How Energy Harvest Controls Can Increase the Benefits of Solar Direct-Drive Refrigerators

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Introduction

Solar-powered refrigeration is currently used for preserving vaccines, medicines, blood, and other temperature-sensitive materials in health care settings. Two energy storage approaches are typically applied to solar refrigeration. The first approach uses a solar-recharged battery to provide continuous power to an active cooling circuit. The second approach uses a thermal mass to enable the active cooling circuit to be directly powered by solar electricity without the need for a battery.[i] Refrigerators that take this approach are commonly referred to as "solar direct-drive" or SDD refrigerators.

SDD refrigeration cooling circuits, including thermoelectric and vapor compression, are powered directly from solar photovoltaic (PV) panels. No electrical storage battery is required for their cooling circuit operation. Instead, a thermal mass is used to provide long-term cooling through phase change during times when solar energy is not sufficient to power the cooling circuit. To provide continual cold storage even during longer periods of minimal solar radiation, the PV panels installed for SDD refrigerator-PV systems are typically larger and provide more power than would be needed if solar energy were consistent throughout the day. As a result, SDD refrigerators do not fully use their entire solar-generation capacity at all times, leaving surplus, unused electricity periodically available for other electric loads.[ii]

Health care facilities that use SDD refrigerators are typically not connected to an electrical grid and would benefit from having access to this excess electricity for other purposes. In fact, this latent demand for electricity leads to connection of additional electrical loads to battery powered refrigerators-PV systems, in some cases degrading the performance of the refrigerator. The purpose of the Energy Harvest Control (EHC) project was to explore the opportunity to allow health care facilities to use the excess electricity produced by SDD refrigerators without impacting the performance of the refrigerators.

Minimum requirements: First, do no harm

The first and foremost requirement of an EHC is that it never interfere with the primary purpose of the refrigerator-PV system. In all operational modes, the EHC must prioritize the cooling circuit operation over any secondary load. This means that the cooling circuit must be the default load in the event the EHC fails to operate correctly. The second requirement is that the EHC must divert some surplus electricity to secondary loads. With these requirements in mind, PATH partnered with the Solar Electric Light Fund (SELF) to develop and test prototype EHCs.

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[i] A specification for use of solar-powered refrigerators for vaccine storage is provided by the World Health Organization (WHO) in the most recent versions of WHO Performance Quality and Safety (PQS) guidelines PQS E003 FZ03, E003 RF05, and E003 RF06. Solar-power system specifications for both battery and solar direct drive are found in WHO PQS E003 PV01.

[ii] An electric load is the electrical energy that is consumed by a component, circuit, device, piece of equipment, or system that is connected to a source of electric power to perform its functions. See http://www.dictionaryofengineering.com/definition/electrical-load.html.

What we learned

Through development, laboratory testing, and field testing of the prototypes, we have confirmed that an SDD refrigerator-PV system can safely provide surplus electricity to power secondary electrical loads with the addition of an EHC. To see the detailed results of the testing, please see our report, titled *Energy Harvesting Controls for Solar Direct-Drive Cooling Systems: Laboratory Testing Report*.[iii]

How we did it

PATH supported SELF's development of three prototype EHCs. From the beginning of the project, the goal was to make any EHC designs that met the minimum requirements broadly available for any interested party to use and improve upon. Toward that end, SELF placed the prototype EHC architectures in the public domain through publication via www.researchdislosure.com on March 18, 2016. Annex 1 reproduces the relevant text and diagrams from SELF's publication.

[iii] The report can also be found at: http://www.path.org/publications/detail.php?i=2699.

Annex 1

This publication describes how systems connected directly to the primary load that generate electricity via a solar direct drive (SDD)—an SDD refrigeration appliance—can use surplus electricity to power secondary electrical load with the addition of an energy harvest control (EHC).

The described EHC concepts have been developed specifically to proportionally manage the flow of SDD-generated electricity to power both primary load and secondary loads. The primary load must be defined within the EHC control logic to enable prioritization and failsafe features. Secondary loads may be defined or undefined. Two broad categories of EHC concepts are detailed below.

