COALITION WARFARE PROGRAM
HYBRID POWER INITIATIVE

LIMITED OPERATIONAL EVALUATION
FINAL REPORT

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14. ABSTRACT
The purpose of the CWP-HPI LOE is to gather objective and subjective data regarding the system in a humid and tropical environment. This document provides the results of the CWP-HPI LOE conducted at AFP WESCOM, Palawan Philippines. This report details the outcome of the evaluation and data analysis of the Coalition Warfare Program and Transformative Reductions in Operational Energy Consumption Program.

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This report describes the findings for the Coalition Warfare Program, Hybrid Power Initiative (CWP-HPI) Limited Operational Evaluation (LOE) at the Armed Forces of the Philippines Western Command Headquarters, Philippines. This document provides the results of the evaluation as collected by the Transformative Reductions in Operational Energy Consumption (TROPEC) Field Experimentation Team (FET).

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March 2015

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Ross Roley
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March 2015

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ACRONYMS

AC	Alternating Current
AFP	Armed Forces of the Philippines
CWP	Coalition Warfare Program
DAQ	Data Acquisition
DC	Direct Current
FET	Field Experimentation Team
FPC	Final Planning Conference
HPI	Hybrid Power Initiative
HQ	Headquarters
ISS/IPC	Initial Site Survey and Initial Planning Conference
LOE	Limited Operational Evaluation
PV	Photovoltaic
TROPEC	Transformative Reductions in Operational Energy Consumption
WESCOM	Western Command

UNITS OF MEASURE

A	Amps
mph	miles per hour
m/s	meters per second
V	Volts
W	Watts
Wh	Watt-hours

EXECUTIVE SUMMARY

This report provides the results of the Transformative Reductions in Operational Energy Consumption (TROPEC), Limited Operational Evaluation of a hybrid power system as part of the Coalition Warfare Program (CWP) Hybrid Power Initiative (HPI).

The hybrid power system was designed to provide uninterrupted power to the Armed Forces of the Philippines (AFP) at remote austere locations. The system consisted of solar panels, batteries, and a wind turbine. In collaboration with the AFP, This evaluation was conducted at AFP's Western Command (WESCOM). The evaluation was conducted in three phases:

- Phase 1 - the initial planning conference and site survey.
- Phase 2 - user training on the set up, operation, and maintenance of the energy system, and the completion of the initial training surveys. Evaluation data was collected for approximately two months.
- Phase 3 - retrograde of equipment. AFP personnel disassembled and packed all the equipment for redeployment in an Extended User Evaluation.

The AFP personnel who were trained gave positive feedback that they were confident and able to assemble, set up, operate and maintain a hybrid power system. The same AFP personnel also expressed confidence in training others. The availability of the required components locally was a significant factor in this success. Further, the AFP has expressed keen interest in continuing with other capabilities, such as water purification, that would build on the initial renewable hybrid energy project.

Based on the results, the HPI team makes the following recommendations:

- Deploy this system to remote austere locations to gather more data on operational efficiency, reliability and durability under environmental and transportation stresses.
- Junction boxes and other electrical connections must be insulated to protect them from the weather and environmental elements which may cause the system to fail.
- The incorporation of a water purification system into the set up would be tremendously beneficial, especially in remote austere locations where drinking water is not readily available.
- Connect a windmill to the system to assess additional benefit to the set up.
- Incorporate a small gas or diesel generator as a back-up power source for mission critical operations.

INTRODUCTION

Purpose

The purpose of the Coalition Warfare Program (CWP) Hybrid Power Initiative (HPI) is to further partnership with the Armed Forces of the Philippines (AFP) by providing an opportunity for AFP to plan, acquire, assemble, operate, maintain, and assess Hybrid Energy Systems. The CWP-HPI conducted a Limited Operational Evaluation (LOE) of a hybrid power system designed to provide uninterrupted power to the AFP at remote austere locations. This evaluation was conducted at AFP Western Command (WESCOM) during the months of October through December 2015. This report provides the findings of the evaluation in partnership with the AFP, and the Transformative Reductions in Operational Energy Consumption (TROPEC) Program.

Background

This project was initiated in response to support future humanitarian assistance and disaster relief missions in remote austere locations within the Philippines. The key imperative and success of this CWP project has been a full and open collaborative approach to research, test and evaluate a low-cost renewable hybrid power solution that would ensure an uninterrupted power supply.

A coalition planning and execution team was formed, a concept developed and coordinated to determine project requirements, approach, and venue. The team also developed a data collection plan and schedule.

The coalition planning team determined that the best approach to ensuring a low cost uninterrupted power supply was to conduct an experiment and long-term assessment of a small-unit transportable, hybrid renewable/alternative energy system. The total cost of locally purchased materials to construct the hybrid renewable/alternative energy systems was less than $5K.

Technology Description

The concept behind this project focused on designing a correctly sized energy system for a given electrical load. This system utilized solar power to provide reliable off-grid power in a remote austere location. The main source of power for this system was from photovoltaic (PV) energy. The PV system, coupled with grid power (used to simulate a backup generator), was capable of producing up to 1500 Watts of hybrid energy. A software package developed to aide in the design and implementation of hybrid energy systems was used to model the system and identify the required components to meet the design specifications. The following is a list of components specified as well as the items locally procured and assembled for the evaluation:

Table 1: Hybrid Power System Equipment

Required Major Component	Locally Procured Item
Solar Panels Requirement: Photovoltaic panels capable of producing a total of at least 700 Watts of energy under full Sun.	 6 x solar panels 120 W each
Solar Charge Controller / Inverter Requirement: A combination solar charge controller and sine wave inverter capable of outputting at least 1000 Watts of power.	 Solar Inverter with built-in charge controller
Deep Cycle Batteries Requirement: A set of deep cycle, non-spillable batteries at least 300 AH.	 4 x deep cycle batteries. 100 AH
Wind Turbine Requirement: A wind turbine to produce power during periods of low sunlight supplementing the solar panels.	 Windmill Non-Locally available, but had system on hand and similar to locally acquired windmills.
Hybrid Energy Software Requirement: A piece of software to aide in the development of a hybrid energy system.	Hybrid Power Modeling Software

These components, along with the Data Acquisition system (DAQ), were combined into the hybrid power system depicted in Figure 1.

