Planetary Habitat Systems Monitoring On a Mars Analog Mission

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Abstract

The NASA funded HI-SEAS (Hawaii Space Exploration Analog and Simulation) is a planetary surface exploration analog site at ~8500 feet on the Mauna Loa side of the saddle area on the Big Island of Hawaii. This first mission will involve six astronaut-like (in terms of education, experience, and attitude) crew members living in the habitat for 120 days under Mars-exploration conditions. The habitat itself has been outfitted with a variety of real time sensors for water, heat, and energy consumption. This data shows a variety of traits within habitat living conditions that can be utilized for energy and water conservation. This mission started in February and will conclude on August 13th. Data of this type will give a picture of what resources are required for exploration or colonization on other planetary bodies. Future steps for habitat monitoring will be presenting outlining a data fusion model. This model will incorporate fuzzy logic for a centralized intelligent monitoring system.

Keywords
mars, analog, sensors, telemetry, habitat, planetary

1. Introduction

Telemetry data for planetary simulations or more specifically water and energy consumption are analyzed from the Hawaii Space Exploration and Analog Simulation (HI-SEAS) which was a 120 day analog mission located on the Big Island of Hawaii in the saddle area on the Mona Loa side. The flagship study for this project funded by NASA was to study food and the differences between pre-prepared and the cooking of five year shelf stable ingredients during an analog mission. The six member crew was selected for their astronaut like qualifications, and subjected to living and working conditions expected on a mission to Mars. The resources that are required by the crew for living and working are revealed during the four month experiment through the collection and analysis of resource usage. To collect these resources a variety of real time sensors have been placed in the system.

Figure 1: HI-SEAS habitat on Mauna Loa volcano

Mars Analog missions have been collecting resource usage in past. The Flashline Mars Arctic Research Station (FMARS) regularly collects water consumption and usage data, along with the Mars Desert Research Station (MDRS). This data collection is done along the lines of manual measurements of resource usage leading to rough approximations of data. The amount of diesel fuel burned by the generator can be used to estimate the amount of power used by the crew. However this does not account for the 'idle' time of the generator, nor the amount of time of draw in high power usage. The amount of water used per day in the main tank can be used to measure water consumption. However, this does not have refined enough data to determine the amount of water used in cooking verses showers by crew members.

The HI-SEAS habitat was outfitted with a number of sensors that allowed for detailed examination of water usage and power consumption to a resolution of five minutes or less. This was achieved through a number of sensors placed throughout the habitat that were collected and streamed to off-site data repositories. Upon the completion of this Mars analog mission, data analysis has shown that routines and rhythms in the habitat allow for modeling and prediction of resource usage. The power needs of a crew of this size have been captured accurately for the first time, and utilizing this data missions can use this data as a benchmark for future missions.

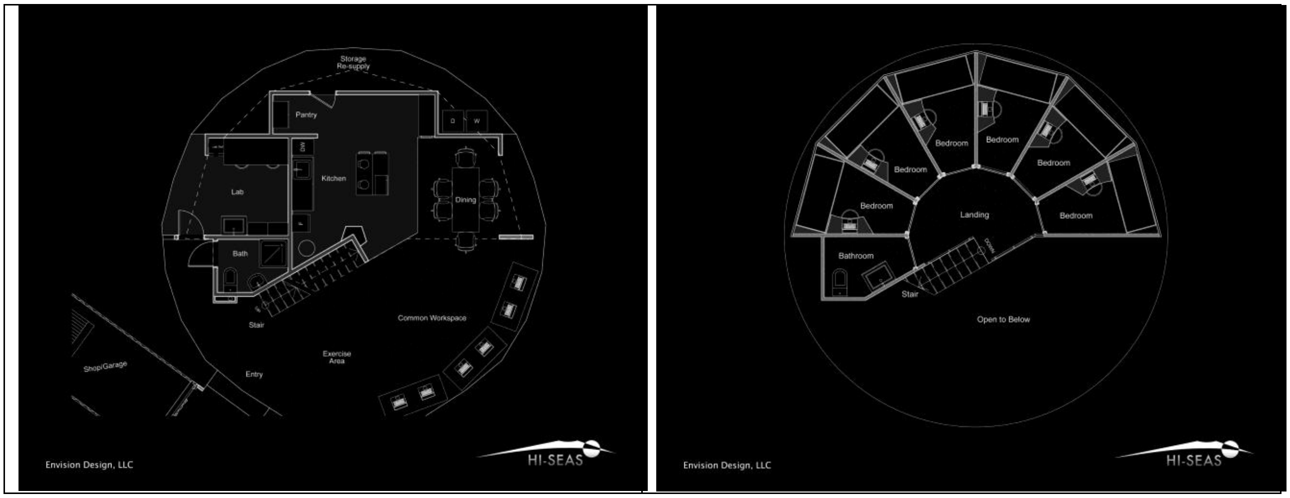


Figure 2: Schematics of the downstairs and upstairs interior of the habitat

2. HI-SEAS habitat

The HI-SEAS habitat is a 36-foot diameter dome that has two levels. The main floor consists of a work area, kitchen, dining room, laboratory, bathroom with shower. It is attached to an 8-foot square airlock that is connected to a 20 foot sea container. There is a portion of the dome blocked off by a back door. This area contains the washer and dryer, and the networking/telemetry room. The area of the first floor is 878-square feet that are usable, however it totals 993-square feet.

The habitat is supplied by a Hybrid Generator from Planetary power, and a Honda Backup generator. It has a 500 gallon main water tank with a 250 gallon backup tank. The septic tank consists of two 250 gallon tanks that are fed by a bifurcation in the outgoing pipe. At the time of writing this document, the septic tank is fed by all habitat systems, except the washing machine. The washing machine water goes into the grey tank. This system setup will change to a more efficient one in the future.

2.1 Main Tank


Figure 3: HI-SEAS crew member taking physical measurement of water tank. The yellow simulation suit is a modified bio-hazard suit. Dr. Sian Proctor

The main water tank is a 500 gallon water tank. It uses a ultrasonic level sensor that can detect the water level down to the nearest millimeter. Unfortunately, then water level sensor was subject to calibration issues due to the physical disruption of the sensor caused by refilling the water tank. However, despite the calibration issue, the level sensor was very accurate in determining the change of water depth in the tank from one point to another. Taking a physical measurement once per day allowed one to keep an accurate picture of the amount of water in the tank, while the depth sensor was able to track the rate of water usage in five minute intervals.

Physical measurement of the tank occurred once per day. The crew engineer would exit the habitat in a simulation suit (often a modified bio-hazard suit) and measure the level of water from the top. Using this information the amount of water in the tank is calculated to an accuracy within five liters.

2.2 Backup tank

The backup tank was a 250 gallon (946 L) tank thank had a ruled gauge on the side of it. If the main tank fell in short supply the crew engineer would have to transfer water from the backup tank by manually placing a water pump in-between the two tanks. Dominantly, this tank was dormant for the majority of the mission.

Figure 4: The 250 gallon (946 L) backup tank with graduated measure on the side of the tank highlighted. Photo Credit: Dr. Sian Proctor

2.3 Septic tank

The septic tank consists two 250 gallon (946 L) tanks. At the current setup of the habitat plumbing, all water minus water from the washing machine flows into the septic tank. The tank did not have a meter and required manual measurements for data collection. The translucent material would show the water level inside the septic tank. By measuring the height of the waterline, the volume of sewage inside the tank could be calculated.

Figure 5 The 500 gallon (1893 L) septic tank being manually measured for its current capacity. Photo Credit: Dr. Sian Proctor

2.4 Gray water tank

The 250 gallon (946 L) grey water tank was filled entirely be the habitat washing machine. Since the septic tank was drained every six days, so was the grey water tank. The graph in Figure X shows the level of the septic tank over time. The crew used an average of XX gallons per week. The crew was restricted to one wash per week with the washing schedule spread out by allowing only one wash per day.

Figure 6 The 250 gallon grey water tank. Measurements were manual using graded markings on side of the tank. Photo Credit: Dr. Sian Proctor

The current washing machine has proven to be highly inefficient using up to 60 gallons of water for a full wash. It was determined that the washing machine would use 16 gallons per wash on the 'small load' setting. This required the crew to be a bit strategic with the laundry machine.

2.5 Planetary power generator

The HyGen system is a trailer with photovoltaic (PV) solar panels. It utilizes a three cylinder disel enginer that is turbocharged to ensure power output is sufficient for an altitude of up to 9000 feet. [2] The generator will produce 90 Hz power output that is converted to alternating current (AC) and direct current (DC) from 350VAC to 395VDC. The direct current is passed through an inverter and converted to 120/208 VAC. The excess power is stored in Lithium Ion (Li-Ion) batteries with a capacity of 7 kWh. The solar panels seen in Image X can produce up to 3kW that is used to charge the batteries. The HyGen is serviced by refueling the diesel supply and monitoring the oil levels of the diesel engine. [2]

Figure 7: Planetary Power generator seen with the Honda backup generator

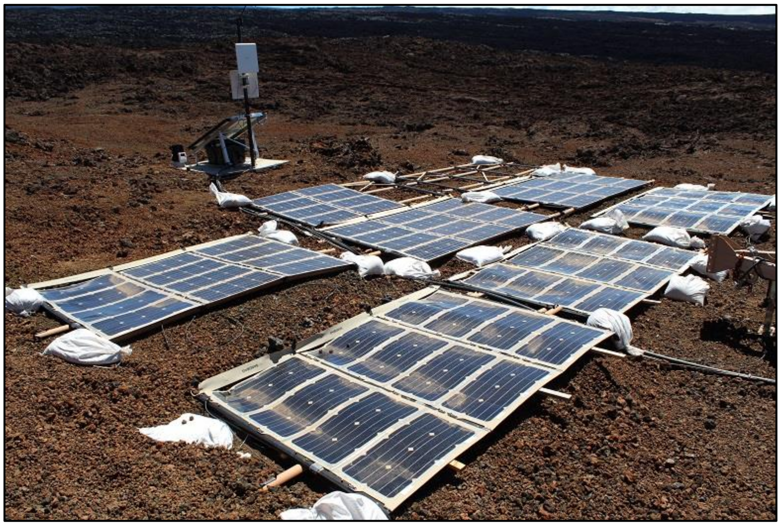


Figure 8 Solar panels provided potential voltage power to the hybrid generator. Photo Credit: Simon Engler

2.6 Backup generator

The backup generator was a Honda EB5000 which output 5000 watts at 120V and 240V. Provides 7,000 watts for 10 secs to start larger equipment. Honda commercial iGX engine and heavy duty frame with Long run time - up to 11.2 hrs and a 120/240V selector switch. When the Planetary Power generator had issues, the Honda generator was used to power the habitat. The generator did well supplying power for a number of days at a time. It would consistently burn 13.5 gallons/day of gasoline. [2]

2.7 Solar water heater

Hot water for the habitat was provided by a solar water heater. This solar water heater would heat water contained in a 150 gallon insulated tank. Hot water was available to the crew well after sundown. This was a passive system and required no maintenance from the crew Engineer. The daily cycle of temperature of the solar heater can be seen in the temperature telemetry of hot and cold water tanks.

Figure 9: The 150 gallon solar water heater. Photo Credit: Simon Engler

2.8 Habitat appliances

Appliances in the habitat consisted of off the shelf equipment that you would find in any home. To measure the power consumption of each appliance in the kitchen, a power gauge was used to measure the average power consumption per week. Table 1 lists the measured average of kWh per week for each appliance in the habitat kitchen.

Appliance	kWh/week
Induction plates (3)	594
Microwave	200
Oven	50
Bread maker	25
Kettle	250
Coffee maker	60

Table 1: Measured weekly power consumption from habitat appliances.

3. Habitat crew routine

The crew would follow a weekly routine that was dominantly consistent. Often patterns in the usage of power and water can be seen to coincide with the schedule of activities within the habitat. The daily schedule was broken down as follows.

Morning workout	0730 - 0815
Breakfast	0830 - 0915

Morning meeting	0930 - 1045 (Average)
Mid-morning workout	1100 - 1200
Morning research	1200 - 1300
Lunch	1300 - 1400
Afternoon research	1400 - 1830
Dinner	1900 - 2000
Free time	2000 - 2200
Quiet hours	2200 - 0730

Table 2: Crew daily routine in the habitat

From this the day can be broken up into four blocks that are used in analysis to evaluate power and water consumption in certain parts of this document.

Morning block	0730 - 1230
Lunch block	1400 - 1630
Dinner block	1700 - 2200
Evening block	2000 - 0730

Table 3: Time blocks used in data analysis

4. Habitat sensor systems

The habitat system was outfitted with a sensor telemetry routing system. A ControlByWeb X-310 web interface was utilized to control and collect sensor information and distribute to a remote location. The X-319 is a Ethernet I/O module with four digital inputs that allows for support of up to four temperature and humidity sensors. It also has the ability to control remote relays which allowed the crew to control in air intake/outtake fan. This sensor was interfaced by the web and could be controlled externally to the environment. It has a built in web-server which allows for direct connection to the module and allows for eternal control in this manner. Using this technology, the habitat was enabled to monitor and log power supply using a customization through a web based control page. Software allowed for graphing of telemetry and also the extraction of the data into CVS files allowed for statistical analysis.

Figure 10: The ControlByWeb X310 Telemetry router

4.1 Sensors and their locations

Sensors were located in a variety of spots in the habitat. All power consumption was routed through a X-310 module attached from each circuit breaker. This was broken up into the Laundry room, Downstairs washroom and laboratory, Upstairs rooms and bathrooms, Living Room, Dining Room, and Kitchen. Power used in any of these areas could be monitored separately. A carbon-dioxide sensor was placed in the dining area of the dome. Temperature sensors were then placed in the Dining Room, One of the bedrooms, and the telemetry room. The main water tank had a laser level sensor, and the Planetary Power Generator computer was able to monitor and track power generation and distribution on its own.

