to have electricity always available except for brief outages due to storms, maintenance, or occasional faults. The grid has been developed and scaled for more than a century into a large and complex system with a power generation, distribution, and billing infrastructure. To introduce clean electrical cooking into disadvantaged areas requires the same infrastructure elements but at a much smaller scale due to logistical, operational, and cost challenges. As mentioned earlier and in the Phase 1 report, a significant cost savings for installation, operation, and maintenance can be achieved by minimizing battery storage and limiting power availability at night. Under this model, customers would cook during the day when power is available, which aligns well with the current cooking schedule of many of these disadvantaged communities.

The goal of the minimized storage strategy leads to maximizing the use of available solar energy that fluctuates with weather, time of day, and time of year (Figure 3). Smart power distribution boxes, efficient end-point cookware, and novel control strategies were successfully designed and tested during Phase I to meet this goal. However, a key factor for this strategy is the ability to determine real-time capacity of the micro grid. For instance, how does the utility know that it is safe to turn a customer's service on for cooking without burdening the grid if minimal storage is installed?

A method and device for determining the real-time capacity of the grid is needed to effectively use minimal storage for PV utility operation. A grid employing batteries can mitigate power grid fluctuations due to load steps and variance in solar irradiation. Interestingly, however, minimal battery storage can also serve as a real-time indicator for solar irradiance conditions. This is accomplished by monitoring the current into and out of the small amount of storage integrated into the PV micro grid. For instance, when the load is being served by the grid and the batteries are charging (i.e., not sourcing power), there is additional solar energy available for use. However, when there is not enough irradiance to supply the desired load, the battery discharges and serves as a stop gap to supply additional power. At this point, no additional loads should be added to the grid and appropriate loads should probably be shed.

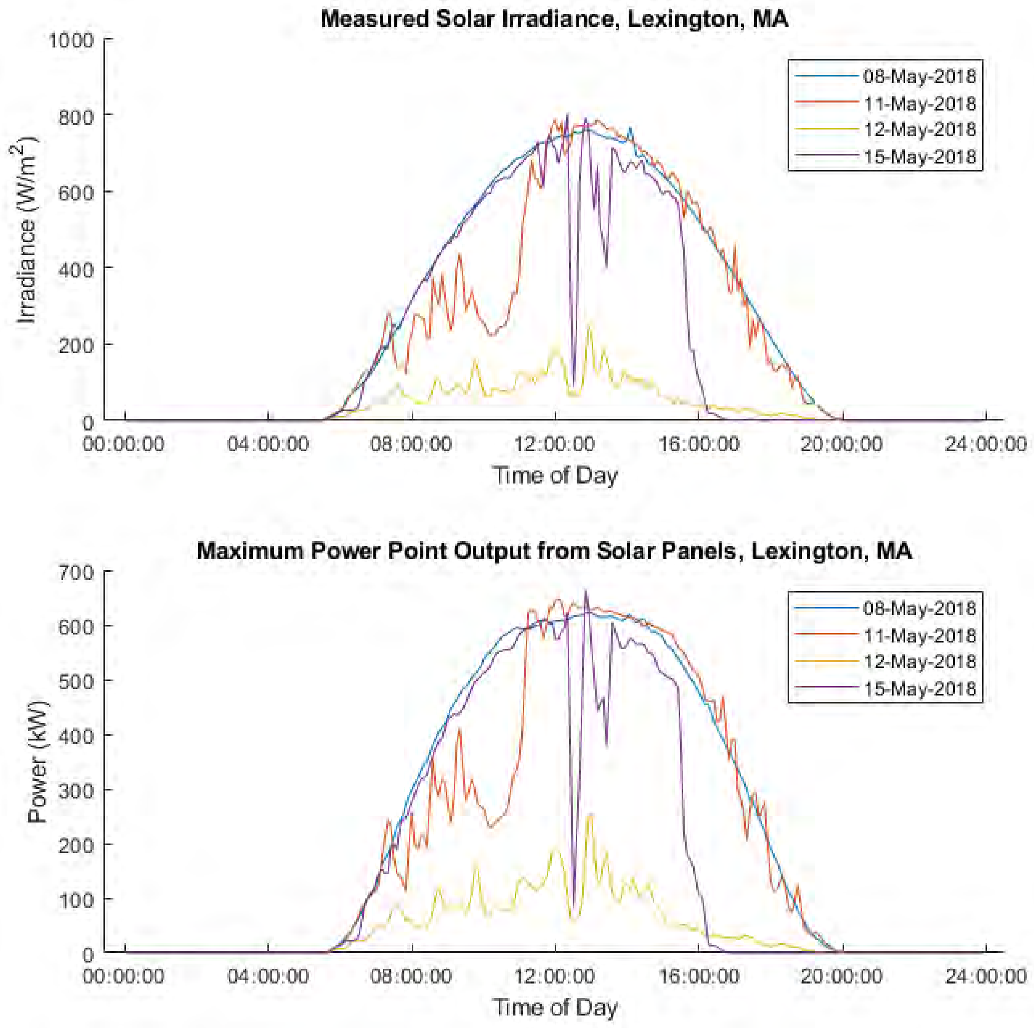


Figure 3. Solar irradiance of Lexington, MA. Data collected from MIT LL solar array.

4.1 CAPACITY SENSOR DESIGN

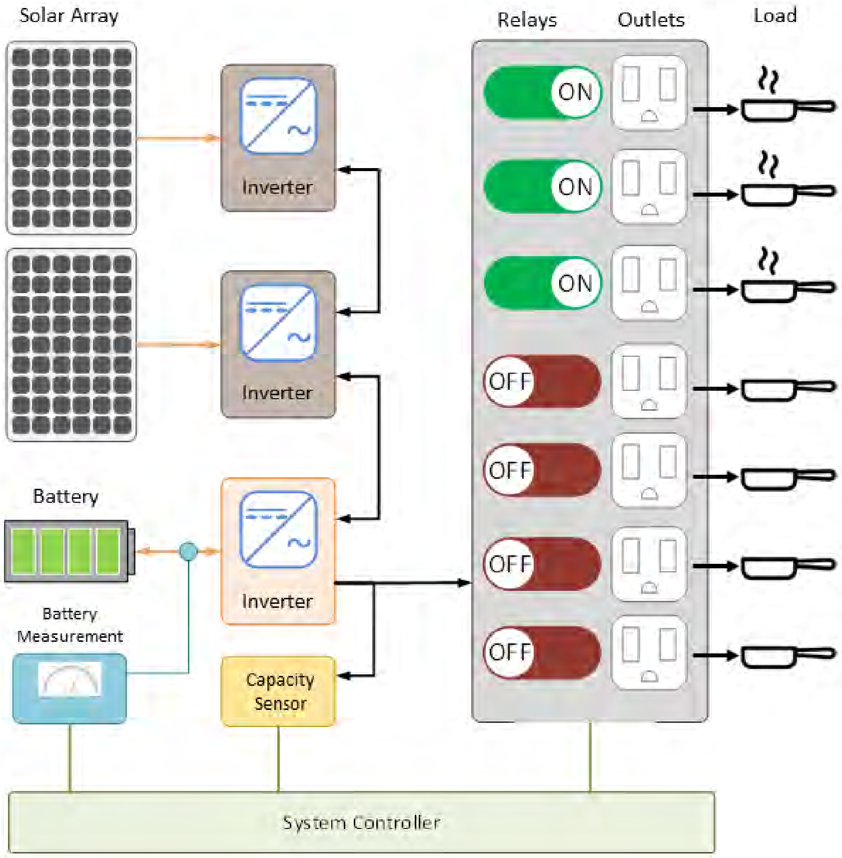


Figure 4. A smart PV grid architecture with integrated load capacity sensor.

To design and test a real-time grid capacity sensor, the team built a smart PV benchtop setup that included an existing off-grid solar inverter system, a battery for a small amount of energy storage, a current sensor connected to the battery leads, a remote controlled capacity sensor with fine resolution, and a system controller (laptop with software) that could distribute power to appliances, apply capacity sensor loads and monitor battery charging status (Figure 4). The capacity sensor, in actuality, is a user-controlled load bank to apply escalating loads to the grid via software. The use of the capacity sensor in the above architecture is as follows:

- The smart PV controller uses the capacity sensor to apply a starting test load to the grid
- Battery current is measured to determine if it is charging or discharging
  - If the battery is still charging, the load would be increased and monitored again

- If the battery is discharging, the capacity of the grid could be determined and appropriate action would be taken

For testing convenience, the solar panels were replaced with a configurable power supply capable of simulating a solar array to allow the team to test and monitor different control strategies in a repeatable fashion unlike in a real solar sourced environment. The max load of the capacity sensor was designed for 1200 watts, which would allow the operation of three rice cookers at 400 watts each. Capacity sensor loads can be applied in 15 watt increments to detect small excesses of grid power that could be distributed for charging cell phones. The sensor's resister loads (Table 1) were wired in parallel and the total load of the system could be calculated by applying Equation 1. Available capacity sensor load points are illustrated in Figure 5. The capacity sensor hardware is depicted in Figures 6–8, and the sensor wiring diagram is depicted in Figures 9–10.

