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Mars Habitat Power Consumption Constraints, Prioritization, and Optimization

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Corresponding Author:	Simon Engler UNIVERSITY OF HAWAII HONOLULU, HI UNITED STATES
First Author:	Ansley Barnard
Order of Authors:	Ansley Barnard
	Simon Engler
	Kim Binsted
Abstract:	The Hawaii Space Exploration Analog and Simulation (www.hi-seas.org) is an experiment that simulates life in a Mars habitat for long duration. Power for the simulation is generated by solar energy which varies in production rates daily. During days with cloud cover, crew need to adapt their work schedule and support systems to ensure they can continue to function over the duration of low power constraints. Presented here is the method developed and implemented by the crew from Mission 5 that creates power budget profiles for low, moderate, and high-power production days. The power budget profile limit which systems and devices can be used and for what duration. The HI-SEAS power subsystem is characterized though power audits and data from daily use trends. Developing tools to enable prioritization of components for crew-member usage and compliance with restrictions are discussed. Data production and usage from all five missions are presented and compared. An optimization method is proposed to discover the most efficient schedule to match power usage profiles.This research is applicable to most manned space systems with the goal of providing the most optimal power consumption in a variety of conditions. Mars habitat, power, machine learning
Suggested Reviewers:	Marco Manzan Univ. of Trieste manzan@units.it Expertise in optimization applications.
Opposed Reviewers:	
Response to Reviewers:	

20th Oct. 2019

M.T. Kezirian
Editor-In-Chief
Journal of Space Safety Engineering

Dear Editor:

We wish to re-submit the manuscript titled "Mars Habitat Power Consumption Constraints, Prioritization, and Optimization." The manuscript ID is JSSE-D-19-00001.

We thank you and the reviewers for the thoughtful suggestions and insights. The manuscript has benefited from these insightful suggestions. I look forward to working with you and the reviewers to move this manuscript closer to publication in the *Journal of Space Safety Engineering*.

The manuscript has been rechecked and the necessary changes have been made in accordance with the reviewers' suggestions. The responses to all comments have been prepared and attached here with/given below.

Thank you for your consideration. I look forward to hearing from you.

Sincerely,

Simon Engler

Simon T. Engler
Department of Information and Computer Science,
University of Hawai'i, POST Building,
Rm 317, 680 East-West Road, Honolulu, HI,
E-mail: simon.engler@hawaii.edu

20th Oct. 2019

Mars Habitat Power Consumption Constraints, Prioritization, and Optimization
MS ID JSSE-D-19-00001

Response to reviewer comments:

Reviewer #1:

This paper discusses crew power consumption behavior during a HI-SEAS mission and aims to propose optimization strategies.

Overall comment: please spell out all acronyms when they appear in the text first time.

We fix text so that all acronyms are spelled out the first time.

Page 2, last paragraph of Introduction and page 3, 2.1.3.: Please make it clear how the discussed in the paper power consumption optimization is/may be related to the safety of the crew and mission operations.

We added to this paragraph and discussed the impact of safety of the crew.

"...automated and critical processes, such as habitat ventilation and heating, powered telemetry equipment, and safety-critical computing equipment were excluded from this prioritization" - Please specify in the results of this study what is suggested for future Mars mission ConOps planning. The crew most likely will be making many their own decisions on the ground without confirming every step with the mission control on Earth (Crew on the ISS: Creativity or determinism? Krikalev, Kalery, Sorokin, ActaAstronautica, 2010).

Text has been added to the discussion addressing what the results of this study can be utilized in Mars ConOps planning.

Page 4: "The minimum required evening RSOC was approximately 60% at sunset if the crew followed aggressive power saving techniques overnight" - Please discuss in the paper (discussion and conclusions) how Martian environmental conditions may affect the development of a parametric model of the habitat power subsystem in the future. PVs on Mars won't be producing power during dust storms for long periods of time and those storms are unpredictable. What can be suggested as a countermeasure for such emergencies? In general, PVs on Mars are only half efficient comparing to Earth, they may be only a complementary power source on Mars and the major power provider has to be independent from environmental conditions (NASA/TM—2004-213367). In such case habitat power production, distribution and consumption operations will be very differ

Text added in the discussion on this topic addressing power during dust storms for long periods.

Mars Habitat Power Consumption Constraints, Prioritization, and Optimization

Ansley Barnard[a], Simon T. Engler[b*], Kim Binsted[b]

[a] *ESTECO North America Inc., Novi, MI, barnard@esteco.com*
[b] *Department of Information and Computer Science, University of Hawai'i, POST Building, Rm 317, 680 East-West Road, Honolulu, HI, simon.engler@hawaii.edu*
[*] Corresponding author

Abstract
The Hawai'i Space Exploration Analog and Simulation (HI-SEAS) is an experiment simulating long-duration life in a Mars habitat. Power for the habitat is generated by a photovoltaic system that exhibits daily variation in production rates. During days with cloud cover, the crew need to adapt their work schedule and support systems to ensure they can continue to function under low-power constraints. This paper accordingly presents the development and implementation of power budget profiles for low-, medium-, and high-power production days during Mission 5 of the HI-SEAS experiment. The applied power budget profiles limit which systems and devices can be used and for what duration. To generate these profiles, the HI-SEAS power subsystem was first characterized though power audits and data from daily crew use trends. The methods used to determine a prioritized list of habitat equipment for crew-member usage and compliance with restrictions are then discussed. Finally, an optimization method is proposed to determine the most efficient schedule to match each power usage profile with respect to crew preferences. The data from this experiment provide a novel opportunity to gain insight into power usage in space exploration habitats, establishing a foundation for the development of proper power generation and management technologies. Thus, this research can be used to provide meaningful guidance to most manned space systems in ensuring optimal power consumption under a variety of power generation conditions.

Keywords: Mars habitat, power consumption, space analog

1. Introduction[1]

The Hawai'i Space Exploration Analog and Simulation (HI-SEAS) is an experiment funded by NASA and operated by the University of Hawai'i at Mānoa. The HI-SEAS habitat consists of a geodesic dome that provides an isolated and confined environment for six crew members on the slope of the volcano Mauna Loa in Hawai'i, shown in Fig. 1. Crew members are selected from an astronaut-like pool of candidates to serve as the subjects of psychological studies of crew composition and cohesion during isolated long-term missions. The habitat and crew schedule were constructed to simulate the daily life of future astronauts on the Martian surface. The habitat features multiple-use spaces, a laboratory, and private crew quarters. Due to its isolated location, the habitat's life support systems rely primarily on renewable or storable resources for power, potable water, heating and ventilation, and communications.

[1] **Abbreviations:** Hawai'i Space Exploration Analog and Simulation (HI-SEAS), National Aeronautical and Space Association (NASA), Residual State of Charge (RSOC), Design of Experiments (DOE), Analytical Hierarchy Process (AHP), Multi-Criteria Decision Making (MCDM), Local Area Network (LAN), Photovoltaic (PV), Extravehicular Activity (EVA), Liquid Propane Gas (LPG), Concept of Operations (CONOPS), Computer Aided Engineering (CAE), Multidisciplinary Optimization (MDO)

As part of the HI-SEAS experiment, NASA has designated a number of red-flag problems that must be solved in preparation for extending manned missions deeper into the solar system, with crew performance and cohesion being major concerns during long periods of isolation [1]. Studies of these red-flag problems have addressed issues of team risk and performance including: team performance task/price of cooperation testing, continuous monitoring of face-to-face interactions with sociometric badges, measurement of emotional and effective states using automated analysis of multiple forms of crew-member textual communication to identify relevant and effective teamwork behaviors, and multiple stress and cognitive monitoring studies [2].

Other previous studies have investigated the power usage and forecasting of energy consumption using machine learning and the crew's overall psychological state (mood) [3] to compare and analyze the parameters and resource consumption of different missions [4]. Additionally, the habitat energy requirements have been broken down into the personal usage of each crew member and task within the various areas of the habitat [5]. The study presented in this paper provides a novel look at power consumption in a simulated Mars habitat and presents tools developed for these specific and unique energy usage situations. By focusing on energy prioritization and the differences between days with high and low energy production, this study endeavors to provide a clear picture of energy needs and adaptability in the face of varying power availability to establish a basis for further work in optimizing crew energy consumption. Effectively managing crew resources on long duration missions will be critical for crew health and safety on Mars, including maintaining energy availability for life support subsystems under variable conditions and reducing potential crew conflict over resource conservation.

