Energy Harvesting Controls for Solar Direct-Drive Cooling Systems

Laboratory Testing Report

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Contents

Abbreviations

DC	direct current
EHC	energy harvesting control
PCM	phase-change material
PQS	Performance, Quality and Safety (WHO)
PV	photovoltaic
SDD	solar direct-drive (refrigerator or freezer)
SELF	Solar Electric Light Fund
SSP	simulated solar power
WHO	World Health Organization

Preface

Photovoltaic (PV) power generation (solar panels) can be a useful means to power equipment essential to storing, delivering, and supplying vaccines in settings where mains power is not available or is unreliable. Solar direct-drive (SDD) refrigerators and freezers are commercially available and are designed specifically to operate with the intermittency inherent to PV power without depending on battery power to operate properly. A number of these appliances are prequalified by the World Health Organization's (WHO) Performance, Quality and Safety (PQS) prequalification team to support safe and effective immunization delivery.

SDD appliances are often installed at health facilities with PV arrays sized appropriately to produce more power than necessary to run the SDD appliance to ensure continual operation and safety of vaccines through expected hourly, daily, and seasonal solar variation. This excess power is generally unused. Because the installations are purposefully installed at locations lacking consistent mains power, this excess energy has high potential to be useful for other purposes in the same location.

If excess power from the installed PV systems is to be utilized, there must be assurances in place that acceptable performance of the SDD appliances will not be hindered. This requires some sort of switching or monitoring mechanism that ensures prioritized and fail-safe operation of the primary SDD appliance while effectively diverting excess power to other power-consuming devices referred to as secondary loads. Toward this purpose, PATH has been working in collaboration with the Solar Electric Light Fund (SELF) on multiple fronts to support implementation of energy harvesting controls (EHCs) by:

- Informing specifications, standards, and testing protocols to ensure that any allowable EHC embodiment will prioritize the primary SDD appliance above all secondary loads, be resilient under harsh electrical and environmental conditions, and fail-safe in the case of realistic failure modes to leave the SDD appliance operable.

- Testing specific prototypes through the collaboration with SELF to gain working knowledge of the controls, test possible failure modes and protocols, verify functionality of the specific prototypes, and anticipate issues in design, testing, and verification of EHCs in general.

- Collecting data to answer questions about the effects of introducing EHCs into the PV-SDD appliance system (for example: If the EHC requires a base amount of power, how much and what is the effect on the SDD appliance? How much energy is harvestable? If the EHC interrupts the SDD appliance at any time, how is the cooling affected and is it acceptable?).

Executive Summary

This report presents the methods and findings from laboratory testing of two energy harvesting control (EHC) prototypes with three different Performance, Quality and Safety (PQS) prequalified solar direct-drive (SDD) refrigerators from three different manufacturers. The primary goals of the testing were to inform potential specifications for EHCs, test the specific prototypes, and collect data to answer a number of questions raised by the possible introduction of EHCs to vaccine cold chain systems.

Testing included a baseline test of each refrigerator without an EHC in the system, equivalent testing with each of the two EHC prototypes produced by a team brought together by Solar Electric Light Fund (SELF), and fail-safe and robustness testing of each combined EHC-refrigerator system. Separate field testing was also led by SELF. See Annex 1 for the full report.

The testing generally confirmed that even at the prototype stage, although there were some failures of the EHCs, they failed-safe. Failing-safe means that during failures the SDD refrigerators continued to function and continued to hold cabinet temperatures within the acceptable, World Health Organization-specified temperature range. Quantitative data including cool-down times during testing, energy use during different periods by the system devices, and energy harvesting are reported. The times required for the refrigerators to stabilize with an EHC connected were generally longer, but on the order of a couple of hours only. This additional stabilization time with the EHC is not significant when compared to the 3 to 7 days the manufacturers of the refrigerators tested specify for cool-down in documentation. Parasitic power draw by the EHCs ranged from approximately 3% of total energy usage to 100% depending on the complexity of the prototype, although the SELF-led design team stated that the higher of the values could be easily decreased in production EHC versions.

No excursions outside of the allowable temperature range of +2°C to +8°C were noted after the initial cool-down periods, although testing did not include extended periods of low, simulated solar radiation. Some issues noted included:

- All prototypes had at least a low baseline power draw for the control mechanisms.
- Negative interactions were noted between specific timing settings in some EHC-refrigerator combinations, which could lead to potential concerns if manufacturers are not aware of or not required to test for these types of issues. Switching, timing, and control mechanisms will need to be carefully addressed in the design of any commercially acceptable devices.
- Although in all failure cases the system failed-safe, the failure modes show some potential for long-term problems if unaddressed in real-world use.

Background

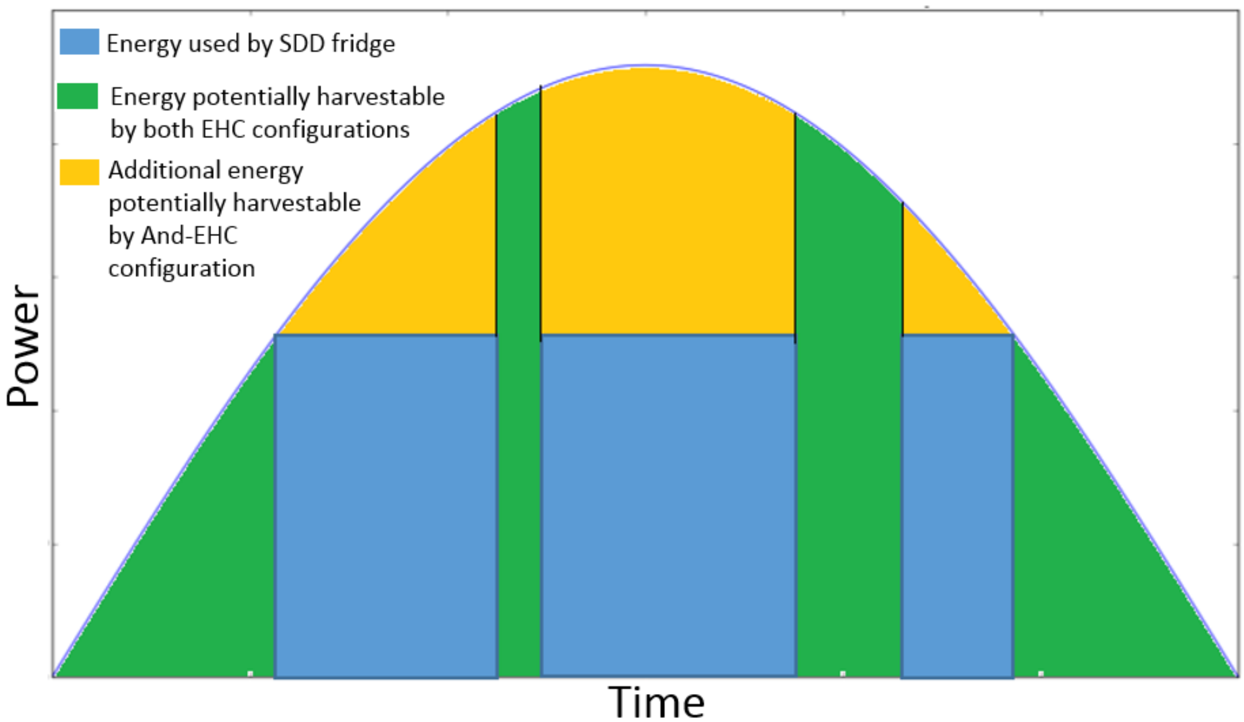
In the 1980s, solar photovoltaic (PV) powered refrigerators used for vaccines and introduced to areas lacking electricity were generally connected to batteries that allowed the appliance to maintain cooling at night.[1] These batteries had short lifetimes on the order of 3 to 5 years.[2] To extend the lifetime and long-term success of installations, the World Health Organization (WHO) Performance, Quality and Safety (PQS) team recommended moving to battery-free, solar direct-drive (SDD) appliances. These SDD appliances generally have thermal energy storage in the form of water or some other phase-change material (PCM), allowing for increased autonomy. In terms of these appliances and as defined in WHO-PQS testing, autonomy is the amount of time an appliance can keep a load adequately cooled with extremely limited power input, as may be experienced during rainy days.[3] Without a battery to provide a buffer of stored electrical energy, solar array capacities for SDD systems are oversized to obtain sufficient daily compressor runtime and ensure adequate cooling during daylight hours. The larger array capacity, however, results in excess energy production. To date, PQS specifications have required solar power to be dedicated to the appliance and specifically prohibit power use for other secondary loads.

Taking an idealized example of the power available over a single day from a PV array, Figure 1 illustrates the potential for harvesting unused energy. The blue areas in the figure represent energy used by the SDD appliance. The remaining area under the curve is energy produced but unused without an energy harvesting control (EHC). There are three general states in which the PV array is producing power unused by the SDD appliance. Firstly, on both the far left and far right ends of the curve shown in Figure 1 there are periods corresponding to lower solar radiation in the morning and evening where the power available to the SDD appliance is less than the minimum needed to run the appliance. Secondly, during the day, and assuming the SDD appliance has already gone through an initial cool-down period, it will generally cycle on and off. This type of cycling is illustrated by the two skinnier green areas in the middle of the graph. While off, essentially all the possible power produced by the PV array is unused by the SDD appliance. Lastly, while on, there is generally more power than the exact amount needed to run the SDD appliance. This excess energy is represented by the yellow areas and could also be harvested.

Continuing to look at Figure 1, there are at least two basic control structures that could be used to govern an EHC. We will refer to them as the And-EHC and the Or-EHC. An Or-EHC is the simpler control structure. Ignoring for now that any SDD appliance likely requires some base-power consumption to run a thermostat whenever very minimal power is available, the Or-EHC will only divert power to secondary loads when the SDD appliance is not consuming power (green areas in Figure 1). In most SDD appliances this corresponds to the compressor being off, although there are some SDD appliances with less conventional cooling technologies that do not use a compressor. Regardless of the cooling mechanism used, if the SDD appliance is consuming power above a base consumption level, the Or-EHC will harvest no energy. These periods correspond to the areas colored yellow and blue in Figure 1.

An ideal And-EHC will harvest all excess energy produced corresponding to both the green and yellow areas under the curve in Figure 1. It diverts power to secondary loads during the green-colored periods when the cooling mechanism is using no power, as well as during time periods when cooling is powered and the PV power produced is greater than that needed by the SDD appliance. More detailed descriptions of actual embodiments of the two general controls are presented in How Energy Harvest Controls Can Increase the Benefits of Solar Direct–Drive Refrigerators.[i]

Figure 1. Idealized graph of the available power from a PV array over a single day with colored areas under the curve separating the utilization of the available energy. The blue areas represent energy actually used by the SDD appliance, and the sum of the yellow and green areas is the energy produced by the PV array but unused without an EHC.



Abbreviations: EHC, energy harvesting control; PV, photovoltaic; SDD, solar direct-drive.

At a basic level, there are three requirements for an EHC to be useful and an acceptable addition to the system. It must:

1. Not hinder the performance of the primary, SDD appliance in keeping vaccines at acceptable temperatures.
2. Leave the SDD appliance uninhibited from continuing to operate correctly in the case of failure, partial failure, or malfunction of the EHC.
3. Divert at least some useful amount of energy to secondary loads.

In addition to those basic requirements, introducing an additional, potentially disruptive component into a crucial system raises some questions that may be answerable by testing. For example:

- After the SDD appliance reaches its operating temperature, do excursions outside of the allowable temperature range occur and are they attributable to the EHC?
- Do the EHCs fail; what are the likely failure modes; will the SDD appliance continue to operate within the allowable temperature in these failure modes?
- Does the SDD appliance take longer to cool down?

[i] See http://www.path.org/publications/detail.php?i=2701 to access the report.

- How are stabilization, cycling, and cool down of the SDD appliance changed, if at all?
- How much additional power is necessary to run the system during normal operation after stabilization?
- What situations would need to occur for autonomy to be compromised by adding the EHC, and are they likely to occur?

Testing

Three categories of testing were carried out to support the exploration, understanding, quantification, and eventual introduction of EHCs for use with vaccine cold chain equipment:

- Baselining and simulated solar cycling
- Fail-safe and robustness testing
- Field testing (Annex 1)

The Solar Electric Light Fund (SELF) brought together a technical team to design and produce two functional prototype EHCs. One was capable of being configured as either an And-EHC or an Or-EHC while the other functioned exclusively as an Or-EHC with more basic control logic. More detailed information about the prototypes is available on PATH's website.[ii] The energy diversion components of both of the prototypes were functionally in parallel to the SDD appliance, whereas the physical box containing the prototypes was connected in series with the PV array and SDD appliance. Both prototypes required some power to continually monitor the operation of the SDD appliance to inform the control logic. Although it may be feasible to produce EHCs that operate passively (completely unpowered until power is available in excess of that used by the refrigerator), the prototypes were not constructed in this way.

Three PQS prequalified SDD refrigerators from three different manufacturers were procured for testing purposes. Most of the tests were carried out on each of the refrigerators with both the And-EHC and one Or-EHC. The multifunctional prototype was primarily tested in the And-EHC configuration and only tested minimally as an Or-EHC due to time constraints.

Testing in the product development shop at PATH in Seattle, WA, USA, was generally carried out with an SDD refrigerator and EHC in an environmental chamber (Espec model ESL-4CA, Hudsonville, MI, USA) set at +43°C with uncontrolled indoor humidity, corresponding to the harshest, highest temperature specified in the WHO "hot" heat zone. No vaccine load was placed inside the refrigerators during any tests, so apart from the thermal mass of the PCMs used in the walls of the refrigerators and other refrigerator components, no thermal load was present during testing. Data acquisition was accomplished with National Instruments SignalExpress software and data acquisition hardware (NI cDAQ-9172 chassis and NI 9211 thermocouple input module, National Instruments Corporation, Austin, TX, USA) measuring the following quantities at a rate of 1 sample/sec throughout most testing:

- Vaccine compartment temperature—type-T thermocouples (5SRTC-TT-T-36, OMEGA Engineering, Inc., Stamford, CT, USA).