Equation 1 – Parallel Resistances

$$\frac{1}{R_{Tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_n}$$

Table 1

Individual Resistors Used

Resistor bank number	Resistance (Ω)	Current @120 Vac (A)	Power (W)
1	1k	0.12	14.4
2	500	0.24	28.8
3	500	0.24	28.8
4	250	0.48	57.6
5	125	0.96	115.2
6	125	0.96	115.2
7	50	2.4	288
8	25	4.8	576

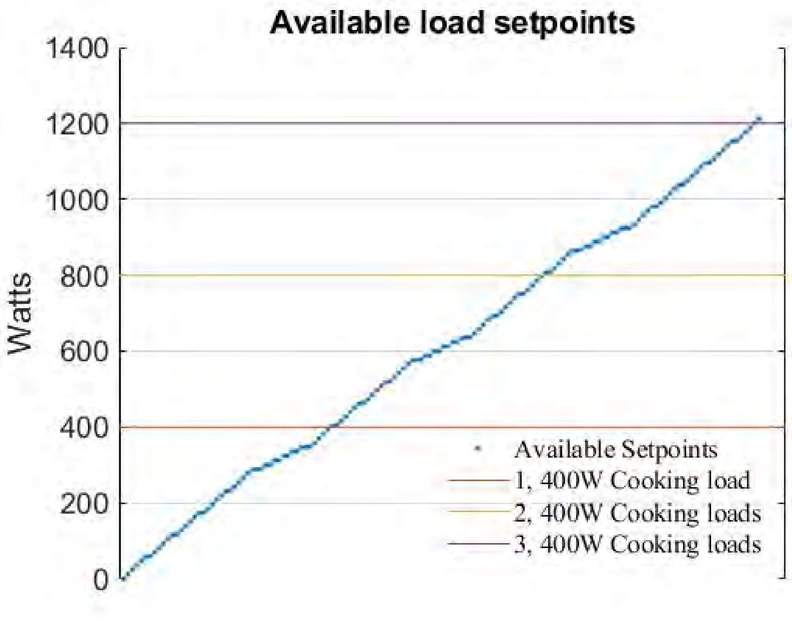


Figure 5. Available capacity sensor load settings.

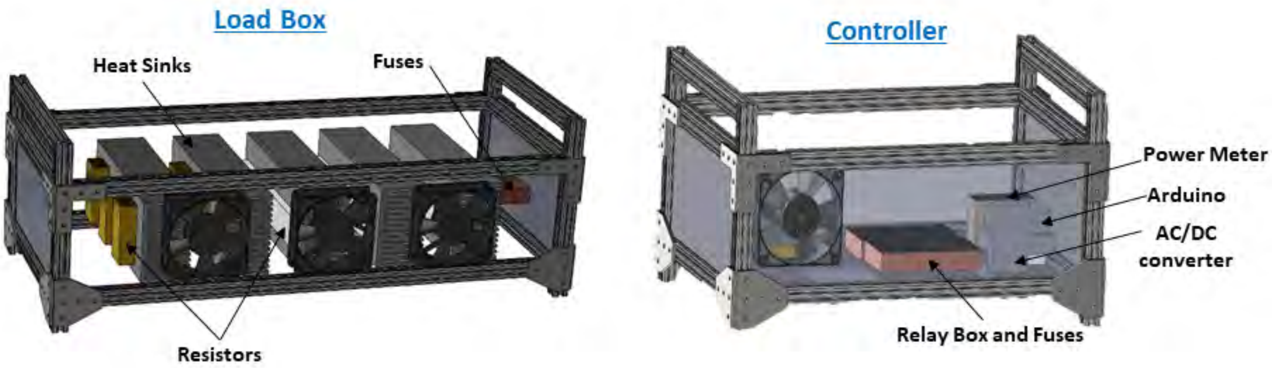


Figure 6. Capacity sensor load box and controller subassemblies.

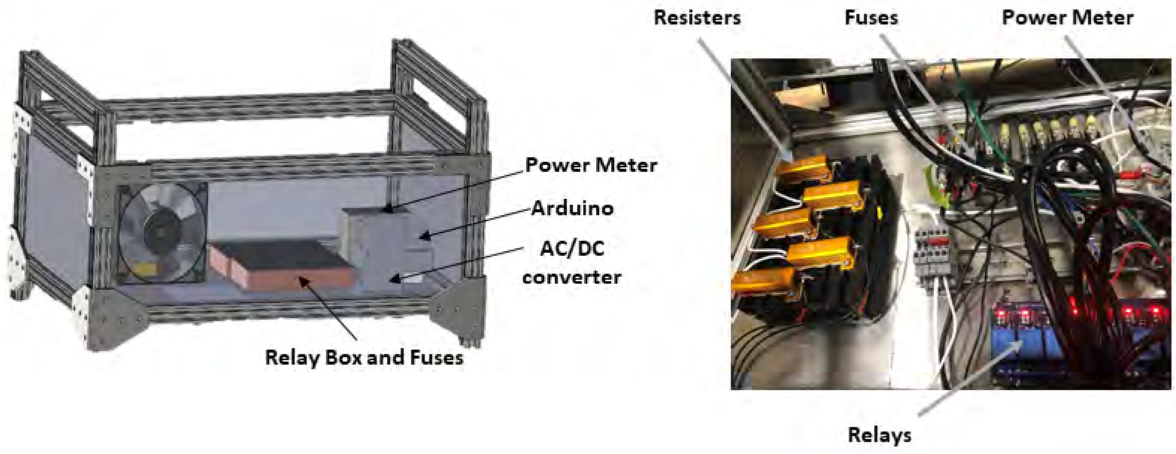


Figure 7. Capacity sensor controller layout and designed hardware.

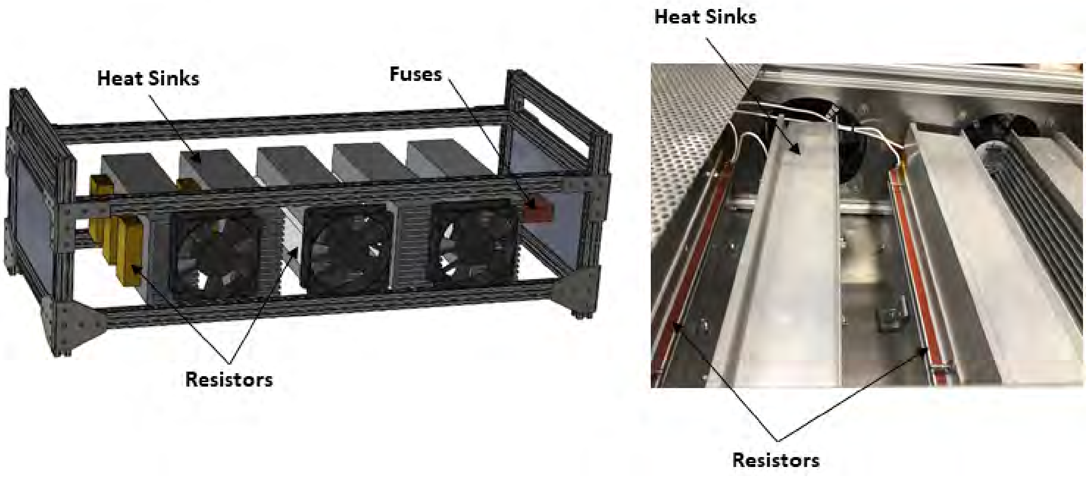


Figure 8. Capacity sensor load box layout and designed hardware.