2. Means and methods

2.1 The HI-SEAS habitat

2.1.1 Power subsystem

Primary HI-SEAS habitat power is generated by a 10 kW photovoltaic (PV) array, shown in Fig. 2, and stored in a 28.5 kWh battery bank for later use. In fair weather, the PV array can fully charge the batteries by mid-morning with a realized efficiency between 0.08 and 0.135 due to hardware and environmental losses. Secondary power is provided by a hydrogen fuel cell, automated to run when the residual state of charge (RSOC) of the batteries drops below 10 %. Low RSOC is most likely to occur in the early morning hours before the sun has begun to charge the batteries through the PV array, while the crew is still asleep and unable to take action to reduce power consumption. The hydrogen fuel cell provides immediate short-term backup power without crew intervention, but is insufficient for long-term use. Long-term backup power is provided by a liquid propane gas (LPG) generator, and requires crew startup and shutdown operations outside the habitat. This can be difficult on poor weather days when extravehicular crew activities are difficult; however, such conditions are also the most likely cause of low solar power generation, requiring this backup power system.

2.1.2 Habitat telemetry and communications

The habitat power instrumentation provides real-time telemetry data on power generation, consumption, and weather conditions affecting PV system performance. The generated solar power is compared to the battery RSOC and current power consumption to determine net power gain or loss in the battery bank. The current pressure in the hydrogen tanks is also measured for the secondary hydrogen fuel cell system. However, LPG pressure for the generator is not measured by the habitat instrumentation and is instead recorded periodically by the crew while on an extra-vehicular activity (EVA).

The telemetry data is recorded locally and is accessible through the habitat local area network (LAN), providing real-time and recorded past values of local irradiance, generated AC power, and AC power consumed by the crew. A 20 minute communication delay is applied each way to all communication between the crew and support personnel to simulate the asynchronous data transfer from Mars to Earth.

2.1.3 Crew operations

Daily crew operations are pre-scheduled, but greater autonomy and flexibility is provided than for ISS crews, to reflect the need for independent decision making on a Martian mission. This is particularly important considering the potential issues inherent to the 20 minute communications delay and challenges of transient weather that can result in the crew's need to autonomously alter their scheduled and unscheduled time to accommodate power conditions. One restriction on self-scheduling, however, is that crew EVAs must be requested and pre-approved by support personnel. As an EVA is required for the crew to turn on the LPG generator, a natural crew preference is created to manage power use by reducing consumption in the habitat before resorting to backup power generation measures. Under this practice, EVA requests place a burden on Mission Support to reply promptly and a risk to crew success when communication turnaround time is long. EVAs for backup power are often time sensitive to fit the additional task into the typical schedule and to increase power available before levels drop below the recommended level for battery longevity (about 10 % RSOC). Additionally, each EVA presents minor risk to crew safety. While EVAs for backup power are in the local habitat area, even short EVAs require a high level of physical exertion inside the analog suits, increase crew risk for lower leg injury (sprains, strains, and abrasions), and have depreciative effects on footwear and equipment. Reducing the number of EVAs for backup power generation protects the integrity of crew planned activities, longevity of equipment and reduces crew exposure to potential EVA health risks.

2.2 Energy consumption

An energy audit was conducted for the habitat during HI-SEAS Mission 5 to establish the standby, average, and peak power consumption of the appliances, laboratory equipment, and crew electronics connected to the habitat power subsystem. For appliances with variable power consumption such as heated kitchen appliances, low-, medium-, and high-power values were recorded using water or food as a typical thermal load. Nominal daily use was characterized for the largest energy consumers to provide baseline typical power requirements for crew research and recreation activities.

Daily PV charging trends were observed from the habitat telemetry establishing the time and efficiency of first morning charge, time to full battery under low, medium, and high available sun conditions, storm and cloud cover characterization, and the time of last charge approximating sunset. Habitat life support usage was monitored during crew sleep hours to establish the inactive baseline for autonomous processes. A portion of Mission 5 was conducted with a long-term plant growth experiment running during day and night hours. To ensure that the predictions were conservative, overnight power consumption was assumed to represent a worst-case baseline that included the plant experiment running 24 hours a day.

The crew developed a numerical model to calculate power consumption trends and used it to predict the hourly and daily RSOC given current conditions and expected cloud cover. As inputs, the model takes the current battery and PV data from the habitat telemetry to determine a power generation rate, and takes all anticipated power loads in the habitat, including expected crew activities for cooking, recreation, and research as power debits. Calculations were then run to project the RSOC value for the following morning assuming a typical overnight power load. Highlighted in this paper are daily power-use trends categorized into high-, moderate-, and low-power generation conditions developed from these daily calculations. These nominal cases were also converted into time-based budgets to guide the crew in setting appropriate limitations on power use when engaging in high power consumption activities over the course of each day.

A set of activities and their associated appliances with the largest effect on power that the crew were able to self-schedule were selected for prioritization according to the analytical hierarchy process (AHP) [6]. The Mission 5 crew completed a survey during week 23 of the 34 week mission to rate the importance of their self-scheduled activities according to personal impression on a scale of 1–9 for each of the following four criteria: mission criticality, necessity for primary research, necessity for personal research, and importance for mental or emotional wellbeing. Relative priority weights for these four criteria were determined through a pairwise comparison by the Mission 5 engineer who acted as the survey administrator and are shown in Table 1. These relative priorities were normalized to a maximum value of 1.0 and applied to the crew survey data as weights. The weighted crew survey data was then aggregated through a comparison matrix, and the final priorities were taken from the normalized eigenvector with a consistency of 7 %.

Out of the several AHP techniques that have been published, a rating analysis was selected for these data to allow a greater number of activities to be compared despite the limitations this method places on aggregating the results for the entire crew [6]. Note that automated and critical processes, such as habitat ventilation and heating, powered telemetry equipment, and safety-critical computing equipment were excluded from this prioritization. Such equipment represents a perpetual minimum power load that must be met by either primary or secondary power supplies, as they are not subject to crew self-scheduling or prioritization.

3. Results

3.1 Mission 5 power usage

The Mission 5 crew typically used 50–60 % of the battery RSOC from sunset to sunrise and could reduce this to a minimum of 34 % on extremely low-power generation days. This minimum consumption supported the mission-critical hardware and life support systems, but did not support activities such as cooking, electronic entertainment, or lighting. On moderately low-power days, the crew reduced consumption by turning off excess lighting, minimizing cooking times, only powering mission-critical research devices or life support, and lowering the thermostat to the minimum required for the composting toilets, resulting in the use of approximately 45 % of RSOC overnight.

The daily crew power use trends and RSOC projections were combined and refined into the power budget profiles given in Fig. 3. The budget prescribes a target RSOC according to time of day for low-, medium-, and high-power conditions. When the solar irradiance was high, the crew was allotted a more aggressive power use profile than when there was more cloud cover. All power budgets were designed to provide a comfortable morning RSOC where moderate heated food preparation and morning hygiene routines could be maintained without resorting to backup power sources. Note that the power budget profiles assume similar sunrise and crew wake times for all days, and crew cooking, computing, and recreational activities were organized to fall within the ranges for each power condition. The minimum required evening RSOC was approximately 60 % at sunset if the crew followed aggressive power saving techniques overnight. This minimum RSOC allowed all habitat power loads to be satisfied by the batteries without necessitating any backup power generation before the PV array began supplying power the following morning, but required considerable adaptability on behalf of the crew that often disrupted the planned activity schedule.

Figures 3 a) and b) show the change in RSOC with time during the morning and evening periods, respectively. Figure 3 a) shows the RSOC from midnight until 08:00 when the habitat life support systems are running autonomously and the crew is resting. Figure 3 b) shows the RSOC from 17:00 to 23:00 when crew is actively consuming power, but generation through the PV array has stopped. Critical power saving actions must be taken during these afternoon and evening hours to preserve battery capacity. These figures show a significant difference between the morning RSOC and evening RSOC according to the power requirements of the life support system and highlight the importance of accurately predicting power consumption, as the consequences of a day’s worth of crew and life support system power consumption will not be realized until the early morning hours while the crew is inactive and before the PV array has started charging the batteries.