4.2 Telemetry

The habitat has two different data links, one for Internet and one for the telemetry. An internet base antenna was placed at the habitat. Another antenna was placed in the Mona Loa Observatory (MLO). A third antenna was placed at the Hawaii Preparatory Academy (HPA). The first link goes from the habitat to MLO to HPA. It is meant to relay telemetry of the habitat and provide backup communication. This link is a A 5.8 GHz 802.11n WAN connection with speeds up to 300 mb/s is transmitted with -50 dB signal strength using a MiMo panel antenna (21 dB) with UBNT Powerbridge units from the Habitat 20 km southeast to the NOAA Mauna Loa Observatory (MLO). [1] From MLO, a pair of 24 dB antennas with UBNT Bullet2HP units then splits the signal into two parallel paths and transmits them with -64 dB signal strength 60 km north to the Hawai'i Preparatory Academy (HPA) on redundant 2.4 GHz 802.11g connections with speeds up to 54 mb/s. [1] The second data link goes from the habitat to Hale Pohaku (HP) on the slope of Mauna Kea. It serves at the primary internet connection and ftp server.

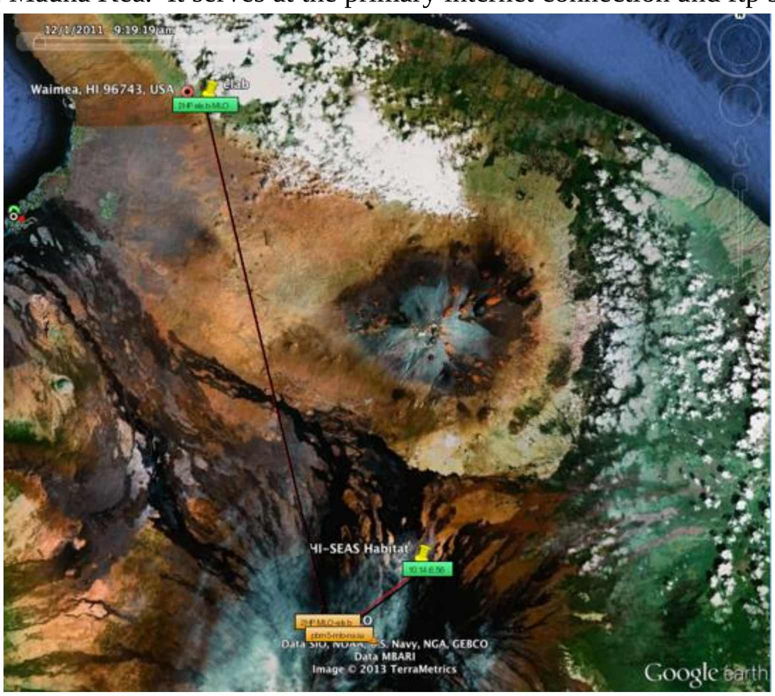


Figure 11: The Hab-MLO-HPA link as shown linking to the HPA over 60 km away [1]

4.3 Sensors and daily rhythm

With water, electricity, and CO2 sensors collecting data every five minutes, it is possible to see the changes that crew members have on the habitat. It was quickly noticed that the habitat had its own rhythm of water usage and crew activity. Water usage followed a repeated cycle over a period of about four days. Figure X shows how the water level is diminished to a nearly empty tank over a period of four days. One of the easiest activities to spot is when the crew wakes or goes to sleep. This is evident simply from the water not being used anymore for long durations.

From the CO2 sensors, the daily cycle and activities of the crew can be determined. When the crew went to sleep they would shut their bedroom doors. This would trap most of the CO2 in their rooms, which would be vented to the outside. As a result, the CO2 levels in the habitat would drop considerably. One can see times that crew members used the restrooms during the evenings by the slight temporary increase in CO2 levels. Once the crew woke up for the day, some members of the crew would engage in their morning workouts. The crew activity would drive the CO2 levels in the habitat up to its highest point of the day. Afterwards, the CO2 levels would drop again once breakfast and the morning meeting had concluded. The crew would then go about their daily business causing fluctuations in the CO2 levels until they went to bed for the evening.

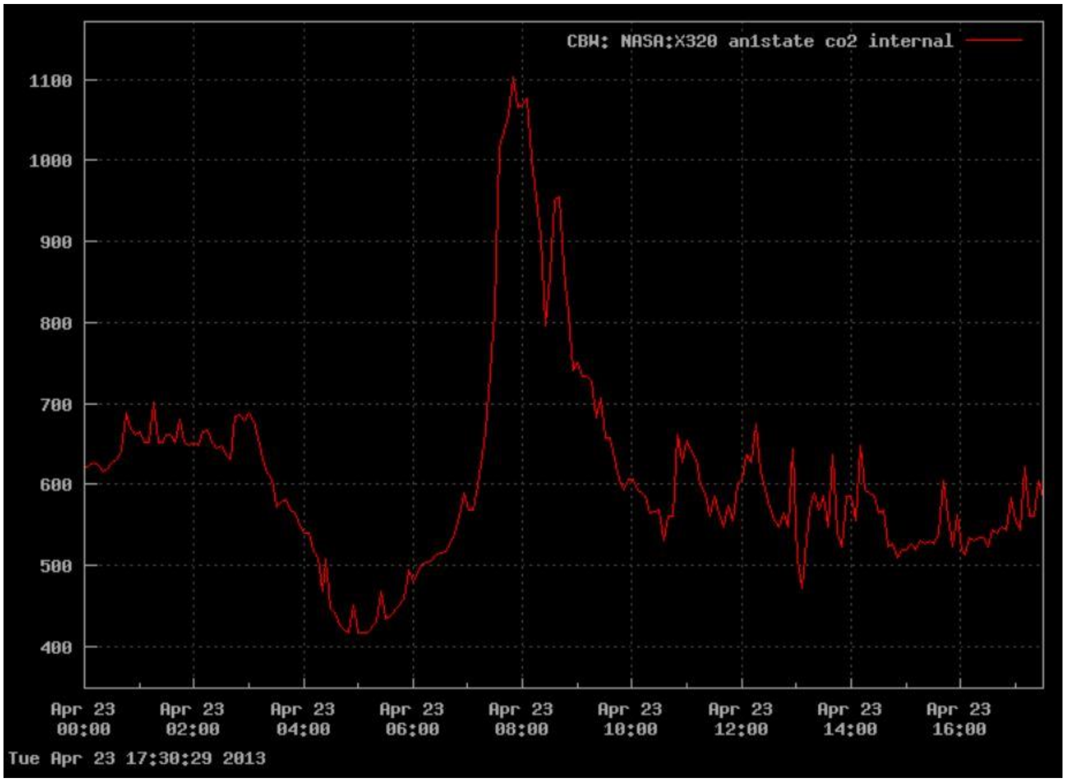


Figure 12: CO2 sensor cycle in the habitat. It is possible to identify crew activities by the changes in the CO2 levels.

These cycles of CO2, water, and electricity usage can be seen in all aspects of the habitat life. Using this information, it should allow for predictions of energy and water usage to a highly accurate degree.

5. Telemetry data analysis

The following diagrams display the data collected from the habitat over the entire four month experiment. The analysis of the data shows the overall usage of water and power, and reveals tendencies and patterns of crew usage.

5.1 Planetary power generator performance

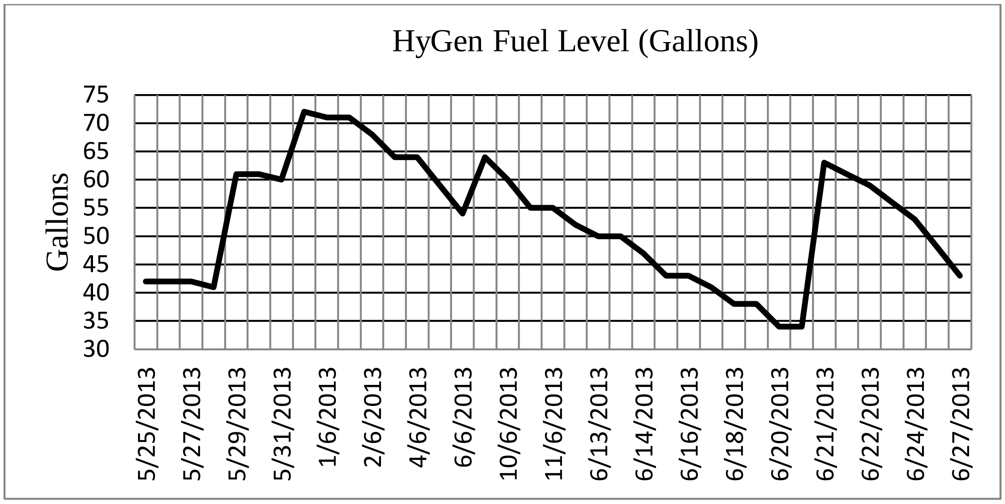


Figure 13: Planetary Power HyGen generator diesel level

Figure 11 displays the performance of the Planetary Power HygGen generator. Performance is directly related to the power usage within the habitat, and the amount of energy collected from the solar panels. Overall, the fuel capacity of the diesel generator was kept high to maintain performance. The average level of diesel fuel was 52.9 gallons with a standard deviation of 9.3 gallons.

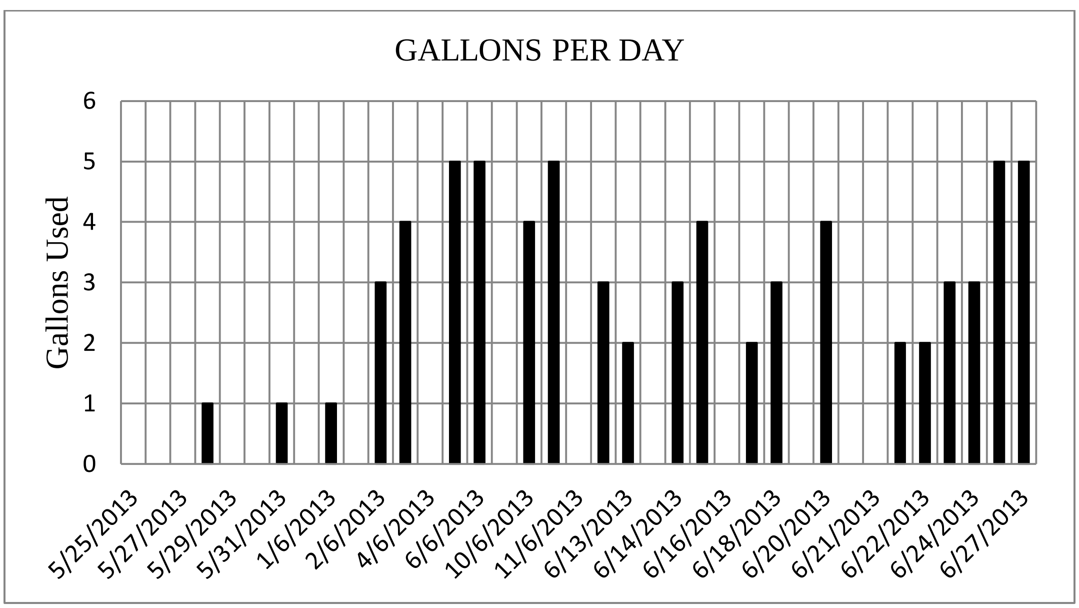


Figure 14: HyGen daily diesel burn rate.

Figure **14** displays the number of gallons burned by the HyGen generator. The average daily burn rate was 3.2 gallons with a standard deviation of 1.12 gallons. The variance in the burn rate was dominantly due to variations in solar energy obtained from the PV panels.

6. Water consumption

Water consumption data is collected by the water level sensor every five minutes. Figure 16 displays the water data usage over a 24-hour period for the entire four month mission.

Looking at Figure 15, one can easily identify areas of high water usage. Dominantly water usage for breakfast, lunch, and dinner can be identified as the most active times. The average water consumption over a five minute period was 1.16 gallons, with a standard deviation of 1.37 gallons. The total amount of water used in the mission during this time block is 26, 523 gallons. Also, between 12:00 PM – 7:00 PM the water usage of the crew appears to be consistently high over the duration of the mission. Using this data we can examine water usage trends more closely in the morning, breakfast, lunch, dinner, and evening blocks as described in table X.