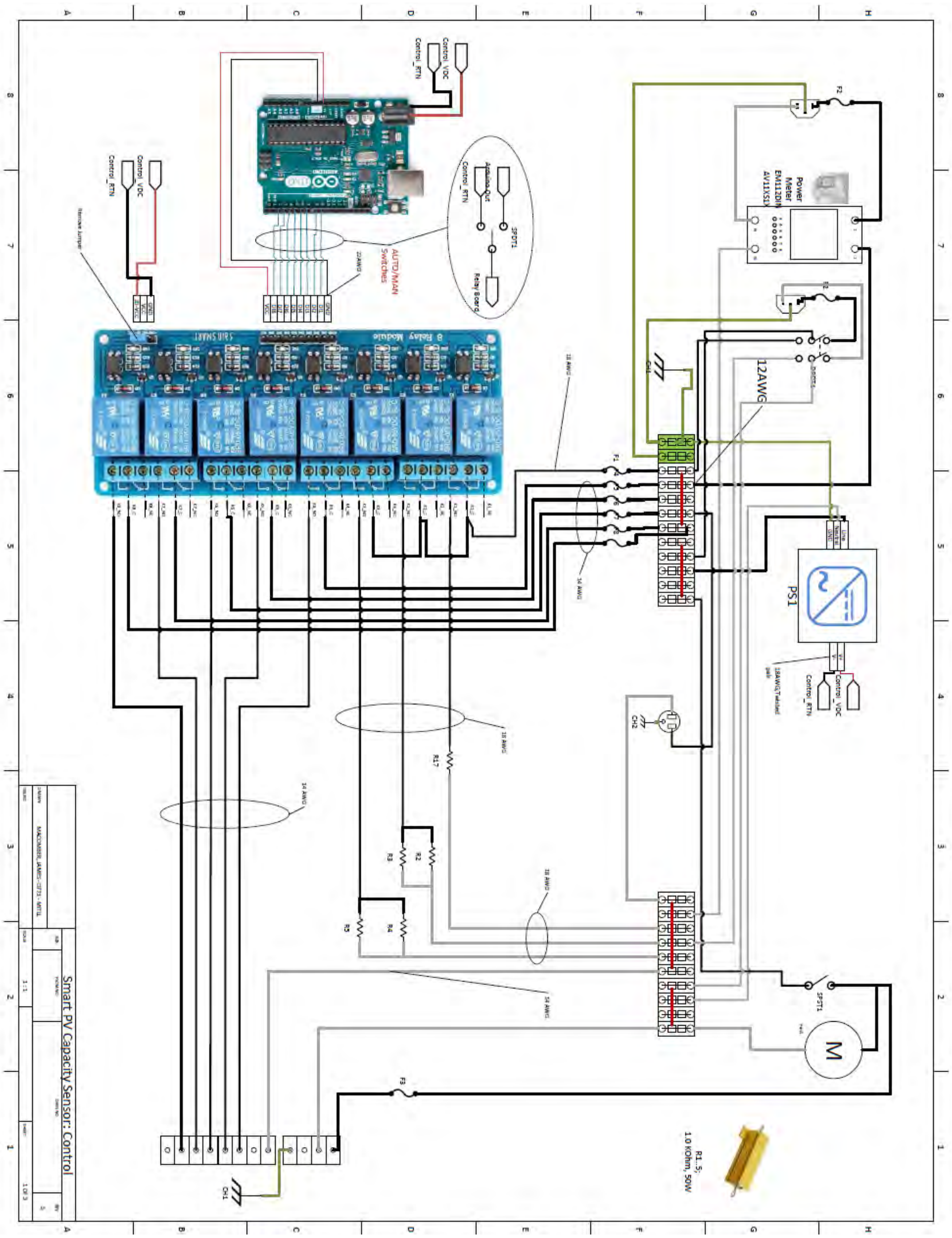


Figure 9. Capacity sensor controller wiring diagram.

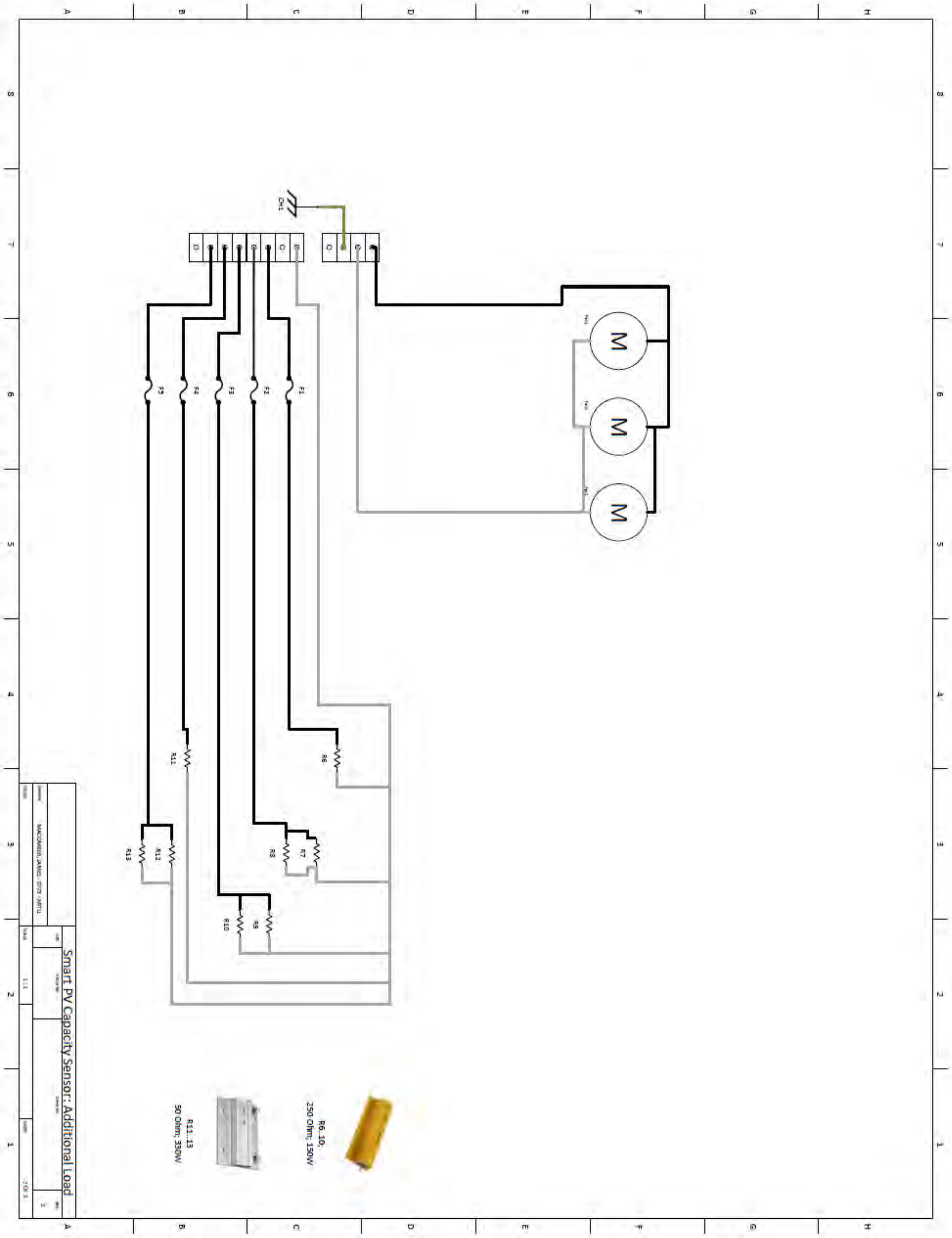


Figure 10. Capacity sensor load box wiring diagram.

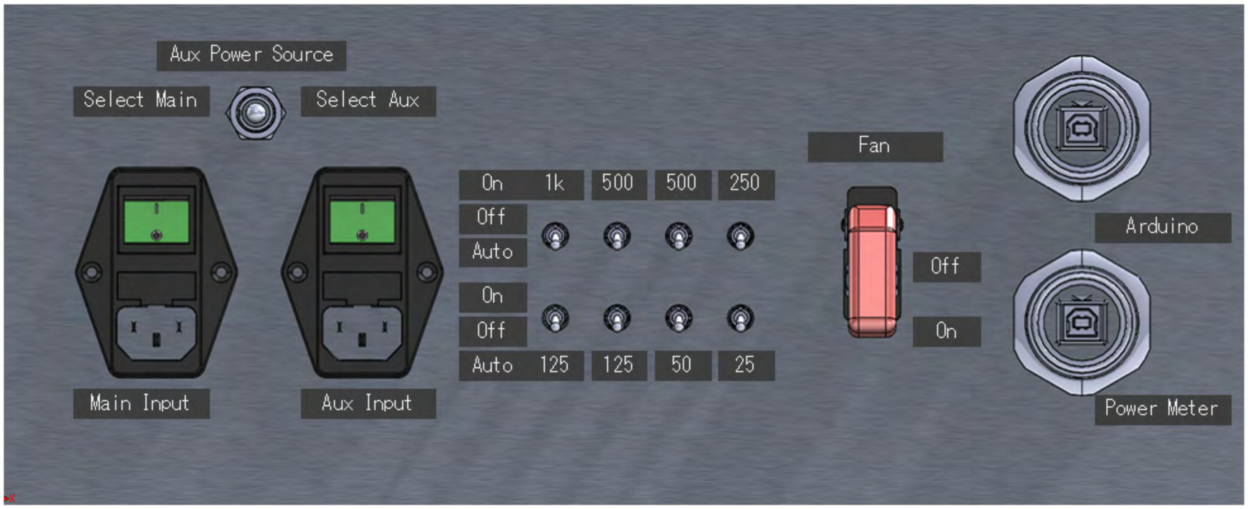


Figure 11. Capacity sensor controller front panel and controls.

The control panel for the capacity sensor (Figure 11) gave additional functionality to user as follows:

- **Aux power source switch**: This switch allows an end user to separate the cooling fan and control load from the metered load. Future iterations of this should be a two-position switch.
- **Auto/manual load switches**: Three-position switch that is connected to the Arduino for “Auto” control, center position for off, and up to manually turn an individual load on.
- **Fan switch**: Covered switch that allows the user to turn the fans off for testing or trouble shooting.
- **Aux load receptacle (not shown)**: A covered NEMA 5–15 receptacle external outlet that allows a load to be connected to the metered output giving the flexibility to directly measure using a power meter.
- **Load bank grounding (not shown)**: The 80/20 framing pieces have an anodization layer on them that is not electrically conductive. Deliberate steps must be taken to ground the framing pieces. The aluminum sheet stock was tied to each other with copper tape as a temporary means of grounding the faces. In future design iterations, either unanodized material or reworked framing should be used for the structure for good grounding.