If the current or projected RSOC was below the threshold value in the early evening, powered activities could be reduced until the usage returned to the trend necessary to avoid the need for secondary backup power measures. This typically necessitated a prioritization of activities so that unnecessary activities were removed from the power plan in order of importance, allowing the crew to achieve their RSOC target with minimal impact to planned work and leisure activities. The aggregated crew priorities from the survey are shown in Fig. 4. Values were determined through the AHP analysis using the category weights from Table 1. The resulting scores provide general guidance on crew preferences when reducing powered activities. Some priorities show close scores, indicating either a lack of consistent preference by more than one crew member or a low but congruous preference for that activity. Access to personal computers and the laboratory freezer were highly prioritized, as both were required to support scientific research tasks. Personal comfort items such as toilet ventilation and a warmer thermostat setting were moderately important to crew members. Specialized tools and equipment were given low priorities, particularly those that were important to only a single crew member. Notably, the crew were asked to rank their priorities without concern for power consumption or other crew members’ needs, but in practice, the Mission 5 crew often negotiated power use for personal projects or for full crew entertainment based on expected power consumption. Indeed, the crew members were often willing to sacrifice or restrict personal priorities to achieve group goals.

A portion of the power audit results are presented in Fig. 5, showing the relative mean power drawn by each appliance in the HI-SEAS habitat. Many appliances are run for an hour or more and are thus considered heavy-load appliances, but the microwave, electric kettle, and toaster are used for minutes at a time and thus considered moderate-load appliances. Most non-heated appliances draw little power, and individual crew members were regularly able to negotiate power allotment for their personal use even on moderate- or low-power days. Over a single day, the toilet fans and experimental plant growth lights required the greatest energy as they ran constantly and were thus largely responsible for the power consumed between midnight and 08:00. Considering both the power audit and prioritization results, Table 2 shows the recommended RSOC thresholds for high-power activities in Mission 5 under high-, middle-, and low-power generation conditions.

At least eight significant low-power days occurred during Mission 5 (determined as days with an RSOC below 77 % at 17:00), and the crew was required to utilize one or more backup power sources for four of these days. These days were heavily overcast, preventing power generation through the PV array and required either the LPG generator to charge the battery bank during the afternoon or the hydrogen fuel cell to turn on automatically in the early morning. Half of these low power days occurred within the first 45 days of Mission 5 when the crew was less adept at changing their behavior to accommodate poor weather. The crew operated under high autonomy with little guidance pre-mission on when to utilize backup power sources. With their operational freedom, the Mission 5 crew prioritized social interaction even if power could not be used by playing games and spending social time together on "dark" evenings. The crew also prioritized power to support research tasks, attempting to keep their assignments on schedule, and to charge equipment like batteries and radios for EVAs scheduled the following day.

3.2 Comparison of power consumption of different HI-SEAS missions

Each of the HI-SEAS mission crews worked hard to ensure that energy would be consumed in a manner that realistically reflected a Mars mission. The crew engineer would indicate a "low power" day in which the crew would need to reduce power usage, mainly due to low solar power production. The low power days are identified for the crews of Missions 2, 3, and 5 in Table 3, which shows the average total power usage on a normal day compared to a power constrained day. Table 3 illustrates the relative difference in average power consumption and savings for each of the missions, in which it can be seen that Mission 2 saved an average of 2.13 % power on low power days, Mission 3 reduced its consumption by 9.3 %, while Mission 5 reduced consumption by a much greater amount of 22.2 % on average.

4. Discussion and conclusions

Prioritization of resources is paramount in advance of emergency low power events to guide power reduction activities. The prioritization presented here focused on crew controlled tasks and individual crew preferences determined by survey. HI-SEAS mission managers do not provide priorities for equipment or tasks at HI-SEAS beyond those critical to primary funded research projects and habitat equipment safety. Crew members operate under high autonomy and comforts like cooking, recreation, habitat HVAC and personal research tasks are largely crew controlled, as is the timing of some primary research tasks. Until the recommendations in Table 2 were created, indication to conserve power was the responsibility of and at the discretion of the Mission 5 crew engineer with only periodic input from other crew members. A Martian surface mission will require a more formalized process determined in advance according to mission goals as well as crew preferences. Current documented mission prioritization has focused on research value such as those proposed by the ad-hoc external advisory committee for Biological and Physical Research Maximization and Prioritization (REMAP). Unlike the operational priorities presented in this study, REMAP considered driving principles such as relevance, impact, scientific benefit and other commitments to determine a roadmap for near and long term payloads to the ISS [7]. Similar prioritization practices would need to be employed before deploying Martian surface payloads, equipment, and habitats. Operational duties and priorities are largely handled by ground crews on current ISS missions with low autonomy. For long duration manned missions with moderate to high autonomy, it would be wise to determine crew-centered priorities early in the systems engineering cycle and support them from a mission architecture perspective. Research indicates that autonomy and relatedness between crew members is positively associated with crew happiness and performance [8]. Team cohesion and the effect thereon from individual crew behavioral health, are of great importance as manned missions extend duration and distance from Earth [2]. Anticipating crew preferences and high autonomy behavior during concept of operations (CONOPS) definition could promote shared leadership between crew and ground through system level development and encourage positive behavioral health outcomes under such isolated extreme mission architectures. CONOPS that support crew autonomy could also increase crew motivation when following resource conservation protocols by supporting personal preference along with mission objectives and giving crew priorities a platform earlier in the development cycle.

The data presented in this paper will eventually be leveraged to create a parametric model of the habitat power subsystem. Similar to the numerical model used during Mission 5, parametric models could support real-time crew prediction calculations or be extended to support mission planning for resource allocation. Model input parameters representing the crew power requirements and duration of powered activities can be used to predict the future RSOC. Varying these inputs and recording the effect on the model outputs creates a broad understanding of the design space for crew activity effects on power consumption. This relationship can then be used for statistical analysis and optimization of crew activities. Fig. 7 illustrates the process flow of the proposed parametric optimization model.

The optimization model can be used by the crew of an extended mission to develop action plans that accommodate in-mission conditions. The user of this model can vary typical crew behaviors parametrically and project the resulting RSOC for the following morning. Constraints can be placed on the inputs to respect mission requirements and to create feasibility conditions on the outputs, i.e. the crew activity set only succeeds if the projected morning RSOC is high enough to prevent the use of backup power. If multiple goals are placed on the model outputs, such as finding a solution for both minimal energy use and maximizing the time spent on preferred crew tasks, the model can serve as a foundation for multi-objective optimization. An optimization of power usage can be carried out for variable solar insolation and to find the closest solutions to a designated power budget profiles. By running this model through parametric optimization software like modeFRONTIER, it can be automated and iterated to develop a large set of solutions that meet RSOC requirements and stated goals. However, it is important to note that such a multi-objective optimization will yield not one solution, but a Pareto set of valid solutions. The selection of a single solution from the Pareto set requires multi-criteria decision making (MCDM) [9]. Prioritization is the foundation of MCDM as informed by the multi-objective optimization of the crew's power consumption. The AHP priority rankings from Mission 5 will be used to weight the Pareto solutions and facilitate the selection of the most favorable solution from the set of successful options.

A simplified design of experiments (DOE) study was run in modeFRONTIER during Mission 5 using the basic predictive power calculator tool as a stand-in for the parametric model. This confirmed the overnight minimum RSOC values observed by the crew, showing that about 60 % of the battery RSOC was required at sunset for the crew to make it through the night. The analysis varied power consumption on a subset of crew activities and held constant the power requirements for the toilets, overnight plant growth experiment, and critical habitat systems. The DOE workflow from Mission 5 is shown in Fig. 8. The future parametric workflow will seek to optimize the time durations of more crew powered activities while maintaining a sufficiently high RSOC to reach sunrise the next day. Three different workflows can then be developed to match the sunny-, moderate-, and low-power budget profiles presented in this paper. Similar tools could empower future crews to make in-mission decisions on resource allocation, reducing the potential for internal crew conflict over energy conservation methods and improving power availability under variable conditions in long-duration missions.

Notably, the baseline life support requirements of the HI-SEAS habitat are predictable and modeled assuming a nominal behavior. Although there is daily and seasonal variation in cloud cover and solar irradiance, the local power generation and consumption for Mission 5 is well understood and easily modeled with linear equations like those in the predictive calculator tool. Atmospheric conditions on the Martian surface and the complexity of a true Martian habitat would require higher fidelity modeling and simulation inside the optimization loop. Creating parametric models for a Martian habitat would require both ground truthing and communication across analysis disciplines. For example, models and simulations for crew power consumption would need to be coupled with subsystem models for thermal and ventilation behavior of the habitat. Most computer aided engineering (CAE) models are parametric and can be coupled inside an optimization loop using multidisciplinary optimization (MDO) techniques. MDO studies are generally built with systems level knowledge and can be leveraged to combine multiple parametric models of habitat functionality, scientific payload, and crew characteristics to optimize for shared goals. Additional challenges are presented by the unique atmospheric conditions on the Martian surface. Dust accumulation, decreased PV performance, and lengthy unpredictable dust storms will all reduce power generation [10, 11]. It is likely that a solar power subsystem will work in cooperation with another power source like hydrogen fuel cells or a nuclear power plant. Parametric models of each other these systems can be similarly coupled for cooperative analysis or even energy balancing between sources and loads. Such methods are already used for sizing and balancing the power generation, storage and energy delivery of renewable energy microgrid systems [12].