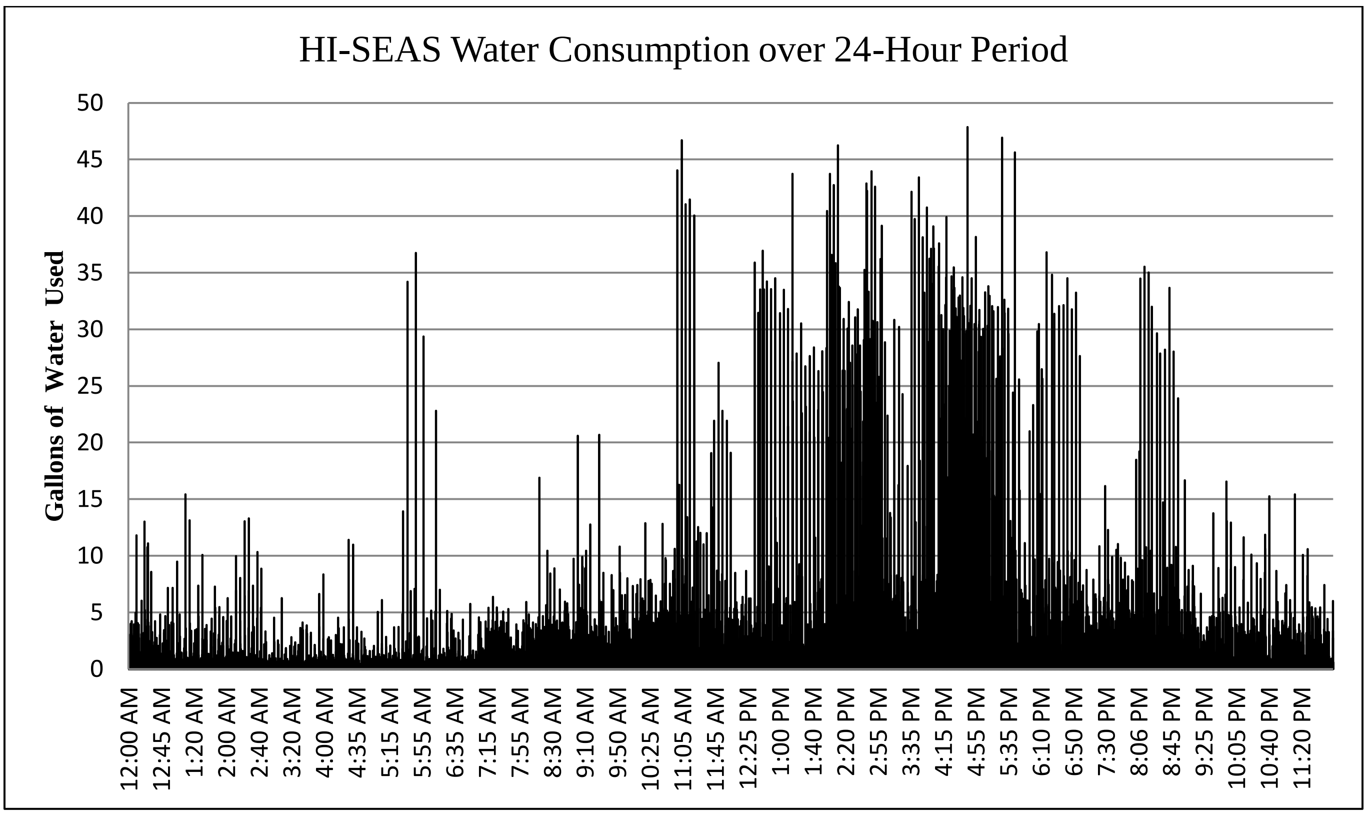


Figure 16: Water consumption in the habitat measuring water usage in five minute intervals, over a 24 hour period. This graph displays data for 120 days.

6.6.1 Morning block water consumption

Water usage in the early morning hours were low in the Habitat . This was to be expected since the crew was dominantly sleeping during this time block. The average water consumption over a five minute period was 0.48 gallons, with a standard deviation of 0.42 gallons. The total amount of water used in the mission during this time block is 2717 gallons.

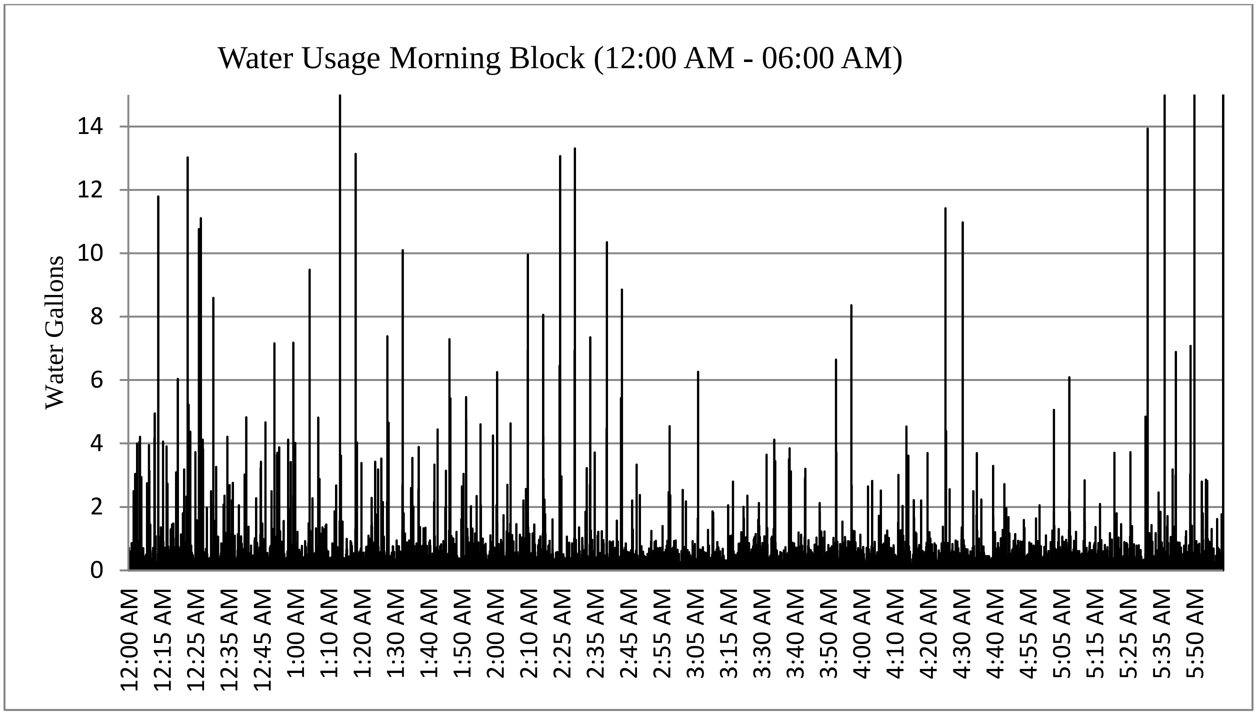


Figure 17: Morning Block water consumption. During the late night hours in the habitat there is consistently little water usage.

6.6.2 Breakfast block water consumption

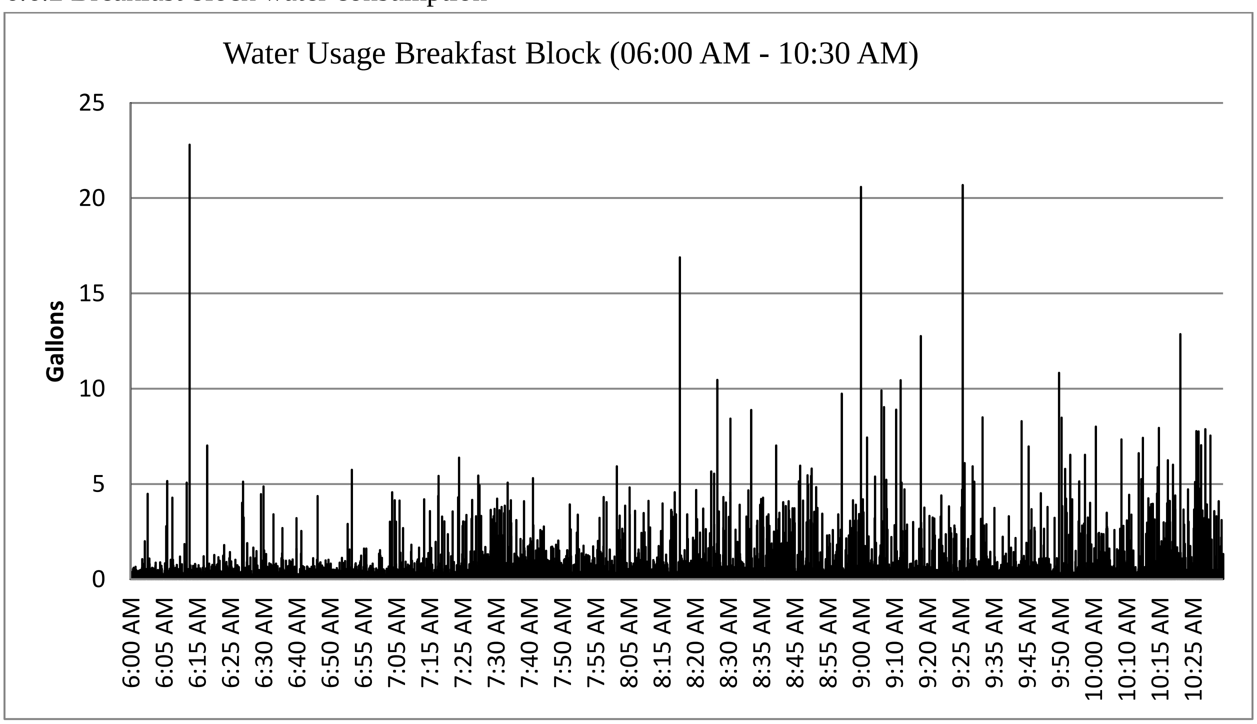


Figure 18: Breakfast block water consumption.

Water consumption during the breakfast block can be characterized by the sudden increase water usage between 7:00 AM – 8:00 AM. This increase coincides with the crew waking from sleep or completing their workouts, and getting ready for breakfast. A second dense usage occurs between 8:20 AM – 9:00 AM, which can dominantly be attributed to water usage for preparing breakfast. Following that, water usage increases again around 10:00 AM and continues for the rest of the block. This could potentially be attributed to crew members starting to prepare lunch early, or to laundry and showering activities. During the four month mission, the crew used 3320 gallons, with a five minute average of 0.76 gallons with a standard deviation of 0.69 gallons.

6.6.3 Lunch block water consumption

Water consumption during the lunch block sees a dense increase of water usage staring between the hours 1:00 PM – 1:45 PM, this coincides with preparing lunch meals. Water usage is then significantly higher between the hours of 1:55 PM -3:25 PM. This time range is consistent with the times crew would be washing dishes from lunch, and would be incorporated to water usage from the laundry machine. Sometimes crew members would start washing dishes at different times during lunch throughout the mission. One can see that the dominant water usage in this block is clearly from washing dishes.

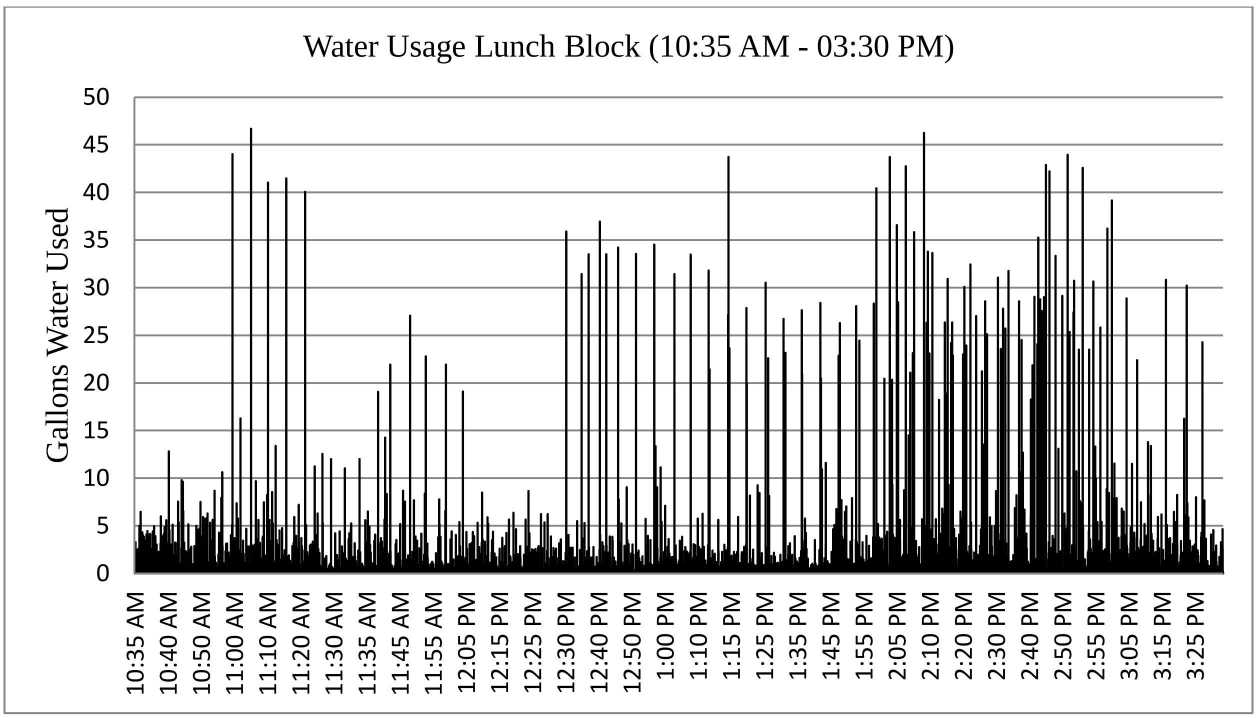


Figure 19: Water consumption over the lunch block.

6.6.4 Dinner block water consumption

Water usage during the dinner block has the highest density between 4:00 PM – 6:00 PM. This is water usage from preparing dinner and doing dishes combined. Dominantly, it is unlikely dishwashing would stay until 5:00 PM at the earliest. From this data, it appears that cooking during the Dinner block uses up more water consumption than any of the other time blocks. During this time block over the entire mission, the crew used a total of 8826 gallons. Over five minute intervals the average water consumption was 1.83 gallons with a standard deviation of 2.3 gallons.