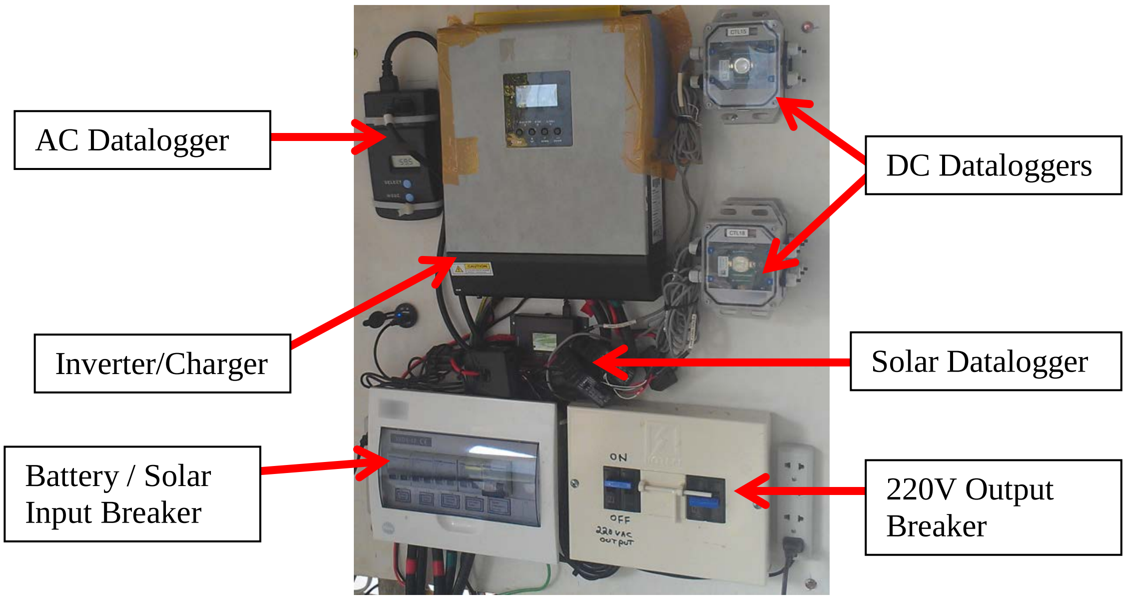


Figure 1: Hybrid Power System Electronic Components.

As seen in Figure 1 and Figure 2, the inverter/charger is the primary component of the system. Cables from the solar panels were fed into the inverter after passing through the breaker boxes for safety. Once the system was set up, the CWP HPI team set up data loggers to sense voltage and current between the breaker boxes and the inverter. The wind turbine, which was not electrically connected to the system, would have been attached to the batteries through a separate charge controller. The grid power, acting as a generator backup, was not metered via dataloggers; however, this can be indirectly calculated using data from the other loggers. The system block diagram is shown in Figure 2.

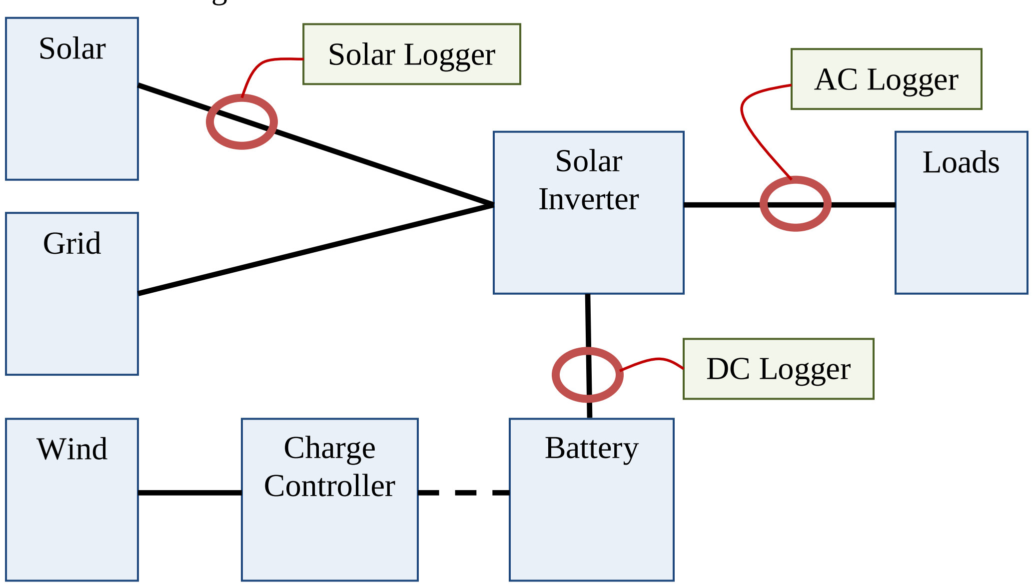


Figure 2: Hybrid Power System Block Diagram

The windmill used in this assessment was part of a separate hybrid system repurposed for this project. According to the manufacturer's specifications, the windmill can deliver 100-150 Watts (W) with winds at 25 miles per hour (mph) and 350-400 W at 35 mph. The solar panels used produce 120 W each and were set up in three parallel sets of two panels that provided up to 730 Watts under full sun. The solar panels and windmill were set up as shown in Figure 3.

Figure 3: Solar Panels and Windmill

General Evaluation Approach

To evaluate the operational performance of the HPI LOE technologies, The TROPEC FET developed the five Functional Areas listed in Table 2. Objective data was gathered via the DAQ and Event Logs. AFP personnel collected subjective data via surveys and interviews.

Table 2: CWP-HPI Functional Areas

Functional Area 1: Power Generation and Consumption
Functional Area 2: Maintenance
Functional Area 3: Deployability
Functional Area 4: Usability
Functional Area 5: Training

Acknowledgements

AFP WESCOM

- Served as host for the CWP-HPI
- Provided a list of typical power loads.
- Provided space to set up the system.
- Provided logistical support, including transportation of equipment.
- Provided operational use of the system.
- Collected subjective data via surveys and interviews

EXECUTION

Schedule

The CWP-HPI Evaluation was conducted in 3 phases. Phase 1 was the Initial Site Survey and Initial Planning Conference (IPC/ISS). During Phase 2, AFP users were trained on the set up, operation and maintenance of the energy system, and the collection of evaluation data began. Initial training surveys were completed during this phase. Phase 3 was the retrograde of equipment allowing AFP personnel to disassemble and pack all the equipment for redeployment in an Extended User Evaluation. Table 3 provides the key CWP-HPI events.