[ii] Visit http://www.path.org/publications/detail.php?i=2701 for more information.

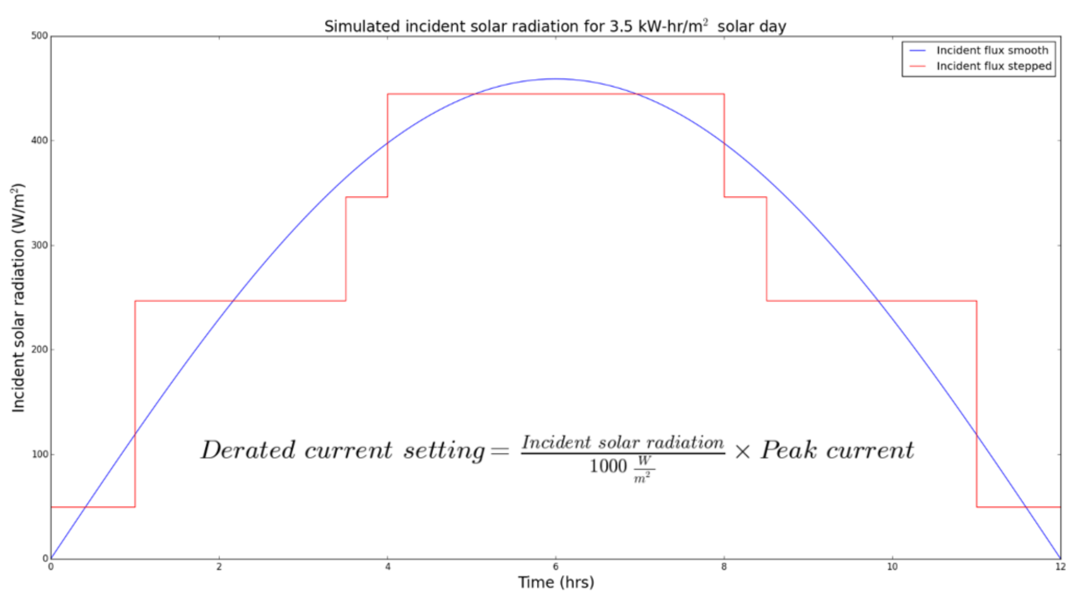
- Current to EHC, refrigerator, and secondary load—input module for differential voltage measurement for current (NI 9125, National Instruments Corporation, Austin, TX, USA) using linear Hall effect current sensors (DFRobot SEN0098 breakout board for ACS758, Allegro MicroSystems, Worcester, MA, USA). Measurements from the current sensors were filtered through a simple RC (resistor, capacitor) low-pass filter circuit with a 5 Hz cutoff frequency.
- Voltage to EHC, refrigerator, secondary load, and thermostat—voltage input module (NI 9221, National Instruments Corporation, Austin, TX, USA).

Replicates of the tests were not run due to the time constraints with the number and duration of the tests, so we could not assess measurement variability. Field testing was directed by SELF and carried out by the CFV Solar Test Laboratory, a third-party solar test laboratory in Albuquerque, NM, USA. Limited information is included in the main text, but the full report is included in Annex 1.

Baselining and Solar Cycles

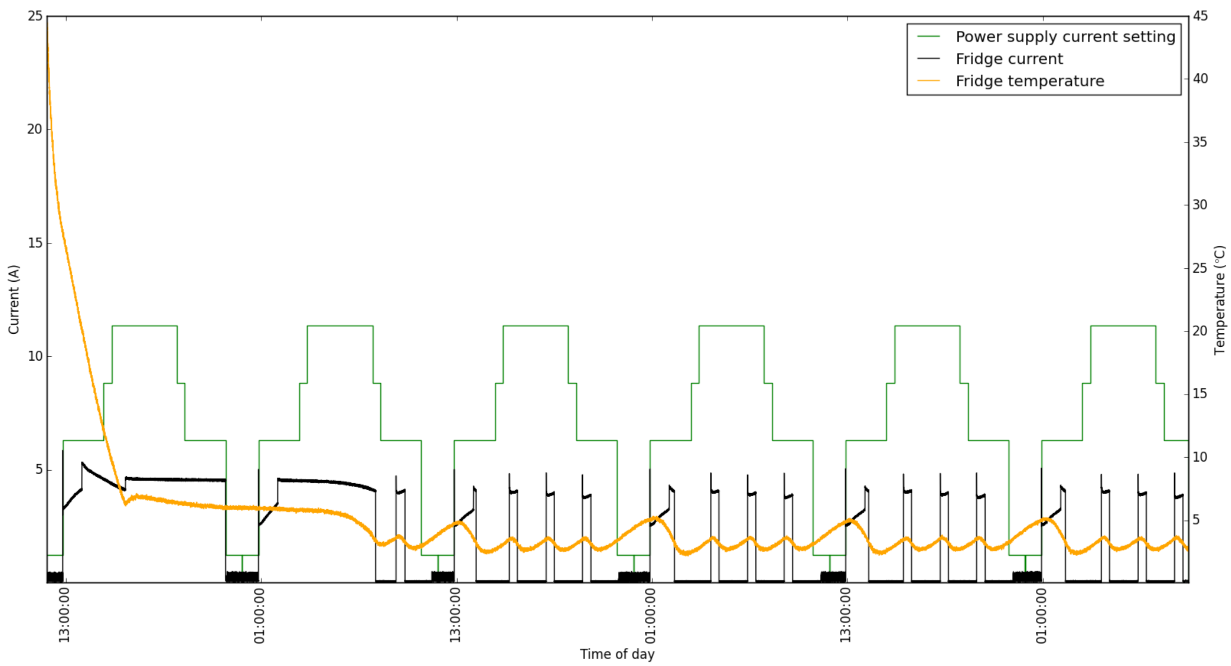
To address a number of the questions identified above about the effects of adding an EHC to the system, a baseline was run on each of the refrigerators without an EHC. For this baseline a 3.5 kW-hr/m^2 solar day adapted from that specified in the WHO-PQS E003/RF05-VP was used. Figure 2 shows the simulated solar power (SSP) profile used as "full solar days" throughout the testing. This stepped, incident solar radiation was then used to create power supply current settings based on an assumed 450 W-rated solar array at 17.6 V yielding a peak current of 25.5 A. SSP was supplied by a BK Precision 9151 programmable DC (direct current) power supply (BK Precision, Yorba Linda, CA, USA) using a Python script to enter and control the output consistently. Refrigerator and EHC combinations were conditioned at the environmental chamber temperature (although in some test cases not fully conditioned) and tested through a number of full solar days to complete cool down. After baselining in this way without an EHC, the same test was run with each EHC.

Figure 2. Stepped, simulated incident solar radiation for 3.5 kW-hr/m^2 full solar days used in testing. The blue curve shows a smoothed version for reference with the same area under the curve.



To accelerate testing, 12-hour solar day cycles were used instead of 24-hour solar day/solar night cycles. The 12 hours without sun (or SSP in the testing) usually used in PQS testing to simulate nights were omitted and 12-hour, daytime, simulated solar cycles were run in direct succession as is evident in Figure 3. Data presented on cool-down times and energies from these tests in the Results section are therefore useful for comparison within this report but are not necessarily good for comparison with other testing data outside this report.

Figure 3. Baseline test data for SDD Refrigerator-1 showing repeated, 12-hour, simulated solar days.



For one of the robustness tests discussed below, a different solar cycle was used to simulate intermittent solar radiation. A baseline for comparison using the intermittent cycle was also run with each SDD refrigerator without an EHC connected. The SSP curve for these intermittent solar days is shown in Figure 4.

Fail-Safe and Robustness Testing

To address the requirement that EHCs do not interrupt the functionality of the refrigerator in the case of failure as well as assess the robustness of the system with an EHC to improper use or stress, a number of fail-safe and stress tests were developed. Although numerical data will not be presented for all of these tests because the outcome is essentially a pass or fail criteria, defining and running the tests was an essential goal of this work to inform prequalification testing and requirements if WHO moves to include EHCs in its list of prequalified cold chain equipment. Specifically, these tests were denoted as:

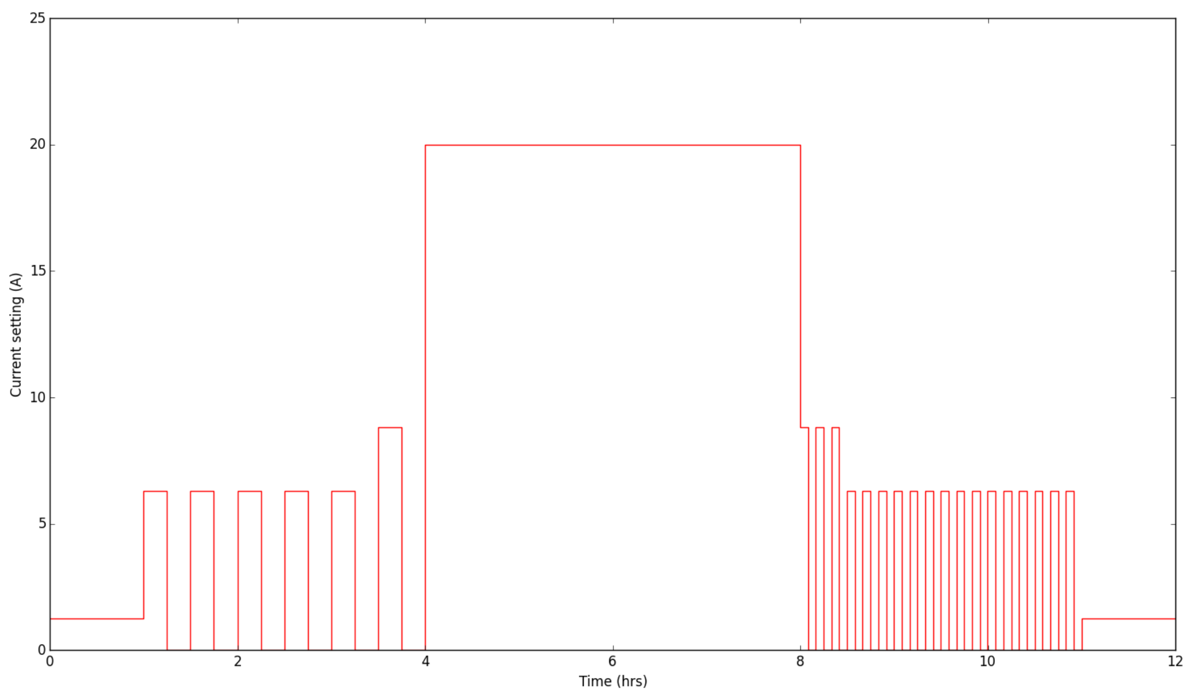
1. Solar radiation variation during cool down
2. Alternate connections
3. Reverse polarity

4. Short circuit
5. Progressive secondary load power draw
6. Inductive load
7. Abrupt current change

Solar Radiation Variation During Cool Down

This test was intended to stress the system with abrupt changes in PV power input that could be expected from intermittent radiation due to cloud cover or any other obstruction. The refrigerator was run during its initial cool-down period to ensure that the control circuit of the refrigerator was constantly calling for cooling. A single intermittent solar day as illustrated in Figure 4 was run without an EHC for each refrigerator during baselining as well as for each refrigerator-EHC combination tested.

Figure 4. Intermittent solar day—intermittent simulated solar power (SSP) for 12 hours totaling 4.1 kW-hr/m^2 with a peak incident radiation of 800 W/m^2. Current settings for the particular, selected photovoltaic (PV) array simulation chosen for testing are shown on the y-axis, as opposed to the incident radiation. Because the specific embodiment of the Or-EHC had an upper limit of 20 A for certain relay components, tests were not run at the 1,000 W/m^2 level that is specified in a draft verification protocol for EHCs that would have corresponded to 25.2 A.



Alternate Connections

Because the connections on the PV array, on the refrigerator, and into and out of the EHC (if the EHC is not integrated into the refrigerator) may all be compatible, there are a number of different ways that a user could conceivably hook up the components incorrectly. If this happens, and power is supplied in any of these alternative connection configurations, ideally all components will continue to function correctly after they are hooked back up correctly. In this test, the three system components were hooked up in each physically possible configuration with correct polarity, power turned on, and outcome observed, and then rearranged and tested for normal operations in the correct configuration. The draft testing protocol that was written after the actual testing was carried out for this report assumed that the output terminals to the secondary load would have different connections that would be more useful to the end user than the MC4 connections usually used with solar PV modules/arrays and SDD appliances. For our testing, however, this assumption was not made and configurations that incorrectly connected the secondary loads in the system were included.

Reverse Polarity

As with the alternate connections test, it would be possible for a user to reverse the polarity of the PV connection to the EHC. This might be difficult if MC4 connectors are used due to differences in the male and female connectors. As above, but with the polarity hooked up incorrectly, power was turned on, outcome observed, and then correct polarity restored and the system components tested for normal operations in the correct configuration.

Short Circuit

This test was intended to confirm the ability of the refrigerator to continue functioning correctly in the case of a complete short circuit between the EHC and the secondary load. The short circuit was established and the system monitored to be sure that the refrigerator continued to receive power and function as normal. A BK Precision 8510 adjustable DC load (BK Precision, Yorba Linda, CA, USA) was used as the secondary load during the test. After correction of the short, continued functionality of all system components was reconfirmed.