The data presented in this paper characterize crew power consumption and prioritization in an isolated Martian analog habitat and present methods used by the Mission 5 crew to accommodate individual preferences for power consumption. It may be useful in planning resources for long-duration missions and determining how crew priorities might affect power use both positively and negatively. In addition to the future applications discussed, it is beneficial to define such crew resource priorities as a way of providing context for resource usage data from high autonomy crews. For long duration isolated space missions, crews' latitude for decision-making will grow and the burden of resource allotment will eventually fall to the crew rather than ground support. These crews must be able to take time sensitive actions without extended analysis from Earth-based mission operations and the methods presented provide a foundation for further work in this area. In particular, reliability of power subsystems for the safety of the crew's life support and scientific success under variable weather conditions will incentivize crews' adaptability to changing energy availability under high autonomy mission architectures.

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Declarations of interest: none.

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Table 1. Priority weightings for AHP criteria.

	Priorities	Normalized Priorities
Mission Criticality	0.461	1.000
Primary Research	0.181	0.393
Personal Research	0.047	0.102
Personal Well-being	0.311	0.675

Table 2. Recommended RSOC thresholds for Mission 5.

Activities	RSOC Sunny	RSOC Mid-range	RSOC Cloudy
Dinner	13%	11%	5%
Toilets	23%	23%	23%
Plant Lights	11%	11%	11%
Personal Computers	9%	9%	1%
Other Loads	7%	4%	4%
Total Battery Used	63%	58%	44%

Table 3. Average energy conservation on low-power days for Missions 2, 3, and 5.

	Mission 2	Mission 3	Mission 5
Number Days with Low Power	4	21	11
Average energy consumed: Low power day (kWh)	138.25	149.06	111.86
Average energy consumed: Normal power day (kWh)	141.27	164.39	143.74
Average conserved energy (kWh)	3.02	15.30	31.94
Percent energy conserved	2.14%	9.31%	22.2%

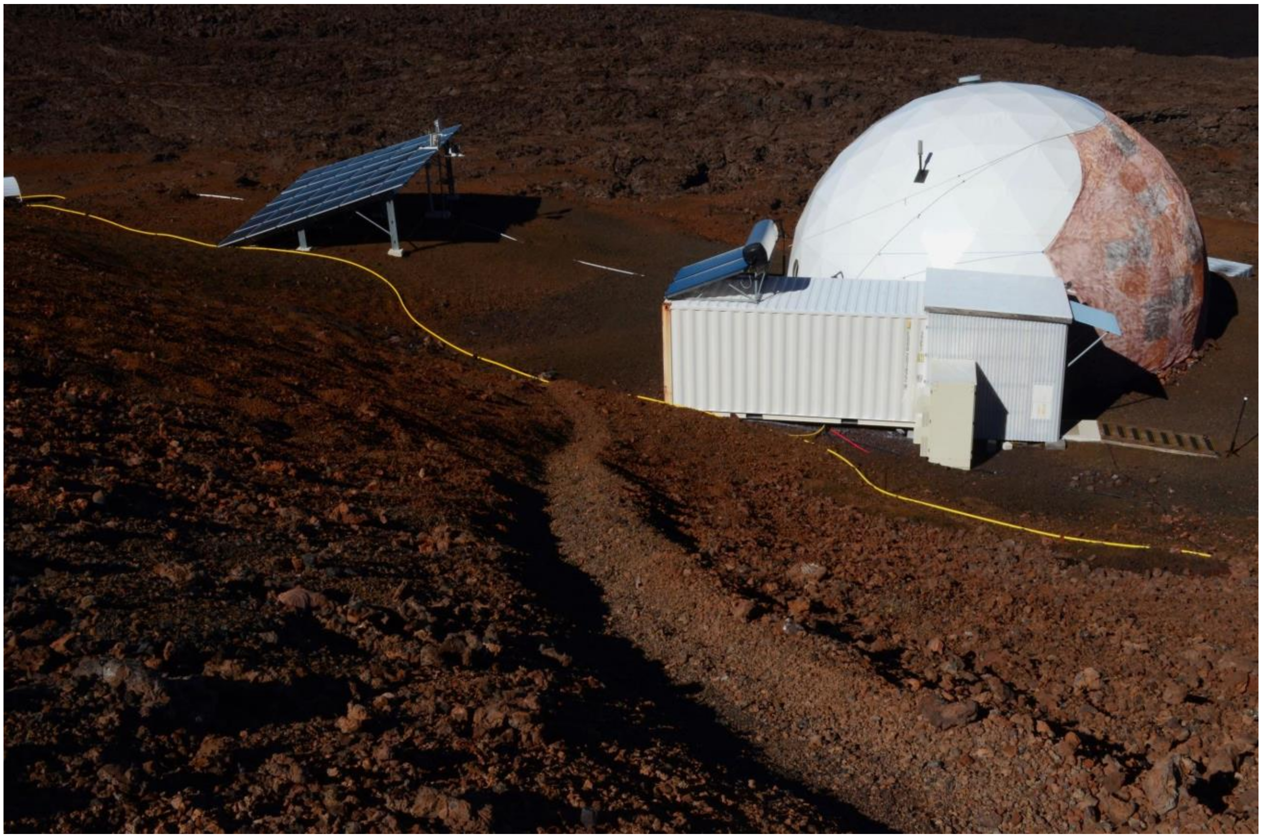
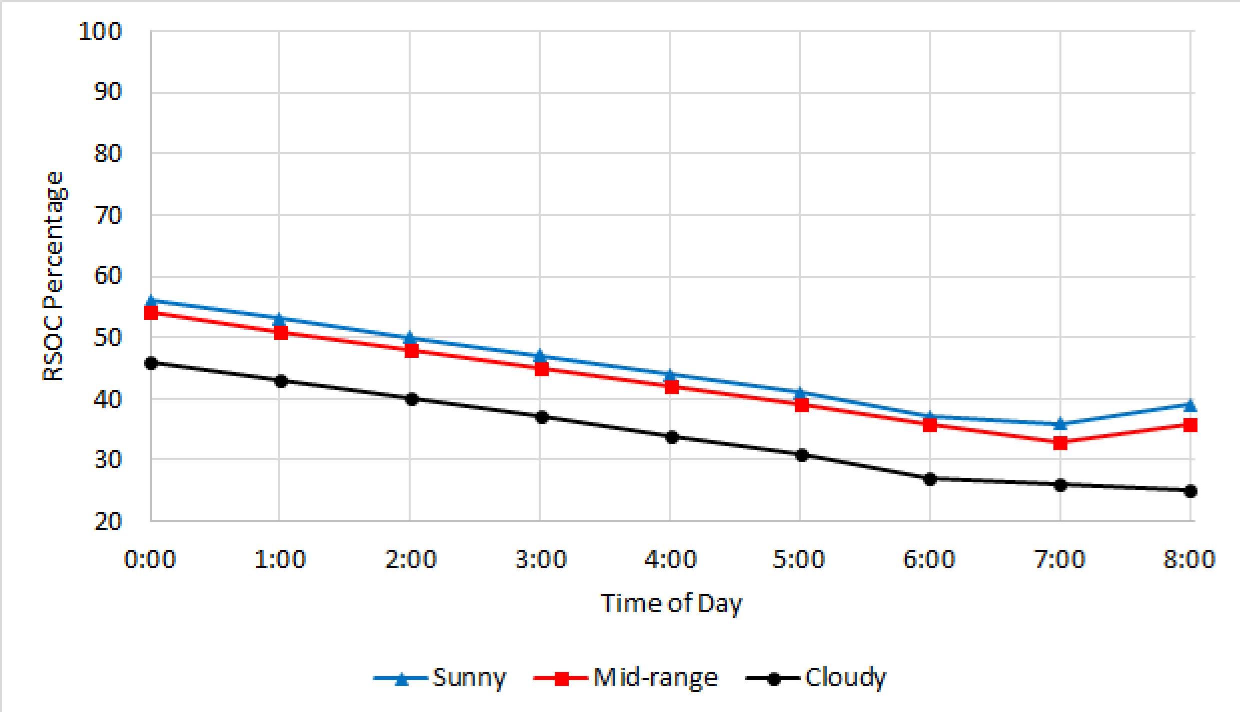
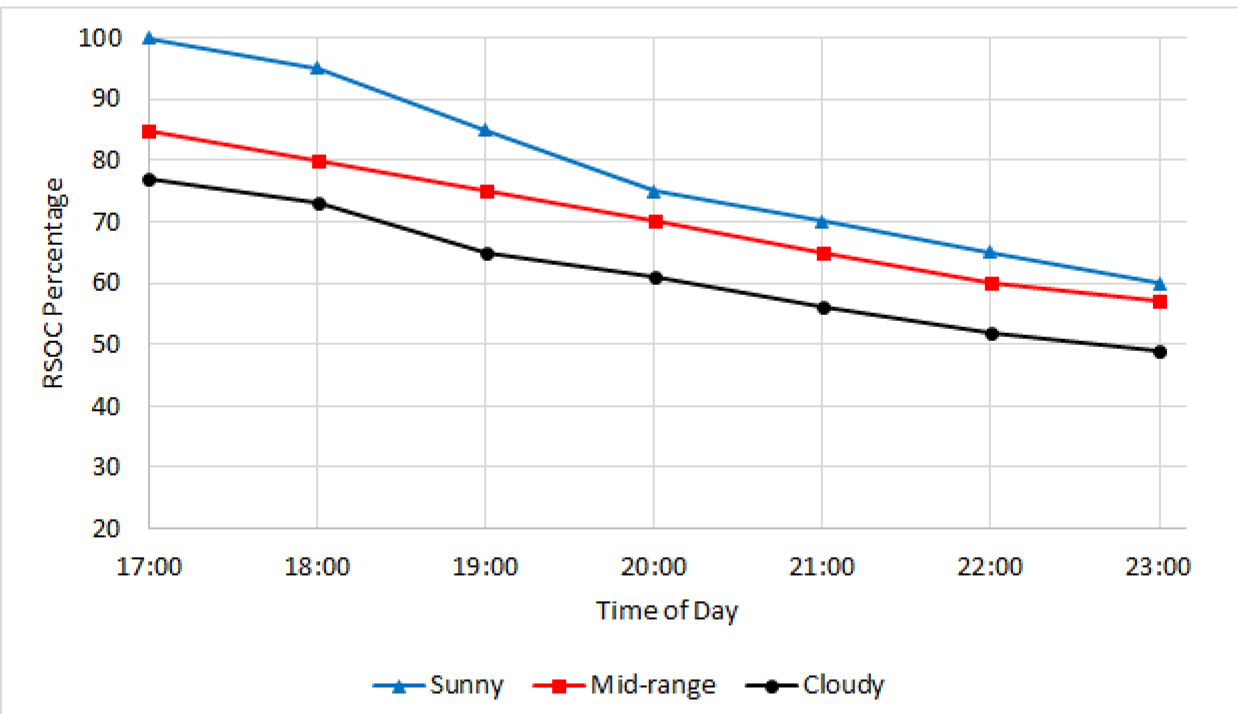


