Project Report
TIP-96

Smart PV Microgrids for Cooking in Heavily Disadvantaged Communities: FY18 HP/ATC/HADR Technical Investment Program

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Lincoln Laboratory
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Massachusetts Institute of Technology
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Group 44

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ABSTRACT

Recently, team members of 44HADR and the Energy Systems Group (73) have developed and tested benchtop components for a Smart PV Micro Grid to supply electricity in heavily disadvantaged communities for clean cooking. Tests of novel, smart power distribution algorithms combined with smart endpoint cooking conducted by the team have shown significant increases in energy efficiencies while decreasing installation costs and maintaining affordable pricing for customers. It is the goal of the team to pilot these technologies with the help of our collaborating partners, Columbia University and the Global Alliance of Clean Cookstoves (GACC) in Haiti or Sub-Saharan Africa in 2019.

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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 six 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 which many countries can't 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 by minimizing the need for battery storage.[*] 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 of time. 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 which reduce cost and strengthen customer loyalty. The overriding goal of this effort 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 microgrid's smart scheduling and distribution system which 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

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[*] Estimate from Columbia University based on their PV installations in Africa.

provide feedback on power utilization while smart outlets and appliances reduce the energy required for daily cooking.

Although cooking has been the primary focus for the Lincoln team, it is important to note that the technology being developed for smart PV microgrids 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 night time 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 microgrid 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 microgrids 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 this effort was to develop technologies that would compel household adoption of electricity for cooking in disadvantaged communities and were focused on the following goals:

- Reduce upfront installation costs of the utility
- Increase the utility's energy and operational efficiency
- Develop efficient, simple and safe cooking methods for customers that have never used electricity for cooking
- Develop tools to simplify and enhance the Customer's user experience with the Utility