4.2 CAPACITY SENSOR SOFTWARE

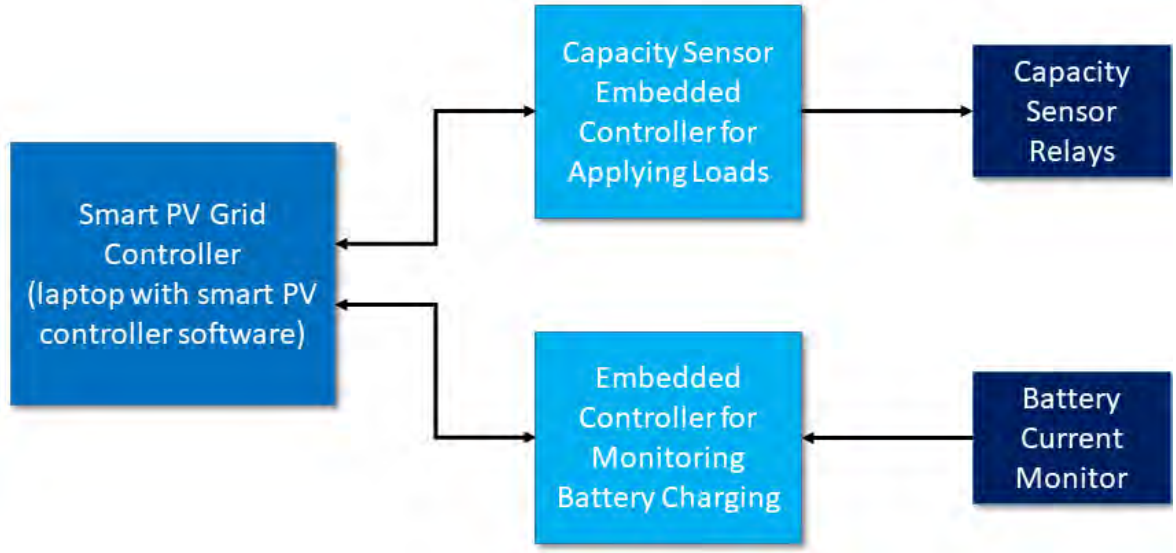


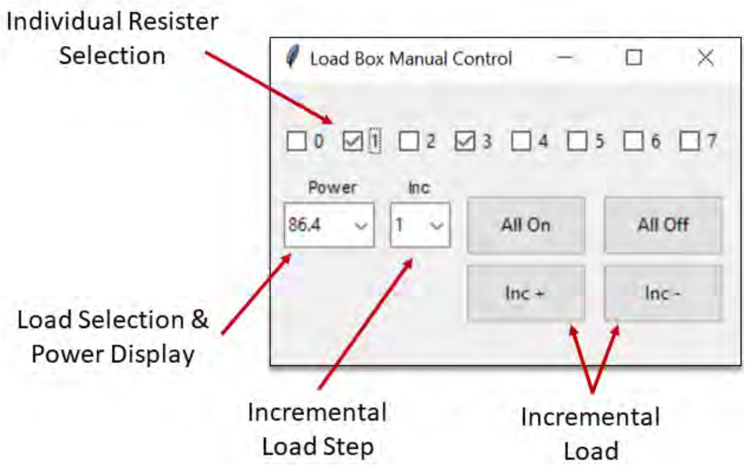
Figure 12. Capacity sensor software control architecture.

Once the capacity sensor system architecture was development, specifications for the sensor's software control library were outlined. Several applications running on several devices are required as shown in Figure 12. A development goal was to create a sensor control library written in Python that could be used in future applications and on multiple platforms. To develop and test the library, several standalone applications were created that are very useful in their own right for testing and debugging systems that employ the sensor. These applications include:

- A manual load selection application with accompanying embedded software that allows the user to select loads to apply to the grid
- A standalone current and voltage monitoring application with accompanying embedded software for sampling and reporting DC voltage and current draw from the batteries.
- A standalone application that automatically searches and detects the real-time grid capacity by monitoring current draw from the batteries.

4.2.1 Manual Load Selection Application

A manual load selection application with graphical user interface was written to allow the user to easily apply different sensor loads to the micro grid. The application uses the sensor's Python library that can be used by the utility for automatic control of the sensor. User selection information is passed to the sensor's embedded controller (Arduino) which turns on the appropriate relays to apply the desired load.



Load Box Manual Control

☐ 0 ☑ 1 ☐ 2 ☑ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7

Power: 86.4

Inc: 1

Figure 13. Manual Load Selection application graphical user interface.

The Python application's graphical interface is depicted in Figure 13 and had the following attributes:

- Configurable resister sets for scaling or future load modifications
- Manual selection of individual resister loads via checkbox
- Displays calculated load of individually selected resisters via checkbox
- Load selection via a dropdown list of unique loads for a given resister set
- Incremental stepping of loads with configurable step size
- All on/off control of resister loads
- Data logging of load changes and errors

Embedded software running on the relay controller (Arduino) is also required to receive instructions from the python application and apply the correct loads via a relay board. Safety was a prime consideration when writing the communication protocol between the applications so that only expected loads would be applied to the grid. Therefore, the Python application and embedded software communicate using the following format:

[255] [255] [# bytes to end of message] [Payload] [254] [checksum C1] [checksum C2] [253]

Where:

- Payload = [relay#, state, relay#, state…… relay#, state].
- Resister loads are easily mapped to relays in the configurable section of the Python application using a simple list (documented in code). The payload consists of relays that need to be updated and their new state. This information can be sent in any relay order.

- C1 and C2 are the output values of a Fletcher Checksum of the communication string.

The communication protocol used to transfer instructions between the main Python application and the embedded processor is as follows (Figure 13):

Python:

Send load control instruction

Arduino:

- Receives instruction
- Decodes instruction
- Computes/compares Checksum values
- Validates payload data
- If correct message:
    - Executes command
    - Returns ACK
- Else:
    - Returns NACK + Error message

Python: Decodes and displays return message

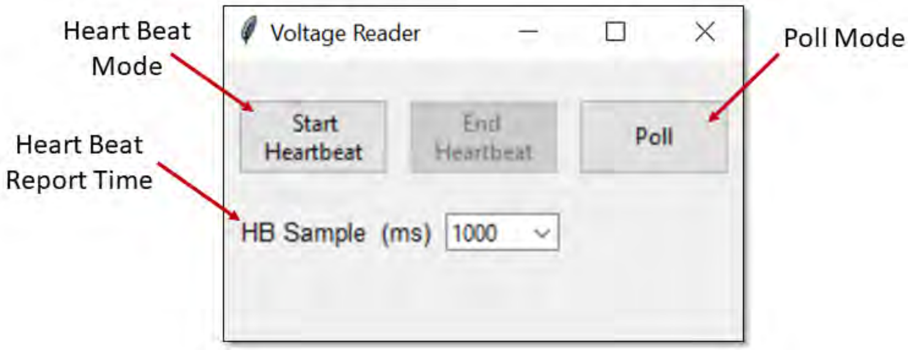
Figure 13. Communication protocol between main application and embedded processor.

4.2.2 DC Voltage and Current Monitoring Application

A DC voltage and current monitoring application with graphical user interface was written to allow the user to monitor the charging status of the battery bank under different load conditions caused by the capacity sensor. If the batteries are still charging under a particular load applied by the sensor, then the grid had that much capacity available. Service to a customer or community asset (cell charging station, water heater) could be added depending on excess capacity. If the batteries are discharging, then that indicated the grid had a smaller load capacity than being applied by the sensor, and smart shedding of service would occur depending on energy draw from battery. This application uses the same Python library and embedded software that can be used by the PV utility for automatic control and operation. The embedded processor has two user modes to relay grid performance information to the main program which are:

- Polling Mode: Single inquiry by the main application
- Heart Beat Mode: The embedded processor outputs information and constant frequency configurable by the user.

Although DC voltage monitoring was incorporated in the library and application, current direction was the predominate factor used during testing to determine grid capacity. The embedded processor continually monitors and integrates the current sensor signal at 4 ms and outputs a voltage which linearly scales with current. This value is relayed to the main application and is used in a calibrated equation to determine if the batteries are charging (capacity available) or discharging (capacity unavailable).



HB Sample (ms) 1000

Figure 14. DC voltage and current monitoring application graphical user interface.

The main application GUI is depicted in Figure 14 and used a similar communication protocol described above to transfer information from the embedded processor monitoring the batteries to the main application.

4.2.3 Automatic Grid Capacity Detection

A Python application using the above libraries was written to test different automatic search strategies and sampling parameters (i.e., dwell and sample interval) to determine grid capacity. These search strategies could then be incorporated into the full sensor Python library for implementing automatic detection at a PV utility. Two strategies were initially written which included:

- Conservative Search – This search starts at the lowest possible load and incrementally steps to the next higher load until grid capacity is detected. This is the recommended search procedure since it is the least stressful to the inverters and only requires one change in condition to determine grid capacity.
- Binary Search – This search starts at a seed load (usually half of the full load capacity) and does a binary search through available loads until grid capacity is detected. This particular search was tested but is not advised. The search can cause the test system to fault numerous times which could damage the inverters. Also, the search requires a sufficient time delay for the system to come back online after a fault condition which reduces any speed advantages of a binary search.