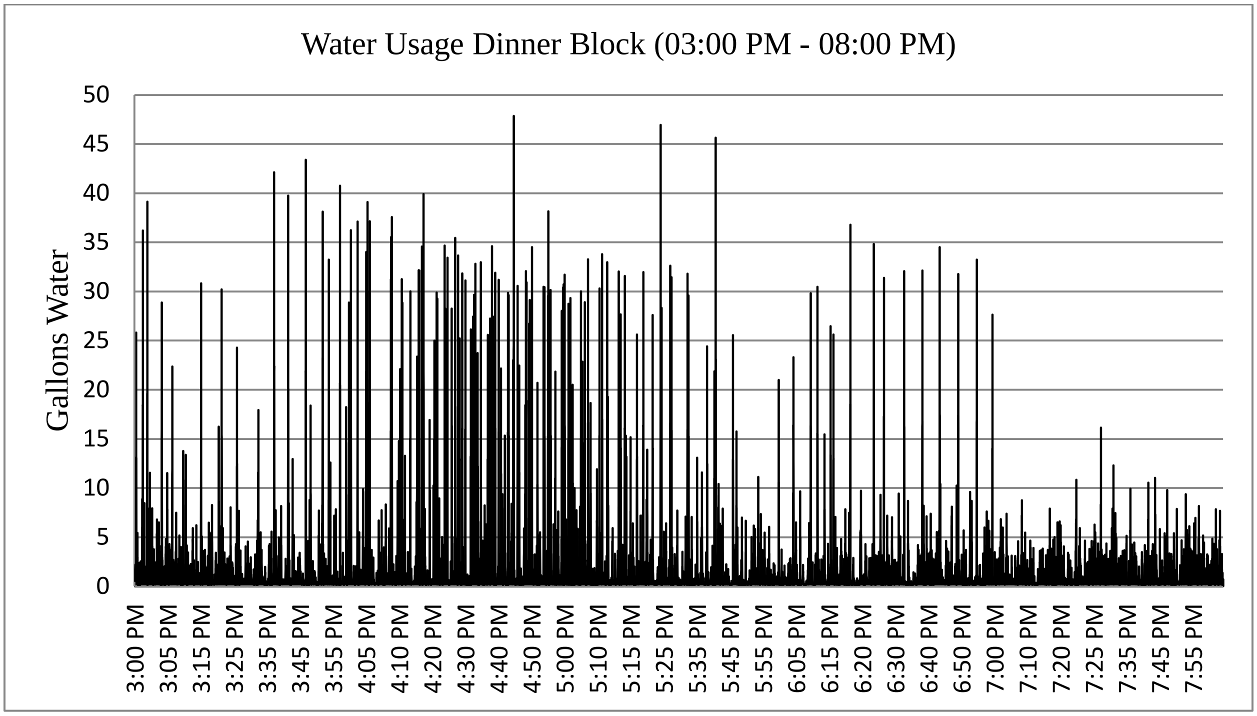


Figure 20: Dinner block water consumption.

6.6.5 Evening block water consumption

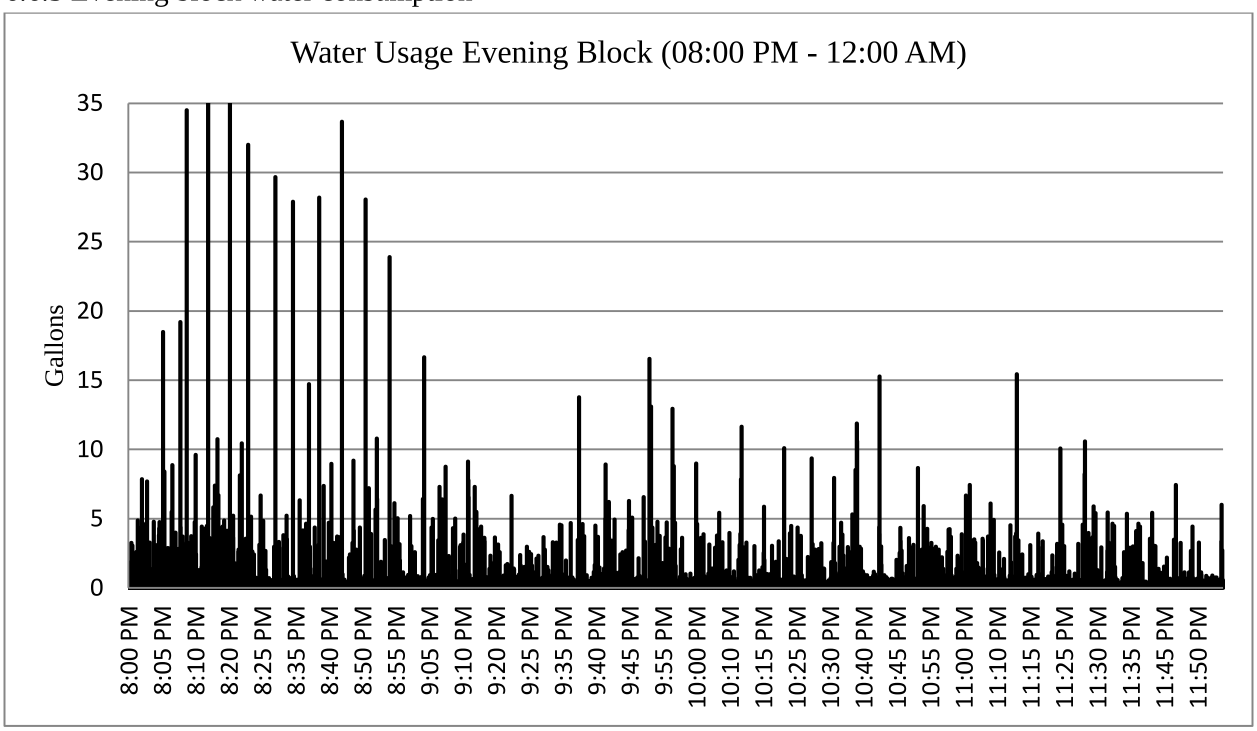


Figure 21: Water usage during the evening block

After dinner time, around 8:00 PM, water usage in the habitat would taper off. Between the hours of 8:00 PM – 8:55 PM there are a number of spikes in the water usage that can be attributed to dish washing. Some of the dish washing evening water usage was significant using up as much as 35 gallons. Over the entire mission, 3334 gallons were used during this time block with a 5 minute consumption average of 0.86 gallons with a standard deviation of 0.95 gallons.

7. Septic tank usage

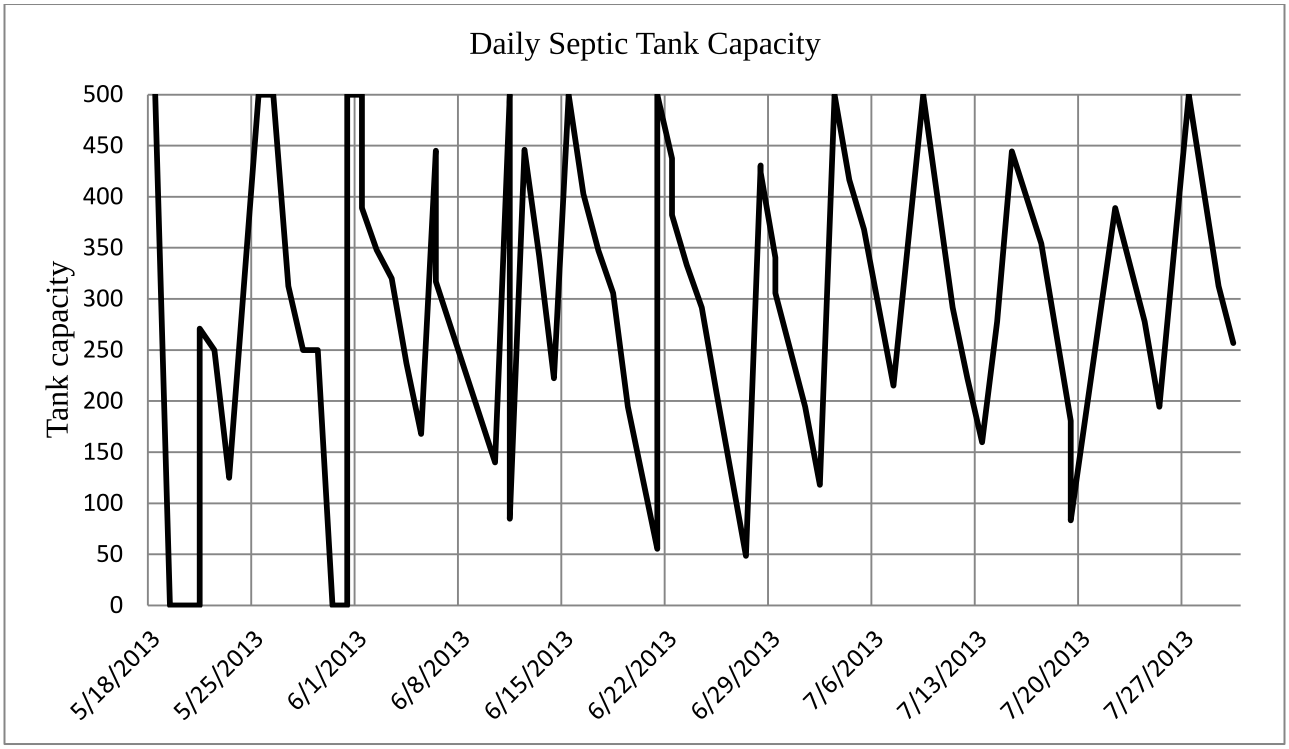


Figure 22: Daily septic tank level over course of the mission

The 500 gallon septic tank would reach its capacity every 6 days. For this reason it was emptied by sea septic removal service. If the septic tank reached its capacity, then the crew would be required to go on water restrictions. This did not occur after the first four weeks of the mission once the crew settled into a regular routine. The septic tank was taking all the water from the habitat, minus water from the washing machine. This was not the ideal setup but was done out of necessity.

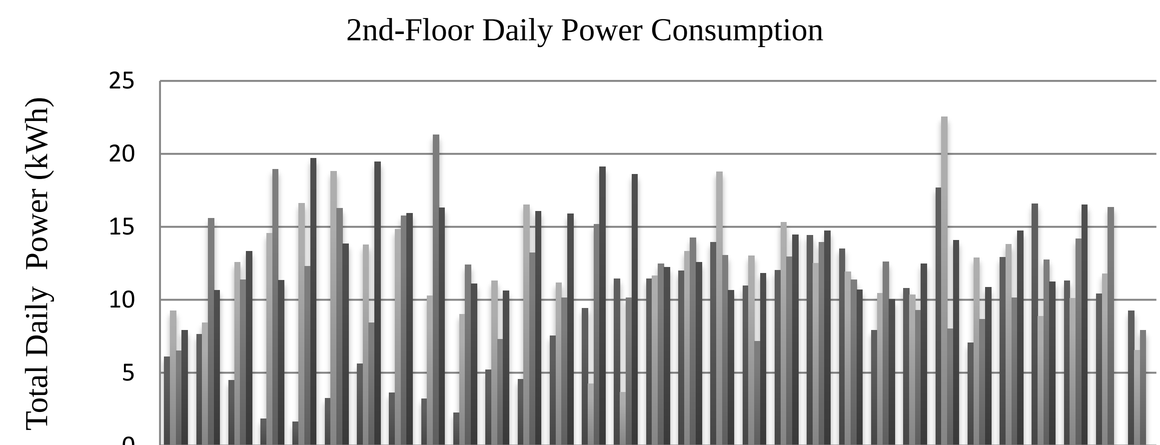
8. Power consumption

This section shows data for the power consumption of the habitat through monitoring of the electricity usage through each of the 2 kW breakers on the habitat power distribution. Each monitored breaker would supply power to the habitat laboratory and main floor bathroom, 2nd Floor rooms and bathrooms, Living Room, Kitchen, Washer/Dryer, and the daily total power usage of the habitat. Telemetry for the power was collected showing total kWh for every five minute period. This data has been collected and split into groups representing each month of the mission. The daily consumption rate for each day, for each month is displayed in section 8.1. Following this, the monthly consumption rates are display, with a final tally of the entire amount of energy consumed in the mission.

8.1 Daily power consumption

8.1.1 2nd floor power consumption

The second floor daily power consumption was on average 11.7 kWh with a standard deviation of 3.23 kWh. There was a total usage of 1426 kWh over the course of the four month mission. The second floor contains the crew rooms and washroom. Power consumption was generally low due to high efficiency lighting, and alarm clocks. Some crew members would work on their laptops in their rooms and this causes some additional power consumption. However, overall the power usage on the second floor is low.