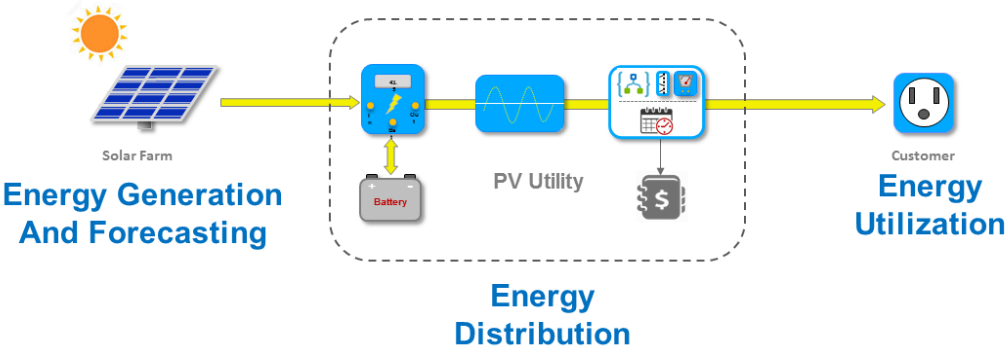


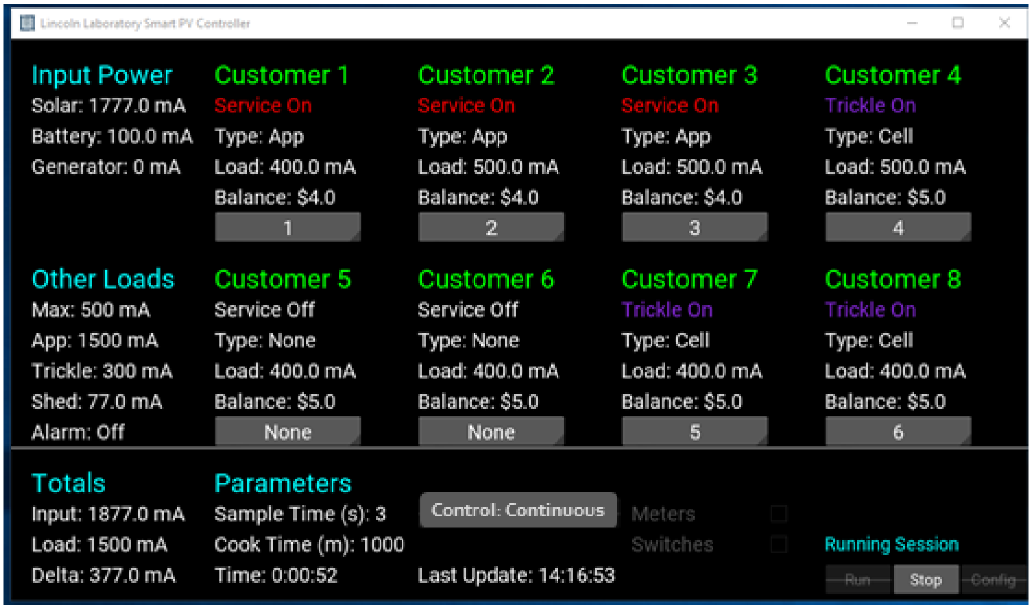
Figure 1 Technology areas for Smart PV development.

Technology areas for a smart PV microgrid can be broken down into three sectors as shown in Figure 1. This effort primarily focused on technology for enhanced energy distribution and utilization. Energy generation and forecasting will play a key role in further development of the smart PV concept in 2019. Several subsystems of the smart PV Micro Grid have been prototyped by the team including a smart power distribution controller with scheduling and billing, a smart distribution box, and a smart endpoint cooking controller. Cooking experiments with these prototype components and novel energy scheduling strategies have demonstrated significantly increased efficiencies over traditional electric cooking methods using power-on-demand strategies.

2.2 SMART POWER DISTRIBTUTION CONTROLLER

One of the first pieces technology developed for this effort was a smart, prioritized scheduler for energy distribution to micro grid customers. To minimize battery storage, the controller needs to distribute real time power capacity of the utility’s solar array to the prioritized, scheduled demand of customers who have signed up to cook at a particular time slot during the day. If real time capacity exceeds demand then customers can be immediately alerted and added to the service. If power capacity wanes, say due to cloud cover, the controller needs to shed service in a transparent, prioritized manner established with the help of the community. In addition, if excess capacity is available but doesn’t meet customer cooking requirements, the controller has the ability to activate cell phone charging service for customers. The controller has the following elements (Figure 2):

- Distributes power based on current capacity and scheduled demand
    - Can differentiate between supplying appliance or cell loads to customers
    - Controls service by utilizing smart meters and switches for each customer
- Selectable power distribution strategies to implement
- Prioritized scheduler
    - Priority rules are set by utility and community
    - Scheduled cooking slots are transparently implemented
- Alert mechanism for customers when excess power capacity is available
- Automatically updates billing and customer accounts
- Logs operational diagnostic data and customer use
- Hooks for activating alternative power if available (i.e. Batteries, Generators)
- Manual operation mode for turning service on/off to customers
- Tablet, smart phone or computer user interface



Input Power
Solar: 1777.0 mA
Battery: 100.0 mA
Generator: 0 mA

Customer 1
Service On
Type: App
Load: 400.0 mA
Balance: $4.0

Customer 2
Service On
Type: App
Load: 500.0 mA
Balance: $4.0

Customer 3
Service On
Type: App
Load: 500.0 mA
Balance: $4.0

Customer 4
Trickle On
Type: Cell
Load: 500.0 mA
Balance: $5.0

Other Loads
Max: 500 mA
App: 1500 mA
Trickle: 300 mA
Shed: 77.0 mA
Alarm: Off

Customer 5
Service Off
Type: None
Load: 400.0 mA
Balance: $5.0

Customer 6
Service Off
Type: None
Load: 400.0 mA
Balance: $5.0

Customer 7
Trickle On
Type: Cell
Load: 400.0 mA
Balance: $5.0

Customer 8
Trickle On
Type: Cell
Load: 400.0 mA
Balance: $5.0

Totals
Input: 1877.0 mA
Load: 1500 mA
Delta: 377.0 mA

Parameters
Sample Time (s): 3
Cook Time (m): 1000
Time: 0:00:52

Last Update: 14:16:53

Meters ☐
Switches ☐

Running Session

Figure 2 Smart PV software controller.