Table 3: Schedule of Events

Date	Event
3-8 August 2014	Phase I: IPC/ISS
5-15 Oct 2014	Phase II: Set up hybrid power system, trained users and administered surveys.
15 Oct-12 Dec 2014	AFP personnel conducted a two month evaluation
13-15 Dec 2014	Phase III: Retrograde DAQ and retrained AFP personnel
15 Dec 2014	AFP redeployed hybrid power system for an Extended User Evaluation

Evaluation Data Sources

Data Acquisition System

The DAQ system was used to gather objective data and capture energy production/consumption data in the form of Voltage and Current over periodic time intervals. As part of the DAQ, a weather station captured atmospheric data such as solar irradiance, wind speed, and temperature data. The DAQ system components are listed in Appendix A: DAQ System Components.

Questionnaires

AFP personnel completed questionnaires designed to gather subjective feedback to assist in the future development of HPI technologies. A separate page of the questionnaire was devoted to demographic information. Appendix B: Survey Response Charts contains the questionnaire responses.

Event Logs

Event logs were used by HPI team data collectors to gather objective data regarding the technical performance of the system. The objective data helped characterize the technical performance of the system while being operated by the end users in an operationally realistic environment.

Photographs

HPI data collectors took photographs to support the evaluation and training. The AFP ensured photographs were unclassified and are approved for release by the appropriate agencies.

Scope and Limitations

This evaluation is designed to limit cost and risk while achieving objectives. Constraints and limitations are noted in Table 4.

Table 4: Constraints and Limitations

Constraints/Limitations	Impact	Mitigation
Equipment not available to provide realistic remote austere location Load	Loading may not represent all equipment needing power.	Smaller system was developed to cover partial loading
Equipment must be available locally to AFP.	Limited equipment selection	Determined minimum components required and procured equipment locally that met the specifications

RESULTS

This section identifies how the team collected and analyzed data during the HPI LOE. The LOE was designed primarily to gather objective data and characterize the technical performance of the hybrid power system in an operational environment. Subjective user feedback was gathered to assist in the future development of the capability. While the results should not be considered conclusive based on the limited sample size and scope, the results do provide an adequate indication of the operational utility of the hybrid power system.

Functional Area 1: Power Generation and Consumption

This functional area seeks to characterize the amount of energy generated by and consumed from the hybrid power system. This was then compared to the energy model developed using the hybrid power modeling software package. The DAQ measured the energy in Watt-hours (Wh) of the system. This logger measured voltage (V) and amperage (A) produced and consumed over an extended period of time. A deployable weather station was also utilized to gather ambient temperature, relative humidity, wind speed, and solar irradiance.

Observation: PV Power Produced is roughly linear with Solar Irradiance
Discussion: The power supplied by the PV panels increased with irradiance. The graph below shows the power supplied from the PV was roughly 1/2 W for each unit of irradiance from the sun. The hybrid power system included six solar panels rated at 120 W. Accounting for the quality of PV panels and environmental conditions throughout the evaluation, this is within expectations. As shown in Figure 4, data points following a horizontal line around 50 W indicate periods where the batteries were fully charged. At this point, the PV panels supplied the 60 W load directly.

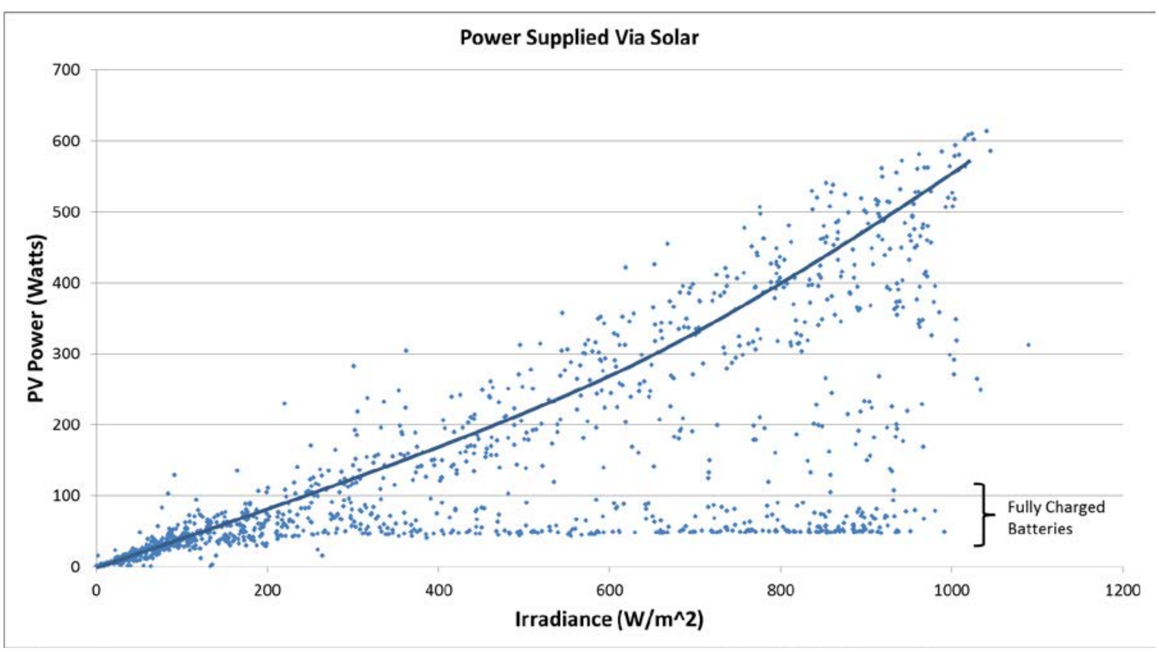


Figure 4: PV Power vs Solar Irradiance

Observation: The hybrid power system was not operated at its maximum designed load.
Discussion: During the evaluation, the maximum power logged was 570 W, likely powering high intensity lights. Average power consumed was 41 W, likely powering an electric fan and minor electronics. The bulk of the AC load consisted of a 60 W fan, several light bulbs, and two cell phone battery chargers. As an experiment, a 1000 W convection stove was connected to the system to cook food and boil water. While connected with other loads, the output of the hybrid power system was observed to be 1506 W, most of which was supplied by the fully charged batteries. However, as seen in Figure 6, the majority of data points fall below a 150 Watts.