The first category of EHC diverts excess solar-generated electricity to secondary loads only when the primary load cannot use the available electricity. Under this approach, electricity is always available to the primary load as required and only diverted to secondary loads when the primary load is not fully activated and cannot use available electricity. Either the primary load or secondary loads receive available electricity, but never both at the same time (OR option; see below).

The second category of EHC diverts excess photovoltaic (PV)-generated electricity anytime surplus electricity is available. Under this approach, electricity is always available to the primary load and only available for alternate loads when the active cooling circuit cannot use all of the available electricity. Both the primary load and secondary loads may receive available electricity at the same time (AND option; see below).

Description of Energy Harvest Control options, operation and configuration

BACKGROUND

Photovoltaic (PV) solar arrays used to generate energy for a specific energy consuming “load” are often specified to generate enough power when operating in less than perfect solar radiation conditions. This specification ensures adequate power for the load when incident solar radiation is reduced by diurnal and seasonal variations in the angle of the sun and/or weather factors. This creates a situation for most solar power generating installations that results in more power being generated by the solar panels than is required to supply the target load during a typical solar day. The energy harvest control (EHC) technology described below is intended to access this previously unutilized energy while prioritizing the power supply to a primary power load. In some situations it is extremely important that any use of excess energy will not interrupt or negatively affect the operation of the primary load (e.g. at health facilities where the primary load is a vaccine refrigeration appliance or other impactful medical equipment).

In order to use the excess energy produced, three control options are described in this publication broadly categorized as either the ‘OR’ option or the ‘AND’ option. With the OR control, no excess power is directed to a secondary load when the primary load is operating. With AND control, power in excess of that demanded by the primary load may be directed to a secondary load when the primary load is operating. Both control options would divert power to the secondary load when the primary load is not operating. One version of the AND control is described. Two versions of the OR control are described as the OR control and as the alternate OR EHC.

Power for the EHC is obtained from the PV solar array and can directly power the EHC or can be stored (e.g. in a battery) to avoid consuming PV array power simultaneous to primary load requirements.

Both the AND and the OR options could be integrated in appliances at time of manufacture or added to existing installations (if properly matched to the existing installation).

CONTROL CONFIGURATIONS

Modes of operation and control configurations are presented for both options. The descriptions below use examples where the power source is a PV solar array, the primary load is a vaccine refrigerator and the secondary load is undefined. Applications of these control options are not limited to the power source, primary load or secondary load used in the examples. If the primary load requires continuous power (e.g. for control functions like thermostat) then the secondary load will always share power with primary load to ensure essential control functions are continuous. Output to secondary loads can be further controlled by establishing minimum/maximum voltage set points based on solar array operating voltage and secondary load requirements. Maximum current to secondary loads can be established to refine control strategies.

A general diagram for both the OR and AND configurations is illustrated in Figure 1. Logic flow for both configurations is described in Figure 2. All values shown in Figures 1 and 2 are for reference only and are not limited to these values. A schematic diagram for an alternate OR EHC is illustrated in Figure 3.

Figure 1: *Control block diagram for both the OR and the AND control (reference purpose only).*