2.3 SMART POWER DISTRIBTUTION BOX

One of the biggest costs for PV micro grid installation next to batteries is the cost of cable to provide service to a household. Ideally, mains service is provided by chaining distribution boxes in a lightening configuration to reduce cable lengths. However, this necessitates installing a meter in the household which is difficult to monitor in real time as well as difficult to maintain. Putting customer meters at the utility makes them easy to maintain and monitor but necessitates wiring households in a star configuration which increases installation costs. To solve this dilemma, the team developed a smart distribution box which allows a lightening configuration distribution while maintaining the meters back at the utility.

The smart distribution box is a simple design using standard COTS relays and a small microprocessor (Figure 3). The microprocessor receives instructions from the smart PV distribution controller to switch service on/off to households by actuating simple relays. Communication between the controller and the microprocessor is established using power line communication (PLC) modules which allows information to be transmitted and received over the existing mains power lines. PLC has been utilized for decades by power utilities and the technology is inexpensive, established and is currently utilized in households for internet connections. Since the controller can direct the smart distribution boxes to turn on/off service to individual households, a single meter can be used for multiple households and maintained at the utility.

Note that PLC modules can be also utilized at the household outlet to allow service only to a particular customer outlet say for only cell phone charging versus a cooking outlet.

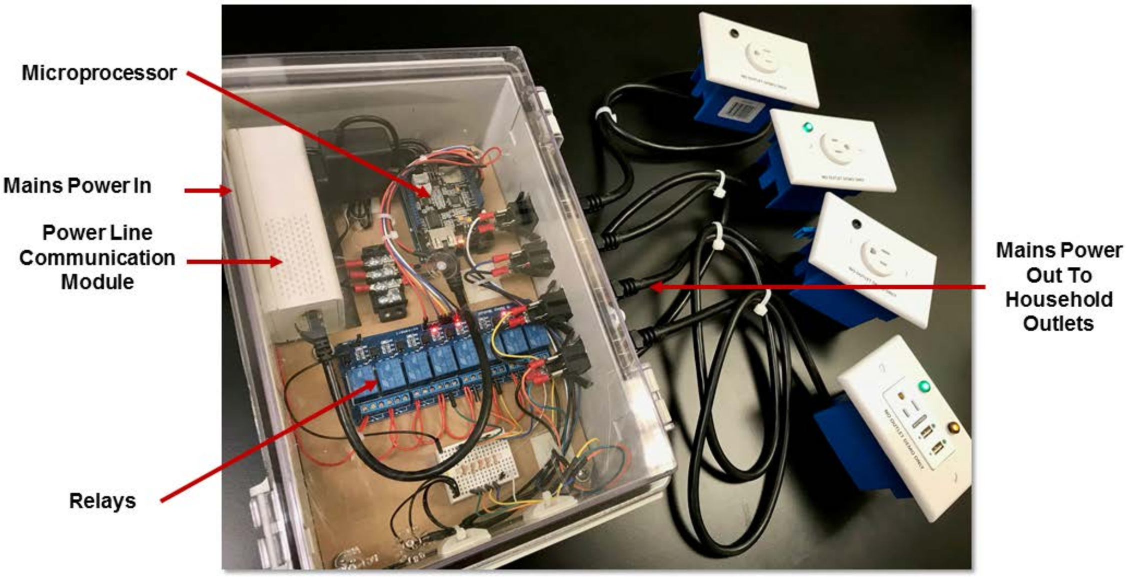


Figure 3 Smart PV distribution box.