Fig. 1. The HI-SEAS Habitat at ~8500 ft elevation on the slopes of Mauna Loa, housing a six-person crew with ~300 square meters of living space. Photo credit: Ansley Barnard.

Fig. 2. HI-SEAS 10-kW solar array.



(a)



(b)

Fig. 3. Power budget profiles showing change in percentage of RSOC (a) over the morning hours, and (b) over the evening hours.

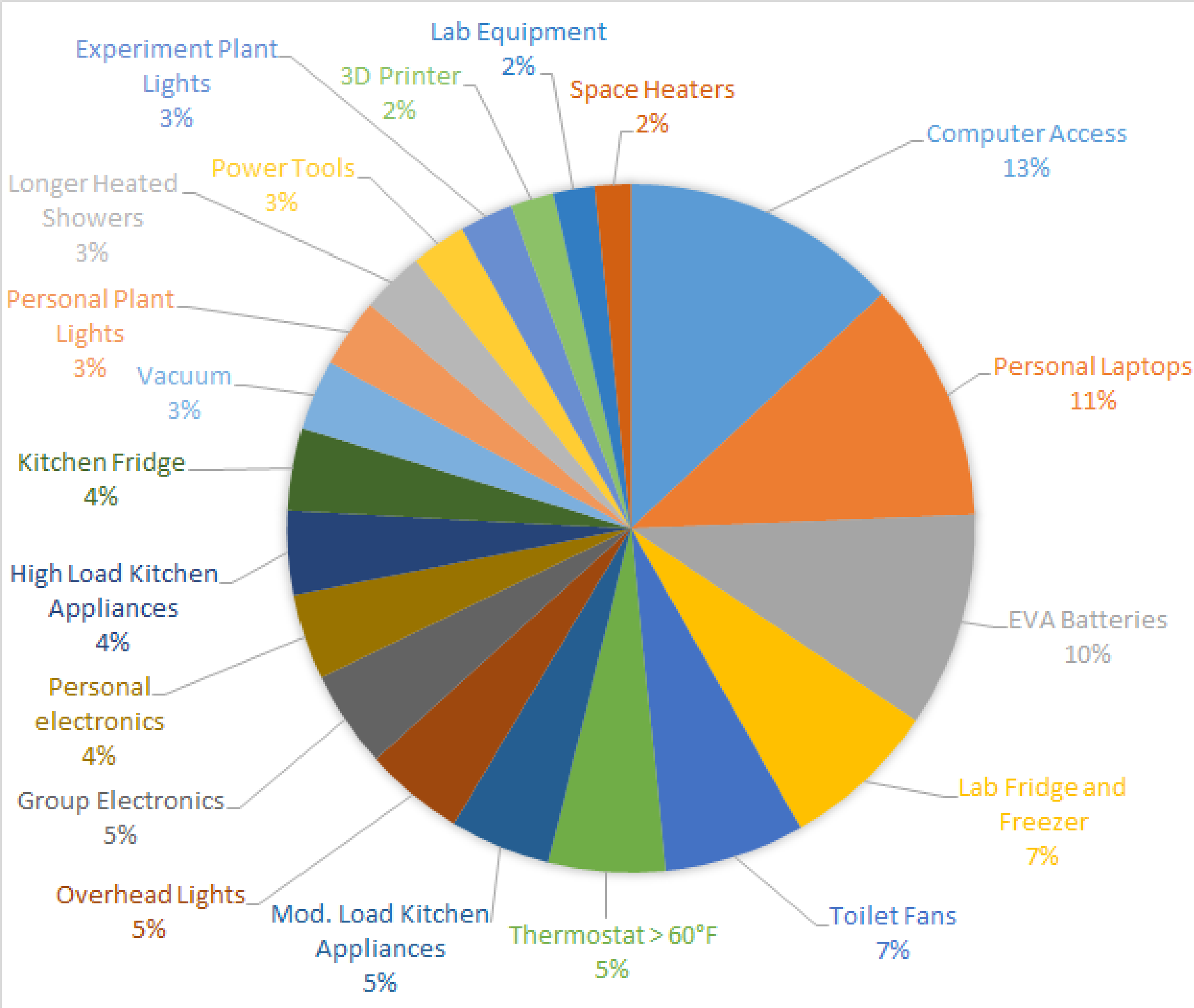


Fig. 4. Relative power priorities for Mission 5 showing aggregated power priorities of appliances used in self-scheduled tasks. Priorities were determined through AHP analysis of crew survey.

