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Nanogrid System Resilience for Ka Honua Momona

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Introduction

Ka Honua Momona (KHM), a small 100% off-grid compound comprising PV and wind generation on Molokaʻi, Hawaiʻi, was used as a proof-of-concept site to demonstrate a control scheme to automatically optimize battery use and reduce inverter losses, and to utilize energy that is otherwise wasted when a battery system can no longer store additional energy due to capacity constraints. KHM is a not-for-profit organization that supports the local Hawaiian community in Molokaʻi by providing sustainable and cultural education that revitalize natural and cultural resources to perpetuate traditions, knowledge, and stewardship, while evolving with modern technologies. The compound includes several site loads: an office, a two restroom/shower building, two outdoor meeting facilities, a storage shed, and an aquaponics operation (Figure 1).

Figure 1. Ka Honua Momona off-grid renewable energy nanogrid site in Kaunakakai, Molokaʻi.

A key factor of KHM's operation is that its use is intermittent and therefore has variable daily loads that range from less than 300 W baseload on unoccupied days to a full 4,000 W load when sponsoring community events. During the unoccupied days, up to 18 kWh of excess renewable energy would be available for PV generation, but is not stored due to full batteries from previous day of non-use. Once a battery is fully charged and in float mode, the available solar energy cannot be converted into useful energy. Under previous APRISES awards, KHM collaborated with HNEI to develop an online dashboard that would provide a visualization of the energy use and renewable energy production of their off-grid energy system for community education purposes.

In 2019, nine Sunverge integrated energy modules (a Li-ion battery storage, inverter, charge controller, and communicator that sensed grid power) were donated from the sponsors of a then-completed grid integration project in Maui. These Sunverge units could not be installed into any of the local utility grids because they no longer met utility inverter requirements; they could only be used for research on an off-grid, non-utility system. Because of its history with HNEI, KHM became a candidate that would benefit from the Sunverge systems and three of these units were allocated to KHM to supplement their existing battery storage. By incorporating a dump load circuit and adding load and storage management controls, the off-grid system would add power-based services (e.g. hot water and water distillation) and qualitative improvements to the KHM operation, while improving the efficacy of their off-grid system.

With 5.3 kW of PV generation, KHM had the potential to generate more useful energy if the energy could be stored or used. During the course of the project, it was found that in an off-utility-grid mode, the Sunverge inverter systems used significant amounts of energy in a non-loaded standby condition, depleting the batteries each night. This necessitated a mid-course correction dubbed "predictive look ahead programming," a network of programmable auto transfer switches (ATS) and controls that reduced the system losses significantly by energizing the inverter only on an as-needed basis. This shift changed the dynamic of the project from that of load-side management to supply-side management, while maintaining the project objectives.

HNEI's objectives for this project were to:

1) Develop a load shifting scheme to maximize utilization on a site whose load profiles have intermittent and varying loads and finite battery storage capacity;
2) Increase system utility by adding load dumps ("opportunity loads") to utilize more available energy and simultaneously improve quality of life services (e.g., domestic hot water and water distillation); and
3) Test a "smart" *predictive look ahead programming* control strategy to match solar generation with partitioned battery storage in order to minimize inverter standby losses as the KHM losses were disproportionately large for a small 5.3 kW renewable grid.

Additionally, KHM's goals were to: 1) reduce dependence on fossil fuel generation; 2) increase useful energy extracted from PV system and minimizing wasted generation; 3) minimize service interruptions; and 4) increase quality of life without sacrificing power delivery.

This project demonstrated that small off-grid renewable energy systems can significantly improve the utilization of the available energy sources (specifically, solar photovoltaic energy) by eliminating unnecessary inverter standby losses and adding opportunity loads to utilize excess available energy that may not otherwise be captured due to limited battery capacity.

Original Site Operational Profile

The initial KHM off-grid system was comprised of eighteen 240W PV panels (5.3 kW), two dual 3600-watt Outback inverters, one 80-amp Outback charge controller, and a dual string of sixteen 6-volt Rolls Surrette, flooded lead acid, deep cycle batteries for 40 kwh of total storage with 20 kWh useful storage, assuming a 50% depth of discharge (DoD).

A small baseload consisting of a refrigerator and office support loads (IT and communication servers and miscellaneous small loads) shaped one of several common daily profiles, while on other days, large on-site gatherings lasting well into the evening, exceeded battery capacity and required supplemental power from the fossil fuel-based standby generator. Figure 2 is an example 24-hour load profile that shows baseload typical operating conditions and a few short spikes of peak load. During a power loss, an electro-mechanical auto transfer switch triggered the auto-start stand-by generator with approximately a 5 second momentary outage. The generator transferred back to battery power when batteries were fully charged and non-essential loads such as air conditioning were shed when on generator power. No hot water existed on the site, in spite of kitchen and showering needs. The schematic of Figure 3 describes the original renewable energy system configuration at KHM.