2.4 SMART COOKING APPLIANCES

Besides developing technology for energy distribution, the team also focused on safe, simple, and efficient electrical cooking appliances. Previous cooking experiments and investigations by the team found that insulated appliances, such as rice cookers, provided a safe simple approach for cooking. The appliances have low energy requirements (~450 watts), have automatic thermal cutoff switches, and are simple to use with consistent results. However several issues were found during the investigation. For instance, there is no temperature adjustment to cook or reheat foods to a specific temperature. Also, although the pots are insulated, the appliances had a constant power draw even when foods had achieved a boiling temperature thus wasting energy.

To address these issues, the team developed and built a new cooking controller for the insulated appliances (Figure 4). A Customer uses a simple dial on the controller to adjust the desired temperature the food is to achieve. A food grade temperature probe feedbacks temperature information to the controller which monitors the cooking process in real time. Once the food reaches the desired temperature, the controller switches off power to the appliance. If the food temperature cools below a certain threshold temperature, the controller will once again turn on the appliance to heat the food. Since the pot is insulated, it was found that food can cook for a very long time with power off to the appliance.

Figure 4 Rice cookers with temperature feedback contro.l

The graphs in Figure 5 show two different cooking experiments using two different temperature thresholds for the controller to maintain. The graph on the left shows the controller trying to maintain a temperature range of 149 – 150 degrees. The insulated pot could maintain that 1 degree temperature differential for approximately 7-8 minutes before the controller had to turn the appliance back on. The graph on the right shows the controller trying to maintain a temperature range of 130 -150 degrees. In this case the controller could turn off the outlet for better than 15 minutes. In each case the smart power distribution controller could redirect energy from this appliance to another household when the appliance was turned off greatly increasing efficiency. Several control strategies were investigated and demonstrated to be up to 67% more efficient then current COTS insulated cookware.

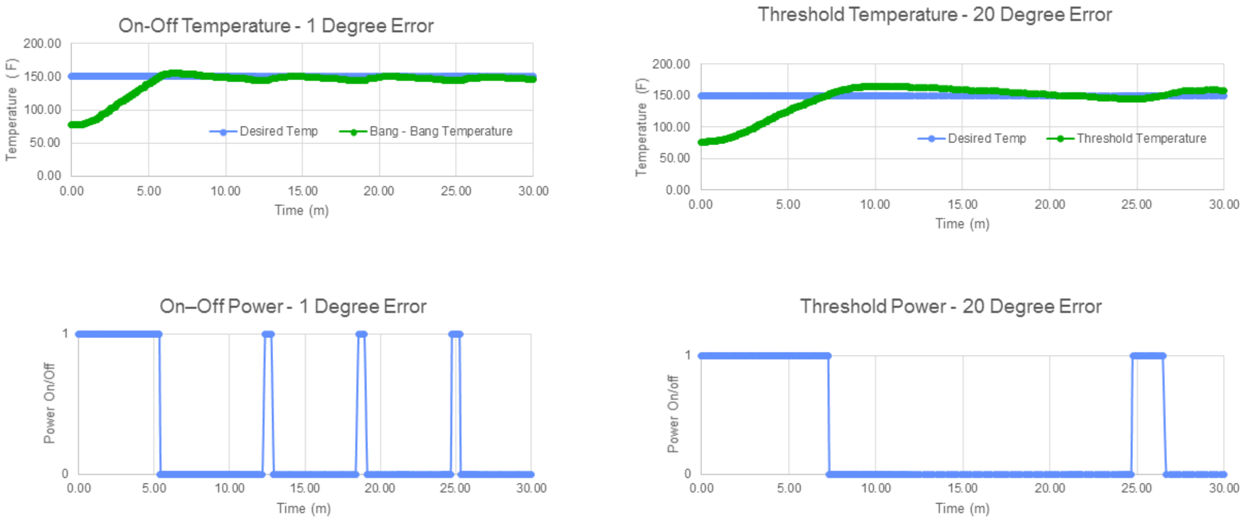


Figure 5 Power vs. time curves for temperature feedback control strategies.