Both strategies were implemented the same way using the following procedure:

- A starting load value was selected and the corresponding relay information was sent to the embedded processor controlling the sensor relays
- The load was applied by the sensor and dwell time occurred
- The DC voltage and current values were sampled from the monitoring embedded processor
- If the batteries were still charging, the next load was selected and administered by the sensor
- If the batteries were discharging, an upper limit of capacity was determined and further refined as needed

4.3 CAPACITY SENSOR TESTING

The capacity sensor and software were tested on a benchtop setup at Group 73's laboratory located at the flight facility. The sensor first underwent load switching using the manual load selection application described above. This test was successful with the sensor hardware working as designed (Figures 15–17). DC voltage and current sensing of the battery bank was then tested. First the system was calibrated and calculated values were entered into monitoring software to calculate the zero point between charging and discharging. Software measurements of current were collected and compared against handheld meter measurements which corresponded very closely. Erratic charging and discharging of the batteries was experienced and later found to be caused by damaged batteries and/or power supply settings. Once the batteries were replaced, charging behavior was as expected. However, the transition from battery charging to discharging was not as predictable using the input power supply as has been seen with solar panel input. Additionally, the small power system we had available could only power the equivalent load of one 400 watt cooker.

Once the sensor's load control and monitoring software was successfully tested, automatic capacity sensing was tested, albeit over a short time period. A binary search strategy was first tested and flowed as expected but with negative results. The strategy caused multiple system faults which could hurt the inverters over a period of time. In addition, after each fault, the system needed 4–5 seconds to reset; however, the search software didn't have the appropriate time delay set and received erroneous results from the current sensor resulting in a wrong capacity detection. This error can be fixed with appropriate parameter value settings. In addition, a more conservative and straight forward search approach that simply escalates loads until the grid capacity could be utilized which might be gentler on the system but would take longer to find grid capacity.

Overall, the capacity sensor testing was a success despite some of the setup issues cited above. The load selection and monitoring system worked well. If the search strategy is changed to a more conservative incremental approach, the sensor should give a very good indication of grid capacity. The standalone applications were extremely useful in testing the system and used the same sensor library that can be incorporated into the utility control software. Scaling to run with solar panel input by using more inverters would eliminate the power supply variables and limitations, but would introduce the variability of incoming solar irradiance making test conditions hard to reproduce. That said, building a test grid that could run longer over a period of time with more capacity would provide valuable data to configure the power supplies for more accurate system emulation. Furthermore, being able to test and collect data with an inverter and energy storage system of the same scale and architecture used at proposed field sites would provide a better model for developing smart PV control algorithms.

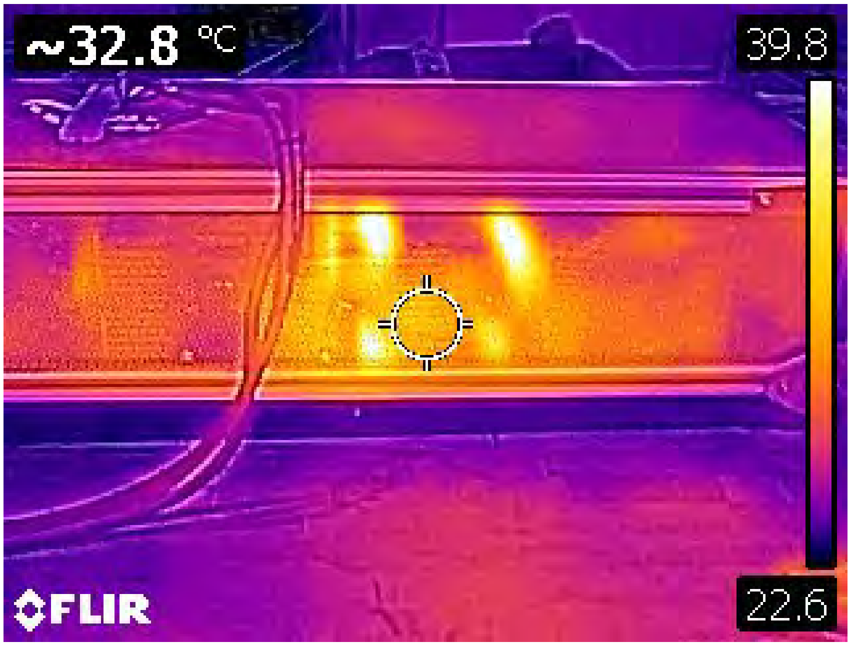


Figure 11. IR photograph of capacity sensor load box exterior under operation.

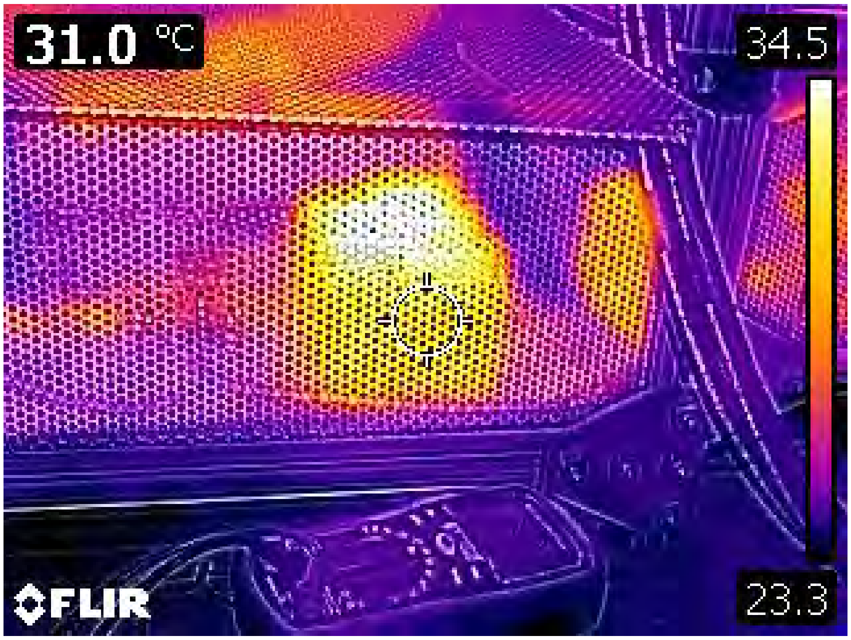


Figure 12. Capacity sensor controller under operation.

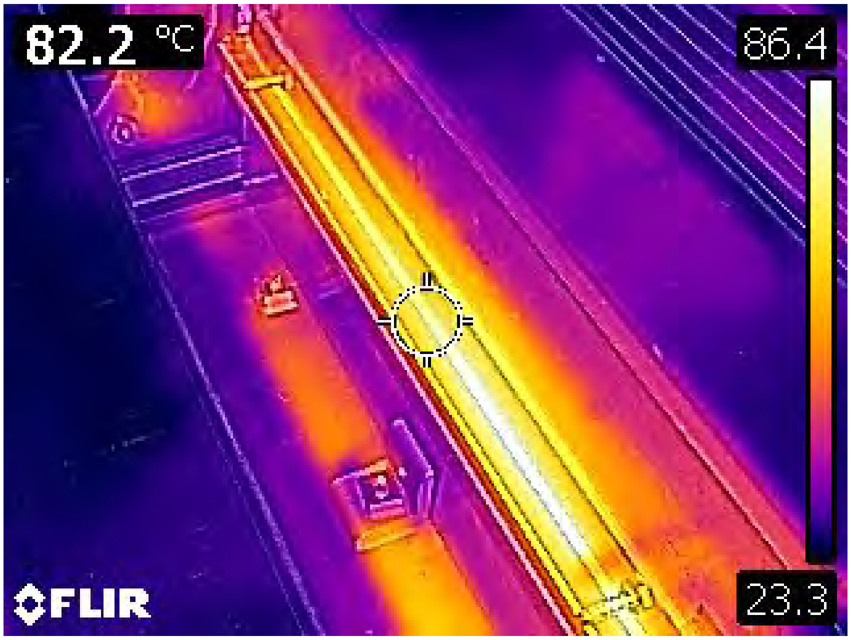


Figure 17. Capacity sensor load box 25 ohm resistor energized.

4.4 UTILITY CONTROL SOFTWARE

An initial utility control architecture (Figure 18) was developed and tested against anticipated use cases for a PV micro grid utility with limited battery storage. Many questions concerning utility policies and processes that greatly impact the control logic of the smart distribution system surfaced during the architecture's development. Some of these questions included:

- Customer Priority
    - How is priority given to customers? Does it change from day to day?
    - If a low-priority customer can't have power one day, do they get a higher priority the next day?
    - Can a lower-priority customer be shed from the grid to power a higher priority customer? What if the higher priority customer is a community device like a medical refrigerator?
- Usage
    - If a customer is not using their scheduled power, is their power turned off and given to another customer or community device?
    - How long does the utility wait to take action on no use?
    - Does the utility cut power to the customer temporarily then restore every so often?
- Shedding
    - What is the criteria for shedding customers? How does that effect billing?
    - How much battery drain can occur before you shed a customer?
- Billing
    - Do people pay for all the power they scheduled or the actual amount of power they used?

Many of these questions still need to be determined through discussions with the utility and the community, therefore, a comprehensive utility control system complete with scheduling, billing, and automatic addition and shedding of customers was not developed for this program. However, the questions raised by this initial architecture are extremely important and need to be addressed for a future pilot to be successful.

For this program, the initial architecture was whittled down to a core logic capable of adding and shedding customers to the grid based on available power and customer priority. This strategy is the basic building block of the utility control system, but in addition, has many other important uses. One example is the case for a micro-grid with limited or no storage powering a pump to lift water to an elevated tank. This basic controller could be used to add other devices, such as a cell charging station, to the grid when excess power is available. There are no customer policies to consider, the number of devices and loads are known, and shedding extra devices has no severe consequences. Yet, it allows the operator to efficiently use the energy generated by the grid.