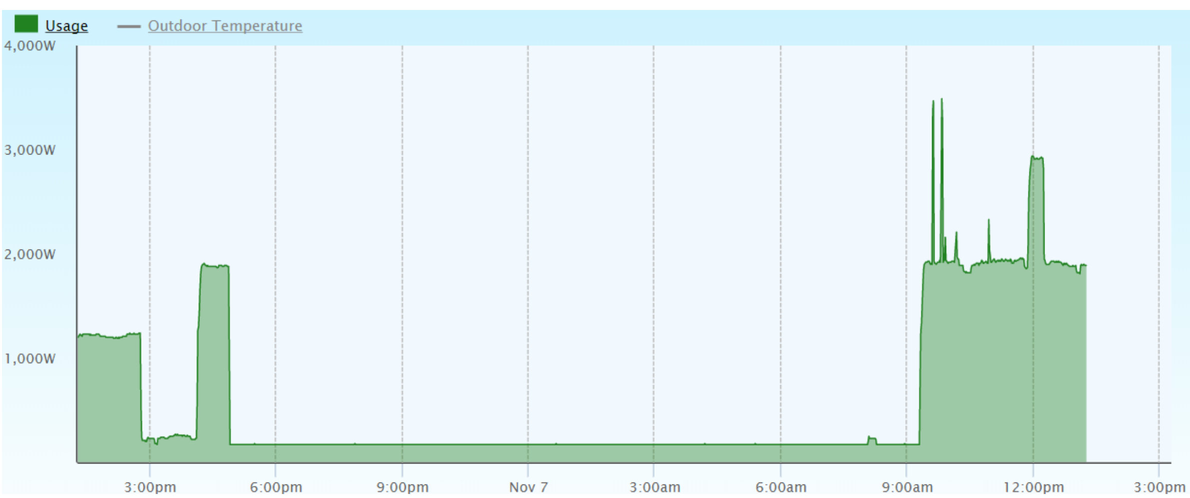


Figure 2. 24-hour load profile with varying load conditions: baseload (250 W), typical (2,000 W) and short peaks (2,700-3,000 W).

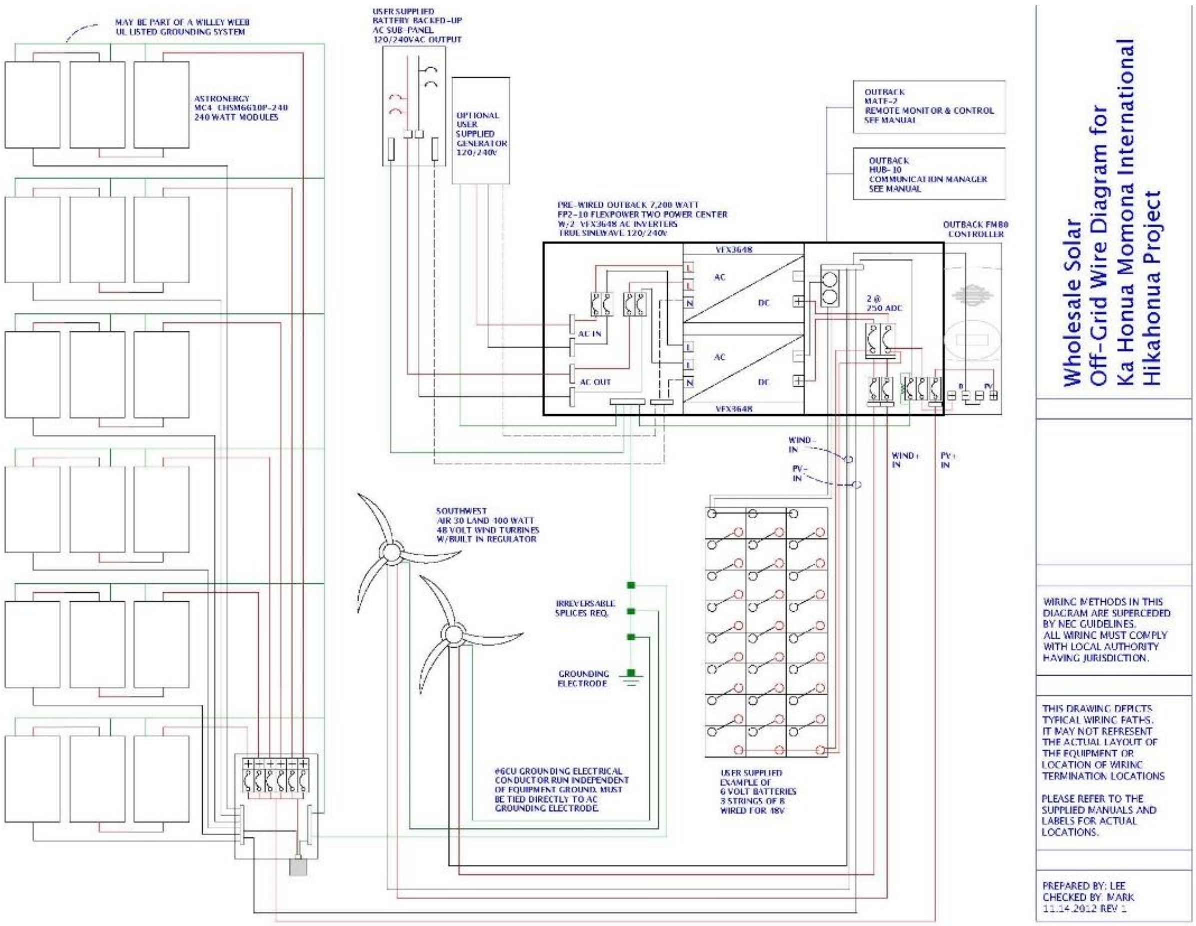


Figure 3. Original KHM renewable energy system design schematic.