Progressive Secondary Load Power Draw

To make sure that the system could deal with large loads drawing maximum power from the system, the BK Precision 8510 adjustable DC load was used to draw progressively more power. With the SSP outputting the rated solar array voltage and current at maximum power point, the secondary load was set to draw 25% of the maximum power point power while the refrigerator was turned off. Then the refrigerator was turned on to confirm correct diversion and functionality. The secondary load power was then increased repeatedly by 25% of the rated solar array power at maximum power point, testing similarly at each value until 100% was reached. A final cycle was run with the SSP output at 135% of its rated maximum current to simulate realistic situations where solar flux in very sunny locations can be above the specified maximum power point of 1,000 W/m^2. At this last setting, the secondary load was set to draw 125% of the PV array's rated maximum. The difference between the output and secondary load percentages was intentional to attempt to ensure that the load was actually drawing 125% of the rated maximum.

Inductive Load

While most secondary loads will be resistive in behavior, it is possible that manufacturers or users may connect DC inductive loads such as electrical motors to the EHC. Inductive loads can generate transient high currents, voltages, and noise that could affect the EHC or refrigerator performance. To assess this possibility, a DC automotive fan (Rapid-Cool 3670, Hayden Automotive, Lewisville, TX) drawing 10 A at 17.6 V was connected to the EHC.

Abrupt Current Change

This test was intended to stress the system by forcing as close to an instantaneous jump in current as possible through the EHC. To do this, the same variable DC load was set to a low current and then increased as fast as the variable load allowed to the peak rated output current of the SSP supply.

Field Testing

A separate report titled *Solar Electric Light Fund Energy Harvest Control Study* and prepared by CFV Solar Laboratories (Albuquerque, NM) is attached as Annex 1.

Results

Beginning with the simplest data set, namely the baseline solar cycling of SDD Refrigerator-1 with no EHC attached, there are a number of useful points to note from the data. Looking first at the temperature curve in Figure 3, the refrigerator internal temperature (with no load in the refrigerator cabinet as noted above) cools down relatively quickly in the first solar day. By the end of the second solar day (with no night period in between as noted above), it is evident in both the temperature and the refrigerator current curves that the compressor has begun to cycle on and off. During all of the subsequent solar days, similar cycling is seen with a larger increase in temperature during the simulated morning and evening periods when there is not enough SSP available for the compressor to turn on.

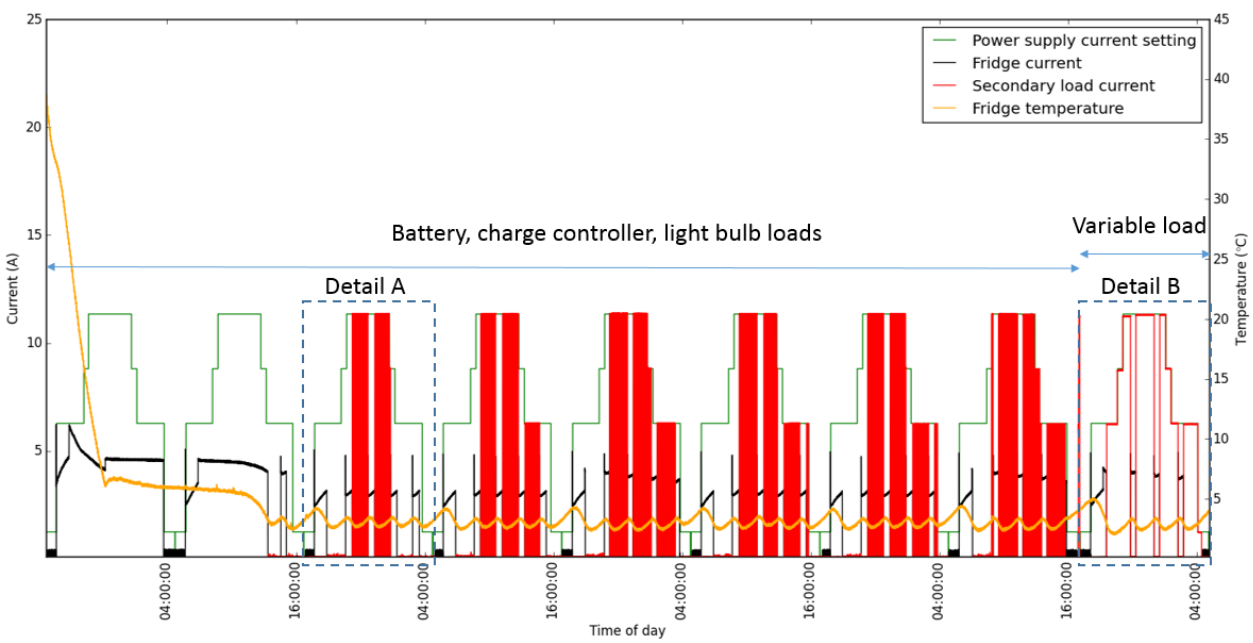
It is useful but somewhat difficult to define a point consistently for all types of refrigerators when the refrigerator could be called thermally “stabilized.” Although the majority of SDD refrigerators are basically boxes lined with a PCM (sometimes water) and have a compressor run by a cooling circuit with a thermostat, alternate designs could include thermoelectric refrigerators, refrigerators with asymmetrical PCM banks cooled by a compressor over which a fan is blown to cool the vaccine compartment, or others. For the purposes of this testing and the data analysis in this report, only currently PQS prequalified refrigerators were considered. We ignored thermoelectric devices and others without compressors. Stabilization could then be defined by the time when the compressor first begins cycling off and on when there is enough power available for the compressor to turn on. The manufacturers of the three refrigerators tested do not specify an exact stabilization time but do note in their manuals or other documentation that 3 days in one case and 5 to 7 days in the other two cases should be allowed for the refrigerator to cool down or stabilize thermally. Other options considered for defining stabilization but discarded for the purposes of this testing and analysis included:

- Smoothing the temperature data and choosing an instantaneous slope or derivative of that data sufficiently close to zero to be called stable.
- Calculating an instantaneous duty cycle (percentage of time running) for the compressor and defining stabilization as the point when the duty cycle reached a certain value.
- Considering the refrigerator stabilized at the first time point the internal temperature reached a certain value.

It is possible, with the selected definition, that the refrigerator is not completely thermally stabilized in the sense that some of the PCM or other appliance thermal mass may still be cooling even when the compressor starts to cycle on and off.

Referring to Figure 5, the Or-EHC was connected to SDD Refrigerator-1 and tested at the same conditions as the baseline. The time to stabilization and the three curves shown in the baseline are generally similar in form with the Or-EHC attached. Some quantitative results for more exact comparison are shown in Table 1. Notably, all of the solar days shown with the compressor cycling look somewhat similar until the final day. In this initial testing of the EHCs, the secondary load was changed between those two days. Figures 6 and 7 show these differences in more detail. In Figure 6, the load was a battery connected to the EHC through a charge controller with a custom load of light bulbs connected to help drain the battery as it charged. The secondary load can be seen to cycle based on the control logic of the charge controller. Detail B in Figure 7 illustrates the functionality of the Or-EHC with the variable DC load connected as the secondary load and set to accept as much power as was available. In this case, the curves look almost exactly as one would expect from an idealized Or-EHC with no power draw while the compressor is running and maximum available power draw when the compressor is off.

Figure 5. SDD Refrigerator-1 with Or-EHC tested through consecutive, full solar days.



During testing, it was evident that the relationship between the specified SSP levels in protocols, the amount of power needed for the compressor of a given refrigerator to turn on and operate, and the baseload power necessary for an EHC is very important. With one of the tested SDD refrigerators, the solar time periods shown in this report of 250 W/m^2 radiation corresponded to an SSP current only slightly larger than the current necessary to run the compressor. In that case, the amount of additional current necessary for the And-EHC to function decreased the current available to the refrigerator enough that it could not turn on during either of two 2.5-hour periods during each solar day. This severely limited the functionality of the refrigerator due to the synthetic nature of stepped SSP in testing as opposed to solar radiation that might be seen in real-world use.

Figure 6. Detail A portion of Figure 5.

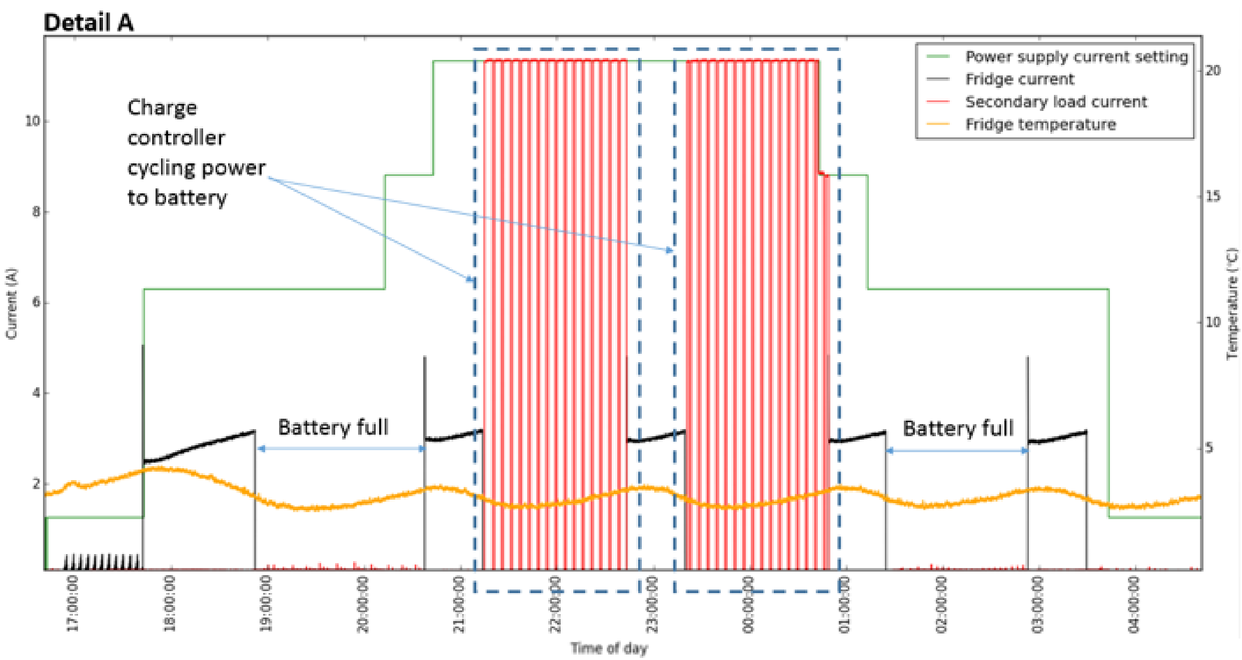


Figure 7. Detail B portion of Figure 5.

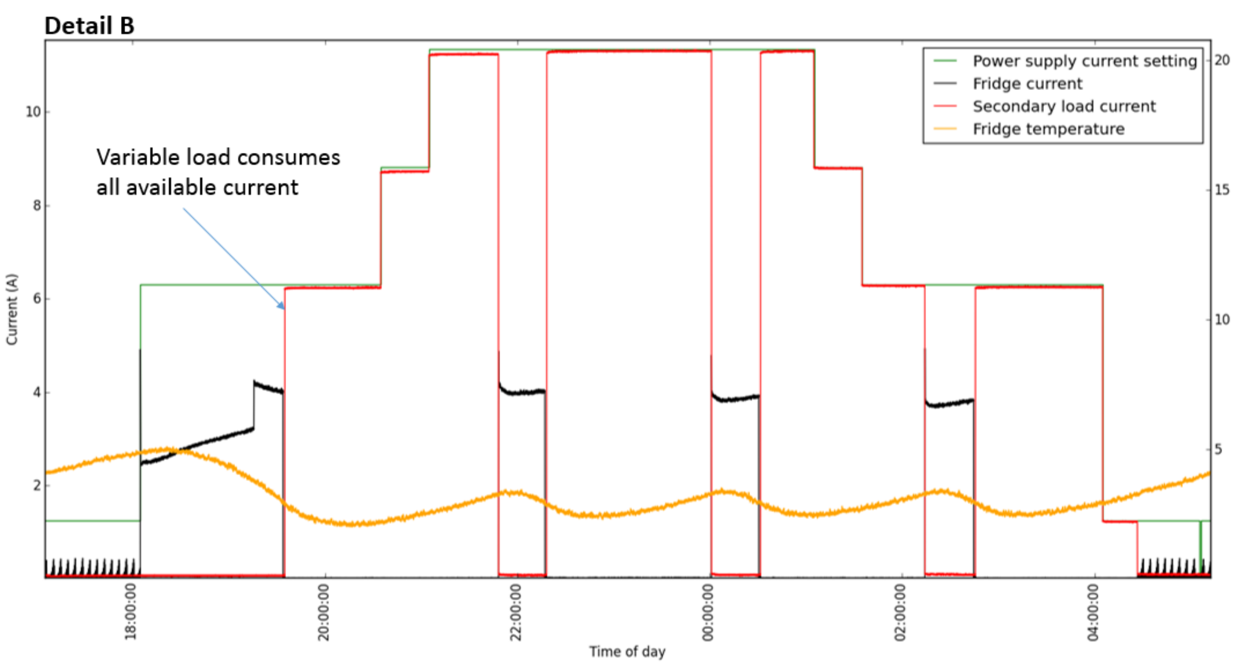
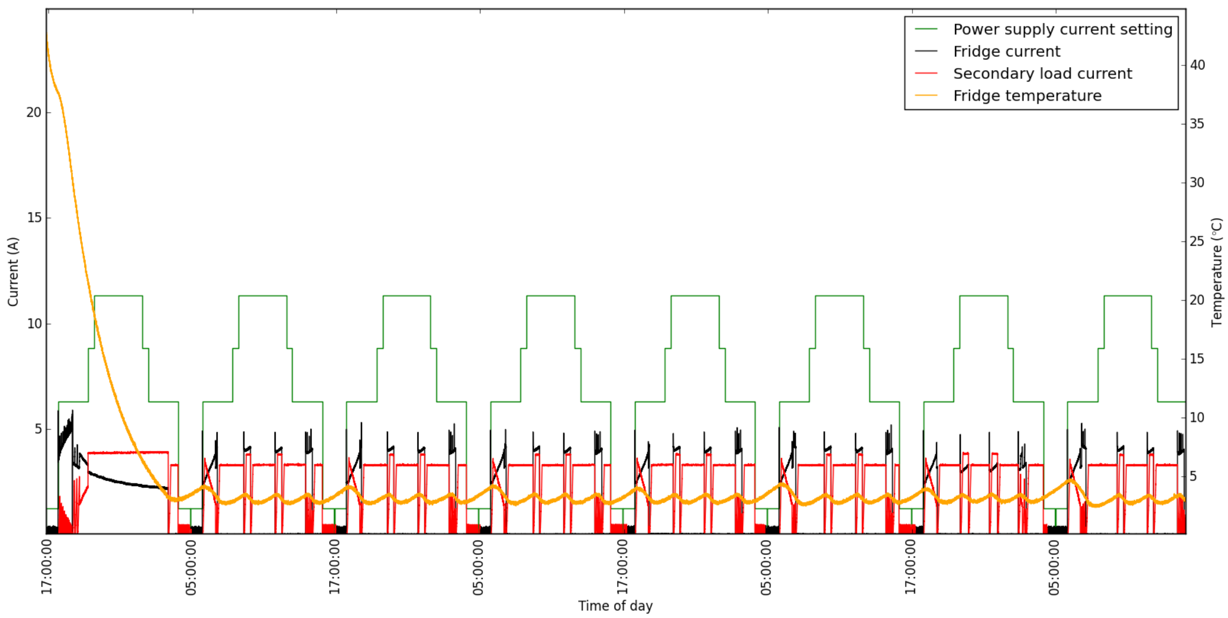