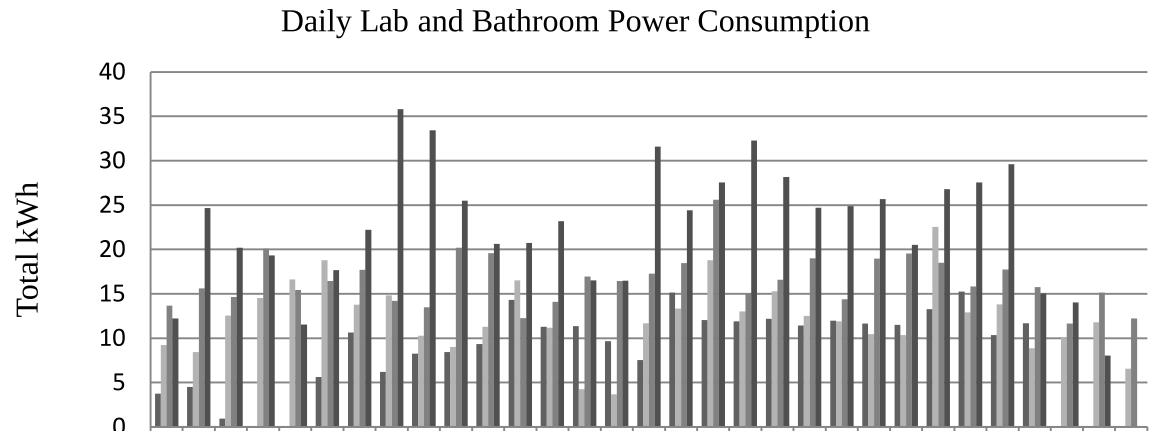


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Month 1	6	8	4	2	2	3	6	4	3	2	5	5	8	9	11	11	12	14	11	12	14	14	8	11	18	7	13	17	11	10	9
Month 2	9	8	13	15	17	19	14	15	10	9	11	17	11	4	4	12	13	19	13	15	13	12	10	10	23	13	14	9	10	12	7
Month 3	7	16	11	19	12	16	8	16	21	12	7	13	10	15	10	12	14	13	7	13	14	11	13	9	8	9	10	13	14	16	8
Month 4	8	11	13	11	20	14	19	16	16	11	11	16	16	19	19	12	13	11	12	14	15	11	10	12	14	11	15	11	16	0	0

Figure 23: Second floor daily power consumption in total daily kWh

8.1.2 Laboratory and downstairs bathroom power consumption

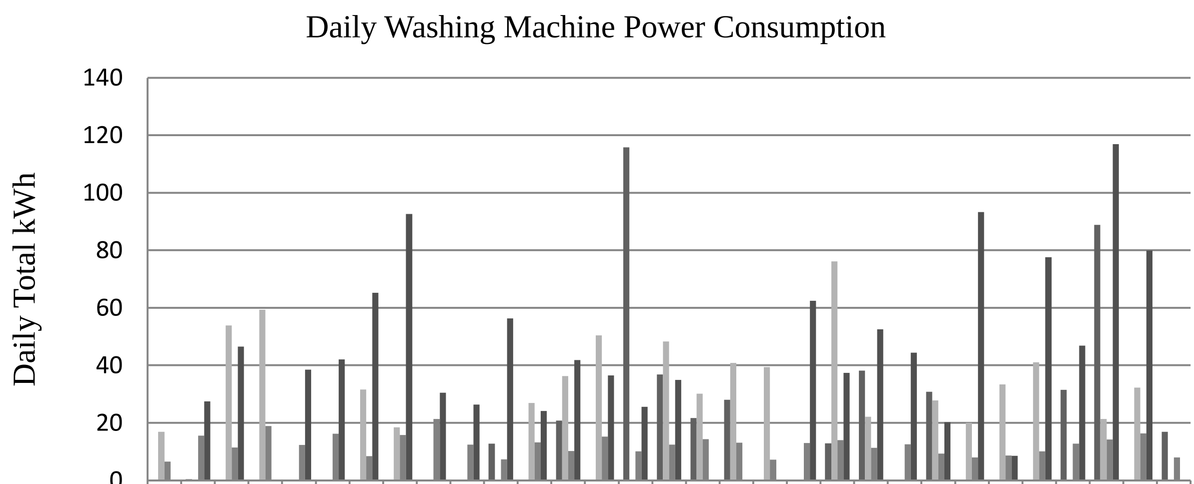
The daily power consumption in the laboratory and main floor bathroom totaled 1832 kWh over the course of the mission. The daily average of power consumption was 458 kWh with a standard deviation of 138 kWh. Power usage in the lab and bathroom tended to increase as the mission went on. This was likely due to the increasing activity in the laboratory for using equipment to incubate and freeze samples.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Month 1	4	4	1	0	0	6	11	6	8	8	9	14	11	11	10	8	15	12	12	12	11	12	12	12	13	15	10	12	0	0	0
Month 2	9	8	13	15	17	19	14	15	10	9	11	17	11	4	4	12	13	19	13	15	13	12	10	10	23	13	14	9	10	12	7
Month 3	14	16	15	20	15	16	18	14	13	20	20	12	14	17	16	17	18	26	15	17	19	14	19	20	19	16	18	16	12	15	12
Month 4	12	25	20	19	12	18	22	36	33	26	21	21	23	17	16	32	24	28	32	28	25	25	26	21	27	28	30	15	14	8	0

Figure 24: Daily lab and bathroom power consumption

8.1.3 Washing machine power consumption

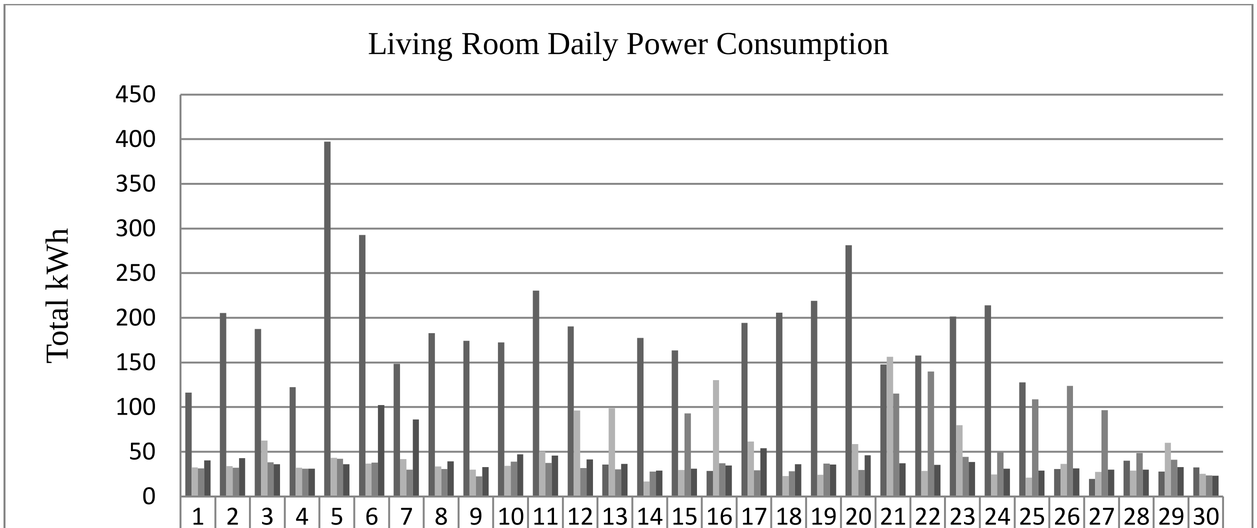


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Month 1	0	0	0	0	0	0	0	0	0	0	13	0	21	0	11	37	22	28	0	0	13	38	0	31	0	0	0	31	89	0	17
Month 2	17	0	54	59	0	0	32	18	0	0	0	27	36	50	0	48	30	41	39	0	76	22	0	28	20	33	41	0	21	32	0
Month 3	7	16	11	19	12	16	8	16	21	12	7	13	10	15	10	12	14	13	7	13	14	11	13	9	8	9	10	13	14	16	8
Month 4	0	27	46	0	38	42	65	93	30	26	56	24	42	36	26	35	0	0	0	62	37	52	44	20	93	9	78	47	11	80	0

Figure 25: Daily washing machine power consumption over four month mission

The washing machine purchased for this mission turned out to be a highly inefficient machine. On a large load, it would consume a very large 62 gallons per wash. This was a significant issue at the beginning of the mission, as it caused a couple days of water shortages due to the unexpected amount of water used. To combat this extreme water consumption rate, crew was restricted to setting the washing machine on the low setting, which used a more reasonable 16 gallons per load. The crew was also assigned a specific day to do their laundry allowing to spread the crew washes over six days, with an extra day for washing dish clothes and other communal items. There was a higher usage of the washing machine towards the end of the fourth month due to some textile studies, and prepping the habitat for the end of the mission. Overall, the washing machine used a grand total of 2790 kWh, with a monthly average of 697 kWh at standard deviation of 279 kWh.

8.1.4 Living room power consumption



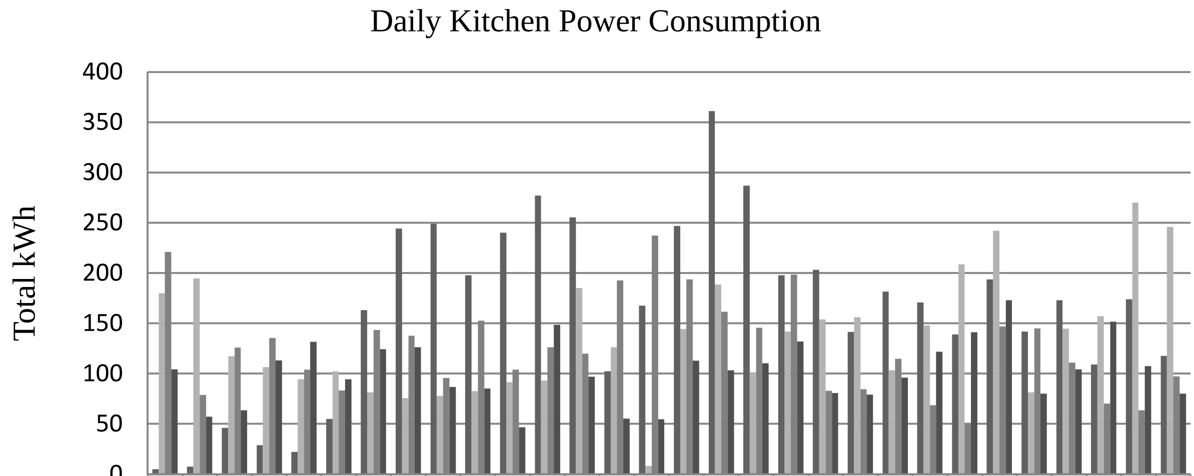
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Month 1	11	20	18	12	39	29	14	18	17	17	23	19	36	17	16	28	19	20	21	28	14	15	20	21	12	30	20	40	28	33
Month 2	33	34	63	32	43	37	42	33	30	34	50	96	99	17	29	13	61	23	24	58	15	29	80	25	21	36	27	29	60	25
Month 3	31	32	38	31	42	38	30	31	22	39	38	32	30	28	93	37	29	28	37	30	11	14	44	49	10	12	96	48	41	23
Month 4	40	43	36	31	36	10	86	39	33	47	46	42	36	29	31	35	54	36	36	46	37	35	39	31	29	31	30	30	33	23

Figure 26: Living room daily power consumption levels

The living room power was significantly higher during the first month of the mission. This was due to the cold temperatures experienced at night time inside the habitat. Heaters would be run nearly continuously in an effort to keep the habitat warm. Each of these heaters rate at 1500 W on full power, leading to a high energy consumption. Towards the end of the first month, the heaters were no longer used causing a significant drop in the power consumption of the living room. The daily average of the living room power consumed is 73 kWh with a standard deviation of 53 kWh

8.1.5 Kitchen power consumption

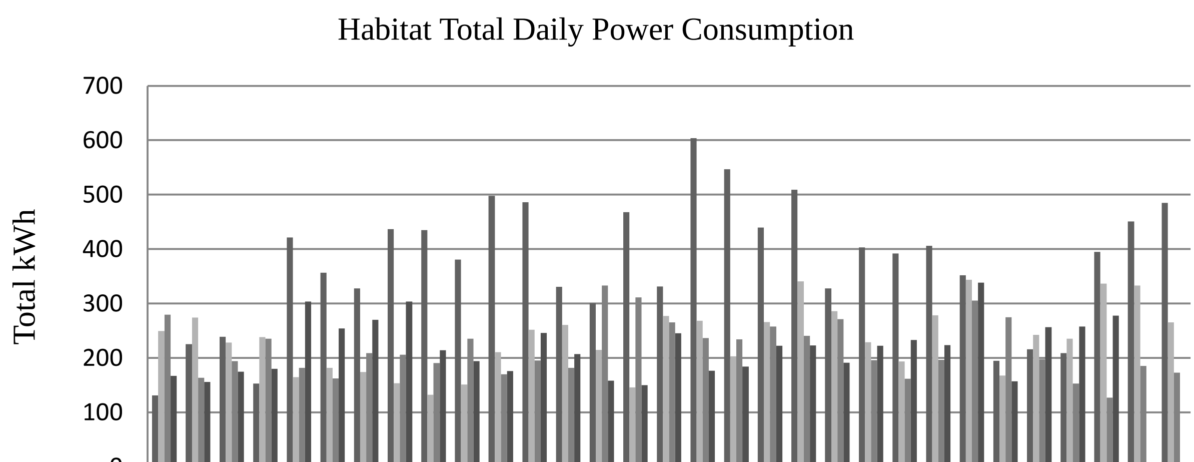
Kitchen power was the dominant power consumer of the habitat. Every cooking appliance, bread maker, oven, dishwasher, etc. are contained within this power sensor. The daily average power used in the kitchen was 133 kWh with a standard deviation of 50 kWh.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Month 1	5	8	46	29	22	55	16	24	24	19	24	27	25	10	16	24	36	28	19	20	14	18	17	13	19	14	17	10	17	11
Month 2	18	19	11	10	94	10	81	76	78	82	92	93	18	12	8	14	18	10	14	15	15	10	14	20	24	81	14	15	27	24
Month 3	22	79	12	13	10	83	14	13	96	15	10	12	12	19	23	19	16	14	19	83	84	11	69	50	14	14	11	70	63	97
Month 4	10	57	64	11	13	94	12	12	87	85	47	14	97	55	55	11	10	11	13	81	79	96	12	14	17	80	10	15	10	80

Figure 27: Kitchen power consumption levels

8.1.6 Total power consumption



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Month 1	13	22	23	15	42	35	32	43	43	38	49	48	33	30	46	33	60	54	44	50	32	40	39	40	35	19	21	20	39	45	48
Month 2	24	27	22	23	16	18	17	15	13	15	21	25	26	21	14	27	26	20	26	34	28	22	19	27	34	16	24	23	33	33	26
Month 3	28	16	19	23	18	16	20	20	19	23	17	19	18	33	31	26	23	23	25	24	27	19	16	19	30	27	19	15	12	18	17
Month 4	16	15	17	18	30	25	27	30	21	19	17	24	20	15	15	24	17	18	22	22	19	22	23	22	33	15	25	25	27	0	0

Figure 28: Total daily power consumption for the entire habitat.