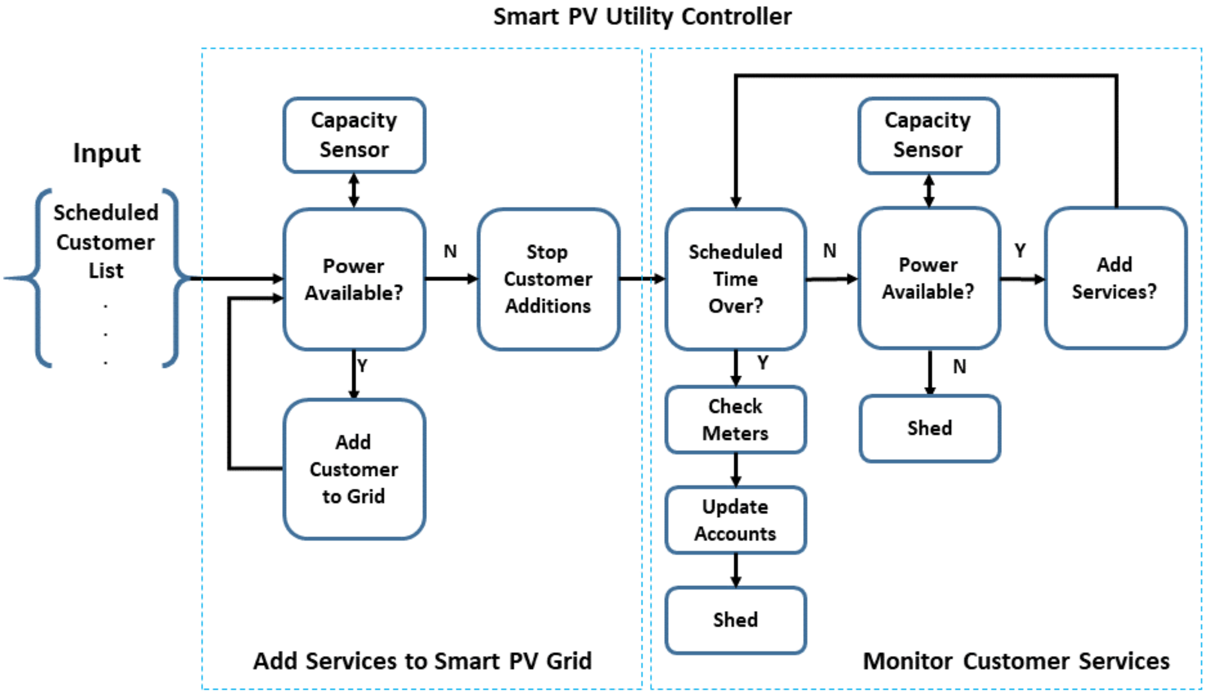


Figure 18. Utility's smart control software architecture.

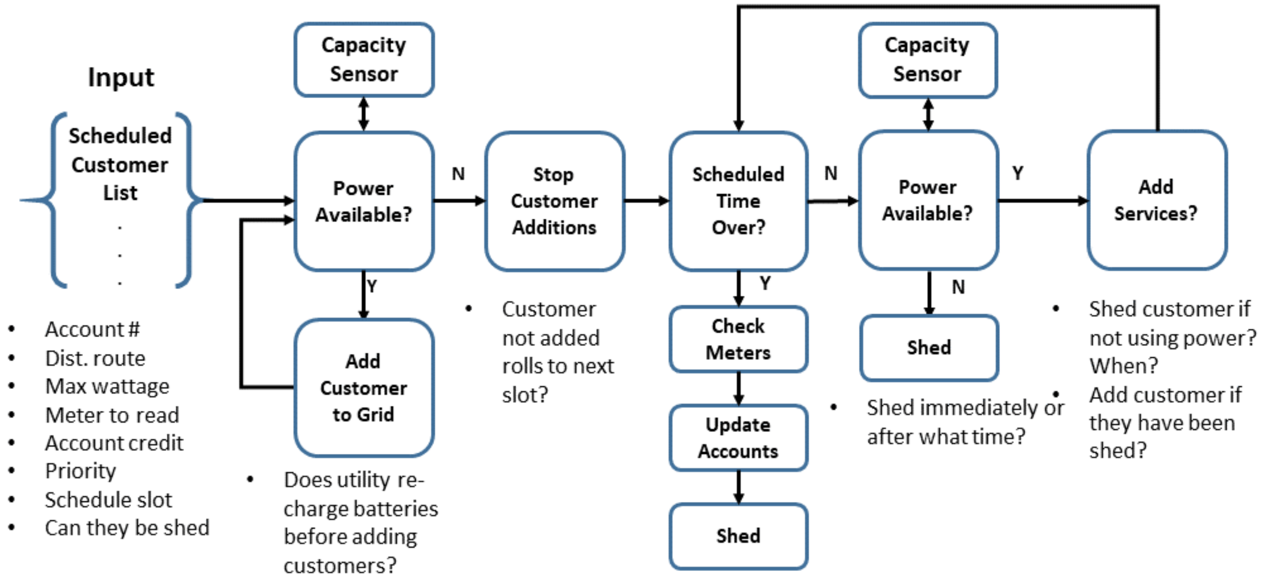


Figure 19. Utility's smart control software architecture and implementation questions.

This control architecture was implemented in a Python program that included manual control and hooks for automatic control using the libraries previously described. The three goals for this initial utility controller included:

- Manual control of system inputs to test control logic and easily demonstrate different use grid/customer cases
- Control logic for adding and shedding customers and device to the grid based upon capacity and priority
- Software hooks for automated utility control for power distribution hardware (Capacity sensor, distribution boxes)

The utility control software (Figure 20) had the following attributes:

- Manual mode to control system inputs
    - Available grid power using a slide control
    - Customer priority
    - Customer peak load
    - Actual customer load
- Automatic mode (software hooks) to use actual system hardware to determine grid capacity and distribute power
- Configurable devices and max loads (Figure 21)
- Automatic power distribution based on capacity and priority

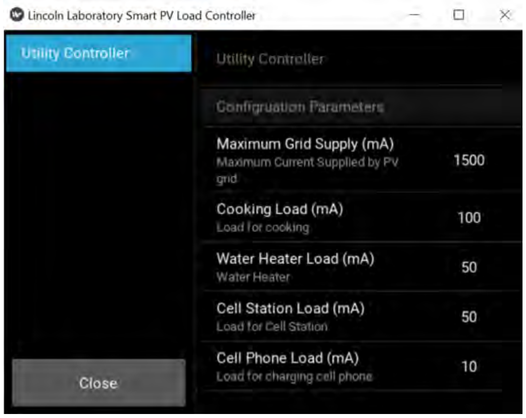
Grid Power W 209

Power Used W 199

Available Power W 10

	Customer	Use	Credit
On	Cooking	100	374
On	Cooking	86	374
Off	Water Heater	35	460
Off	Cell Station	32	460
On	Cell Phone	6	458
On	Cell Phone	7	467

Figure 20. Utility controller graphical user interface.



Configuration Parameters

Parameter	Value
Maximum Grid Supply (mA) Maximum Current Supplied by PV grid	1500
Cooking Load (mA) Load for cooking	100
Water Heater Load (mA) Water Heater	50
Cell Station Load (mA) Load for Cell Station	50
Cell Phone Load (mA) Load for charging cell phone	10

Figure 21. Utility controller configurable device and loads.

5. ENERGY UTILIZATION – SMART APPLIANCE TECHNOLOGY

Endpoint appliances are an extremely important factor for adopting electricity for cooking in heavily disadvantaged communities. Cooking with the appliance is the customer's primary user experience with electricity which is why the space is so focused on these devices. "Will I be able to cook the same way?" "Will the food taste the same?" "How hot does the pot get?" are all typical questions when customers are considering a new cookstove.

During the Phase I effort of the Smart PV program, the team conducted many experiments using different appliances and methods for cooking and determined rice cookers to be the appliance best suited for these communities. They rely on insulation to be highly efficient, have integral switches for safety (thermal and weight), can cook a variety of foods (i.e., rice, soups, beans, teas), and don't required new additional cookware to be use properly. In addition, compared with Instapot and pressure cookers, ingredients can be added when desired and the contents can be seen, stirred, and sampled at will which is highly important for the cook.

During the Phase I effort, new rice cooker controllers were developed that used a food grade probe for temperature feedback of the contents. Different cooking strategies were investigated as well, and one, in particular, showed very promising results. The strategy was to power the rice cooker on until the contents, rice in this case, was close to boiling. Power was then turned off, but due to the appliance's insulation, the rice still cooked while it slowly decreased in temperature. When the rice temperature decreased to ~190°F, power was once again restored and the process was repeated until the rice was cooked. An energy savings of ~40% was seen by using this method to cook rice with only a small change in cook time.

Although the strategy is efficient, the team was concerned about the robustness of using a temperature probe (Figure 21) in a real-world environment. The probe is susceptible to being damaged in the kitchen, especially by playful kids. Clearly, temperature feedback is an advantage, but could a non-contact temperature sensor, hidden and protected inside the rice cooker, be used to gain the same results?