Figure 8 shows curves of the same refrigerator, SDD Refrigerator-1, operating with the And-EHC. Although the temperature curve in this case remains somewhat similar, it is noticeably different. The shape of the curve in the first day is smoother and takes a longer time to cool down to approximately +5°C. However, the compressor then begins cycling earlier. There is also more noise or variation in the compressor current curve than was apparent in the baseline or with the Or-EHC. This is only a single run, so it is possible that these differences are due to test variability. However, it seems more likely that these changes are due to the addition of the And-EHC to the system. Although not shown explicitly in this report, the specific And-EHC prototype tested produced some higher-frequency oscillations in the voltage and current going to the compressor. The cause of this was not definitively established, but it seemed to be related to power regulation circuitry in the And-EHC.

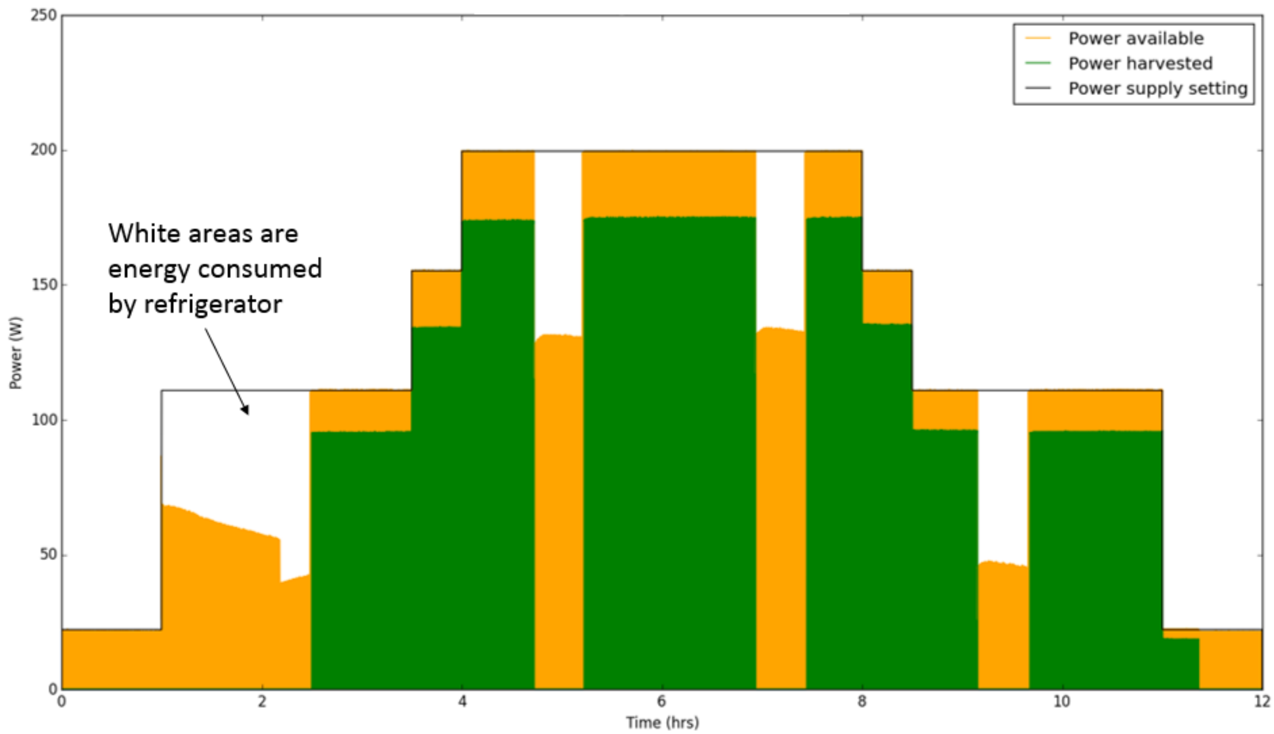
Figure 8. SDD Refrigerator-1 with And-EHC, full solar day cycles.



The cycling of the compressor during most of the solar days in Figure 8 is also different from the cycling in Figure 5 with the Or-EHC, showing one more cycle most days with the Or-EHC than with the And-EHC or in the baseline. It is also clear in Figure 8 that the And-EHC is not harvesting as much current (proportional to power) as the Or-EHC during periods when the compressor is off. This is not an intrinsic characteristic of And-EHC logic. The specific And-EHC prototype constructed for testing had additional, built-in current limiting and voltage regulation controls that limited the amount of power the EHC could harvest for the secondary load. The power-limiting controls built into the And-EHC prototype may be useful in commercial products but are not necessary to the energy diversion task. Part of the control logic also included time delays for starting to divert power and increasing power diversion after initiation. We found that these types of delays can cause system operation to be less than ideal. In one case, the delays in the refrigerator cycling by the thermostat control circuit and the delays built into the EHC were timed similarly, and the aligned cycling led to poor interaction and very limited power diversion.

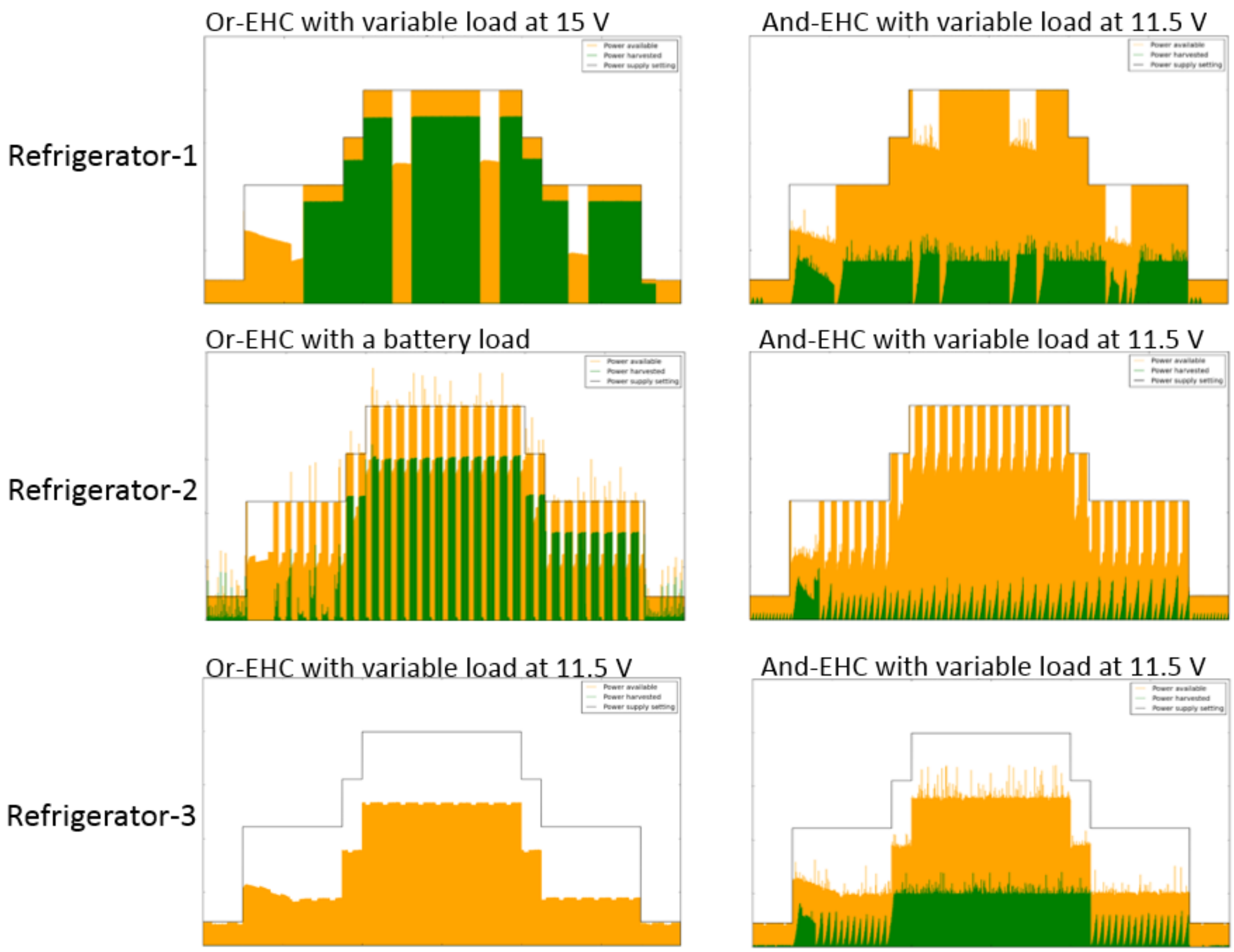
Until this point, we have discussed temperature and current measurements only. Figure 9 shows the power consumption and diversion during the last full solar day of the test of SDD Refrigerator-1 with the Or-EHC connected and the variable DC load connected as the secondary load. The area under the power supply setting curve shown as white represents the energy consumed by the primary, SDD refrigerator load. The yellow area represents the energy available for harvest that was not harvested (i.e., the energy supplied by the power supply minus the energy consumed by the SDD refrigerator and secondary load). The green area is energy diverted to and used by the secondary load. During time periods when the compressor is running, there should be no power diverted by the Or-EHC as seen in the graph. It is notable in Figure 9, however, that the yellow areas during times when the compressor was off and power was being diverted to the secondary load signify power available for the secondary load that was not being used. Most of these yellow areas are due to the fact that although all available current was being diverted at those times, the variable load was voltage limited in the testing. This would be similar to cases in reality where either an EHC would be designed with voltage limitation, or a secondary load itself would not consume all the power available to it through the EHC. Figure 10 illustrates, among other things, some effects of voltage limitation. In the upper-left graph of Figure 10 (the same plot as Figure 9 repeated for easier comparison), the variable load was set to maintain a constant voltage of 15 V. This value was chosen as a reasonably close value to the SSP supply voltage of 17.6 V. Setting the voltage slightly below the SSP voltage technically available ensured that the variable load would pull as much current as the power supply could draw without lowering the system voltage appreciably. Because the And-EHC included charge controller functionality similar to that used for 12 V batteries, the variable load was set to 11.5 V in constant voltage mode to simulate a discharged battery for tests using the And-EHC.

Figure 9. A single, full solar day showing power and energy for SDD Refrigerator-1 with the Or-EHC.



Five other full solar days are shown in Figure 10 with the same colors indicating energy as areas under the power curves. These six graphs illustrate some of the complexities present that complicate energy diversion and usage compared to how the idealized EHCs would work. The combination of SDD Refrigerator-2 with the Or-EHC and a battery load shown in Figure 10 indicates that the control compared to SDD Refrigerator-1 leads to much more frequent switching. Additionally, early in the solar day the battery had not sufficiently discharged to trigger the battery charge controller to accept any power. Thus, at least four factors are limiting the amount of energy harvested—voltage limitation in this case carried out by the charge controller, time delays in the EHC logic, the control structure of the refrigerator, and the type and state of the connected secondary load. In the graph directly to the right, the frequency of the switching by SDD Refrigerator-2 combined with the slow ramping of current diversion by the And-EHC prototype dictated by the control structure lead to very little energy being harvested.

Figure 10. Examples of single, full solar days and the energy and power available and used with all refrigerator/EHC combinations. In each graph, the white area under the power curve is energy used by the refrigerator, the green area is energy harvested and used by the secondary load, and the yellow is unharvested energy available from the SSP supply.