Project Approach

The original project plan was to utilize the three 9 kWh Sunverge Li-ion bundled systems to function in a manner analogous to a utility grid backing up a grid-tied solar PV system. The systems could also serve new opportunity loads (dump loads) once the primary batteries reached full capacity and entered float mode. The opportunity loads consisted of a new 40 gallon domestic water heater to serve the kitchen area and a new dedicated circuit with a power outlet installed in the kitchen to serve a small water distillation system or a countertop ice machine.

This approach involved allocating battery storage into two partitions: a primary storage bank using the existing Outback and a combination of existing lead-acid and new absorbed glass mat (AGM) batteries, plus an additional secondary back-up bank using the donated energy Li-ion storage systems. The site load would then be served by the primary bank on most typical, low-use days. The secondary bank would back up the primary system on higher demand days and would otherwise serve the new opportunity loads when excess power could be generated.

While it was hypothesized that the Sunverge batteries would emulate grid support (backup) to the primary battery source serving the site load. Sunverge units were designed to tie into a continually powered utility grid, sending pulses to sense line loads that would signal its *internal* auto transfer switches to engage the system when primary power is lost. These pulses were picked up by the new *external* electro-mechanical auto transfer switches that connected the two storage systems and it was found the internal and external switching protocols were incompatible.

The KHM power system attempted to auto switch between the primary "Outback" power system and the Sunverge units, but failed as a result of the conflicting protocols. The incompatibility of the built-in Sunverge control systems with the KHM system's controls deemed it necessary to eliminate the Sunverge inverter, charge controller, and related on-board controls while salvaging the Li-ion batteries and building a new central control scheme to manage load and storage distribution.

The overnight inverter losses for both the Outback and the Sungold systems contributed to overall system inefficiencies. The Outback's overnight voltage drop from over 53 V to less than 49 V (Figure 4) was a result of both standby losses and baseload demand from the site. The overnight voltage drop on the Sungold system (Figure 5) was a result of no-load, standby losses only. The continual 24/7 load of the Sungold standby power was over 3 kWh a day, equivalent to about 3 PV panels production. Table 1 summarizes the measured daily losses for each of the inverters.

Figure 4. Overnight losses for Outback inverter, includes baseload and standby losses.

Figure 5. Overnight losses for Sungold inverter, includes no-load standby losses only.

Table 1. Typical measured standby losses for the 4 inverter types used on-site.

Inverter	Measured stand-by losses, no connected load (W)	Daily equiv. stand-by losses (kWh)
Outback	200	N/A
Sungold	200	3.6 – 5.0
Sunverge	166	3.0
Xijia*	7	0.13

**A Xijia inverter was later included in the reconfiguration of the battery storage systems (see next section).*

Adding a Supply-Side Management System

Due to the high inverter standby loss issues, the project evolved from a purely *load-side* management system (dump loads were to be added to utilize excess generation) to include a *supply-side* management system that managed the deployment of battery power to minimize standby losses and increase reliability. Supply-side power management utilizes web-enabled auto transfer technologies and strategic partitioning of battery storage systems to provide high speed, no interruption circuit transfers to serve the load.

The team developed "predictive look ahead programming," an approach that utilizes programmable electronic automatic transfer switches (ATS) and voltage sensing relays to activate the backup system prior to full discharge and disconnection of the primary bank. A brief overlap of both systems allows for a seamless, high-speed, no-blink transfer of battery banks, analogous to a utility power plant maintaining spinning reserve. This solution enables the Sungold inverter to remain OFF, rather than in standby mode, and to be automatically powered up shortly before the load is transferred from the primary Outback system, eliminating gaps in power delivery.

To manage the power flows from the PV systems to the battery storage and the flows from the batteries to the loads, a system that allocated the PV panels into discrete, assignable PV banks and battery partitions was designed to optimally match generation and stored energy to demand.

Battery storage was partitioned into three groupings. The "Outback" system used the existing 7,200 W inverted power with 20 kWh of AGM battery storage as the primary storage to initially serve the site load. The secondary battery partition, "Sungold/1, 2" consists of 18 kWh of Li-ion storage batteries (using 2 of the 3 repurposed Sunverge batteries) fed the 6,000 W Sungold inverter, is automatically dispatched when the primary system approaches its low battery cut out (LBCO). A third storage system, "Xijia/A," used the third 9 kWh Sunverge battery with an Xijia inverter and principally feeds the opportunity/dump loads when generation exceeds demand and all battery partitions are full, as well as serving as a tertiary backup to the primary system.