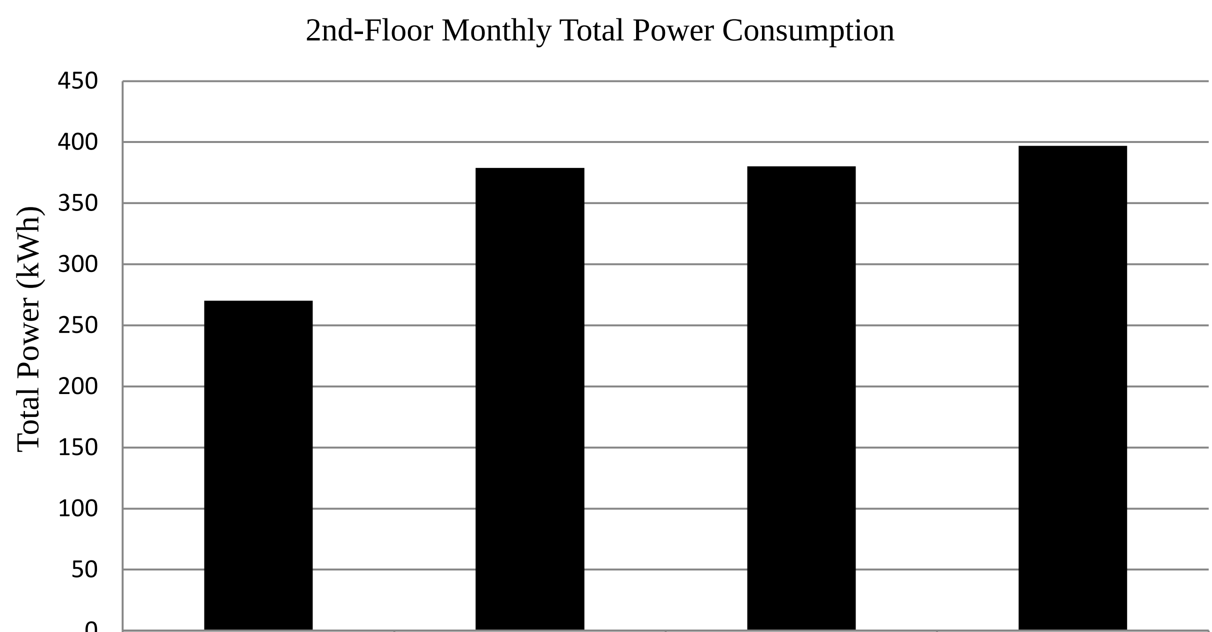
The total daily power consumption in the habitat was an average of 260 kWh with a standard deviation of 75 kWh. Power consumption was significantly higher in the first month. This was dominantly due to the use of heaters to keep the habitat warm in the cool conditions.

8.2 Monthly power consumption

This section tallies up the kWh used each day in the habitat and packages it into monthly bar graphs. Using this information, monthly trends in habitat power consumption can be identified and quantified.

8.2.1 2nd floor power consumption

The total power consumption on the second floor over the duration of the mission was 1425 kWh with a monthly average of 356 kWh at a standard deviation of 11 kWh. The usage of power on the second floor was dominantly consistent each month for the duration of the mission. The first month, the crew used less power on the second floor, as the crew was working on the main floor at the start of the mission.



	Month 1	Month 2	Month 3	Month 4
Series1	270.162	378.964	380.086	397.07

Figure 29: Monthly second floor power consumption in kWh

8.2.2 Laboratory and downstairs bathroom power consumption

The monthly power consumption in the lab and bathroom increased linearly over the mission. The laboratory was used with increasing frequency during the mission, with a larger amount of biological samples to incubate and store. The total amount of power consumed over the four months is 2461 kWh. The average power consumption per month was 458 kWh with a standard deviation 138 kWh.

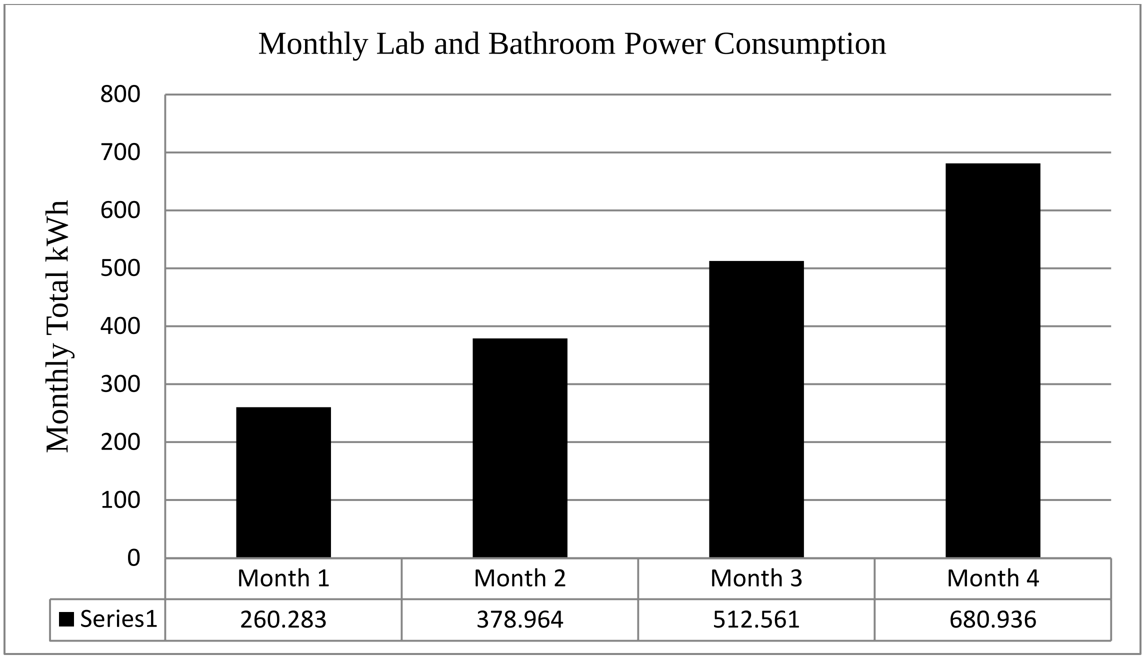


Figure 30: Monthly lab and bathroom total power consumption

8.2.3 Washing machine power consumption

The total monthly power consumption of the washing machine varied throughout the mission. In the fourth month of the mission, the washing machine was used more frequently due to washing necessary for textile studies. For the entire mission, the washing machine consumed 2790 kWh of energy with a monthly average of

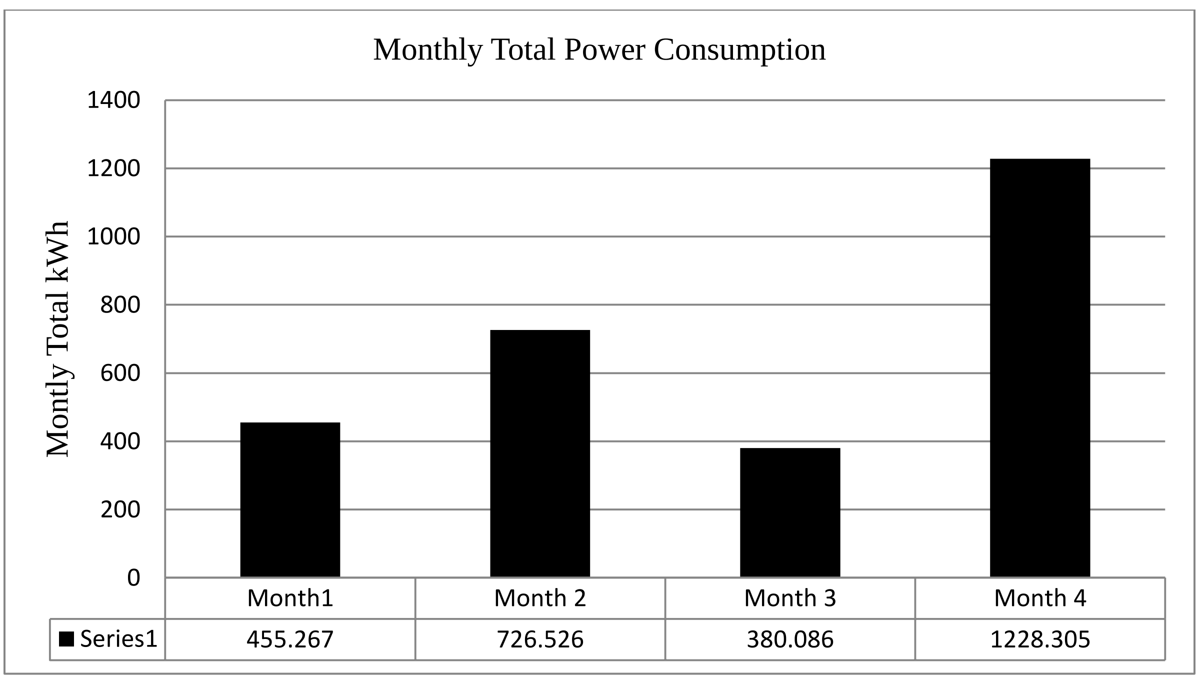


Figure 31: Monthly total power consumption of washing machine

8.2.4 Living room power consumption

The monthly power consumption in the living room is dominated by the first month, which is about four times the amount than the rest of the month. As seen in the daily power consumption levels, this was due to the use of heaters during the first month of the mission.

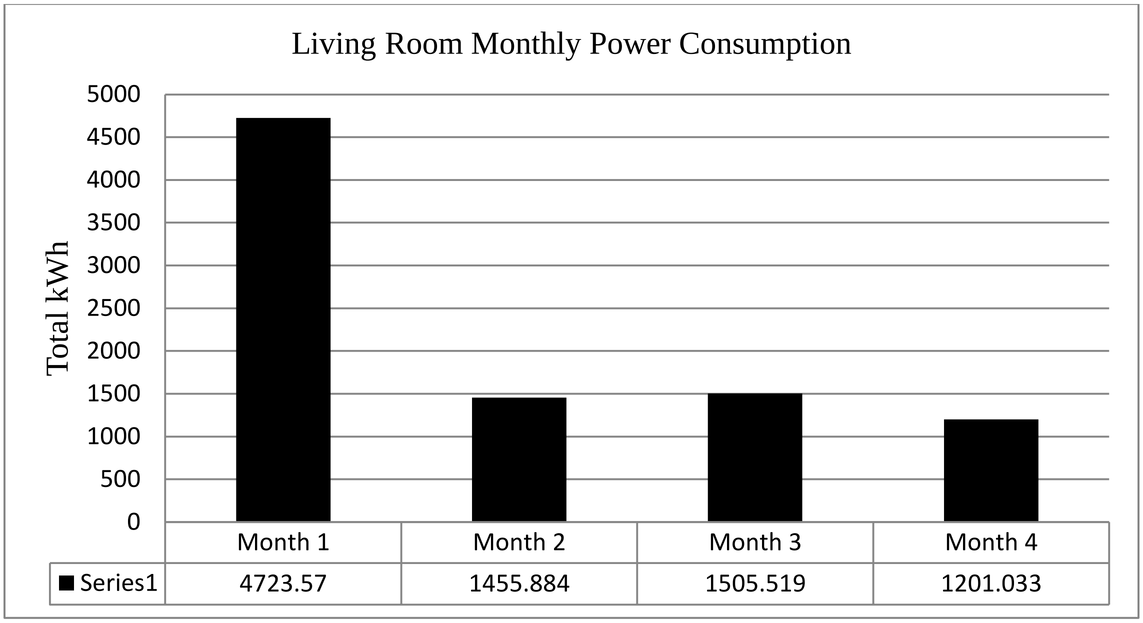


Figure 32: Living room power consumption

8.2.5 Kitchen power consumption

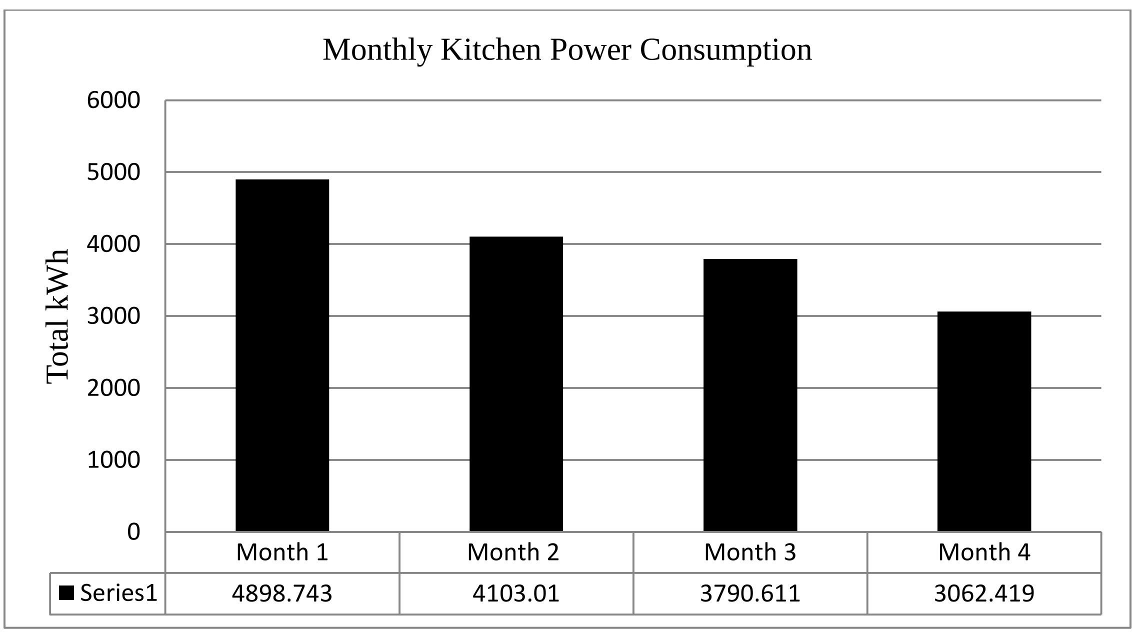


Figure 33: Monthly kitchen power consumption

The monthly kitchen power consumption had a trend downwards each month. This is possibly due to the crew getting more efficient at cooking the various meals. The monthly average was 3963 kWh with a standard deviation of 536 kWh. The total amount of power used in the kitchen over the course of the mission is 15,854 kWh.