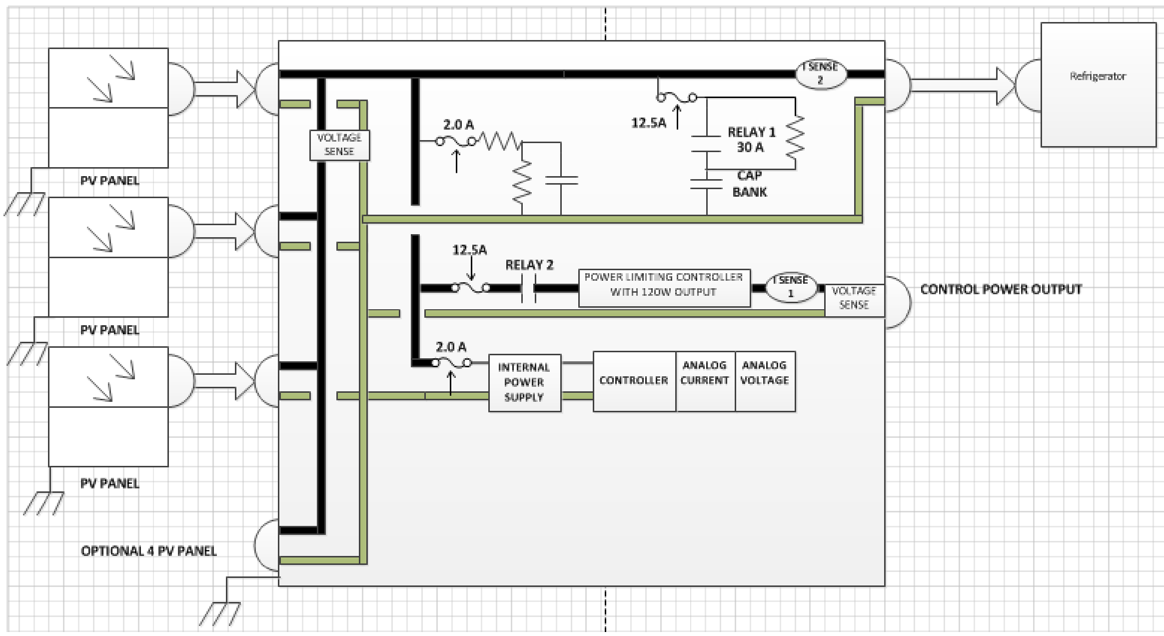
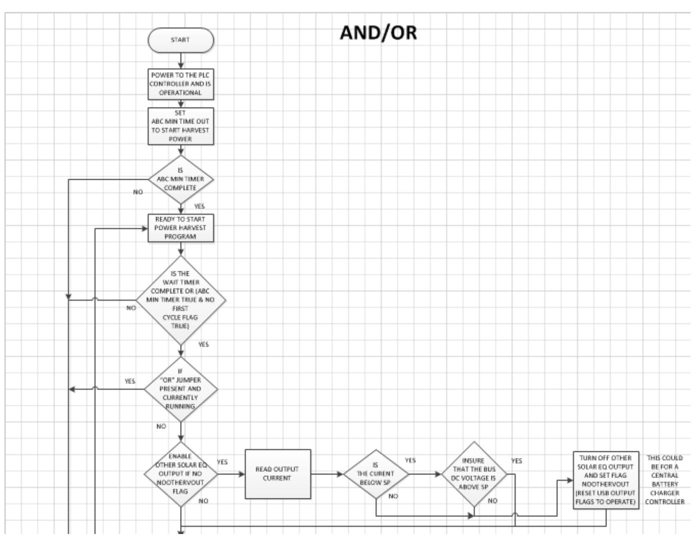
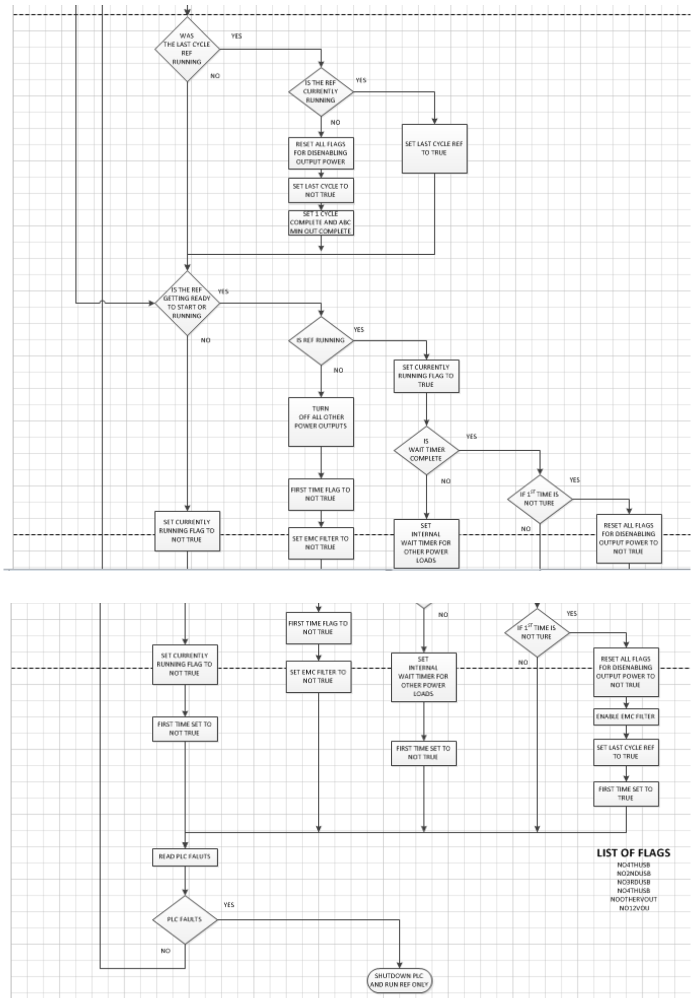