To prioritize the allocation of PV generation to primary storage and to maintain maximum flexibility and efficiency in sequencing load transfers, the 24 PV panels were divided into groups assigned to the three battery partitions. Twelve panels are dedicated to the primary Outback storage. The other twelve panels are allocated into three switchable groups, one group of 6 and two groups of 3, and assignable to either of the Sungold/1,2 or Xijia/A systems. The system uses web-programmable switches to sense the battery bank voltages directing the PV groups to the primary or backup battery banks, depending upon their states of charge.

Sequence of Operations

An electronic ATS monitors the primary Outback storage voltage, which normally shuts down when its primary storage voltage reaches low battery cutout of 42 V. Once the Outback storage drops to 44 V, the ATS turns on the backup Sungold inverter ahead of the primary dropping out (predictive look ahead). At 43 V, a second ATS transfers the load from the Outback system to the backup Sungold/1,2 system. This avoids having the Outback system automatically shut down at 42 V and allows it to remain online until the PV panels assigned to it increases to 50 V. At 50 V, the main building power ATS seamlessly transfers the system power back to the Outback system.

Should the Outback system drop offline for reasons other than depleted storage capacity, protective relays wake up the Sungold/1,2 backup system and transfer power to it. This failsafe operation sees a momentary outage of about 5 seconds as the Sungold/1,2 system boots, which is noticeable to KHM circuits that are not on UPS (e.g. lights). An outage from an unexpected failure of the Outback system would only be avoidable if the Sungold/1,2 system was constantly online in standby mode, but as mentioned earlier, resulted in unacceptably high standby losses for a small, off-grid system. Thus, with the standby Sungold/1,2 system normally off, very little restorative charge is required the next day.

Similarly, a third electronic ATS reads the 18 kWh Li-ion secondary storage batteries units, transferring the load to the 9 kWh of Li-ion battery storage, should the 18 kwh of Li-ion secondary storage be depleted. Operation has shown that the Li-ion batteries have small losses, and if no load, the voltage remains stable for weeks. With standby losses in the inverter and backup storage systems minimized, the new system provides virtually instant standby power and automated, undetectable power transfers.

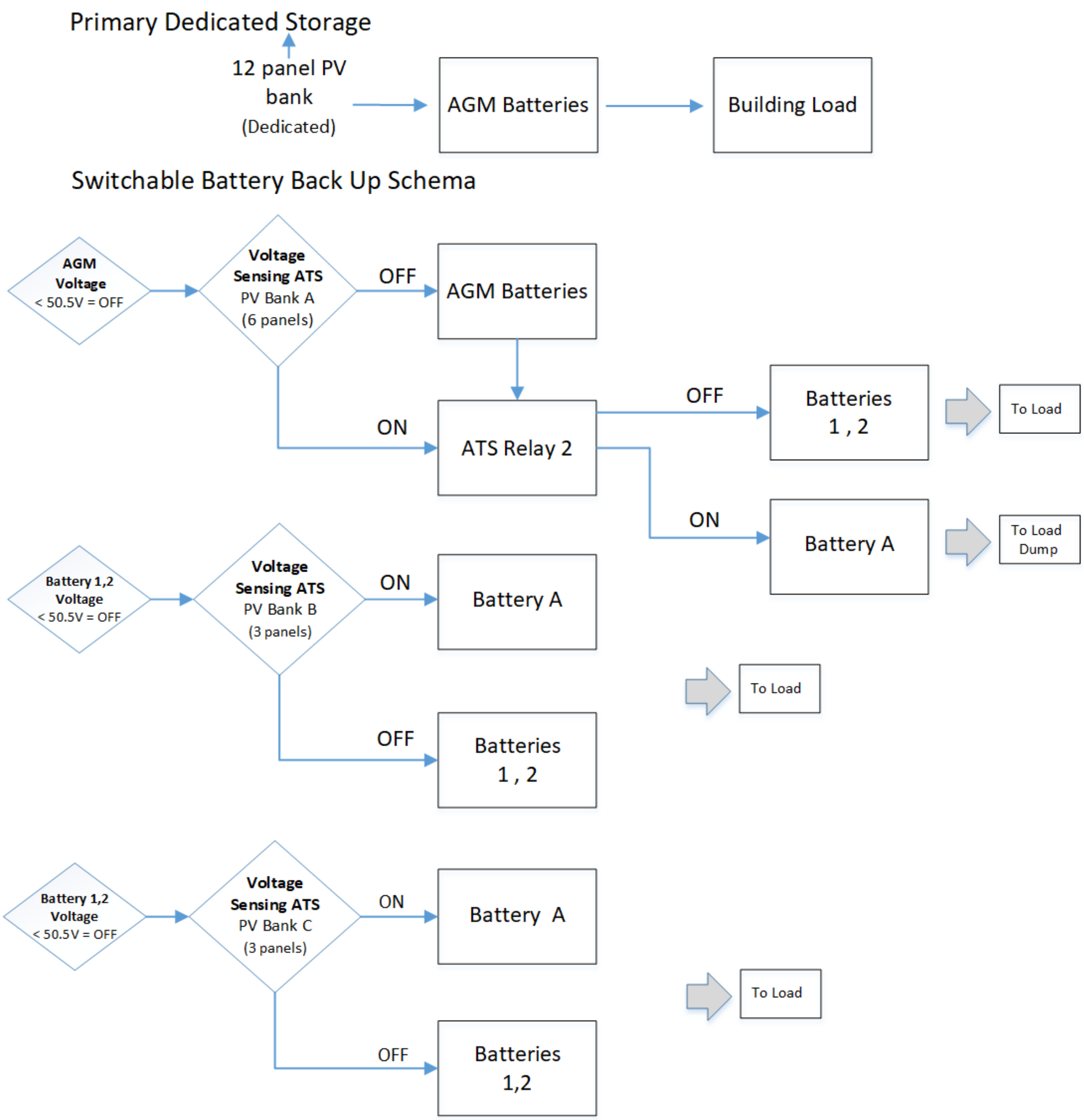
Table 2 summarizes the sequence of storage transfer based on voltage to the primary load. The PV and battery switching configuration shown in Figure 6 depicts the sequence of switching operations.