8.2.6 Total power consumption

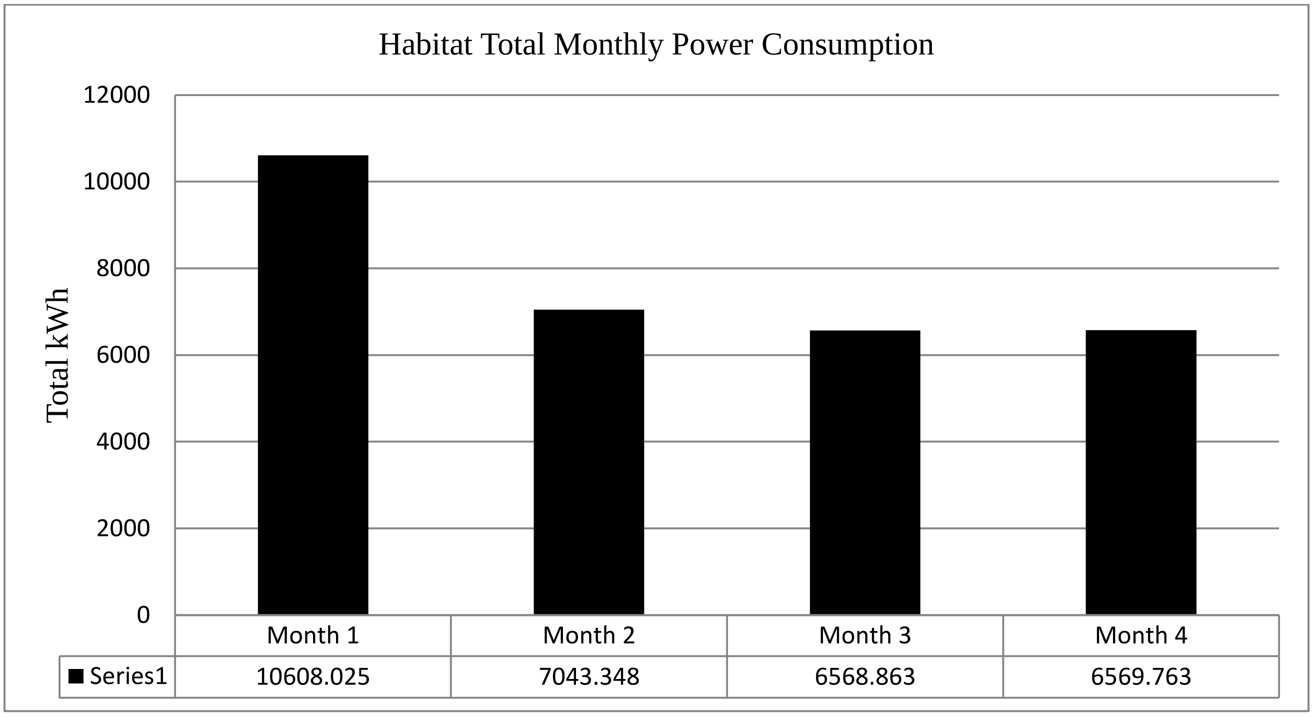


Figure 34:Total habitat Monthly power consumption

The total monthly power consumption of the habitat shows that again the first month is significantly higher due to the use of heats. Subsequent power consumption over the following three months had very little variance in total power usage. The total power consumption over the entire mission was 30,790 kWh with a monthly average of 7697 kWh with a standard deviation of 1455 kWh.

8. Thermal analysis of habitat

8.1 Methods

A FLIR T300 thermal imager was used to acquire infrared images of the dome interior and the attached storage container at different time points in the diurnal cycle. Reported temperatures were calibrated by adjusting for thermal emissivities of known materials, particularly the Polyvinyl Chloride (PVC) of the dome, and a thermocouple was used to verify calibration. Thermal emissivities of most objects within the habitat ranged from 0.94 to 0.99, and a mean emissivity value of 0.96 was used to assemble thermal panoramas presented in this paper. In addition, a network of both wired and wireless temperature sensors was used to verify the results of thermal imaging and conduct continuous temperature monitoring within specific locations of interest. Temperatures reported by all of the OMWT-TEMP15 wireless sensors, as well as most of the habitat’s built-in temperature sensors, were in close agreement (within 1 °C) to those obtained by FLIR thermography. One exception was the internal temperature sensor in the kitchen, which often reported temperatures ~2 °C higher than either the FLIR or the adjacent OMWT-TEMP15 unit. It is hypothesized that this discrepancy was due to the sensor's relative lack of shielding and proximity to radiative heat sources such as heaters and kitchen appliances. In general, however, there is a high degree of confidence in the temperatures reported here due to the several implemented cross-controls.

The FLIR T300 imager was coupled to a Gigapan Epic 100 unit to perform automated thermal scanning within the habitat. This allowed rapid collection of a large set of thermal images covering a specified area, which was typically defined as 360° × 180°, thus encompassing everything that could be observed from a given location with the exception of a small area directly beneath the scanning platform. The resulting thermal infrared image data was then calibrated and processed using the FLIR ExaminIR software, with results output as standard bitmap images. These images were then stitched into panoramas using Gigapan Stitch software, generating the final products presented here.

8.2 Daytime and nighttime thermography

A comparison of daytime and nighttime spherical (360° × 180°) thermal panoramas encompassing the central dome area of the hab, as well as a visible-light panorama for context, are presented in Figure 35**:**

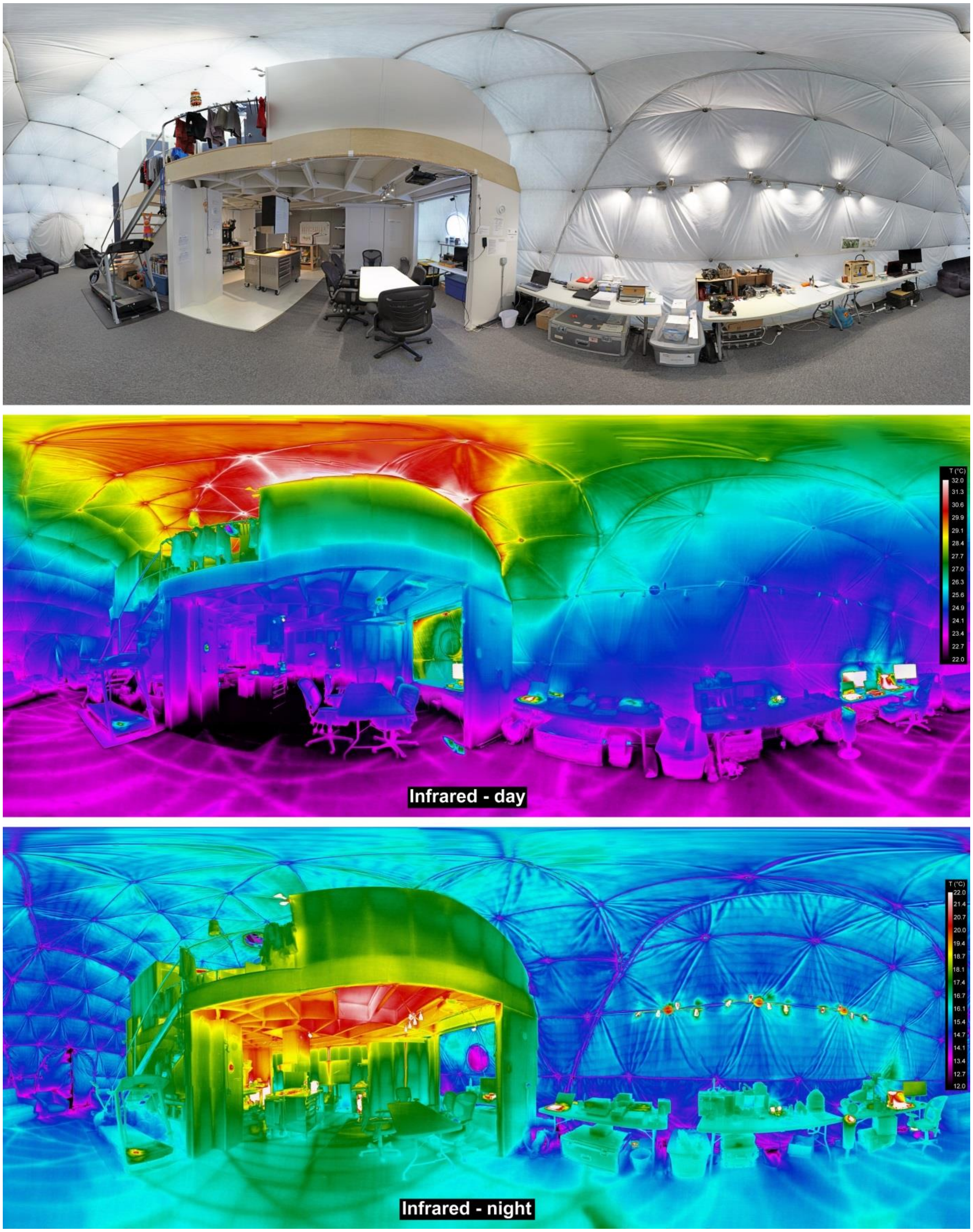


Figure 36: A photograph and thermal images of the habitat at day and night.

The daytime panorama was acquired in the afternoon of 7/10. Weather conditions as reported by the habitat's weather stations were clear skies, light and variable winds, and an ambient temperature of 23 °C.

Observed temperatures range from a high of ~34 °C along ceiling of the dome to a low of ~18 °C. There is a strong vertical temperature gradient present; temperatures increase with height from ~21 °C underneath crewmembers' work desks to over 34 °C at the dome ceiling. The highest temperatures are concentrated in the southern quadrant of the dome and above crewmembers' staterooms.

The nighttime panorama, acquired on 6/21, provides a thorough overview of the temperature distribution in the hab during the evening. Weather conditions at the time were clear skies, calm winds, and an ambient outdoor temperature of ~10 °C. The mean temperature of the PVC cover is ~15 °C. Heat loss along the side and bottom seams, and especially along the airlock door is clearly visible. A modest temperature gradient of ~2 °C is noted along the walls of the dome, with the ceiling being warmer, likely due to rising air currents. Heat produced by various electrical appliances, particularly the space heater, electric tea kettle, and the dishwasher is clearly visible. Heat appears to be trapped below the floors of the second-floor structure, and appears to be particularly concentrated below room #1 for reasons that are not entirely clear.

9.3 Change detection and mapping

Temperature changes over relatively short periods of time are illustrated in Figure 37 by two 250° × 180° spherical thermal panoramas of the central dome area of the habitat, acquired on 7/4 approx. 1.25 hours apart. The mean temperature of the PVC cover is ~22.5 °C in the top image and ~21 °C in the bottom image. A decrease in overall temperatures of ~1.5 °C is noted between the two panoramas. A temperature gradient of ~2 °C is present along the walls of the dome, with the ceiling being warmer due to the rising air currents. Significant vertical temperature gradients of ~2.5 °C are noted along the walls of staterooms in the upper image. Atmospheric conditions were cloudy and foggy with calm winds at the time imaging was performed.