Figure 5: 1500W reading on AC Logger

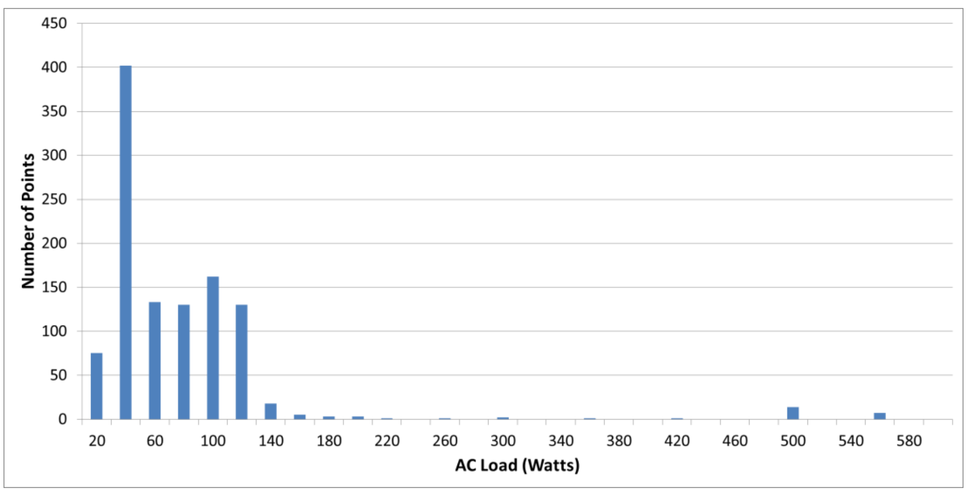


Figure 6: AC Load Histogram

Observation: The batteries were charged during daylight hours.
Discussion: Figure 7 depicts the average daily profile of the battery current. Positive values indicate the batteries are charging. Negative values indicate the load is drawing current from the batteries, therefore draining them. During the day, the solar panels provided enough energy to simultaneously power the load and charge the batteries. The boxes in the figure represent the first and third quartile of the data during the specific time interval; 50 % of the data falls within this range. The thin lines on top and bottom represent the minimum and maximum values. Data in this figure does not include battery charging via the grid.

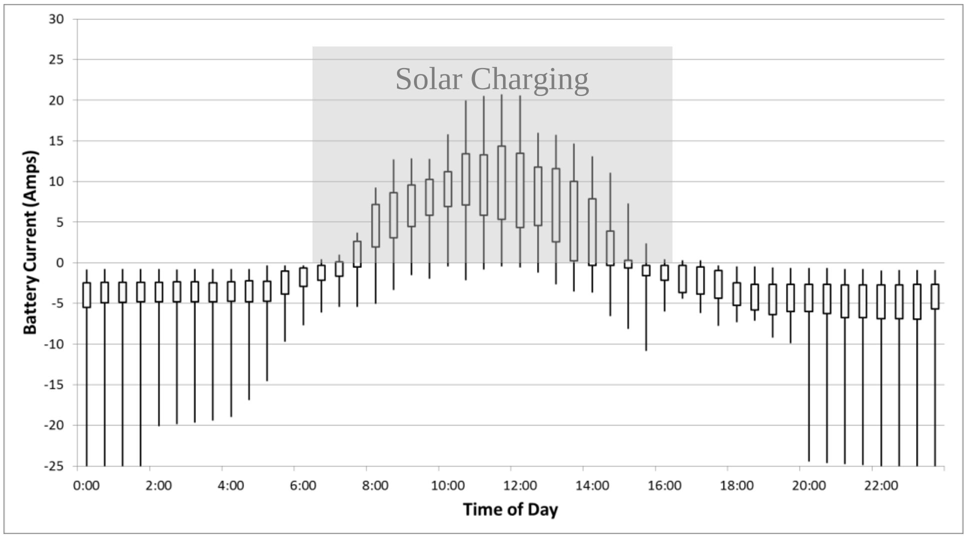


Figure 7: Battery Current

With such a small load on the system, the batteries were never depleted while the solar panels remained fully operational. The batteries maintained some charge during periods of extended cloud cover from 1-3 November. During this time, the batteries were the primary source for energy both day and night and still held enough power to avoid a system shut down. Assuming depleted batteries and no load, the solar panels are capable of fully charging the batteries in 4.5 days. This was calculated by taking the battery capacity, 400 Ah at 24 V, and dividing by the average PV power produced per day, 2186.3 Wh/day.

Observation: Energy was required from a back-up system to ensure uninterrupted operation.
Discussion: In lieu of a generator, 220 V electric grid power was connected to the system. In a remote austere location where grid power is not available, a gas/diesel powered generator might be used as a back-up power source. For this evaluation, grid power, rather than a generator, was utilized via a manual switch. Grid power was only used when the batteries were near depletion. Also, it should be noted that grid power was only used during nighttime hours. Based on the average power draw of 41 Watts, the batteries alone theoretically could last 9 days before being depleted. Alternatively, at 500 W, the batteries would only last 19 hours. Grid power was used to aide in charging the system during periods of degraded solar power.

$$\frac{Battery\ Capacity * Battery\ Voltage}{Average\ Load} = \frac{400\ Ah * 24\ V}{41\ W} * \frac{1\ day}{24\ h}$$

$$= \frac{9600\ Wh\ days}{984\ Wh} = 9.75\ days$$

Observation: The windmill was not operational due to voltage incompatibility.
Discussion: Due to the proprietary design of the hybrid windmill system, HPI personnel were unable to electrically connect it to the hybrid power system. Further, the windmill operates at 12V DC, while the HPI system utilized a 24V DC system and the team did not want to cut into the proprietary system to rewire it. Regardless, the windmill component was erected and the HPI team taught AFP personnel how to theoretically connect it to the hybrid power system. AFP students understood the need for an additional charge controller to interface a store bought windmill with the batteries.

Observation: During the evaluation wind speed was too low to generate power.
Discussion: According to the windmill manufacturer's specification sheets, the windmill should produce 100-150 W at 25 mph, and 350-400 W at 35 mph. Figure 8 shows the average wind speed throughout the day. As shown, the average wind speed was consistently around 10 mph over an average 24 hour period. This correlates to the generation of approximately 9 W, based on a theoretical power generation profile and adjusted for the size of this windmill, as seen in Figure 10.