Table 2. Battery utilization sequence based on voltage of battery serving the load.

Initial State	**Voltage**	**Next State**	**Load Dump**
Outback	54.0V	Outback serves bldg.	ON
Outback	@ 50.5 V	6 PV panels diverted to Outback	OFF
Outback	@ 44.0 V	Outback ON / Sungold/1,2 ON	OFF
Outback	@ 43.0V	Outback OFF / Sungold/1,2 ON	OFF
Sungold/1,2	@ 44.0V	Sungold/1,2 ON / Xijia/A ON	OFF
Sungold/1,2	@ 43.0V	Sungold/1,2 OFF / Xijia/A ON	OFF

<u>Photovoltaic - Storage Charging Sequence Diagram</u>

Primary Storage: 20 kWh AGM batteries (50% DoD); (12) dedicated PV panels
Backup Storage: 18 kWh Li-ion (“1,2”@90% DoD); (12) assignable PV panels
Backup and Load Dump Storage: 9 kWh Li-ion (“A”@90% DoD); (12) assignable PV panels



Notes: PV banks A, B, C all assignable to backup banks 1,2 or A, depending on the state of charge of primary and backup. B and C banks can be manually assigned via web app to either storage, e.g., 3 to one, and 3 to the other, or 6 to either. The load dump circuit is dedicated to Bank A, and will only operate when primary and secondary remain above 50.5V.

Figure 6. Supply side PV panel and battery assignment logic diagram (“AGM Batteries” refers to the Outback system, “Batteries 1, 2” refers to the Sungold/1,2 system, and “Battery A” refers to the Xijia/A system).

Load Dumping

The key element of an automated load dumping control system is a circuit dedicated to the dump loads, served by the Xijia/A battery bank that cannot be accessed by the primary or the backup systems. The dump loads consist of a 40 gallon water heater and a household 110V outlet that serves a countertop ice maker and a small water distiller, but not both simultaneously.

The default PV assignments allow maximum load dumping and recharge by initially directing all 12 switchable PV panels (6+3+3) to the Xijia/A system, the only battery system tied to the load dump circuit. The Xijia/A system supplies power to the load dump loads and continues to be recharged by the 12 switchable panels until the primary system voltage falls below a 50.5 V set point. At this voltage, the dedicated battery voltage sensing auto transfer relays redirect 18 PV panels to the Outback system (the dedicated 12 panels plus 6 switchable panels (PV bank A) and the 6 switchable PV banks (PV banks B and C) to the standby Sungold/1,2 batteries. As such, powering the load dump circuit can only take place when both the primary and the backup batteries are full, above 50.5 V.

Failure or complete depletion of the Xijia/A system has no effect on the power supplied to KHM and thus is completely transparent to KHM. Should both the Outback primary and Sungold/1,2 backup fall below their respective LBCO's, the Xijia/A system will serve as a third backup to serve the building load.

Predictive Look Ahead Programming

To minimize the waste of stored energy in a small off-grid system, standby losses must be reduced. As previously discussed, a series of programmable voltage sensing and electro-mechanical ATS were deployed to manage dispatch of the primary, backup, and load dump battery storage to the main site load, based on the voltages of each. While the diagram in Figure 6 illustrated the supply side sequence of charging the batteries, Figure 7 shows the schematic for the predictive look ahead programming. This configuration allows the Sungold/1,2 backup system to remain OFF, eliminating standby losses, until the primary system approaches the programmed set point of 44 V, 2 V above LBCO, when the backup system is energized. At 1 V above LBCO, the building load is switched from the primary to the backup system in 8 ms, or 1/3 cycle. The primary is still above LBCO, and with no load, the dedicated PV panels begin to immediately recharge the system.