Still looking at Figure 10, the behavior of the system with SDD Refrigerator-3 is markedly different from the other two refrigerators. SDD Refrigerator-3 had a very different mechanism for controlling temperature, which led to the compressor running much more continuously. Thus, the Or-EHC diverted no power. The And-EHC controller was programmed to shut off power diversion to the secondary load whenever the refrigerator compressor turned on and then slowly increase power diversion. So the more continuous compressor operation of SDD Refrigerators-1 and -3 allowed more energy harvesting than the frequent on-off cycling of the compressor of SDD Refrigerator-2.

Table 1. Aggregated test data for comparison between refrigerators and EHCs.

Solar day type	Refrigerator	Baseline	Or-EHC	And-EHC
Time to 8°C (hours)				
Intermittent	Refrigerator-1	6.71	7.53	7.61
	Refrigerator-2	-[a]	8.16	>12[b]
	Refrigerator-3	>12[b]	>12[b]	>12[b]
Full	Refrigerator-1	4.2	4.9	6.9
	Refrigerator-2	7.0	-[a]	8.5
	Refrigerator-3	16.9	-[a]	-[a]
Time to stabilization (hours)				
Full	Refrigerator-1	20.2	20.7	10.2
	Refrigerator-2	-[a]	-[a]	19.3
	Refrigerator-3	90.2	-[a]	-[a]
Energy used to reach 8°C (W-hr)				
Full	Refrigerator-1	240	320	320
	Refrigerator-2	400	-[a]	410
	Refrigerator-3	1,070	-[a]	-[a]
Base-power consumption of refrigerator[c] and EHC during first full, 12-hour day after stabilization (W)—EHC base-power consumption in parentheses				
Full	Refrigerator-1	61 (NA)	54 (0.8[d])	66 (16[e])
	Refrigerator-2	53 (NA)	56 (0.8[d])	55 (14)
	Refrigerator-3	61 (NA)	-[f]	-[f]
Energy consumed by refrigerator[c] and EHC during first full, 12-hour day after stabilization (W-hr)—EHC energy in parentheses				
Full	Refrigerator-1	170 (NA)	190 (9.8[d])	190 (190[e])
	Refrigerator-2	310 (NA)	350 (9.8[d])	350 (170)
	Refrigerator-3	430 (NA)	-[f]	-[f]

a. Timing of testing using full and intermittent solar days did not allow calculation due to incomplete conditioning for some tests.

b. Only a single intermittent solar day was run, allowing calculation for only periods of less than 12 hours.

c. Base-power consumption was calculated as the total energy used by the refrigerator only during periods of compressor operation divided by the length of time the compressor was operating. Energy calculations in this table additionally include time periods when the control circuit of the refrigerator was consuming small amounts of power.

d. Power measurement uncertainty was greater than the power consumed by the Or-EHC. The reported power consumption could thus not be reliably determined from data collected in these tests. Power consumption by the Or-EHC prototype estimated from data reported by the Or-EHC designer was approximately 0.82 W. This value was used throughout power and energy calculation involving the Or-EHC throughout Table 1.

e. This calculated value for the And-EHC is not from the first full, 12-hour solar day after calculation, but from the final solar day of the test run due to a current sensor malfunction during part of the test.

f. The compressor of SDD Refrigerator-3 never began to cycle during testing with the EHC and no calculations after stabilization could be made.

Tables 1 and 2 contain data on a number of different metrics that can help to answer some of the questions identified in the Background section above. In terms of the energy harvesting data in Table 2, it should be noted that the primary goal of the testing carried out was not to optimize the energy harvesting capabilities of the prototypes. Although the data are informative in terms of what general amounts of energy might realistically be harvested, a number of different loads and conditions were being tested, so the data are not all easily and directly comparable. The energy harvested depends strongly on the load used, any voltage or current regulation at the EHC or loads, and the interaction between specific EHC and refrigerator combinations. Settings like current ramping times, current and voltage regulation, delays in the control logic to check signals, etc., can all have very large effects on energy harvested and would likely be better optimized in a future, commercial system.

Table 2. Energy harvesting summary—all values are for the final full day of testing with full solar days.

Refrigerator	Excess energy available (W-hr)	Excess energy harvested (W-hr)	Excess energy harvested % of avail.	Did compressor shut off?	Load
Or-EHC					
Refrigerator-1	1,392	945	68	Yes	Variable load set at 15 V
Refrigerator-2	1,303	430	33	Yes	Battery + charge controller
Refrigerator-3	908 [a]	NA [a]	NA [a]	No	Variable load set at 11.5 V
And-EHC					
Refrigerator-1	1,378	327	24	Yes	Variable load set at 11.5 V
Refrigerator-2	1,299	95	7	Yes	Variable load set at 11.5 V
Refrigerator-3	939	303	32	No	Variable load set at 11.5 V

a. Because the compressor never shut off during testing with SDD Refrigerator-3, no energy was harvested with the Or-EHC.

Fail-Safe and Robustness Results

Although no quantitative data are reported here from the stress testing of the devices, there were some qualitative results. In terms of failing-safe, the two prototypes passed all of the testing performed under the criterion that the refrigerator still operated after each test. In recommending a process for PQS prequalification of EHCs, PATH has suggested that subsequent to the EHC tests outlined above, the refrigerator must then be subjected to the standard PQS testing for SDD appliances using the verification protocol E003/RF05-VP with the EHC and a defined load in place. Because this testing was not carried out as part of the effort described here, we cannot provide any results confirming whether the SDD appliance prequalification testing with the EHC would be passed or if there was any degradation to the EHC or SDD appliances during the robustness testing that would lead to decreased performance or failure of the final testing.

There was one notable instance of EHC failure during the laboratory testing. During the short circuit test, the And-EHC blew a fuse that was meant to limit the current to the logic controller in the And-EHC. When the fuse blew, the refrigerator continued to operate. After replacement of the fuse, the And-EHC secondary load power regulation did not function properly, but the refrigerator continued to operate normally and some power continued to be diverted to the secondary load. Subsequently, during the progressive secondary load power draw test, the And-EHC power regulation to the secondary load failed completely, though the refrigerator again continued to operate. As a result of the failure of the And-EHC controller, stress testing was suspended and the inductive load and abrupt power change tests were not completed.

Additionally, the Or-EHC exhibited abnormal operation during field testing. Although the EHC did still harvest some energy it clearly was not operating correctly—the amount of energy harvest was lower than expected and LEDs (light-emitting diodes) installed in the prototype signaled that it was compromised. The refrigerator again remained un-impacted by the EHC malfunction. The root cause was not discovered but seems to have been linked to some sort of compatibility issue between the EHC and charge controller hooked up to the battery used as a secondary load in the field testing.

Conclusions

Referring back to the three primary requirements of an EHC, this round of testing indicates that at least two of the primary requirements can be and were met by the prototypes tested. The SDD refrigerator was left uninhibited from operating correctly in the case of failures and malfunctions tested and observed and the EHCs diverted some useful amount of energy to secondary loads in all cases but one (the Or-EHC connected to Refrigerator-3 did not divert any power, though it likely would have diverted power during a longer test).

It should be noted, however, that although the SDD refrigerators continued to operate correctly during the testing, the failures experienced may be concerning when long-term operations are considered. In the case discussed in the Results section above of the And-EHC issues, the failure mode led to a cycle of very frequent switching that could be damaging to the electronic systems if left unrepaired. After being damaged, the EHC would begin trying to divert current to the secondary load at a larger value than before the failure. It would then quickly increase the current diversion to a value higher than the output current from the SSP, which would cause the EHC to switch off diversion while also inducing a temporary drop in the voltage seen by the refrigerator. The refrigerator would continue operating and the EHC would restart the same cycle of diversion and then switching off. This continual stress on the system could lead to more catastrophic failures in the long term, although this round of testing cannot confirm any long-term outcome.

The third requirement, that the EHC not hinder the performance of the SDD appliance in normal operation, was potentially met depending on how this requirement is viewed or defined. Final vaccine compartment temperatures after cooling down during tests with both of the EHC configurations were not significantly different from the baseline and were within the requirements of SDD refrigerators. In this sense the requirement was met. However, cooling times to +8°C during repeated full solar days are longer with both EHC prototypes, though not by more than a few hours. If the SDD refrigerators are receiving relatively continuous solar power during the day, this extended cool-down time may be acceptable when compared to manufacturer documentation for the refrigerators, which specify cool-down times of 3 to 7 days. There is a possible situation that was not thoroughly or explicitly tested in which solar radiation could be low for an extended number of days, which might lead to detrimental performance differences with an EHC in place. It would be difficult to assess this risk with the current data. Instituting the testing requirement that each EHC-refrigerator combination pass the verification protocol E003/RF05-VP for

SDD appliances should be sufficient to ensure that systems incorporating an EHC perform to the minimum requirements of current WHO prequalified refrigerators.

Returning explicitly to the questions regarding performance posed in the Background section above:

- *After the SDD appliance reaches its operating temperature, do excursions outside of the allowable temperature range (+2°C to +8°C) occur and are they attributable to the EHC?* No excursions occurred during the laboratory testing even in the case of the EHC failing.
- *Do the EHCs fail; what are the likely failure modes; will the SDD appliance continue to operate within the allowable temperature in these failure modes?* Both of the prototype EHCs experienced at least partial failures as discussed above. The failures seem to be linked to power limitation functionality built into the EHC or connected to the EHC. Although likely necessary, power limitation is not intrinsic to the EHC itself. Although the SDD refrigerators operated within temperature during the failures, it is not clear that they would be able to continue to operate correctly if the failures observed in the EHC testing were left unresolved for longer periods of use. The testing accomplished does not provide an answer to the question of long-term operation of the system with a compromised EHC.
- *Does the SDD appliance take longer to cool down?* Yes, all combinations tested took longer to cool down (at least to +8°C) than the baseline. This makes sense in that the EHC prototypes tested require a base amount of power to operate their control circuits. Although controls that do not draw any baseload power from the solar array unless excess power is available may be feasible, no prototypes of this configuration were tested.
- *How are stabilization, cycling, and cool down of the SDD appliance changed if at all?* The post-stabilization compressor cycling was generally altered by the inclusion of an EHC. Although this did not hinder the ability of any of the tested refrigerators to maintain stabilization temperatures, it may change the duty cycles, and average power usage increased in some cases, but not all cases (see Table 1). As discussed above, cool-down times were extended.
- *How much additional power is necessary to run the system during normal operation after stabilization?* The prototype EHCs themselves added only approximately 3% to total energy usage (excluding secondary loads) in the case of the less complex Or-EHC. This value had to be based on power usage provided by the engineer who designed the prototype because the amount of power used was small enough to be within the estimated error of the test setup. However, power use was increased by up to 100% in the case of the And-EHC, due in part to the additional functionality included in the prototype. Although replicates of tests were not run, it appears that the addition of an EHC does not cause much if any increased energy usage by the SDD refrigerators themselves outside of what appears to be testing variability in the data collected. Values with the EHCs showed slightly increased average power usage by the SDD refrigerator as compared to the single baseline run for the same refrigerator in most runs (but slightly decreased in one case). Total energy consumption (Table 1) consistently shows increased energy use by the refrigerators over the entire days calculated with an EHC in use, but by less than 13%.
- *What situations would need to occur for autonomy to be compromised by adding the EHC, and are they likely to occur?* It is not possible with the data collected to usefully assess the likeliness of these situations to occur. However, it is possible to consider situations in which autonomy could be compromised if solar radiation was very close to supplying the minimum power from the PV array

needed to run the cooling system for extended periods of time. In this case, the minimal amount of additional power need for the EHC could keep the compressor from turning on and thus compromise autonomy.

Further Development and Testing of Energy Harvesting Controls

Definitive evaluations of the relative effectiveness of And-EHCs versus Or-EHCs cannot be easily made with the data collected. There are two main reasons. Firstly, the testing was not intended to assess energy harvesting effectiveness, and secondly, many other control structures could be imagined and built for either category of EHC that may be more or less effective. One could assume that production models would use different or at least more optimized control logic and timing. There are trade-offs between the two categories. Theoretically the And-EHC should be able to harvest more energy, but the logic of the Or-EHC is inherently simpler. Illustrating these trade-offs, in the case of the two specific prototypes built and tested, the And-EHC required more base power for the control circuit because of the increased complexity of the control logic and timing circuits (refer to How Energy Harvest Controls Can Increase the Benefits of Solar Direct–Drive Refrigerators for a discussion of the two logical structures).[iii] The And-EHC had additional voltage regulation functionality, which limited energy harvesting further and made the EHC itself more complex. In this testing, these factors led to the Or-EHC harvesting more energy than the And-EHC in some cases.

Differences among refrigerators, EHCs, and secondary loads can lead to multiple suboptimal outcomes. Some issues were noted during testing of the EHC prototypes and three refrigerators. Depending on the base-power draw of an EHC, in testing it may prevent the refrigerator compressor from turning on during constant, lower SSP periods when the compressor would normally have enough power to function. In actual use, this might be a negative factor if the PV installation location often has long periods of low to medium solar flux during which this additional base-power draw of the EHC would prevent the refrigerator from functioning. In terms of designing and testing the EHC, manufacturers need to be aware of the relative levels of the EHC baseload power, the minimum power for the specific SDD appliance to run, the SSP levels specified in testing protocols, and actual field conditions.

Even in the small selection of refrigerator and EHC combinations tested, some of those combinations had a large negative effect on energy harvesting ability. In the case of the Or-EHC with Refrigerator-3, no energy was harvested, and in the case of the And-EHC with Refrigerator-2, very little was harvested due to the interaction of the control circuit cycles of the two components. Sometimes the interaction was due to the control delays of the EHC and refrigerator aligning poorly and causing non-ideal, cyclical switching at certain power levels. Although many of these issues would likely be resolved before commercial production by manufacturers, the likelihood of an after-market EHC as an add-on to refrigerators having universally good performance seems low. Thus, qualifying specific refrigerator/EHC combinations each tested separately may be a workable solution but will increase testing burden. These types of considerations will be essential for manufacturers.