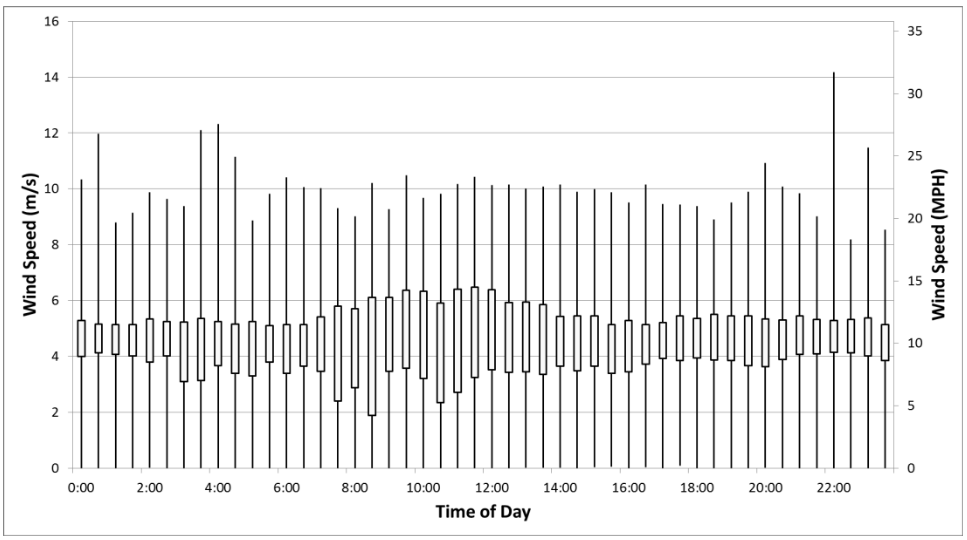


Figure 8: Wind Speed Profile

However, across the evaluation period, wind speed was more variable. Figure 9 shows wind speed over time. During the period between 14-16 October, wind speed averaged about 8.5 m/s. At this wind speed, the windmill should produce about 6 W of power to the system. Overall the windmill would not have produced a significant amount of power. This may be due to the selected location since it was bordered by numerous trees. However, it is likely in remote conditions, there will be similar obstructions. If the windmill was taller and capable of operating at lower wind speeds it should provide more energy.

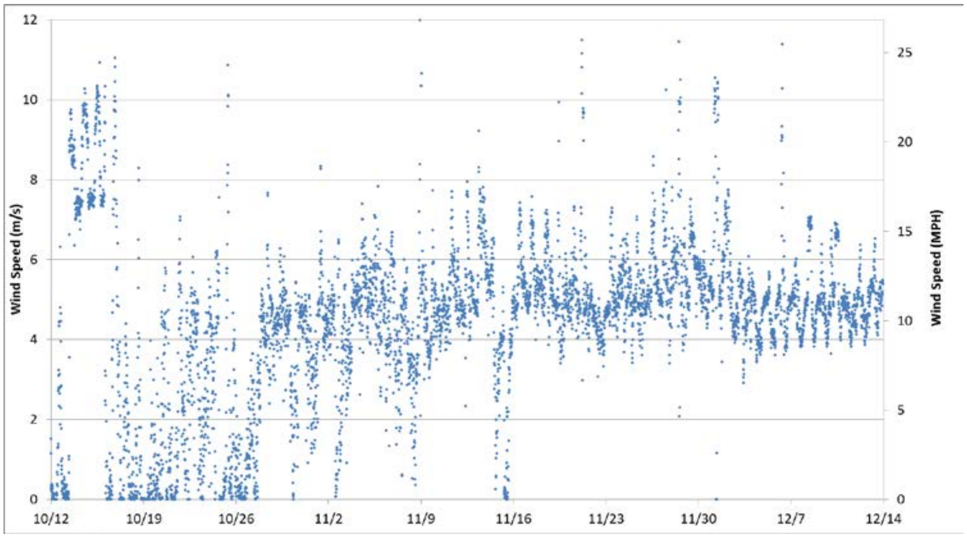


Figure 9: Wind Speed vs Time

The theoretical power generation profile for this windmill is depicted in Figure 10. As shown, wind speed would have to consistently reach 20 MPH to match the 50W load on the system. This would be enough to power the average loads observed, but would not recharge the batteries or handle higher loads without an additional power source.

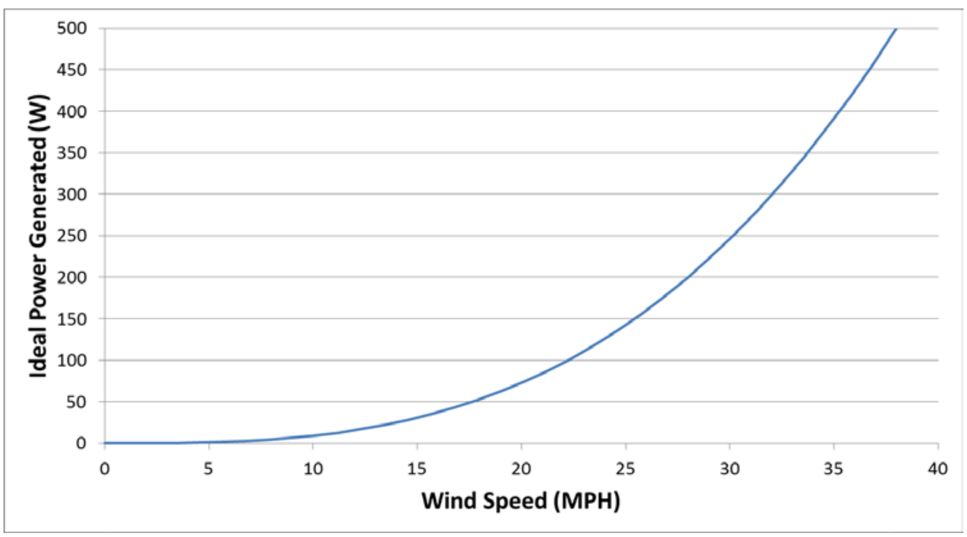


Figure 10: Theoretical Wind Turbine Power Profile

Functional Area 2: Maintainability

This functional area seeks to characterize the maintainability of the hybrid power system. The reliability and durability of the equipment was evaluated through user feedback and data collector observations. Environmental impact on the hybrid power system was also evaluated through user feedback. Reliability was determined by the number of failures of the system over the evaluation period. Maintainability of the system was determined by the number of maintenance actions performed throughout the evaluation period.

Observation: The hybrid power system operated for two months with one malfunction.
Discussion: Around 11 November, approximately half way through the evaluation, a circuit breaker tripped causing the entire system to shut down. This was likely due to a short circuit resulting from water infiltration somewhere in the solar panel wiring. Upon inspection of the wiring, water was found to have penetrated a junction box where the PV panels were connected. The connections were allowed to dry and were subsequently reconnected to the system. Normal PV wattage levels were then observed, but due to time constraints, the system was not run long enough to fully determine if the repair was successful. Figure 11 depicts the PV output in Watts. As shown, the power supplied by the solar panels drops around November 16 and does not return. Solar irradiance continued to maintain normal levels; however, PV wattage did not. Due to this electrical short, much of the power produced by the solar panels was wasted and could not be used to power the system. Data from this period of degraded operation was not included in Figure 7: Battery Current.