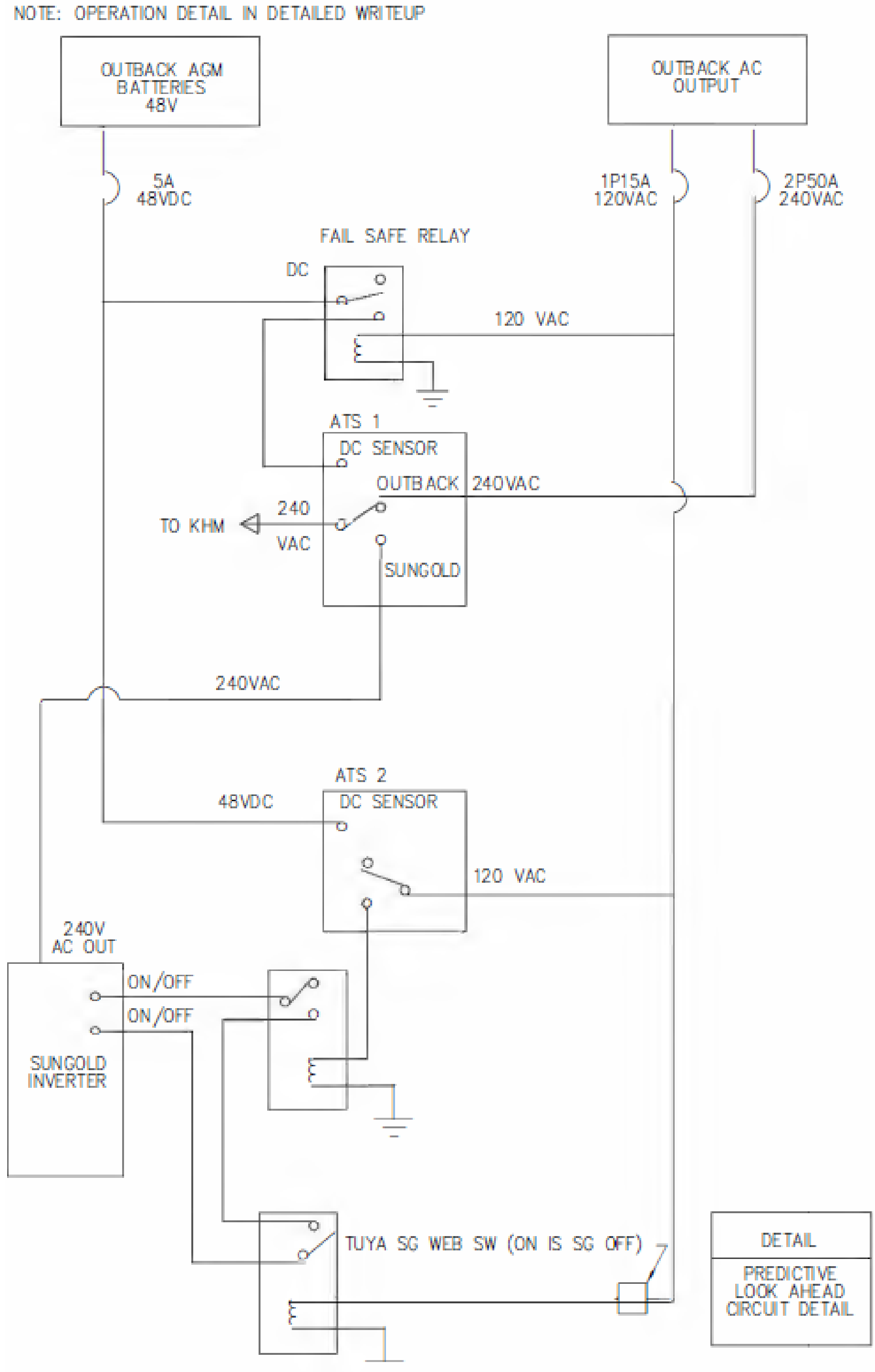


Figure 7. Switching schematic for Predictive Look Ahead Programming.

Table 3 details the *Predictive Look Ahead Programming* transfer sequences programmed into the automatic transfer switches to eliminate a momentary outage that would otherwise occur when switching between multiple storage banks. It also details the PV panel assignments that are dependent upon the state of charge of the primary and backup storage systems. The basis of the programming logic is that the normally OFF backup inverter is activated when the primary storage is 2 V above its 42 V LBCO. Since the backup inverter requires a minimum 6 second boot up period, disrupting service, it is activated prior to cutoff. The backup inverter is kept in a normally OFF mode in order to eliminate standby losses that can deplete a small, off-grid system.

Table 3. Predictive Look Ahead Programming detailed battery and PV panel transfer sequence.