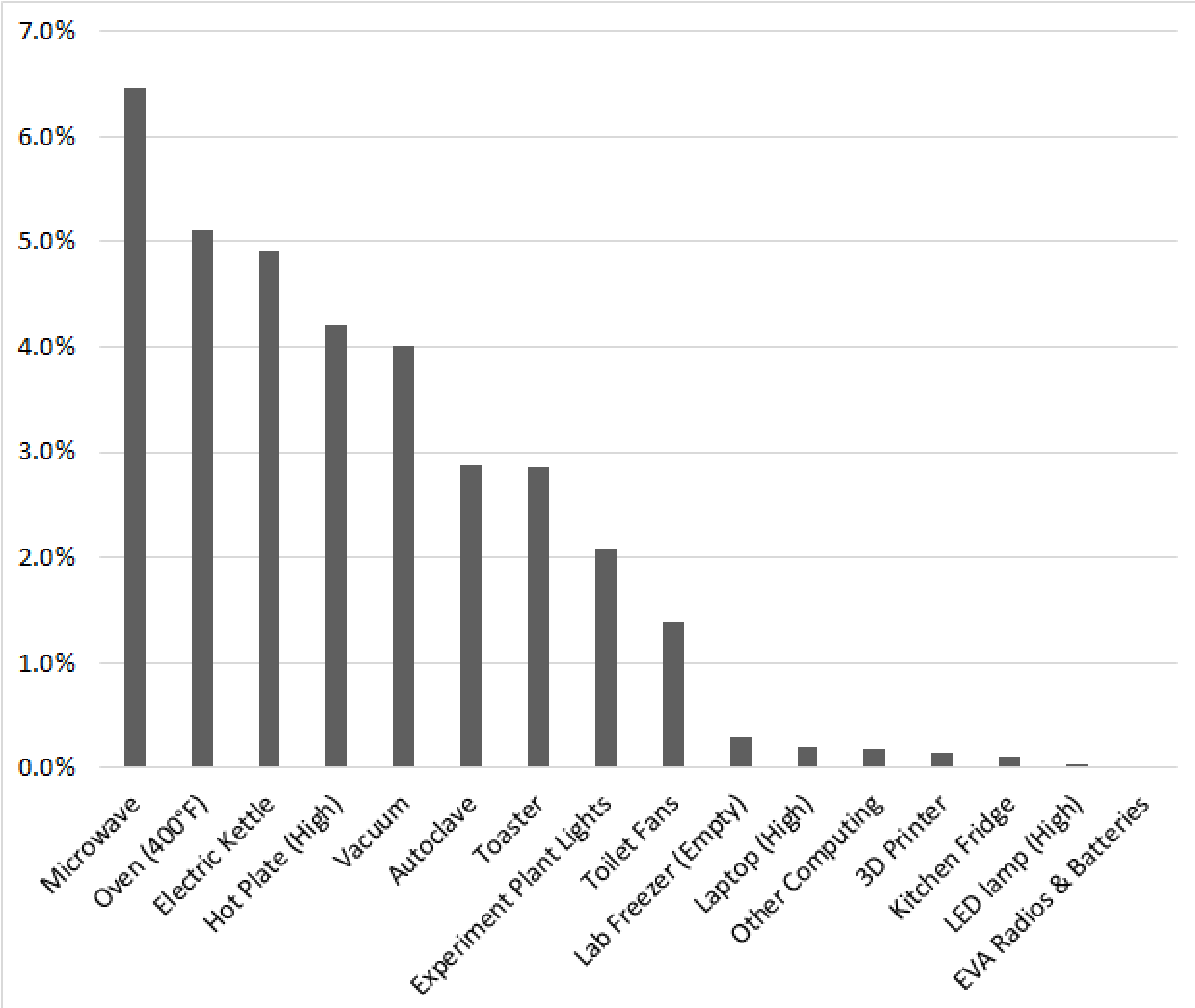


Fig. 5. Hourly mean steady-state power consumption for common habitat appliances during Mission 5. Power consumption was determined through a manual audit of typical use and normalized as a percentage of battery capacity.

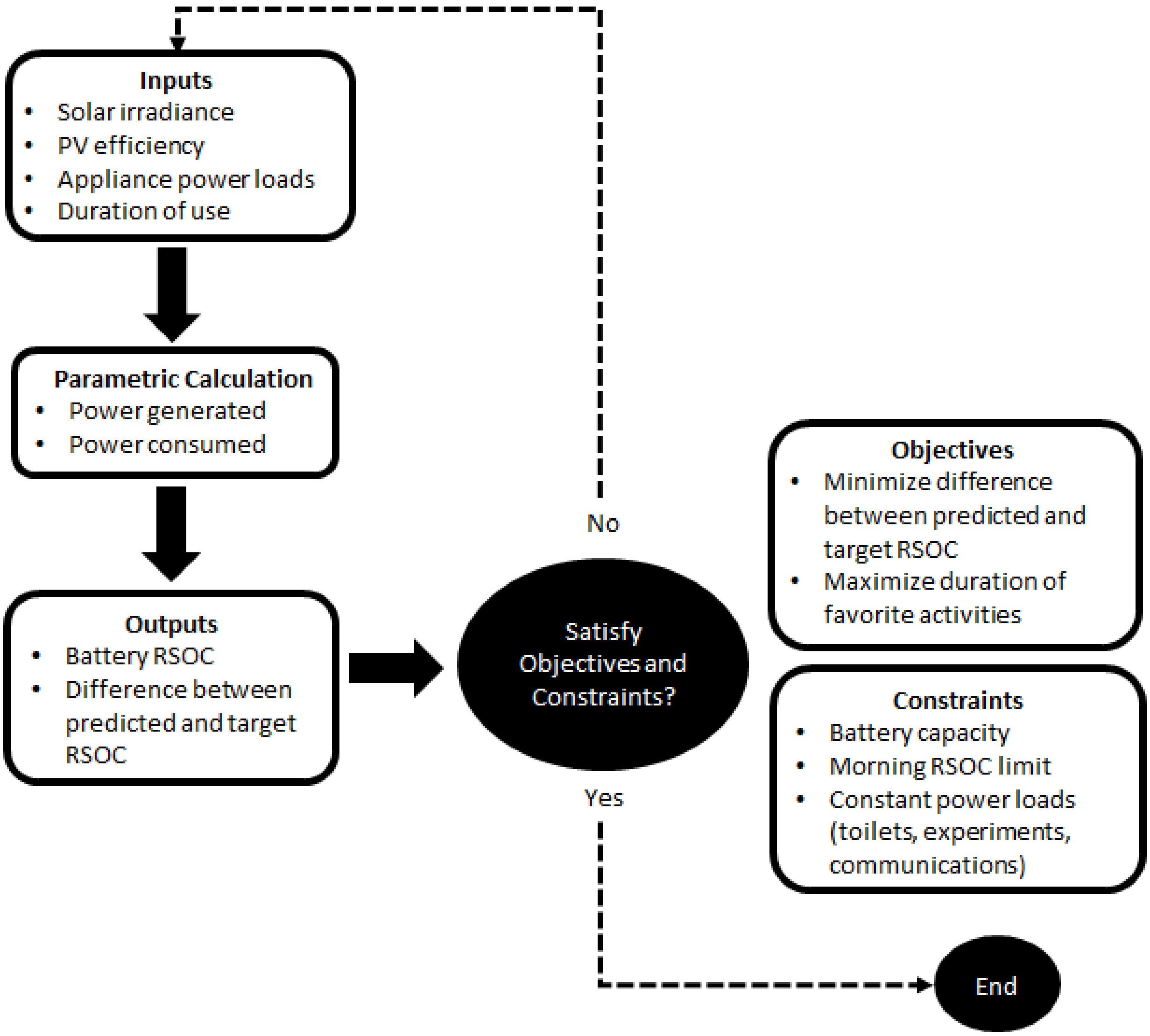


Fig. 6. Flowchart showing resource prediction calculation inside an optimization loop.