3. FUTURE DEVELOPMENT

3.1 NEXT STEPS

The next development stage is to assemble a field deployable Smart PV Micro Grid capable of being piloted in Sub-Saharan Africa or Haiti in 2019 with our on-the-ground partners, Columbia University and the Global Alliance for Clean Cooking. This development effort will be a collaboration between Groups 44, 43, and 73 over the course of a year. As stated earlier, the main goal of the 2019 effort is to have electrical cooking adopted in disadvantaged communities in Haiti. There are three primary efforts that will be underway.

1. Installation of a PV Micro Grid in a pilot community. The site will provide electrical power to 40 – 50 customers for cooking. Since adoption of electricity for cooking is the goal, the site will have ample storage to always meet the needs for the customer needs for cooking. Hooks and interfaces will be built into the site, however, to pilot vetted technology to increase efficiency and operation and decrease cost.

2. Continued development of a Smart PV distribution controller. The smart controller has generated lots of interest by the community particularly for its prioritized scheduling and smart distribution strategies for excess/ insufficient capacity. The team is focused on escalating the implementation of the controller at the pilot site.

3. Development of a safe, simple, and efficient Cooking appliance. Safety and simplicity of the cooking appliance is of prime concern by all party since the customer base will have never used electrical burners for cooking. In addition, temperature control is highly valued by the customer and can greatly increase efficiency in cooking. Figure 6 shows different concepts of incorporating temperature in inexpensive electrical appliances.

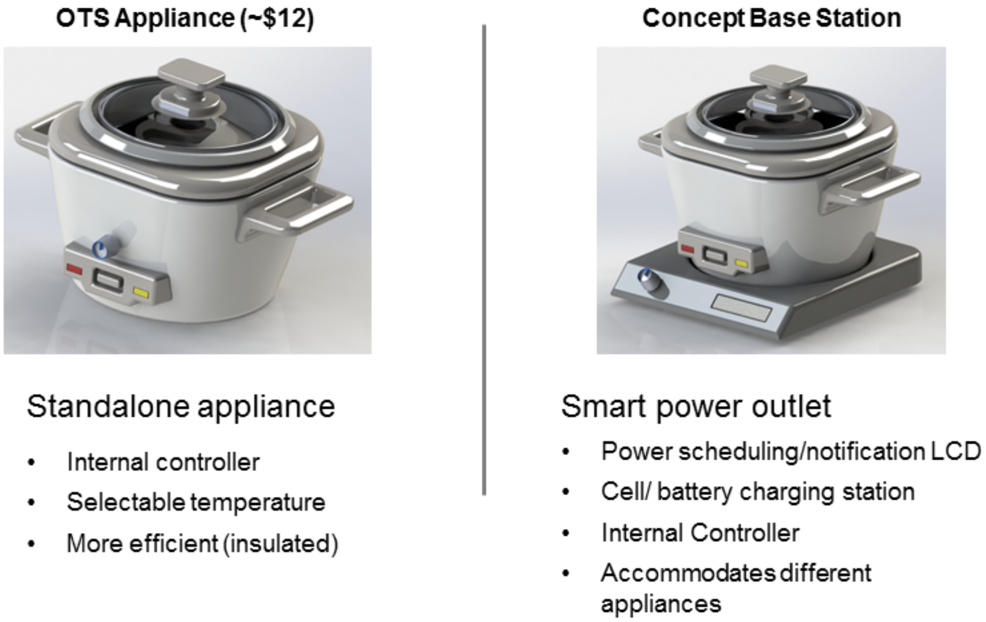


Figure 6 Packaging concepts for smart cooking appliances with temperature feedback.

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[1] Bizzarri M., Bellamy C., Katajisto M., Patrick E., “Safe Access to Firewood and Alternative Energy in Kenya,” World Food Program Report (2010): 15-16.

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