Initial State	Voltage	Next State	Panel Assignment	Load Dump
Outback ON	54.0V	Outback serves site load	12 dedicated to Outback 12 PV to Xijia/A	ON
Outback ON	@ 50.5 V	6 PV panels diverted to Outback	12 PV dedicated to Outback 6 PV relayed to Outback 3 PV relayed to Xijia/A (alt. Sungold/1,2)* 3 PV relayed to Xijia/A (alt. Sungold/1,2)*	OFF
Outback ON	@ 44.0 V	Outback ON Sungold/1,2 ON	12 PV dedicated to Outback 6 PV relayed to Outback 3 PV relayed to Sungold/1,2 (alt. Xijia/A)* 3 PV relayed to Sungold/1,2 (alt. Xijia/A)*	OFF
Outback OFF	@ 43.0V	Outback OFF Sungold/1,2 ON	12 PV dedicated to Outback 6 PV switch to Outback 3 PV relayed to Sungold/1,2 (alt. Xijia/A)* 3 PV relayed to Sungold/1,2 (alt. Xijia/A)*	OFF
Sungold/1,2 ON	@ 44.0V	Sungold/1,2 ON	12 PV dedicated to Outback 6 PV relayed to Outback (alt SG or Xijia)* 3 PV relayed to Sungold/1,2 3 PV relayed to Sungold/1,2	OFF
Sungold/1,2 OFF	@ 43.0V	Xijia /A ON	12 PV dedicated to Outback 6 PV relayed to Outback (alt. SG or Xijia)* 3 PV relayed to Sungold/1,2 3 PV relayed to Sungold/1,2	OFF

**All relays are programmable relays. Panel assignment may be switched manually through app. First entry is default, but may be overridden for an alternate selection.*

Upon project completion, the KHM system comprises the following equipment, partitioned into a primary and 2 virtual backup systems:

- (24) 240 W photovoltaic panels - (12) dedicated to a primary bank of batteries and (12) switchable to all remaining batteries;
- (2) Outback 3,600 W inverters (primary storage);
- (1) Sungold 6,000 W inverter (backup storage);
- (1) Xijia 3,000 W inverter (load dump/backup storage);
- (1) 80 Amp Outback charge controller (serving 18 panels);
- (1) 60 Amp PowMr charge controller;
- 20 kWh Absorbed glass mat (AGM) batteries (50% depth of discharge);
- 27 kWh Li-ion batteries (90% depth of discharge);
- Multiple web programmable automatic transfer switches; and
- Tuya web enabled switch.

Additionally, New Opportunity Loads (load dumps) on a dedicated circuit served by the Xijia/A subsystem include one 40 gallon domestic hot water heater and one Kitchen 120 V power outlet that services (not simultaneously) a 500 W countertop water distiller or a 200 W countertop icemaker. Figure 8 is the schematic diagram of the final system design.