[iii] See http://www.path.org/publications/detail.php?i=2701 to access the report.

References

1. McCarney S, Robertson J, Arnaud J, Lorenson K, Lloyd J. Using solar-powered refrigeration for vaccine storage where other sources of reliable electricity are inadequate or costly. *Vaccine*. 2013;31(51):6050–6057.

2. PATH, World Health Organization (WHO). Direct-drive solar vaccine refrigerators—a new choice for vaccine storage [evidence brief]. Seattle: PATH; 2013. Available at: http://www.path.org/publications/detail.php?i=2336.

3. WHO. Refrigerator or combined refrigerator and water-pack freezer: compression-cycle. Solar direct drive without battery storage [performance specification]. WHO/PQS/E003/RF05.3. Geneva: WHO; 2012. Available at: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=17.

Annex 1. Field Report: Solar Electric Light Fund Energy Harvest Control Study

CFV solar test laboratory

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Solar Electric Light Fund Energy Harvest Control Study

Report Date:	August 19, 2016
CFV Project ID:	16029
Customer PO#:	Q20160329-SELF-PATH-03-29-2016
Customer Contact:	Steve McCarney Solar Electric Light Fund 1612 K Street, NW, Suite 300 Washington, DC 20006

1 **Project Summary:** CFV Solar Test Lab conducted an energy monitoring study on three vaccine refrigerators with five different controllers on behalf of the Solar Electric Light Fund (SELF). Each system consisted of a WHO PQS prequalified vaccine refrigerator, a PV solar array, a custom controller, and various loads to simulate use cases for off-grid systems designed to power vaccine refrigerators and provide additional energy for small, off-grid loads.

2 **Executive Summary of Results:** All system configurations successfully maintained vaccine refrigerator operation throughout the test period, despite technical difficulties that affected the energy harvest system. Ambient temperatures near the refrigerators ranged from +3.5° C to +44.8° C while solar radiation ranged from 3.2 kWh/m^2/day to 7.2 kWh/m^2/day with peaks of over 1300 Watts instantaneous. The temperatures inside the vaccine refrigerators remained between +2° C and +8° C, except immediately following the introduction of 4 liters of warm water bottles to simulate loading and for some period afterwards while the temperature stabilized. The potential energy from the PV solar array exceeded the combined demand loads by 40% to 80% during this test period, depending on the system configuration and the available sunlight. The detailed test data is documented in an Excel workbook titled "16029 CFV Project Workbook SELF Fridge Study.xls". Any opinions and interpretation of data in this report are those of CFV Solar Test Laboratory.

Report authorized by:

Jim Crimmins General Manager	James P Crimmins Digitally signed by James P Crimmins DN: cn=James P Crimmins, o, ou, email=jim.crimmins@cfvsolar.com, c=US Date: 2016.08.19 13:15:18 -06'00'	Larry Pratt Laboratory Manager	Larry Pratt 2016.08.19 13:11:02 -06'00'

3 Procedures:

3.1 Incoming Inspection and Labeling: The components were unpacked and labeled according to CFV Solar convention. The CFV IDs and the component descriptions were recorded in the Excel document.

3.2 Outdoor Energy Monitoring: Two rounds of monitoring were completed at CFV's outdoor test yard. Figure 3.2 shows an aerial view of the test yard with the location of the three 360 Watt PV solar arrays and the electronics shed. The solar modules were mounted side-side on a fixed tilt rack and connected four in parallel for each of the three systems. The DC cables were run above ground to the electronics shed containing all the vaccine refrigerators, monitoring equipment, batteries, charge controllers, and custom controllers. The shed also held two 6 kW inverters and some monitoring equipment related to a separate project. The resistive loads for Round 1 were mounted in metal boxes outside the shed. Round 2 of testing replaced the resistor load with commercially available DC lights. Current, voltage, and temperatures were all monitored at points within the system and recorded in an Agilent data logger. Power and energy were calculated for the PV solar array, the refrigerator, and the load for each system independently. There were two temperature sensors attached to the inside of each vaccine storage compartment, one near the bottom and one near the top of the cooled compartment. Ambient temperature was also measured inside the electronics shed and just outside the shed under the eve. Irradiance data in the plane of the PV solar array was measured and recorded, as well. Once per weekday, the lids were opened and eight water bottles were removed from each fridge and replaced with eight warm water bottles that had were stored in the electronics shed. This procedure was not done on the weekends. The water bottles held 0.5 liters each. The lids were left open for 10 minutes and then closed again until the next day.

Figure 3.2 Outdoor test yard at CFV Solar showing locations of PV array and electronics shed

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The first round of monitoring lasted for four weeks and the second round lasted for one week. Table 3.2 provides the details of each setup. According to the requirements of the system, the energy from the solar arrays was distributed to the vaccine refrigerators as a priority. Excess energy was distributed to the battery and/or the external load, as governed by the logic of the specific custom controller and system configuration under evaluation.

Table 3.2 System configurations for Round 1 and Round 2 testing

Round 1 Testing (4 weeks)

Description	System 1	System 2	System 3
Controller	OR1	OR2	AND1
Fridge Location	Right	Back/Center	Left
Refrigerator	Appliance 1	Appliance 2	Appliance 3
Solar Array	4 x SLP090-12	4 x SLP090-12	4 x SLP090-12
Load	15 A , 12 VDC resistor *	15 A , 12 VDC resistor *	15 A , 12 VDC resistor
Battery	1 x Deka Solar	1 x Deka Solar	1 x Deka Solar
Charge controller	Morningstar Prostar	Morningstar Prostar	Morningstar Prostar
Harvest Eff (%)	0.11	0.07	0.21

Note: * Added a second resistor in series on 5/16/16

Round 2 Testing (1 week)

Description	System 1	System 2	System 3
Controller	OR3	AND2	AND1
Fridge Location	Right	Back/Center	Left
Refrigerator	Appliance 1	Appliance 2	Appliance 3
Solar Array	4 x SLP090-12	4 x SLP090-12	4 x SLP090-12
Load	2 x 12 VDC, 12 W CFL	8 x Pico Lamp	8 x Pico Lamp
Battery	New 1 x Deka Solar	NA	NA
Charge controller	New Morningstar Prostar	NA	NA
Harvest Eff (%)	0.15	0.01	0.02

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The data was analyzed based on daily averages and based on the individual measurements, depending on the objective. For the daily averages, the data was filtered to provide daily summary statistics based on a balanced number of observations across all systems. The first two weeks of Round 1 data was excluded because of a number of issues. The batteries died within six days for the OR1 and OR2 controllers. After the resistive load was re-configured, the systems generated useful comparative data without draining the batteries. Prior to the batteries depleting, there was an issue with the location of the current shunt for the load monitoring, and one of the shunt monitors was reversed. On June 3rd, three hours of data are missing between 9:00 am and 12:00 PM, so that day was excluded in the daily summary statistics. On Saturday, June 4th, the data logger lost communication, so June 4 and Sunday, June 5 were excluded from the Round 2 test data. The remaining 15 days from Round 1 and 3 days from Round 2 provided good sample of clean data for the analysis. All three refrigerators continued to run during the setup issues, so the dead batteries affected the energy harvest but not the refrigerator performance.

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4 Discussion of Results:

4.1 Daily plots: Daily plots were used to monitor the systems on a regular basis. Figure 4.1.1 shows trends from a cloudy day for each of three systems being monitored. Figure 4.1.2 shows trends for the same three systems from a clear sky day. Each plot consists of a trend for current from the array and current to the fridge and load. The "tstat" measures voltage change at the thermostat and indicates when the refrigerator is calling for cooling and thus correlates with the current flow to the refrigerator. The upper and lower temperatures are within tolerance (+2ºC to +8ºC) except for the period immediately following the 10 minute period when the lid was opened and bottles were swapped in order to simulate a use case. 5/21/16 fell on a Saturday, so the lids were not opened and thus the temperature profiles were flat.

Figures 4.1.3 and 4.1.4 show similar daily trends for Round 2 testing. The AND1 system was the same for round1 and Round 2 test, but the other two systems were modified.

Figure 4.1.5 shows daily trends for the PV array current measured from each system and the available current available from the array. The available current was simply calculated as the measured irradiance/1000 * 4 * 5.11, since each array consisted of 4 modules in parallel with an STC current at maximum power of 5.11 A. These plots were included to provide an estimate for the power available from the array that was not being used by the refrigerators, the loads, or the controllers.

The same four days were used for all plots. 5/21/16 and 6/8/16 were chosen as the clear sky days for Round 1 and Round 2, respectively. 5/18/16 and 6/7/16 were chosen as the cloudy or partly cloudy sky days for Round 1 and Round 2.