To answer this question, an experiment using an IR sensor (Figure 22) to detect different temperatures at different locations on the cooker was conducted. For one location, a hole was drilled into the side wall of the cooker so that a small IR sensor could determine the temperature of the removable cooking pot of the appliance (Figure 23–24) The IR sensor was also used to determine the temperature of the exterior wall of the cooker, the cooker's lid temperature, and the temperature of the contents when viewed from above. The data is shown in Figure 25.

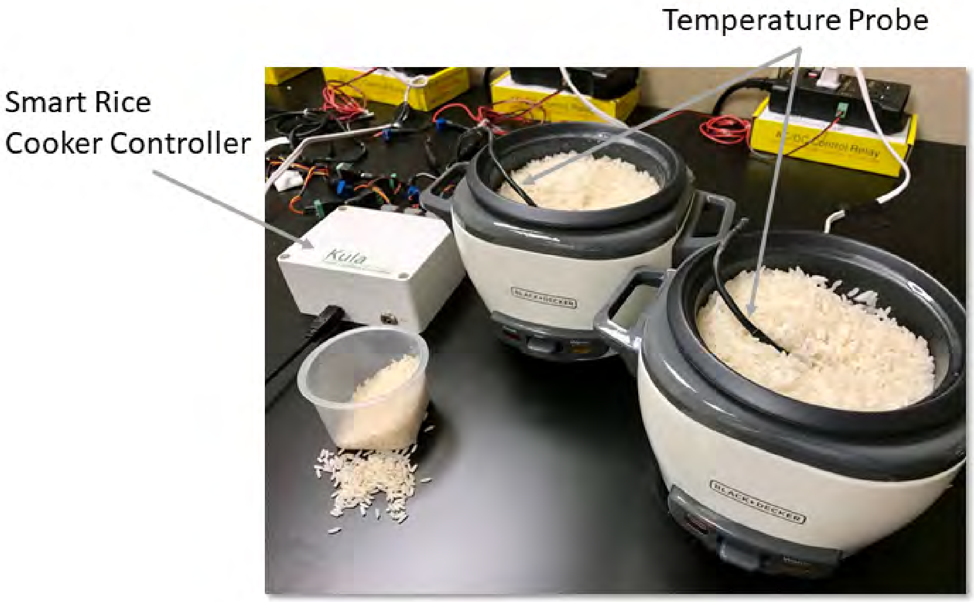


Figure 21. Smart rice cooker with temperature probe.

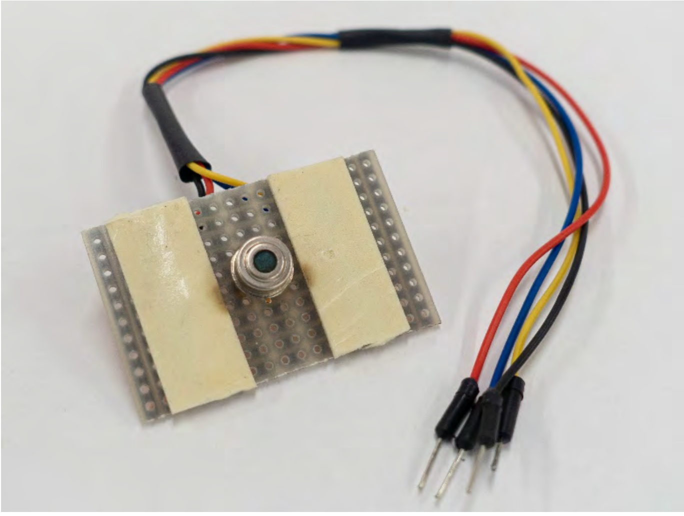


Figure 22. IR sensor and mounting board.

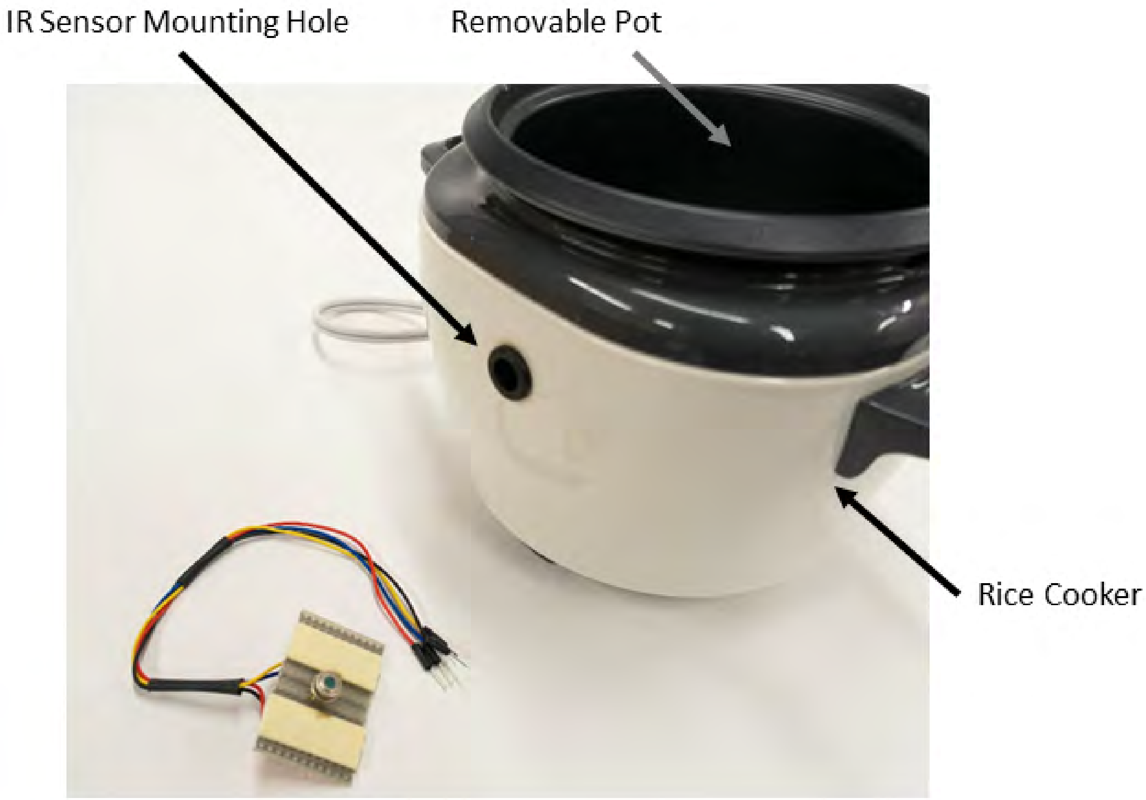


Figure 23. IR sensor and modified rice cooker.

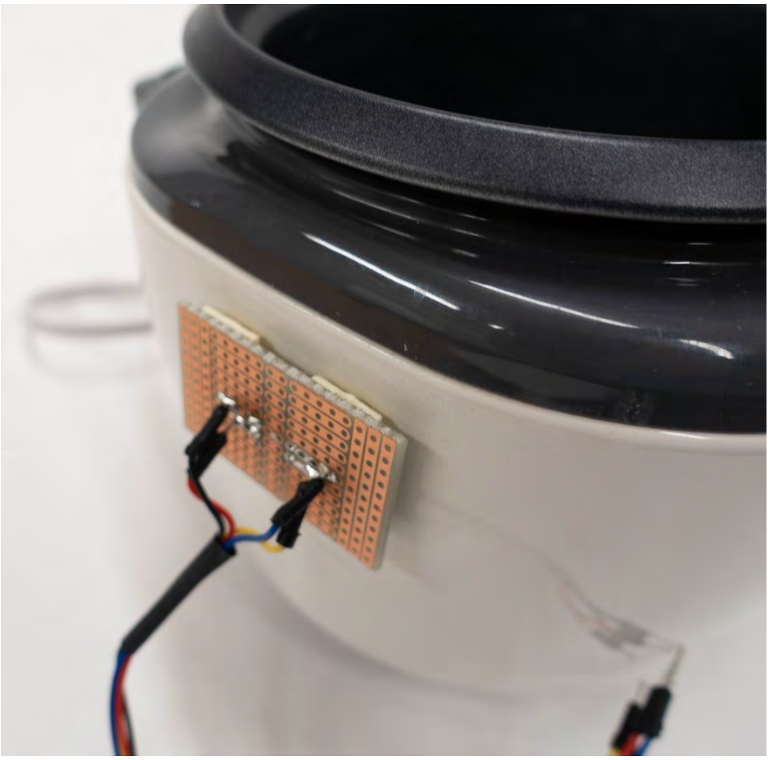


Figure 24. Mounted IR sensor pointed at removable rice cooker pot.