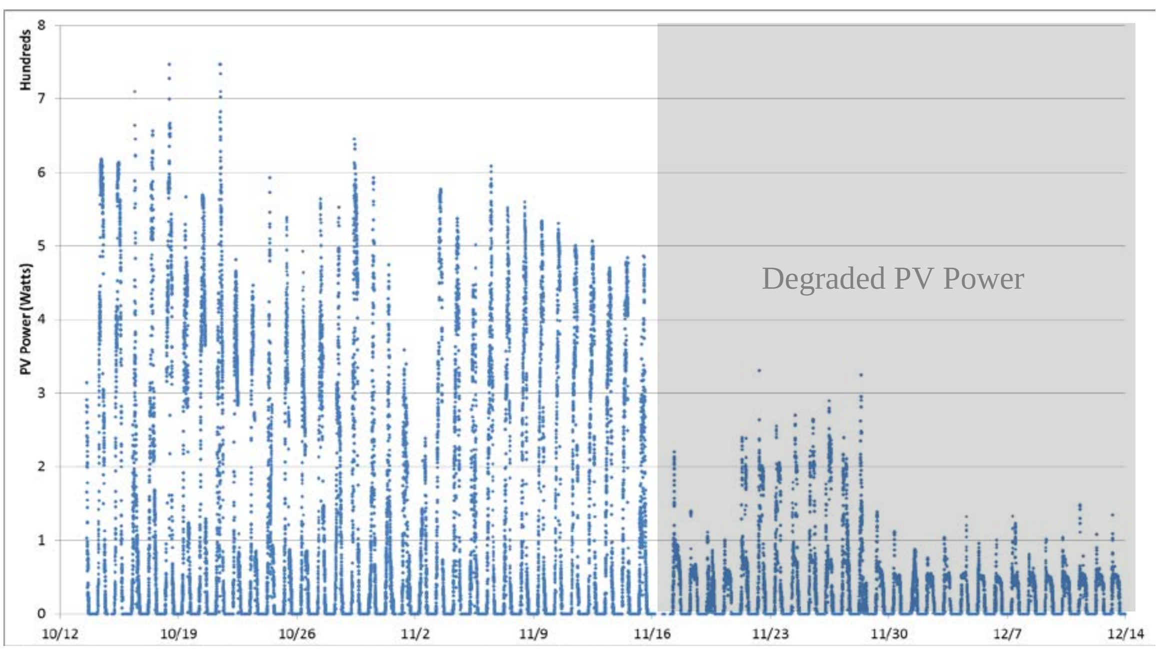


Figure 11: PV Power vs Time

Functional Area 3: Deployability

This Functional Area seeks to characterize the size, weight, and bulk or volume of the hybrid power system. The total cubic feet and weight of the system determines the minimal transportation requirements. The number of people required to operate the system includes those personnel required to build/set up and operate the technology. Durability was evaluated through user feedback and is defined as how well the system held up under the environmental and transportation stresses.

Observation: In all, the components were about 32 cubic feet in volume and weighed about 550 lbs.
Discussion: The hybrid power system components consisted of six solar panels with a bamboo frame, four wet cell batteries, a control panel box with inverter and charge controller, and various switches with cables/wires attached to it. The solar panels were attached to a support frame made of bamboo. The system control panel, which was comprised of the inverter with built-in charge controller and other switches, was mounted on a wooden board. The control panel was enclosed in a wooden box with a hinged plastic cover to protect it from the environment.

Observation: Two people were required to set up the hybrid power system.
Discussion: It was observed that two people are capable of setting up the hybrid power system in a couple hours. Once the system was operational, only one person is required to conduct system monitoring to ensure all components function as required. Even then, the system is self-regulating and required only minimal human presence when an alarm was tripped.

Functional Area 4: Usability

This functional area seeks to characterize the ease of use of the hybrid energy system and the HOMER software. Usability is an umbrella term for several areas of evaluation that can include human performance, technology design, and human-computer interaction. Usability of the hybrid power system was determined by relying on subjective feedback from AFP personnel gathered via interviews and questionnaires. Appendix B: Survey Response Charts contains the interview responses.

Observation: Users strongly agreed that they felt capable using the hybrid power modeling software.
Discussion AFP personnel were given basic working knowledge on how to use the hybrid power modeling software. Survey responses indicate that 11 out of 12 respondents believe they are capable of using the hybrid power modeling software.

Observation: Users are confident in their ability to operate the hybrid power system.
Discussion: Feedback from the questionnaires indicated that the AFP personnel who were trained are confident that they will be able to easily operate and maintain the hybrid power system. Survey results indicated all respondents are confident in operating the hybrid power system on their own. WESCOM intends to deploy this system in a remote location as part of an Extended User Evaluation. This plan will be an opportunity for extended operational use and is expected to yield the desired data that will validate the usability of this hybrid system.

Functional Area 5: Training

The suitability of training and supporting documentation has been determined by collecting subjective data in the form of surveys and data collector observations. AFP personnel have rated the adequacy and time allocated for demonstration and hands-on training as well as the adequacy of the equipment/components and training material. Appendix B: Survey Response Charts contains the survey responses.

Observation: AFP personnel were confident in planning a hybrid power system and using the hybrid power modeling software.
Discussion: The HPI subject matter expert demonstrated and trained AFP personnel on the hybrid system by discussing the different components, their functions and how to assemble and set up the system. AFP personnel were given a thorough demonstration of how the system works and then the students were given the time to have actual hands on operation of the system. The survey responses showed that all respondents were confident in planning for a hybrid power system; and 11 of 12 were confident in training others. Personnel were confident in the planning of the hybrid power system; some said they would use the “knowledge to plan to install solar power at home.”

Observation: Users felt confident they could procure the required components for a hybrid power system.
Discussion: All components required to assemble and set up the hybrid power system were purchased from a local supplier. The tools required to set up the system were also readily available at a local hardware store. From the surveys, all respondents were confident in their ability to procure the components required for a hybrid power system.

CONCLUSION AND RECOMMENDATIONS

Conclusion

WESCOM leadership desires to continue the project to gain additional experience in operating and maintaining renewable hybrid power systems. In the January – May 2015 timeframe, the AFP conducted an Extended User Evaluation. The AFP plans to disassemble, pack, transport, set up, operate, and maintain the system in an operationally realistic environment. Further, the AFP has expressed keen interest in continuing the CWP with other capabilities such as water purification that would build on the initial renewable hybrid energy CWP-HPI.

The AFP personnel who were trained gave positive feedback that they were confident and capable to be able to assemble, set up, operate and maintain a hybrid power system. The same AFP personnel also expressed confidence in training others. The availability of all the required components locally was a significant factor in this success.