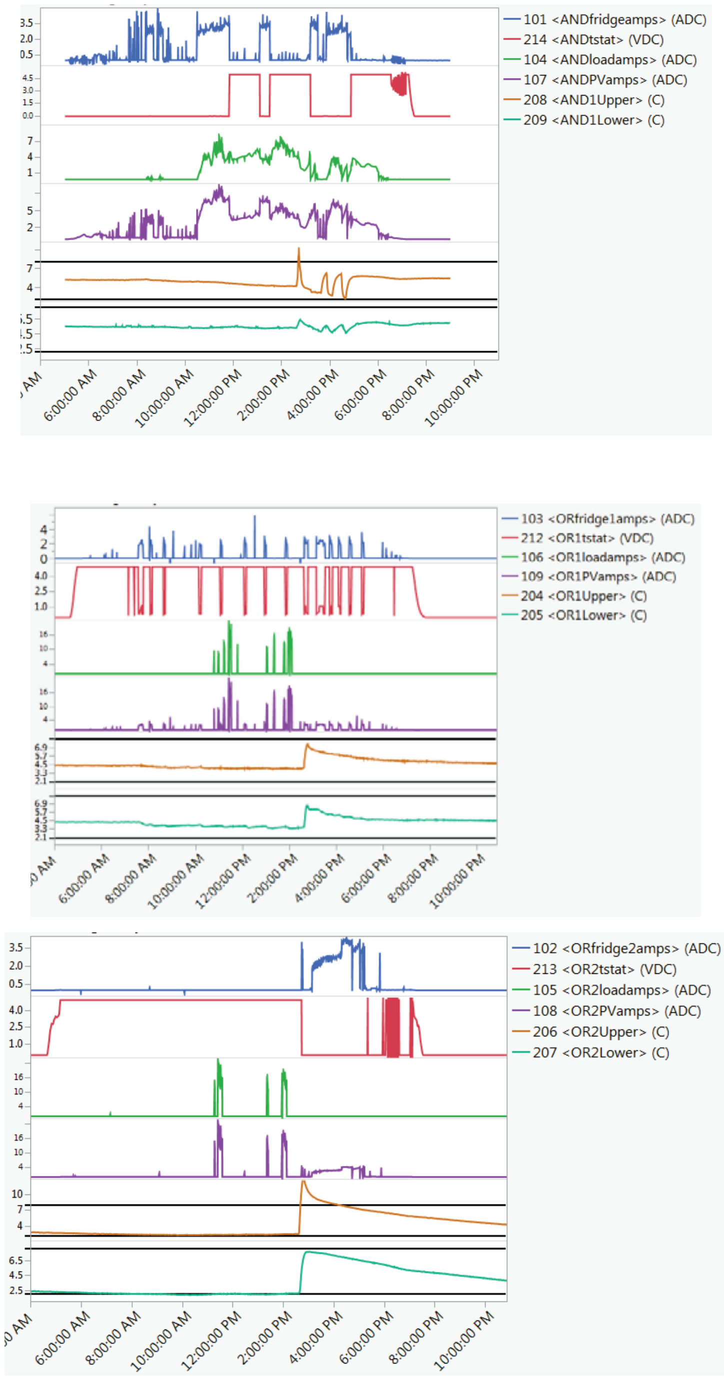

Figure 4.1.1 Round 1 cloudy day (5/18/16) for AND1, OR1 and OR2 controllers

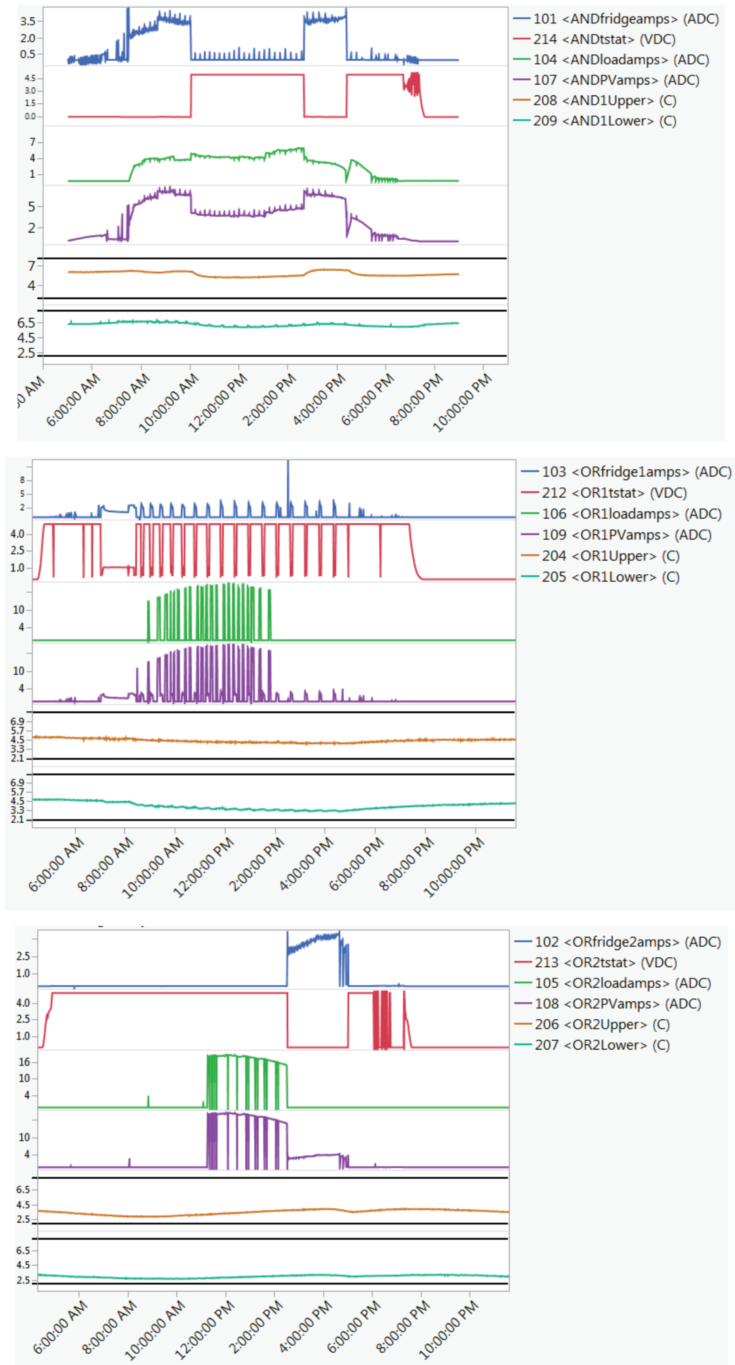

Figure 4.1.2 Round 1 clear day (5/21/16) for AND1, OR1 and OR2 controllers

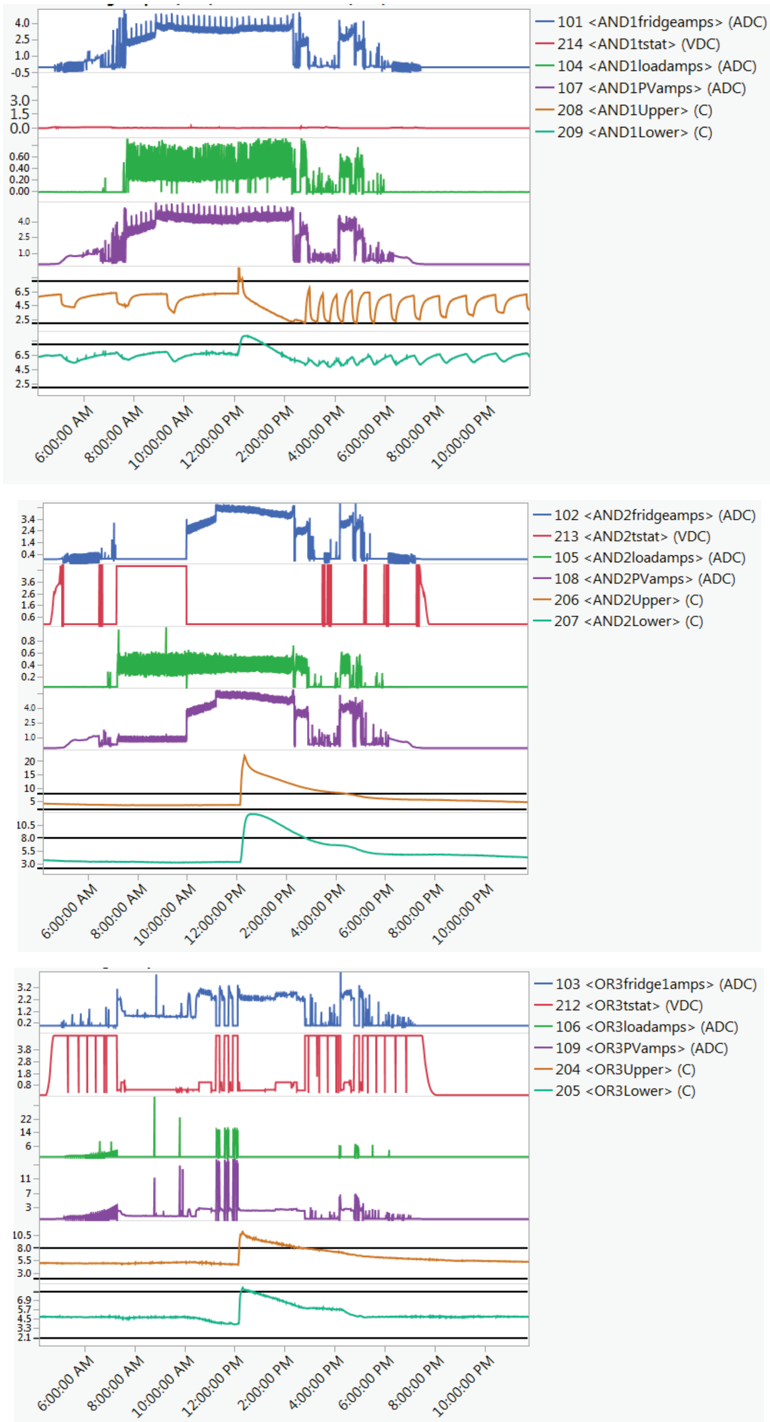

Figure 4.1.3 Round 2 partly cloudy day (6/7/16) for AND1, AND2 and OR3 controllers

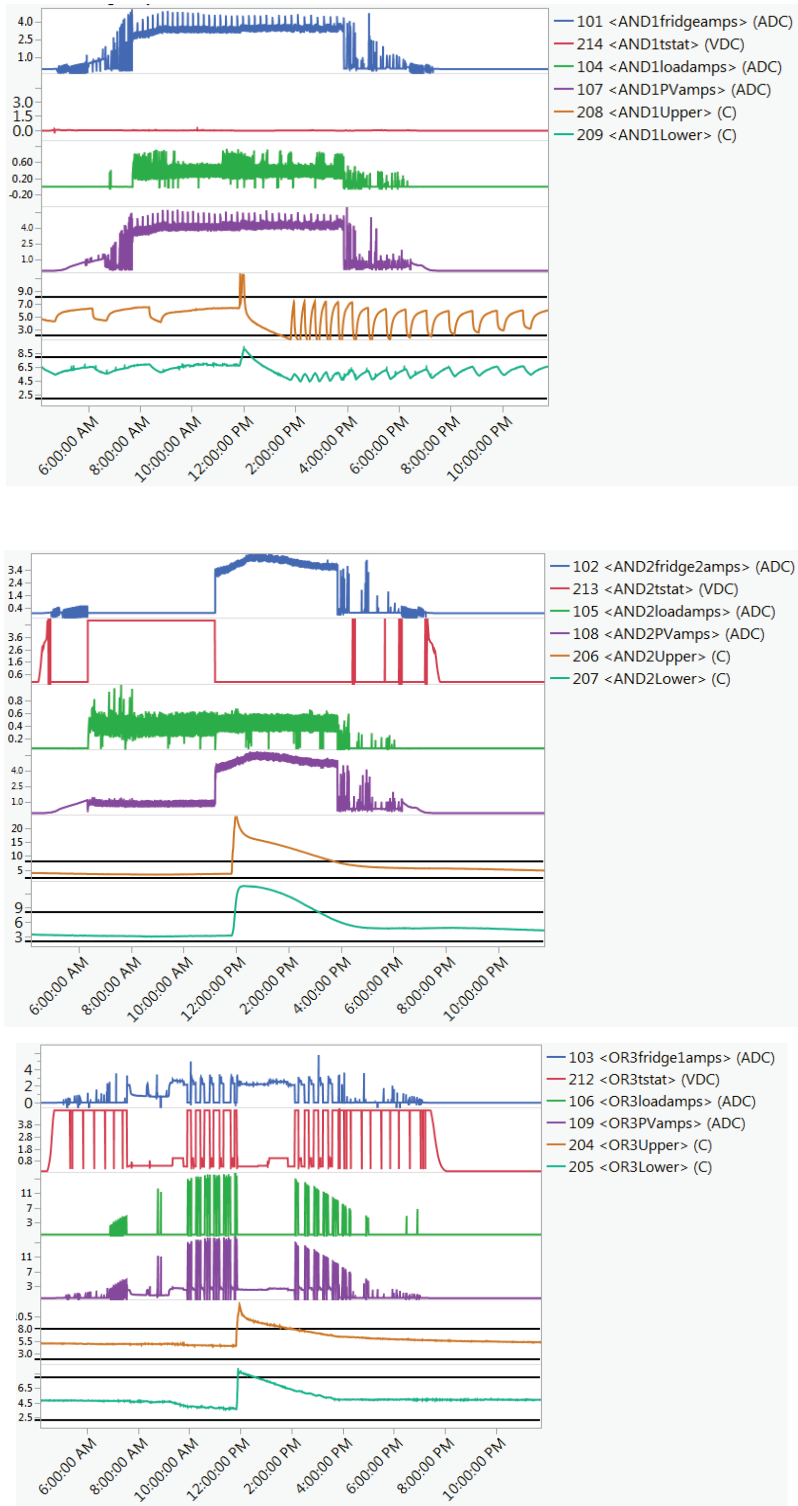

Figure 4.1.4 Round 2 clear day (6/8/16) for AND1, AND2 and OR3 controllers

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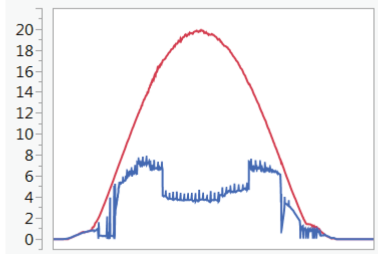
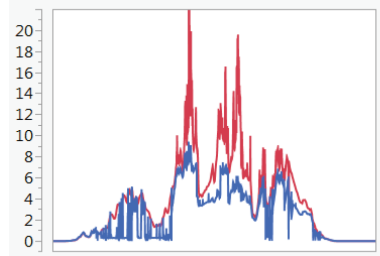
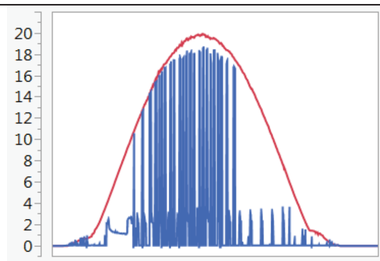
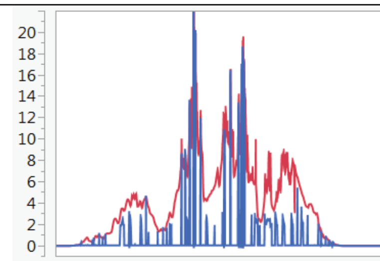
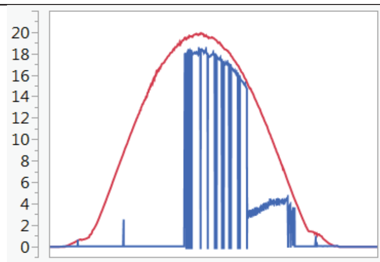
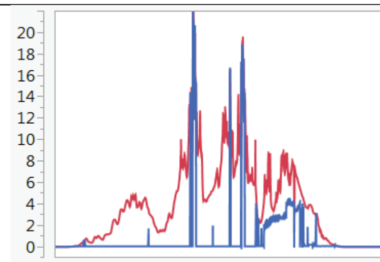
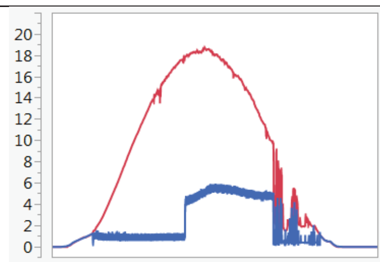
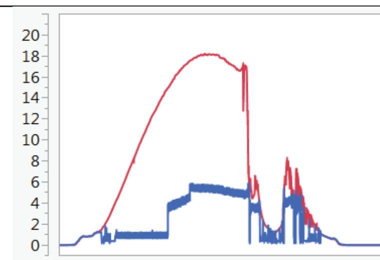
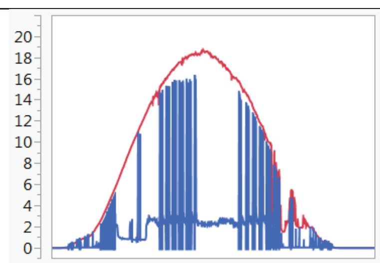
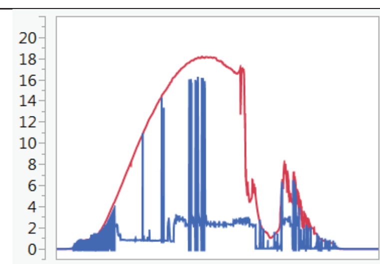
	Clear	Cloudy/Partly Cloudy
Round 1 AND1		
Round 1 OR1		
Round 1 OR2		
Round 2 AND2		
Round 2 OR3		

Figure 4.1.5 Actual PV current (blue) versus available current (red) in Amps (0-22 A) versus time of day

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4.2 Temperature Trends: Figure 4.2.1 shows the temperature trends from inside the refrigerators for both Round 1 and Round 2 system configurations for the entire monitoring period, both night and day. The spikes correlate to the lid opening each day. The weekends, holidays, and end of Round 1 show no such spikes because the refrigerators remained closed. The Appliance 2 unit showed the most extreme temperatures in the upper portion of the compartment, peaking around +25ºC following the lid opening. The Appliance 1 and the Appliance 3 peaked around +15ºC. The temperature sensors (TCs) in the Appliance 1 unit were attached directly to the interior wall of the vaccine compartment, while the TCs on the other two units were attached to the wire baskets.