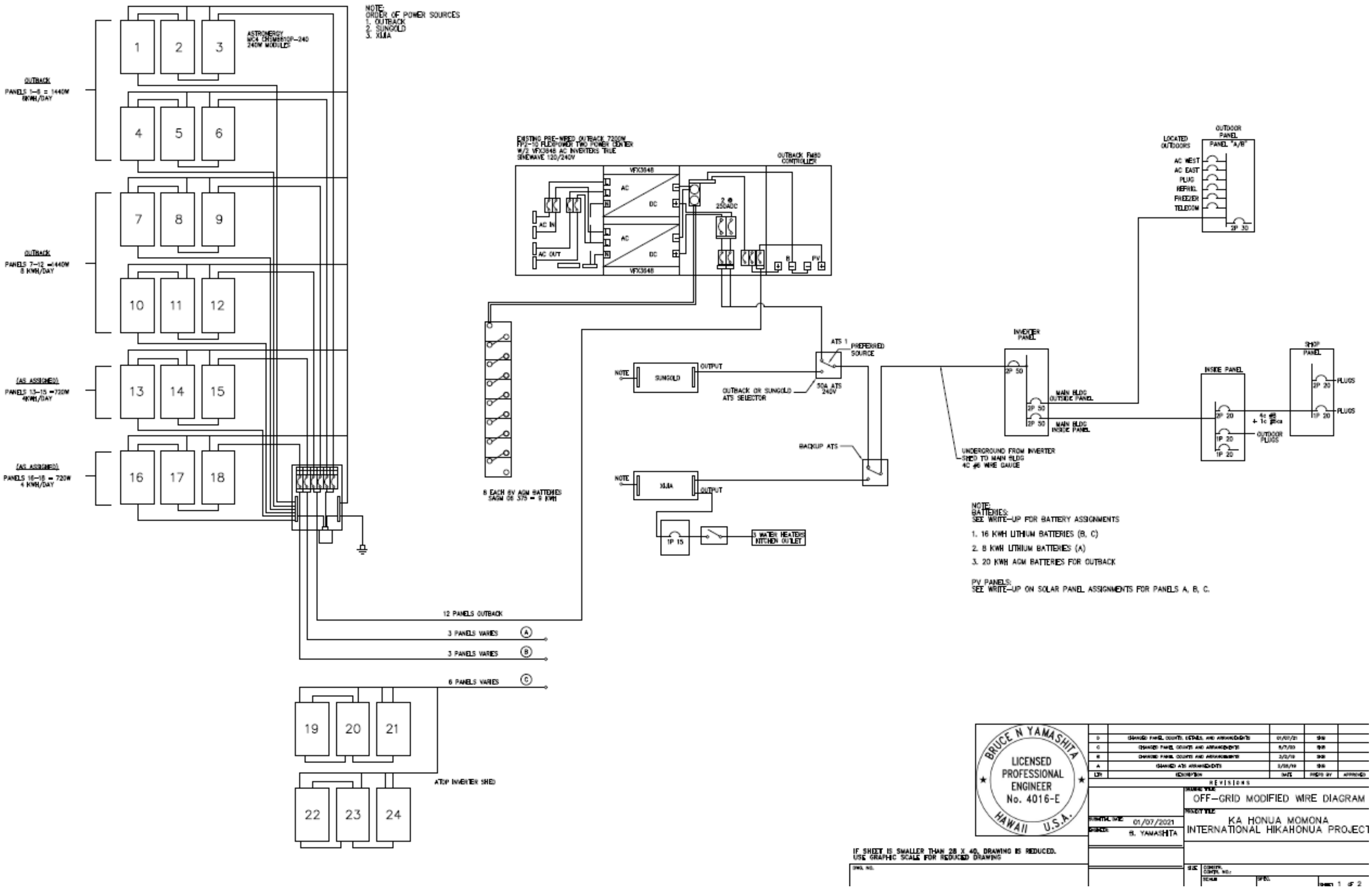


Figure 8. Schematic of final KHM off-grid system configuration.

Results and Conclusions

By integrating programmable and voltage sensing auto transfer switches with electro-mechanical ATS and adding new opportunity load dumps that are isolated from the primary and backup supply sources, the KHM small off-grid system captures more energy with fewer power interruptions, and provides new qualitative services on site. Predictive look ahead programming also eliminated unnecessary system standby losses. Battery partitioning provided a solid backup (spinning reserve) for the primary battery system.

Figure 9 illustrates the transfer of power from primary to back up systems over a three-day period. The backup systems remain fully charged with no standby losses until the primary is near LBCO, auto transferring to the next backup at the programmed cut in voltages.

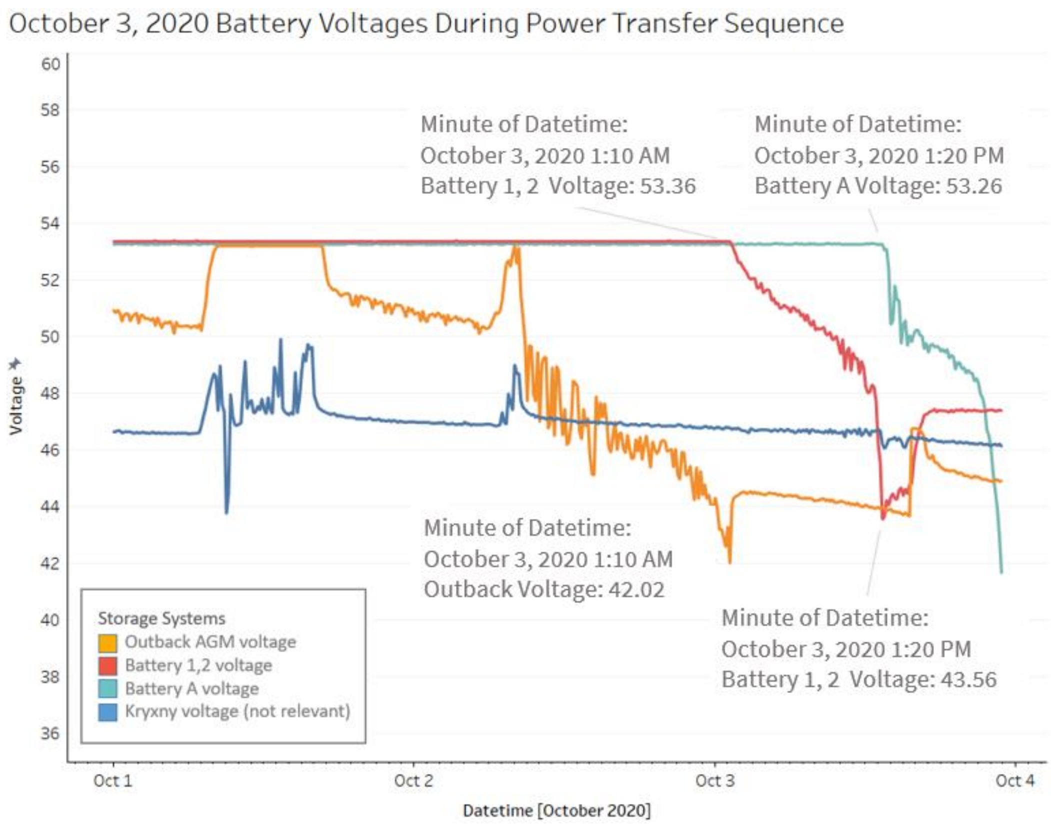


Figure 9. Transfer of load from primary to backup storage systems based on battery voltage (“Battery 1, 2” refers to the Sungold/1,2 system and “Battery A” refers to the Xijia/A system).

PV panel management selectively directs PV generation to specific battery banks on an as-needed basis. Dedicated and isolated load dumping circuits provide quality of life improvements by capturing and utilizing energy that would be foregone in a conventional battery capacity constrained system in a float mode. While it is acknowledged that the system design is more complex and expensive than a conventional single inverter system, it improves reliability and adds services that might not otherwise be available to a system constrained by battery capacity, greatly increasing the amount of useful energy captured.