Recommendations

Based on the results, the CWP-HPI team makes the following recommendations:

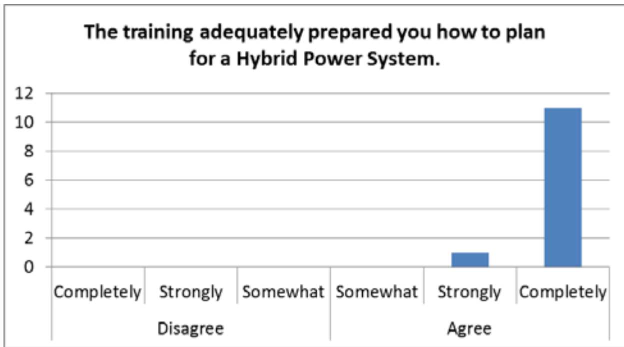
- Deploy this system to remote austere locations to gather more data on operational efficiency, reliability and durability under environmental and transportation stresses.
- Junction boxes and other electrical connections must be insulated to protect them from the weather and environmental elements which may cause the system to fail.
- The incorporation of a water purification system into the set-up would be tremendously beneficial, especially in remote austere locations where drinking water is not readily available.
- Connect a windmill to the system to assess additional benefit to the set-up.
- Incorporate a small gas or diesel generator as a back-up power source for mission critical operations.

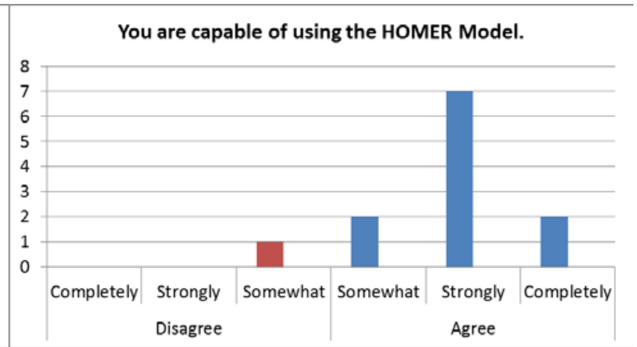
APPENDIX

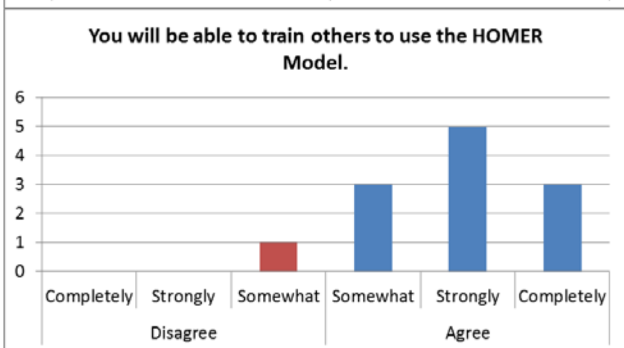
Appendix A: DAQ System Components

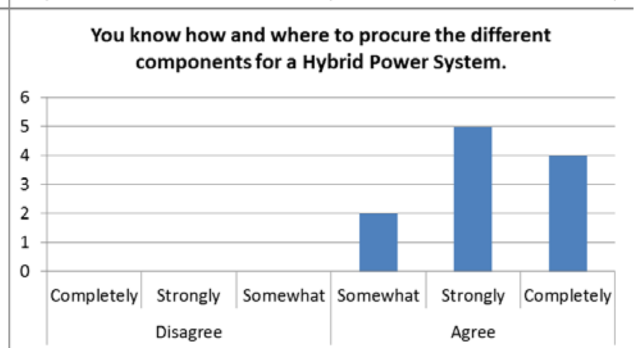
	**Equipment**: AC datalogger **Data Collected**: AC Power (kW)
	**Equipment**: Weather Sensor and Data Logger Pyranometer Solar Panel Tripod Kit **Data Collected**: Temperature, relative humidity, rain, wind, barometric pressure and solar irradiation
	**Equipment**: Voltage sensing Data Logger DC Current Transducer **Data Collected**: DC Current
	**Equipment** Datalogger offloading device **Data Collected**: Download data from datalogging equipment