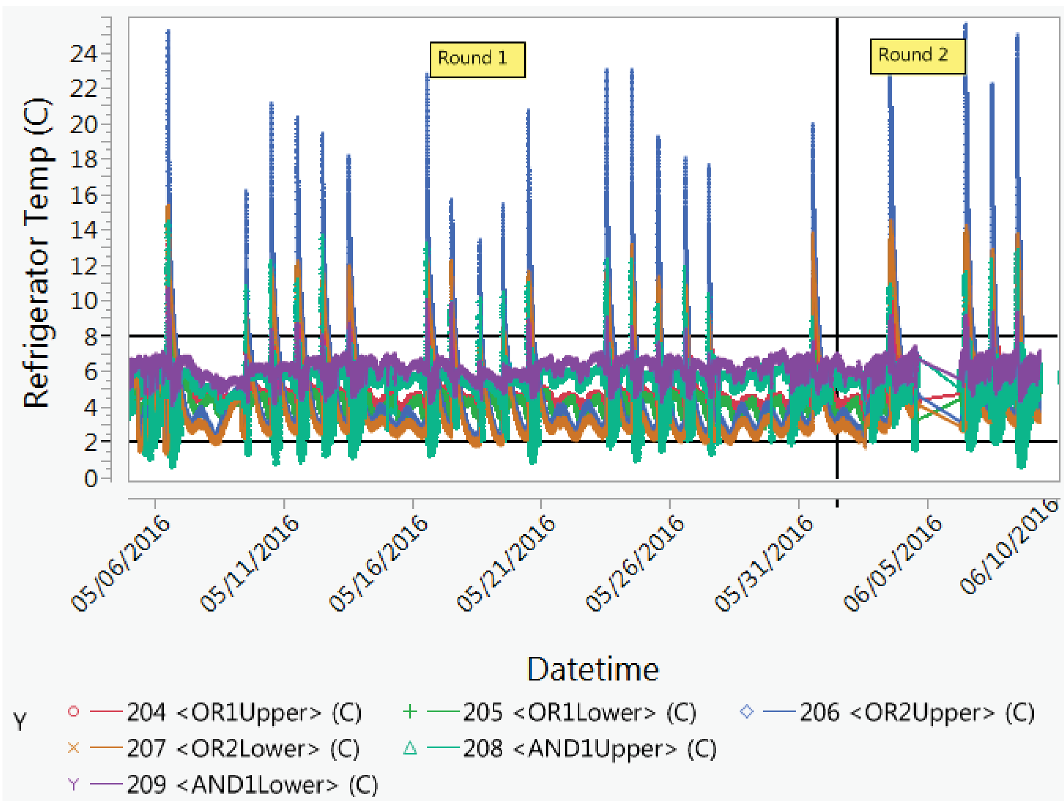

Figure 4.2.1 Temperature trends inside the refrigerators

The majority of the excursions below +2ºC were observed on the AND1 controller system, upper TC. This sensor was deliberately placed inside the vaccine basket but directly in the airflow stream from the ice bank. Figure 4.2.2 shows the recovery period for the upper temperature on the AND1 controller following a lid opening event. This example is taken from May 11. The AND1 controller tended to porpoise up and down following a lid closure, and often times exceeded the lower threshold of +2º C. The OR controllers and the AND2 controller tended to recover temperatures in a smooth fashion, thus avoiding the overcorrection.

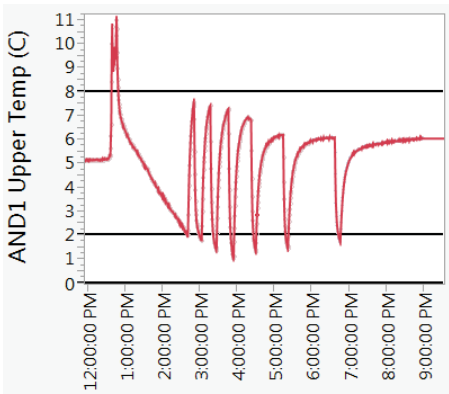

Figure 4.2.2 Upper temperature trend inside the AND1/Appliance 3 system May 11, 2106

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4.3 Energy Monitoring:

Table 4.3.1 shows minimum, maximum, and average values for the important parameters monitored during this study. The data are presented for Round 1 and Round 2 separately. The data logger channels were dedicated to each of the refrigerators, so the naming convention in the "description" field is dual-purposed. For example, in the table 4.3.1 the description "Appliance 1 OR1/OR3 Upper Temp" indicates the fact that the Appliance 1 was controlled with the OR1 controller during Round 1 and the OR3 controller during Round 2. Similarly, the Appliance 2 was controlled by the OR2 in Round 1 and the AND2 in Round 2. The Appliance 3 was controlled by the AND1 in both Round 1 and Round 2.

Table 4.3.1 Summary statistics for Round 1 and Round 2 data.

			Round 1				Round 2			
Index #	Description	Units	# of obs.	Minimum	Maximum	Average	# of obs.	Minimum	Maximum	Average
1	Ambient temp outside shed	C	98962	2.9	41.3	20.9	39335	16.6	45.8	29.5
2	Ambient temp inside shed	C	98962	3.5	39.6	21.2	39335	16.8	44.8	29.3
3	Appliance 1 OR1/OR3 Upper Temp	C	98962	3.8	13.2	5.0	39335	4.2	29.6	5.8
4	Appliance 1 OR1/OR3 Lower Temp	C	98962	3.0	12.8	4.5	39335	3.2	26.4	5.0
5	Appliance 2 OR2/AND2 Upper Temp	C	98962	1.6	25.1	4.6	39335	3.0	25.5	6.3
6	Appliance 2 OR2/AND2 Lower Temp	C	98962	1.1	15.3	3.9	39335	2.7	14.4	5.4
7	Appliance 3 AND1 Upper Temp	C	98962	0.7	14.4	5.4	39335	0.7	12.8	5.2
8	Appliance 3 AND1 Lower Temp	C	98962	4.3	10.6	6.1	39335	4.5	9.2	6.3
9	POA Irradiance 45 deg	W/m2	98962	0	1304	NA	39335	0	1074	NA
10	POA Insolation 45 deg Daily Average	Wh/m2/day	15	3179	7176	6185	3	4075	6508	5660
11	Available energy from array (assuming 13% eff.)	Wh/array/day	15	1074	2425	2091	3	1377	2200	1913
12	Appliance 1 OR1/OR3 Energy Daily Average	Wh/day	15	85	189	140	3	244	276	256
13	Appliance 2 OR2/AND2 Energy Daily Average	Wh/day	15	8	345	175	3	343	368	354
14	Appliance 3 AND1 Energy Daily Average	Wh/day	15	199	388	285	3	450	538	492
15	Energy harvested from OR1/OR3 Daily Average	Wh/day	15	73	328	212	3	107	431	275
16	Energy harvested from OR2/AND2 Daily Average	Wh/day	15	0	713	124	3	26	37	31
17	Energy harvested from AND1 Daily Average	Wh/day	15	137	462	366	3	36	39	37

The temperature data includes all the recorded day time and night time observations. None of the recorded temperatures inside the refrigerator compartments ever dipped below +0.7 C. The irradiance and energy data was summarized to the daily level, and then the maximum, minimum, and average of the daily values were reported for valid days only. The refrigerator energy was summed up for each day and then the minimum, maximum, and average were reported. The "Available energy from array (assuming 13% eff.)" was calculated from the minimum, maximum, and average of the daily insolation values multiplied by the area of the array (2.6 m^2) and then multiplied again by 0.13. The PV module has a rated efficiency of 13.9% at STC, so the reduced efficiency of 13% is an approximation to account for reduced performance at higher temperatures and different irradiance values. This value was calculated in order to estimate the potential energy available from the array that was not harvested due to lack of load. Finally, the "Energy harvested …" fields represent the energy harvested by the external loads, excluding the refrigerators. In Round 2, the OR3 controller shows a much higher energy harvest than the AND1 or AND2. This could be due to the controller itself or to the load or the combination. The OR3 was dumping load continuously 24 hours per day through the Deka battery, while the AND controllers were dumping load through 8 Pico lamps each on continuously until depleted.

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Table 4.3.2 shows the energy harvest efficiency for each system and round of testing. This metric was calculated by summing up the energy required to run the refrigerator (Fridge Energy), the actual energy harvested across the load (Measured harvested energy), and the estimated available energy from the array assuming a 13% efficiency, and then computing the efficiency per Equation 4.3.1. These energy estimates were made for each observation from the 15 complete days in Round 1 testing and the 3 complete days from Round 2. The AND1 controller harvested 20% of the available energy during Round 1, while the OR controllers only harvested 11% and 6%, respectively. The OR3 controller harvested the most energy in Round 2. The energy harvesting was likely limited by the loads connected to the systems.

$$Eff = \frac{Measured\ harvested\ energy\ (Wh)}{\left[Insolation\ \left({}^{Wh}\!/_{m^2}\right) * 2.6\ m^2 * .13\right] - Fridge\ Energy\ (Wh)}$$

Equation 4.3.1 Calculation of the energy harvest efficiency

Table 4.3.2 Energy harvest efficiency of for each system

Controller for Round 1 / Round 2	Round 1	Round 2
AND1/AND1 harvest efficiency	0.20	0.02
OR1/OR3 harvest efficiency	0.11	0.15
OR2/AND2 harvest efficiency	0.06	0.02

Table 4.3.3 shows summary statistics for energy during specific days chosen to reflect a daily snapshot across a range of insolation.   The potential energy was calculated as a function of the measured insolation, the array area (2.6 m), and an assumed module efficiency of 13%. The energy required to run the refrigerators during Round 1 ranged from 85 Wh to 272 Wh per day during Round 1.   The energy consumtion increased to between 249 Wh and 539 Wh during Round 2. The temperature inside the shed was approximately 8ºC hotter during Round 2, which may explain some of the increased energy demand by the refrigerators. The PV array output correlates with insolation for most systems. The PV output is also a function of the total load on the system, so the output can be limited on load side as well as the supply side (available sunlight). The harvested load for the AND1 system dropped dramatically in Round 2 due to a reduced load. In Round 1, AND1 was connected to a battery and a 15 A resistive load. In Round 2, it was connected to 8 Pico lamps, a much reduced load. The load on the OR1/OR3 system changed from a battery and resistive load in Round 1 to a load consisting of a battery and 2 x 12 Watt compact flourescent lights (CFLs) that were constantly illuminated in Round 2. The load on the OR2/AND2 system changed from a battery and resistive load in Round 1 to a reduced load of 8 Pico lamps in Round 2. Finally, the last three columns show the difference between the measured energy out of the PV arry and the combined load from the fridge and the external load. The delta is largest for the AND controlled systems. Based on lab tests done elsewehere on behalf of SELF, the AND controls consume approximately 0.78 A at 18 VDC, which would add up to 337 Wh per day.   That's more than enough to account for the additional energy out from the PV array that was not captured by the monitors on the refrigerator loads and the external loads. Based on the data in the table and prior testing, the OR controllers use significantly less energy than the AND controllers.

Table 4.3.3 Energy statistics for selected days representing a broad range of insolation

						Refrigerator (Wh)			PV Array (Wh)			Load (Wh)			PV out - Combined Load (Wh)		
Round	Weather	Date	N Rows	Insolation (Wh/m2)	Potential Energy at 13% Eff. (Wh/day)	AND1	OR1 / OR3	OR2 / AND2	AND1	OR1 / OR3	OR2 / AND2	AND1	OR1 / OR3	OR2 / AND2	AND1	OR1 / OR3	OR2 / AND2
1	Clear	21-May-16	1798	7120	2407	260.5	130.6	171.7	924.4	428.8	925.6	462.2	271.7	713.5	201.8	26.5	40.4
1	Partly Cloudy	26-May-16	1798	5840	1974	271.8	175.5	194.1	901.2	494.3	564.6	436.0	283.9	345.8	193.3	34.9	24.7
1	Cloudy	18-May-16	1796	3142	1062	211.3	84.9	126.2	665.6	170.2	221.9	287.0	73.5	84.2	167.3	11.8	11.5
2	Clear	8-Jun-16	5391	6437	2176	538.4	248.9	342.7	695.2	566.0	555.3	35.7	285.8	36.9	121.1	31.2	175.8
2	Partly Cloudy	7-Jun-16	5398	5732	1937	486.5	276.1	367.8	640.4	399.1	565.5	35.6	107.4	30.2	118.3	15.5	167.5

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Table 4.3.4 shows the fraction of potential energy harvested by the system. The measured PV array output versus the potential array output ranged from 16% to 63%. The largest percentage of available energy from the array was harvested during Round 1 using the AND controller. The energy harvest percentage correlated with the available sunlight during that test period, as well. During a clear sky day with high insolation, the system only harvested 38% of the potential energy. During the cloudy day with low insolation, the system harvested 63% of available energy. This suggests more energy could be harvested on sunny days from this AND system provided there is sufficient load connected to the system. In general, between 37% and 84% of available energy is not being harvested due to the limited load and control logic.

Table 4.3.4 Energy harvesting efficiency

			PV Output / Potential Energy		
Round	Weather	Date	AND1	OR1 / OR3	OR2 / AND2
1	Clear	21-May-16	0.38	0.18	0.38
1	Partly Cloudy	26-May-16	0.46	0.25	0.29
1	Cloudy	18-May-16	0.63	0.16	0.21
2	Clear	8-Jun-16	0.32	0.26	0.26
2	Partly Cloudy	7-Jun-16	0.33	0.21	0.29

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5 Revision Control

Revision	Date	Description of Change
Original	June 17, 2016	Original
20160714	July 14, 2016	Corrected upper temps for Appliance 1 in Round 2. Minor edits. Expanded the Daily Plot section
20160819	August 19, 2016	Replaced the specific manufacturer names with Appliance 1, 2, and 3