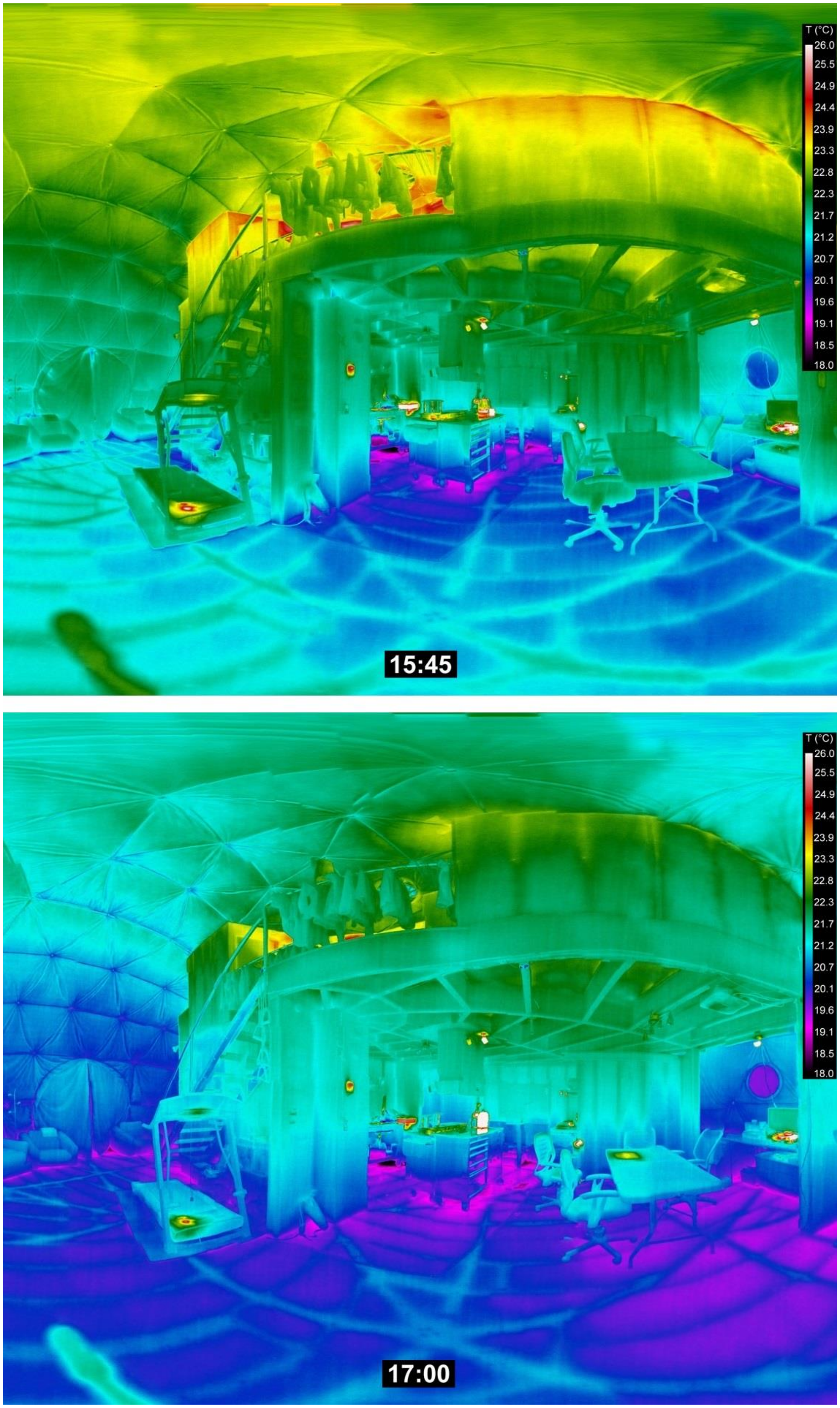


Figure 38: Changes in thermal properties over short periods of time.

9.4 Storage container thermal monitoring

The main food storage area in the HI-SEAS habitat is along the east wall of the steel shipping container that is also used as a workshop and robot garage. Because of concerns of possible food spoilage due to perceived high temperatures within the container, particularly in the afternoons of sunny days, OMWT-TEMP15 wireless temperature sensors and thermal imaging were used to evaluate the diurnal temperature distributions within the container and assess their impact on food storage. The results, including a sample late afternoon spherical (360° × 180°) thermal panorama, a visible-light panorama for context, and data from temperature sensors are presented in Figure 39.

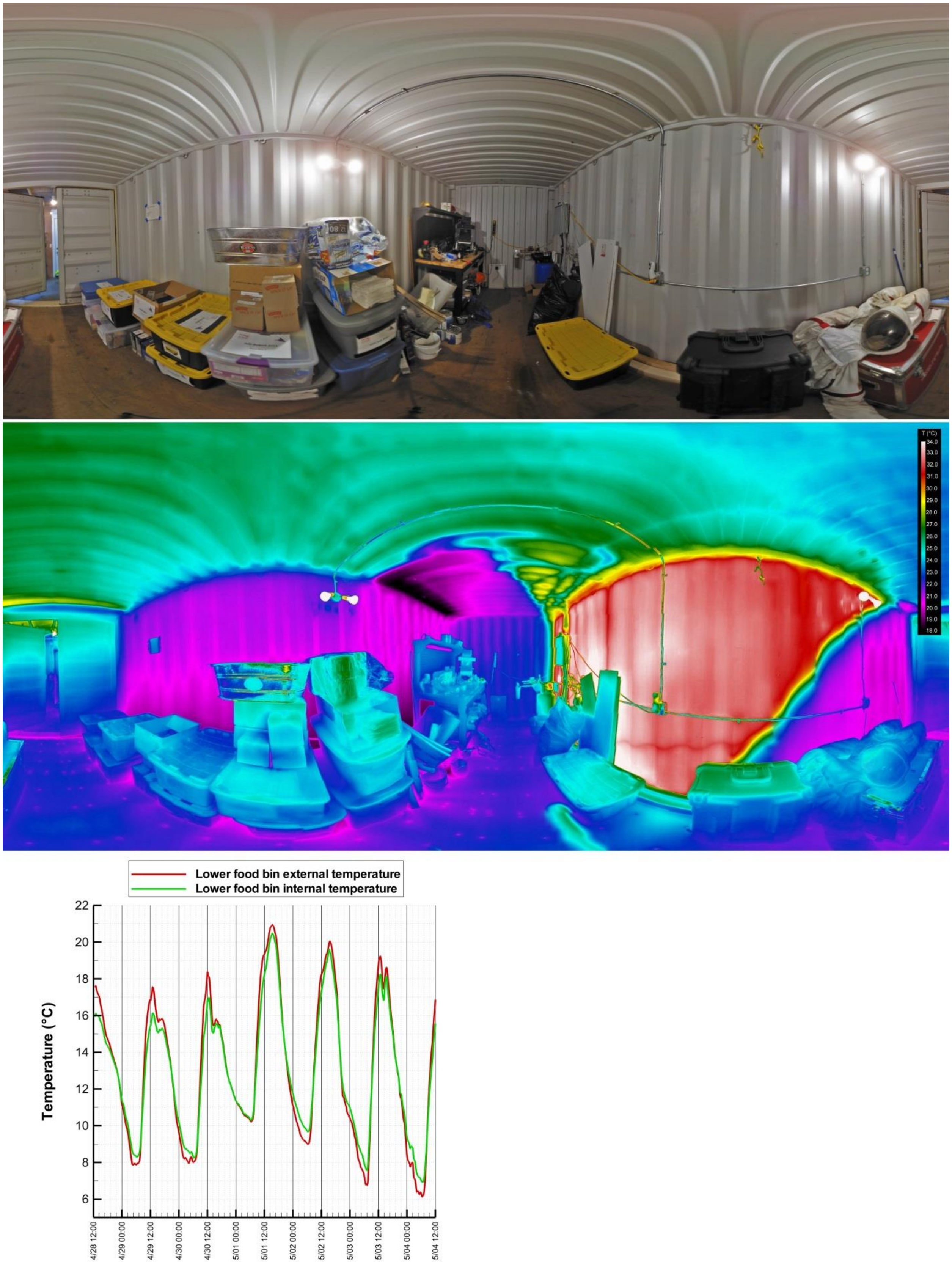


Figure 40: Thermal properties of sea container used for food storage.

The thermal panorama of the storage container shown in Figure 41 was acquired on July 8 at 16:00. Atmospheric conditions at the time of imaging were clear skies and winds averaging 16 mph from the north. Observed temperatures range from a high of 34 °C along the west well to a low of 17 °C in the southeast ceiling quadrant. The high temperatures along the west wall are explained by direct incident sunlight in the late afternoon, and the low temperatures in the southeast part of the ceiling are due to shade provided by the solar panels and the hot water tank installed in that area (Fig. **9**). In general, the ceiling area remains fairly cool despite direct sunlight due to a layer of insulation present there. The second-coolest locations are near the container floor and the east wall, which is adjacent to a cinder cone (Fig. **9**) and remains mostly shaded throughout the day. Temperatures increase with height, and both horizontal and vertical thermal gradients are present across the food storage boxes. Temperatures of the lowermost food boxes have range from 19 to 22 °C.

In addition, a wireless temperature sensor was placed inside a sterilized plastic food storage bin positioned on the floor of the container, while another temperature sensor was placed on the lid of the same bin to record external temperature. Temperature data from a period of six diurnal cycles is presented in Figure 42**,** (bottom).

The overall conclusions from this assessment were as follows: (i) Temperatures within the lower bins are acceptable for food storage; they had a mean of ~13 °C during the observation period and briefly reached a maximum of ~20 °C on the hottest day of the week. (ii) Food storage acceptability decreases with increasing height above the container floor. It was recommended that foods with any degree of perishability (processed cheese, cured meats, etc.) are only stored in the lower bin, or, at most, near the wall-facing side of the upper bin. (iii) Only very temperature-stable foods should be stored in the cardboard boxes above the bins. (iv) Insulation and/or a reflective layer added to the west wall of the container would significantly reduce daytime temperature spikes.

9.5 Stateroom temperatures

Figure 43a presents data collected in May from a wireless temperature sensor in stateroom #4, and, for comparison, one in the kitchen/dining room area. Prior to May 10, it was standard practice to leave one of the portable 1500-watt Lasko heaters running overnight on the ground floor. The results of turning off the heater beginning the night of May 10 – May 11 are clearly visible in Figure 44a. The dining room temperature decreased ~2.5 °C from the baseline mean; however, the effect on bedroom temperatures was significantly less pronounced, with a decrease of ~1-1.5 C from the baseline mean, suggesting that the heating benefits were fairly marginal and did not outweigh the electrical power costs of running the heater overnight.

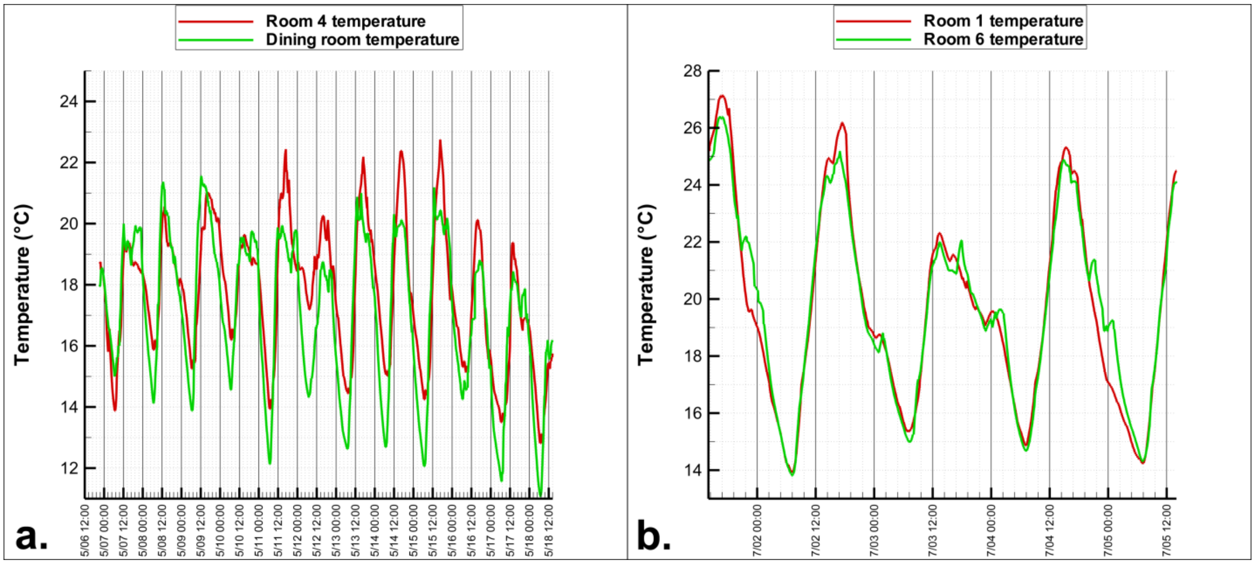


Figure 45: Temperatures in habitat staterooms

The effects of installing single-paned acrylic windows on May 15 are also apparent, with daytime highs in both the dining area and the bedrooms being ~1-2 °C lower. Based on this data, it was recommended that the window in the lab be removed and replaced with the PVC cover that was there previously, and the window in the dining room area be double-paned.

In addition, wireless temperature sensors in staterooms #1 and #6 were used to evaluate the differences in temperature at the opposite ends of the second floor and determine whether there was a significant lateral temperature difference across the second floor. The data collected from OMWT-TEMP15 sensors at these locations for four diurnal cycles in July is presented in Figure 46b. The results indicate that, although stateroom #1 experienced higher daytime temperature peaks, the difference is relatively small, being ~0.5 to ~1 °C.

11. Conclusions

Utilizing the data collected in the analog mission, an understanding of water, and electricity consumption was obtained. In the short term, this data can be used to strengthen future analog missions. Having detailed knowledge of the weekly water and power consumptions will allow for accurate planning. In the long term, daily power and water consumption trends can be used to predict water and power usage for specific activities. It can be surmised that in planning out daily activities, it will be possible to predict with great accuracy water and power usage of a crew over short term activities. What this allows for is a more dynamic model that will be able to accurately predict consumption even when there are major changes in routines. Every statistical model that utilizes statistics from routine behavior seen on the large scale will break down almost immediately when the model is changed even moderately. However, because we are able to see extremely fine resolution of crew activities and consumption, it will be possible to model consumption on a fine resolution of activity. This fine resolution of statistical data provides tremendous flexibility in the models. Creating a fuzzy logic system to predict these consumption rates and compare to the real world is the next step in this research.

With the thermal imaging data, it was found that the integrated and mostly automated use of thermal imaging and temperature sensors presented here allowed for comprehensive monitoring of the thermal state of the HI-SEAS analog habitat. The near-real-time feedback provided by this methodology allowed for rapid identification of heat sources and sinks within the habitat, and resulted in several immediate improvements to temperature control in the habitat. Specific findings included the relative ineffectiveness of centrally-located portable heaters for increasing temperatures in crewmember staterooms, the significant loss of heat due to (originally) single-paned windows, temperature distributions in the storage container and locations acceptable for food storage, and pronounced temperature gradients within the dome (as well as within individual staterooms) during daytime hours.

12. Acknowledgements

Processing of thermal imaging data by Jennifer Steil (HI-SEAS first-tier support) is gratefully acknowledged.

13. References

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