Figure 2: *Logic flow chart for both the OR and the AND control options (reference purpose only).*





<u>OR Configuration</u>

Modes of operation for an OR control: When designed and operated as an OR control, and considering a cooler (refrigerator or freezer) as the primary load, the principal modes of operation are:

- O1.) No power available;
- O2.) Power available and insufficient for cooling, cooling required but power directed to secondary load;
- O3.) Power available, cooling required and all power directed to the primary load; or
- O4.) Power available, no cooling required and power directed to the secondary load.

If the primary load requires multiple levels of continuous power (e.g. low power requirement for control functions like the thermostat, high power requirement for compressor operation), then secondary loads will always share some base power with the primary load to ensure essential levels of continuous power are available to the primary load. These considerations are specific to the application and intended loads.

Specific OR Embodiment: This embodiment of an OR configuration is the simpler of the two configurations having only four modes to which the logic must respond. The logic employed effectively simplifies operation to three possible modes, combining numbers O2 and O4 above.

Ignoring for now the possibility of any need for continuous power for the primary load, consider an average day of solar radiation with no clouds or obstructions. Before sunrise no power is available as mode O1. As soon as a small amount of base power is available from the PV array the control device begins continuously checking (at a preset or adjustable interval) whether the primary load is running or starting to draw current to initiate cooling. If it is not, all power is directed to the secondary load as mode O2 or O4. If the primarily load starts drawing current, all power is cut to the secondary load and directed to the primary load, switching to mode O3.

When the system is in mode O2, the simplest version of an OR control is operating non-ideally. In this case, the EHC will periodically cut power to the secondary load at the frequency with which the thermostat of the primary cooling load attempts to turn on the compressor. This issue could be resolved if the EHC were further integrated into the control circuitry of the primary cooling load itself and the EHC could respond directly to input information from the thermostat and primary load internal control system. The intermittent power due to frequent thermostat cycling would also be less of an issue if the secondary load were a battery or device with an internal battery.

In order to carry out the logic discussed above, the current sensor labeled ‘I SENSE 2’ at top right of the block diagram in Figure 1 signals the controller (uP, DSP, Discrete, or PLC) if the refrigerator is operating in cooling mode (e.g. compressor operating). When there is a value from the sensor (whether in line or field effect) the control will disconnect all power to ‘Control Power Output’ (secondary power output) and direct all power to the refrigerator. When the refrigerator current drops below a preset value, then the Controlled Power Output (Secondary Power Output) diverts all excess power from the solar array to the secondary load.

<u>AND Configuration</u>

Modes of operation for an AND control: When designed and operated as an AND control and considering a cooler (refrigerator or freezer) as the primary load, the principal modes of operation are:

- A1.) No power available;
- A2.) Power available and sufficient only for cooling, cooling required and all power directed to primary load;
- A3.) Power available and sufficient only for cooling, cooling not required and power directed to secondary load;

A4.) Power available and insufficient for cooling, cooling required but power directed to secondary load;

A5.) Power available and insufficient for cooling, cooling not required and power directed to secondary load;

A6.) Power available and in excess of cooling requirement, cooling required and power directed to both primary and secondary load; and

A7.) Power available that would be in excess of cooling requirement, but cooling is not required and power directed to secondary load.

In addition to these 7 modes, the AND control may be configured to have minimum power requirements for output to secondary loads when there is not sufficient power for cooling mode operation. Output to secondary loads can be further controlled by establishing minimum/maximum voltage set points based on solar array operating voltage and secondary load requirements. Maximum current to secondary loads can be established to refine control functionality.