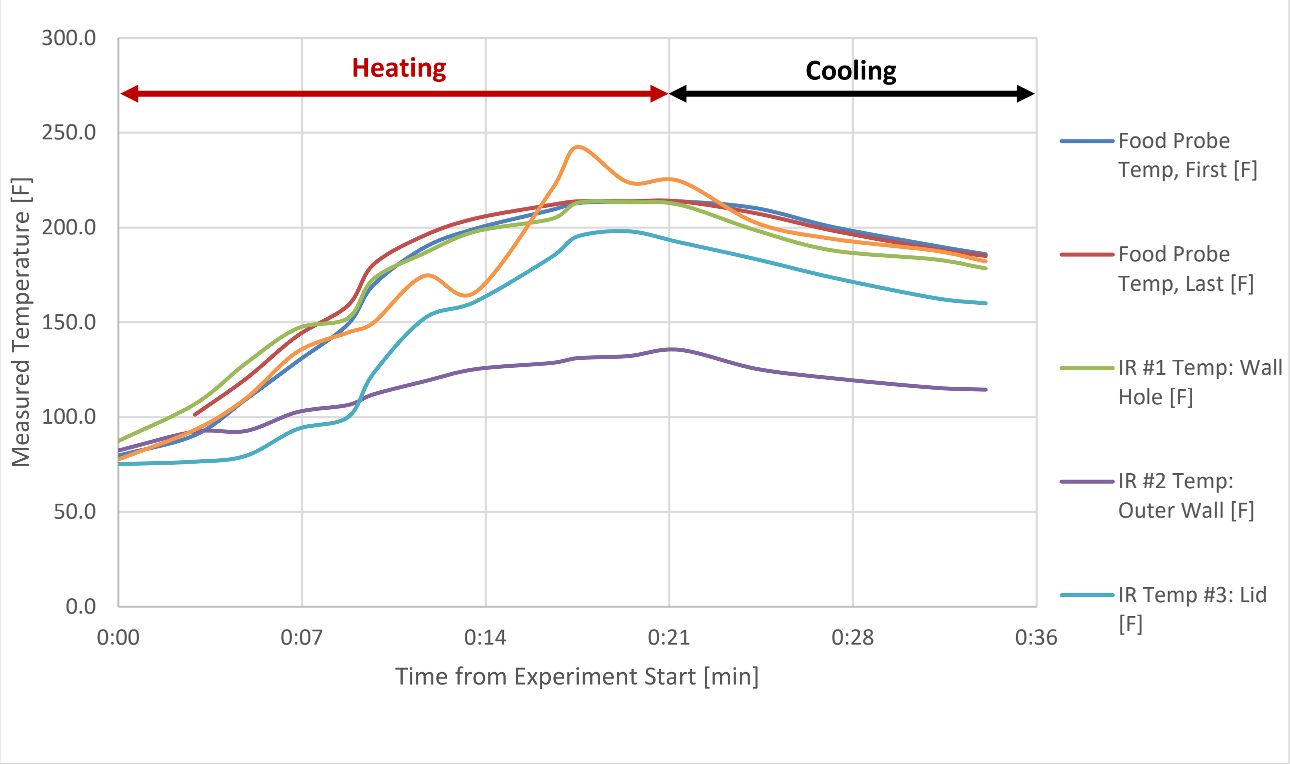


Figure 25. Data from rice cooker experiment comparing temperature probe to IR sensor data at multiple locations around the appliance.

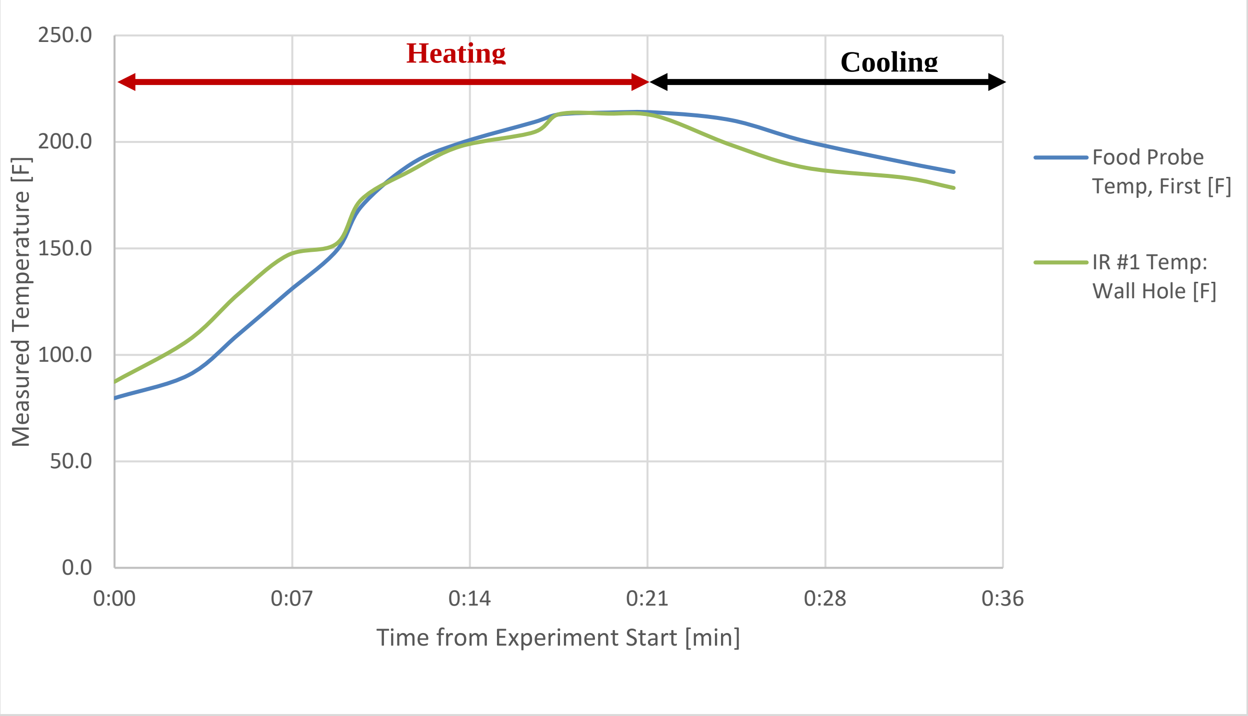


Figure 26. Data from rice cooker experiment comparing temperature probe to IR sensor data taken at side through hole viewing removable pot.

Temperature of the contents and that of the removable pot tracked very closely as the temperature of the contents increased as seen in Figure 26. This leads the team to believe that there is a good possibility that an IR sensor could be packaged inside the appliance and be used with an energy saving strategy to cook rice. Clearly the IR sensor could be used to directly or indirectly (i.e., temperature stabilization) determine the point of boiling which the energy efficient strategy relies upon. Temperature data from the IR sensor peering through the lid also tracked with the probe data and could be used to determine if the contents reached boiling indirectly through temperature stabilization. However, the sensor may be hard to package where it will be out of the way for the cook (i.e., stirring, adding ingredients) but still have a good view of the contents. An additional investigation needs to be conducted in order to determine the optimal sensor, packaging location, view, and control strategy to further refine the design for use in the field.

6. SMART PV MICRO GRID – HAITI PILOT

A key focus of Phase II of the Smart PV program was to leverage the power distribution and endpoint cookware being developed at MIT LL to support a CCA pilot program for clean cooking in Haiti. The goal of the pilot was to introduce electricity into highly disadvantaged communities in Haiti and document the factors contributing to adoption by the community. CCA, CU, and MIT LL were to partner with established PV utility operators, such as Sigora Haiti, to implement the pilot. Unfortunately, during the beginning of Phase II, when pilot discussions were underway, political unrest surfaced in Haiti and continues until this day. All required paperwork submitted to work and operate in Haiti has been put on hold and the U.S. State Department travel advisories are currently at level three due to crime, civil unrest, and kidnapping. In addition, funding for the CCA Haiti pilot has also been put on hold.

In February, CCA was given a second opportunity for a cooking pilot in a heavily disadvantaged African community possibly located in Uganda. Unfortunately, in mid-2019, an Ebola crisis broke out in the Democratic Republic of the Congo and U.S. State department travel advisories were issued for that region delaying the pilot. Currently, CCA is in negotiations with MIT LL to assess additional African sites for the pilot.

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7. SUMMARY

The Phase 2 efforts for the Smart PV Micro Grid program resulted in a new grid capacity sensor and control strategy for efficient operation of PV micro grids, a new IR sensor and packaging strategy for more robust smart appliances, and valuable insights into critical factors impacting community adoption of electricity for cooking. The team's first foray into irradiance forecasting revealed that models for longer term forecasting (~days) need further development. Future work in this area should expand to investigating shorter term forecasting (~hours) using onsite instrumentation and tracking hardware to alert customers of possible service interruption. Advances in irradiance forecasting will increase customer confidence in scheduled cooking and could lead to continued adoption.

The development and testing of a real-time grid capacity sensor and software library was an important advancement for employing a smart PV micro grid with minimum storage into a community. This will allow for smart addition and shedding of services for optimizing grid efficiency. The initial development of the utility's smart control software can be scaled for growing communities and be applied to other solar-powered activities (i.e., solar pumping) thereby efficiently distributing energy to customers and community devices. In addition, the team's efforts to incorporate inexpensive IR sensors into new rice cooker packaging designs will further increase the robustness and efficiency of the utility by freeing energy to power additional services.

The team looks forward to the political strife in Haiti subsiding and the Ebola crisis ending in the DRC. Our hearts go out to those countries and communities. In the meantime, CCA is still pursuing initiatives for a solar-powered electrical cooking pilot elsewhere in Africa, and MIT LL is currently in the planning stages for assessing their potential pilot sites for 2020. Important insights for the introduction of electricity for cooking in disadvantaged communities were developed during both phases of this program. These insights brought to bear important questions impacting community adoption and will definitely affect planning, scheduling, and scaling of a future pilot.

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