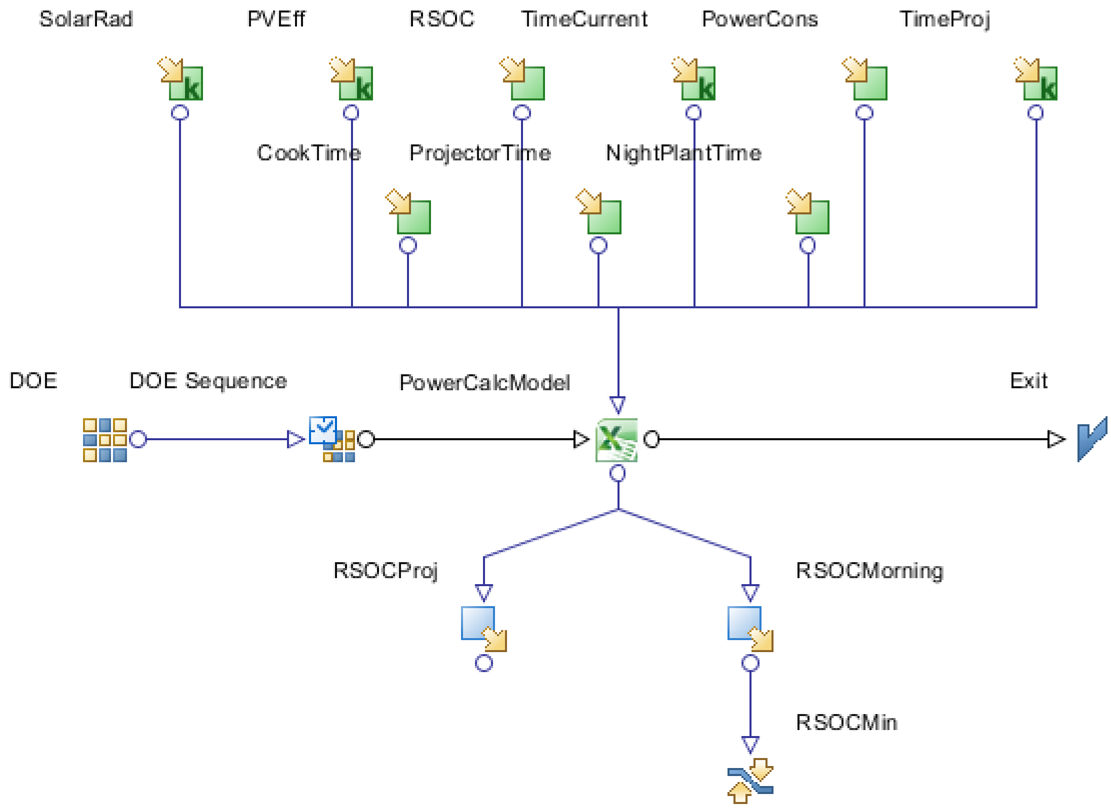
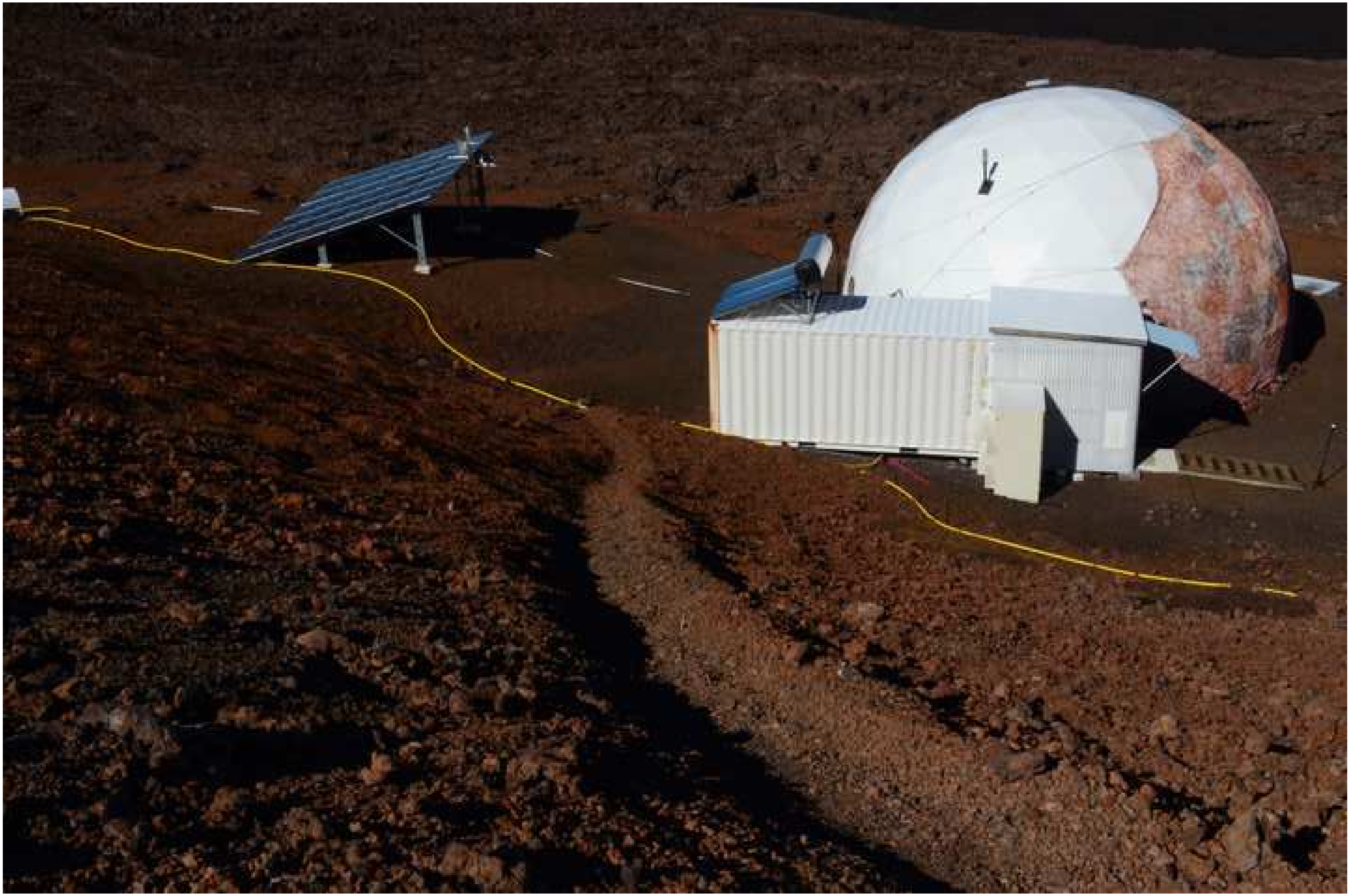
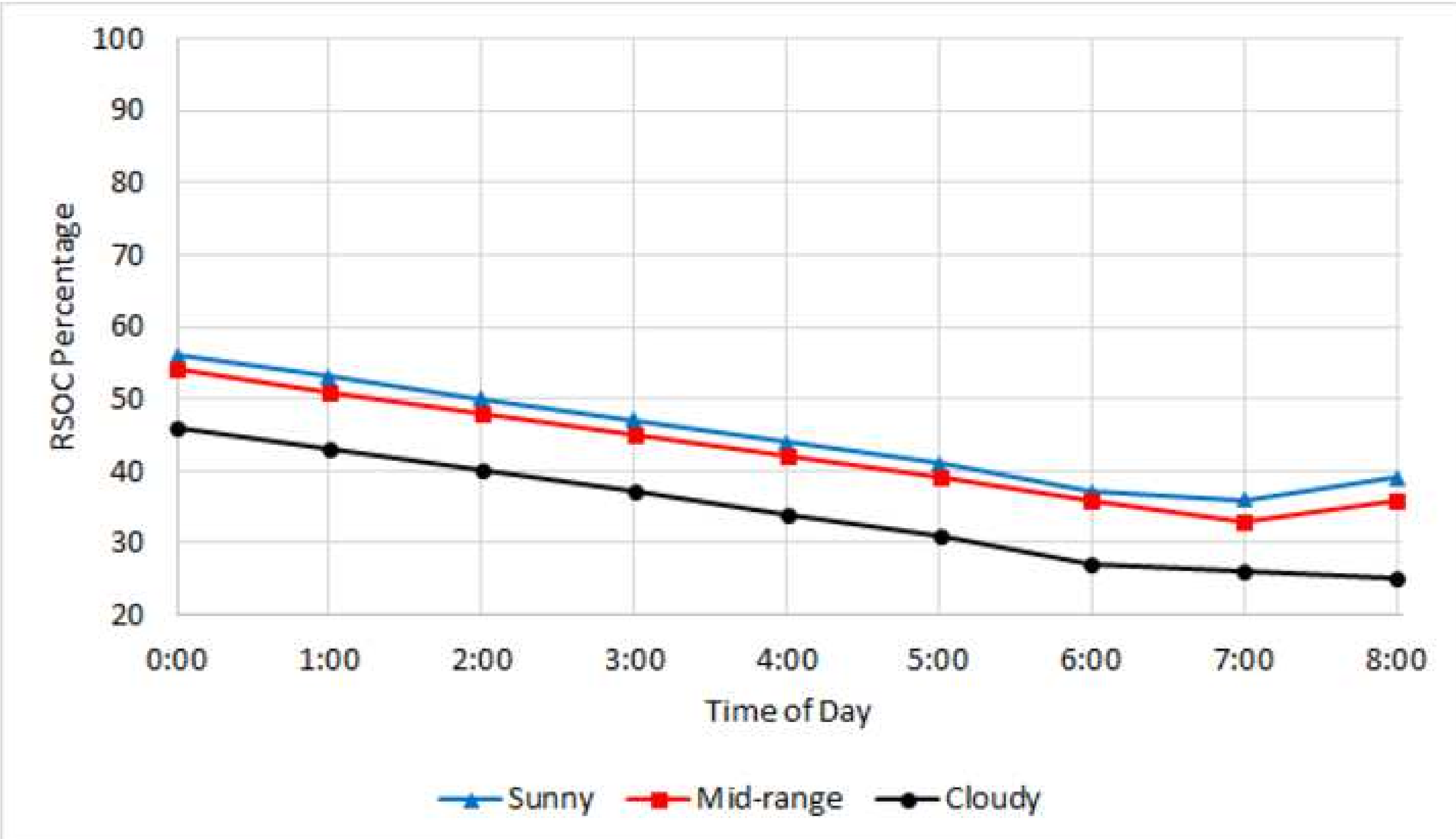
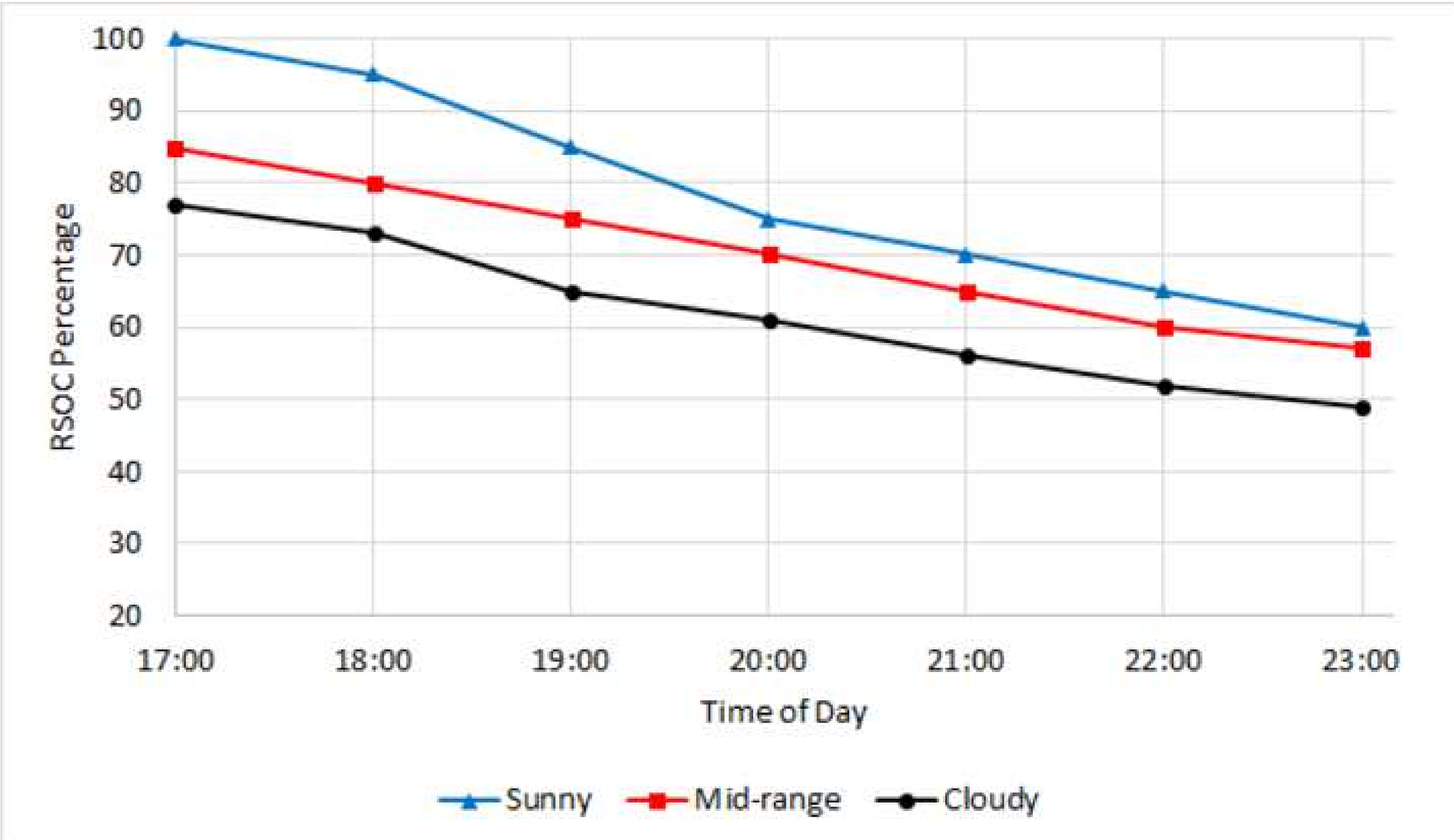