Specific AND Embodiment: The AND configuration is the more complex of the 2 configurations. The AND operation should supply power to the secondary load in three general cases: when the voltage from the PV solar array is above an established upper input voltage set point matched to the primary load requirement as modes A6 and A7; there is no requirement for power to the refrigerator as modes A3, A5, and A7; and when cooling is required but there is insufficient power as mode A4. Theoretically all energy produced by the PV array could be utilized in this configuration although the need for set-points and switching timing will make any control less than ideal in practice. In contrast to the OR configuration, excess power can be diverted and used in mode A6 with the AND switch.

To illustrate a specific embodiment of the AND configuration, again consider an average day of solar radiation with no clouds or obstructions. Before sunrise no power is available as mode A1. As soon as a small amount of base power is available from the PV array the control device begins continuously checking (at a set interval) the output voltage of the PV array. If it is above the upper voltage set point, the power available to the secondary load output will be gradually increased by the control. This will continue until one of four conditions exist:

A. The PV output voltage to the system drops below the upper input voltage set point,
B. A maximum power output to the secondary loads is reached (assuming the device is being used as a regulator in addition to a switch),
C. A maximum secondary load voltage set point based on the secondary load requirement is reached (e.g. charge termination voltage for a rechargeable battery)
D. Or a maximum current is reached (assuming the device is being used as a regulator in addition to a switch).

If the maxima of B or D is obtained, then the secondary power output will remain at maximum power until either the system voltage drops below the upper input voltage set point (e.g. the secondary load pulls so much current that the system voltage drops below the upper input voltage set point) or the maximum voltage set point based on the secondary load requirement is reached (e.g. charge termination voltage for a rechargeable battery). The secondary load continues to receive power in modes A6 and A7 until the evening when the available power from the PV array begins to decrease. If the PV solar array voltage drops below the upper input set point then the available power to secondary loads will be gradually reduced until a cutoff input voltage set point is reached. This allows the secondary loads to continue receiving lower amounts of power until they need to be cut off when mode A2 is reached. In this embodiment the cutoff input voltage set point is set much higher than necessary for the primary load to continue operating. A large safety factor is programed into the control to allow for fail-safe operation of the primary load when the AND EHC is in the system between it and the PV power supply.

Additional Considerations

It may be apparent that the specific AND embodiment discussed above utilizes less energy than it possibly could. Because the primary load may be critical, as in the case of vaccine cold chain equipment, some sacrifices to ideal energy harvesting operation may be worthwhile. The specific embodiment will not divert energy to secondary loads during some operation in modes A4 and A5 (the 'tails' of a time vs power or energy graph). Some energy will also be lost in modes A6 and A7 by using voltage set points that ensure uninhibited operation of the primary load dependent on the safety factor used in dictating the set point values.

The circuit to the left of the current sensor labeled 'I SENSE 2' in Figure 1 is to improve the power quality to the refrigerator and extend the life of the refrigerator. This circuit is not needed for OR operation or AND operation. Because the PV output is more a current source than a voltage source, when relay 1 is closed it will act more like a voltage source and not a current source. Relay 1 closes after the refrigerator is started so that the startup sequence of the refrigerator controller does not need to be modified, and is controlled by a time constant. This is true for both configurations.

Description of an alternate OR EHC design

A control strategy for an alternate OR EHC is shown in Figure 3. In this control strategy the OR EHC is connected directly to the output of one or more PV panels. The power produced from the PV is connected directly to the primary load (e.g. a solar direct drive (SDD) refrigerator). This OR EHC controller continuously monitors inputs from the SDD. These inputs can be, but are not limited to, the refrigerator thermostat, current sensing of compressor running, or compressor fan.

When this OR EHC determines the SDD refrigerator compressor is operating or in the startup mode, the OR EHC relay disconnects the PV from the secondary load, making available all PV power to the SDD refrigerator.

When this OR EHC determines the SDD refrigerator compressor is not running and the voltage of the PV is above a predetermined level (ensuring that the system voltage is adequate enough that the SDD refrigerator controls have the ability to monitor and restart the compressor as needed) the relay is energized, diverting all available PV power to a solar charge controller or a dedicated load such as, but not limited to, a cell phone, laptop computer, portable lighting and/or motor loads.

Figure 3: *Schematic drawing of an alternate OR EHC.*