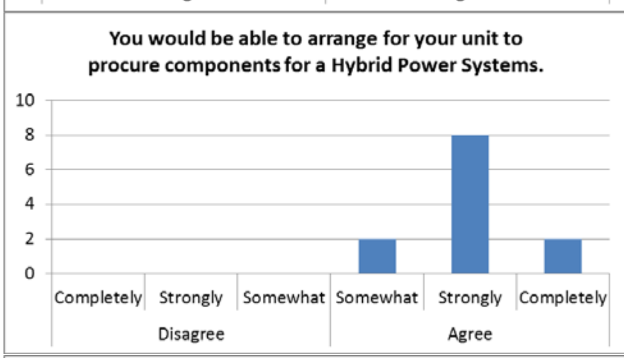
Appendix B: Survey Response Charts

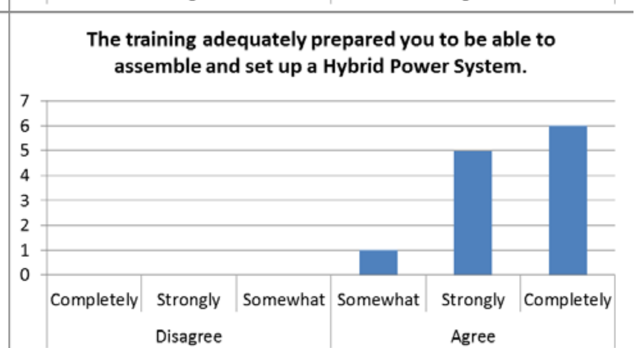


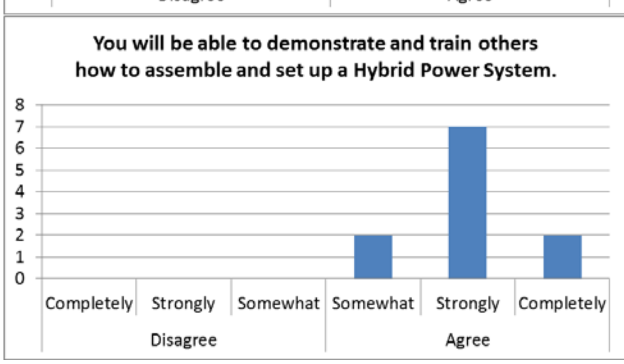


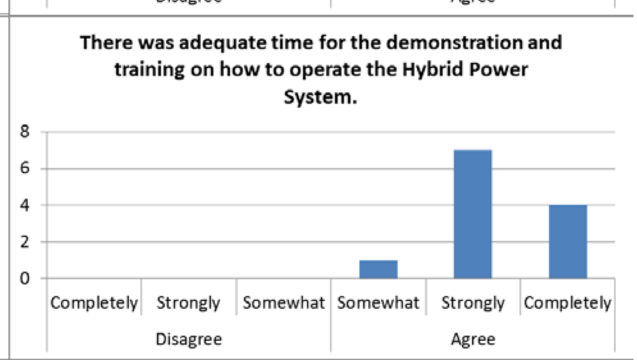


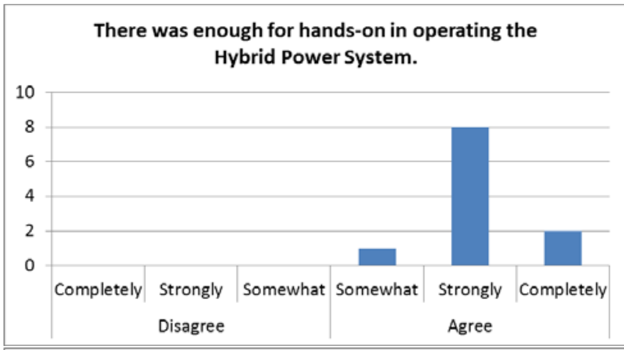


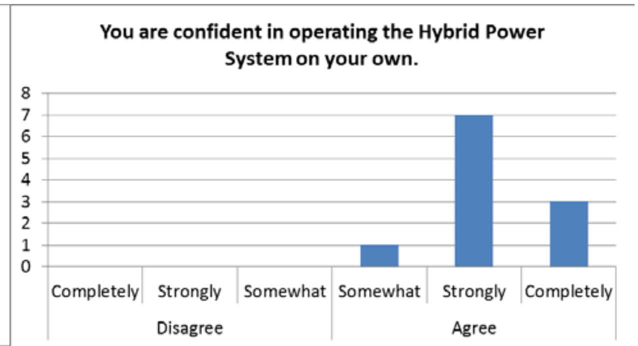


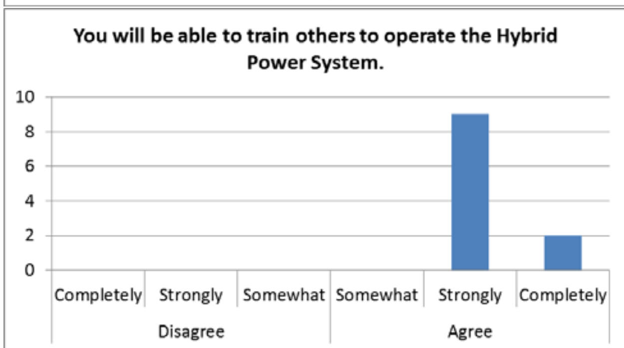


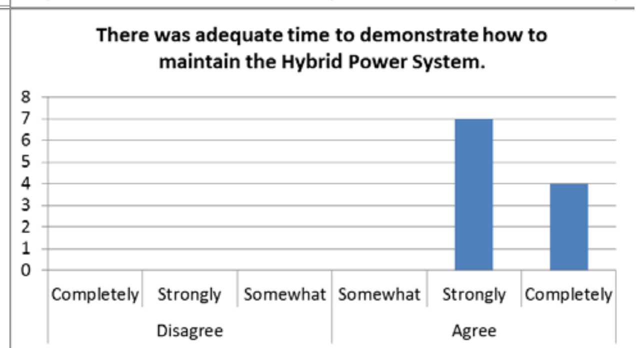


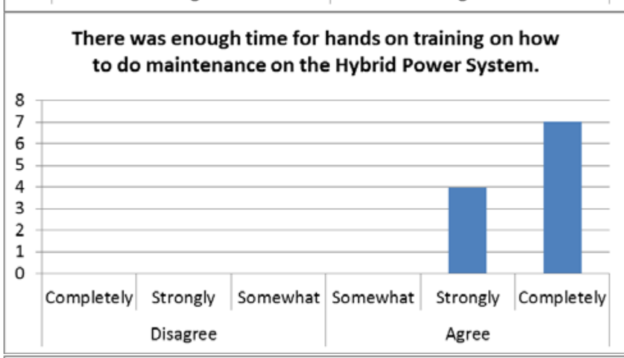


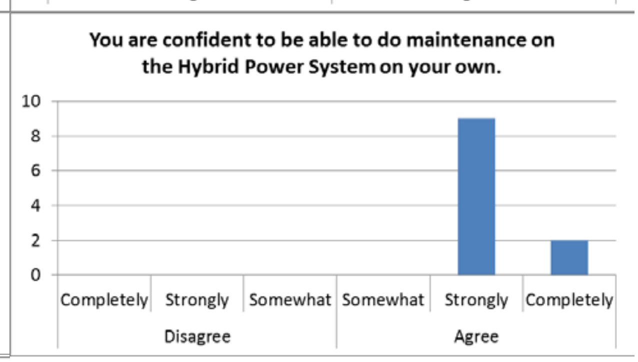

There was enough for hands-on in operating the Hybrid Power System.
0 2 4 6 8 10
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree

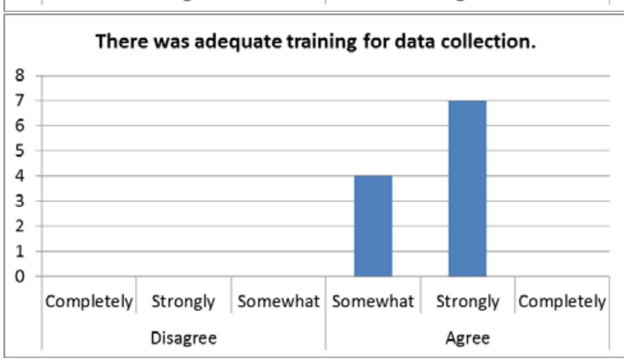

You are confident in operating the Hybrid Power System on your own.
0 1 2 3 4 5 6 7 8
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree


You will be able to train others to operate the Hybrid Power System.
0 2 4 6 8 10
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree


There was adequate time to demonstrate how to maintain the Hybrid Power System.
0 1 2 3 4 5 6 7 8
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree


There was enough time for hands on training on how to do maintenance on the Hybrid Power System.
0 1 2 3 4 5 6 7 8
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree


You are confident to be able to do maintenance on the Hybrid Power System on your own.
0 2 4 6 8 10
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree


There was adequate training for data collection.
0 1 2 3 4 5 6 7 8
Completely Strongly Somewhat
Disagree
Somewhat Strongly Completely
Agree