Fig. 7. The modeFRONTIER workflow for the DOE study from Mission 5 exploring the response of battery RSOC to crew evening activities and weather conditions.




100
90
80
70
60
50
40
30
20
RSOC Percentage
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
Time of Day
Sunny
Mid-range
Cloudy

Click here to access/download;Figure;Figure_3_b.png



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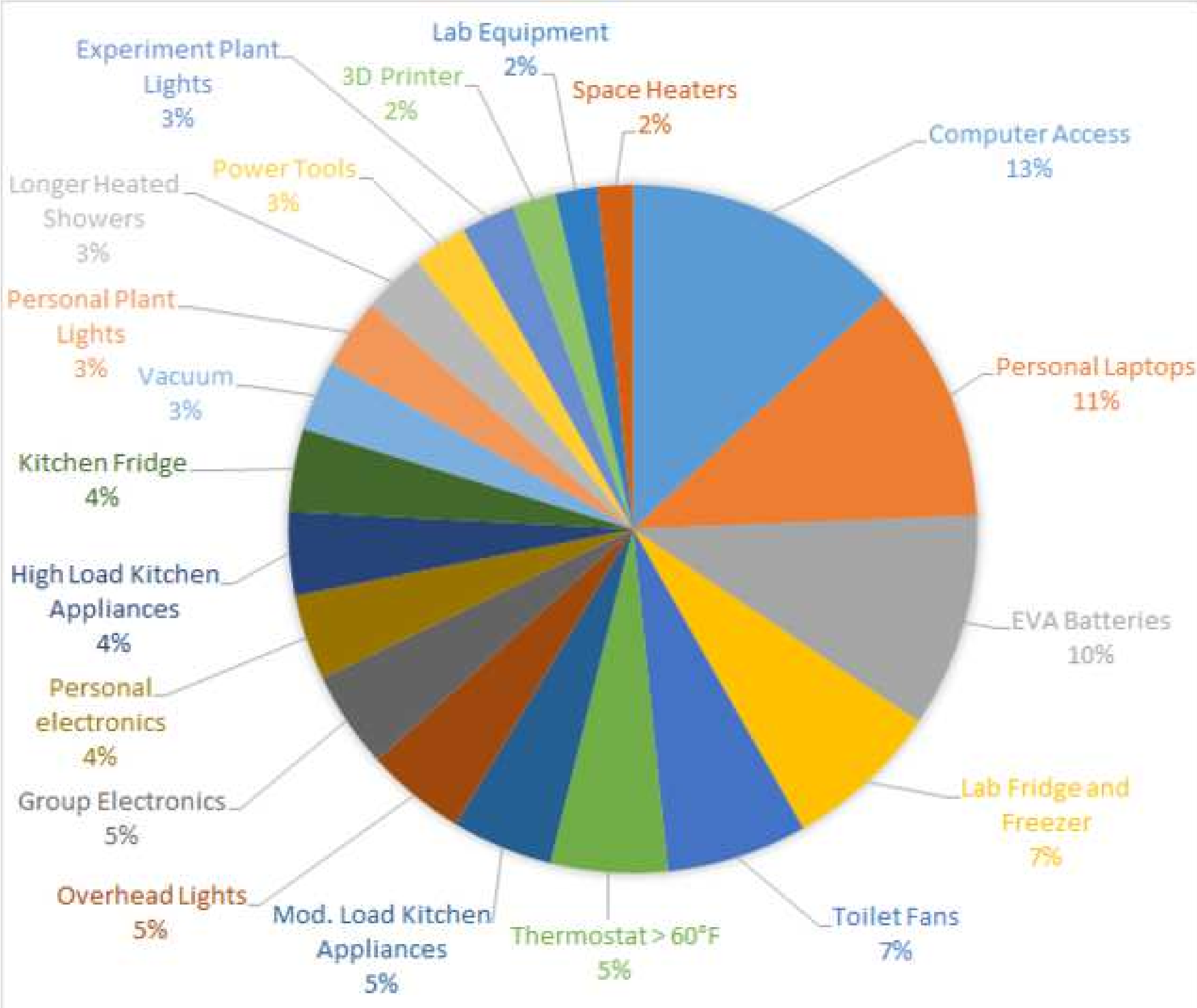

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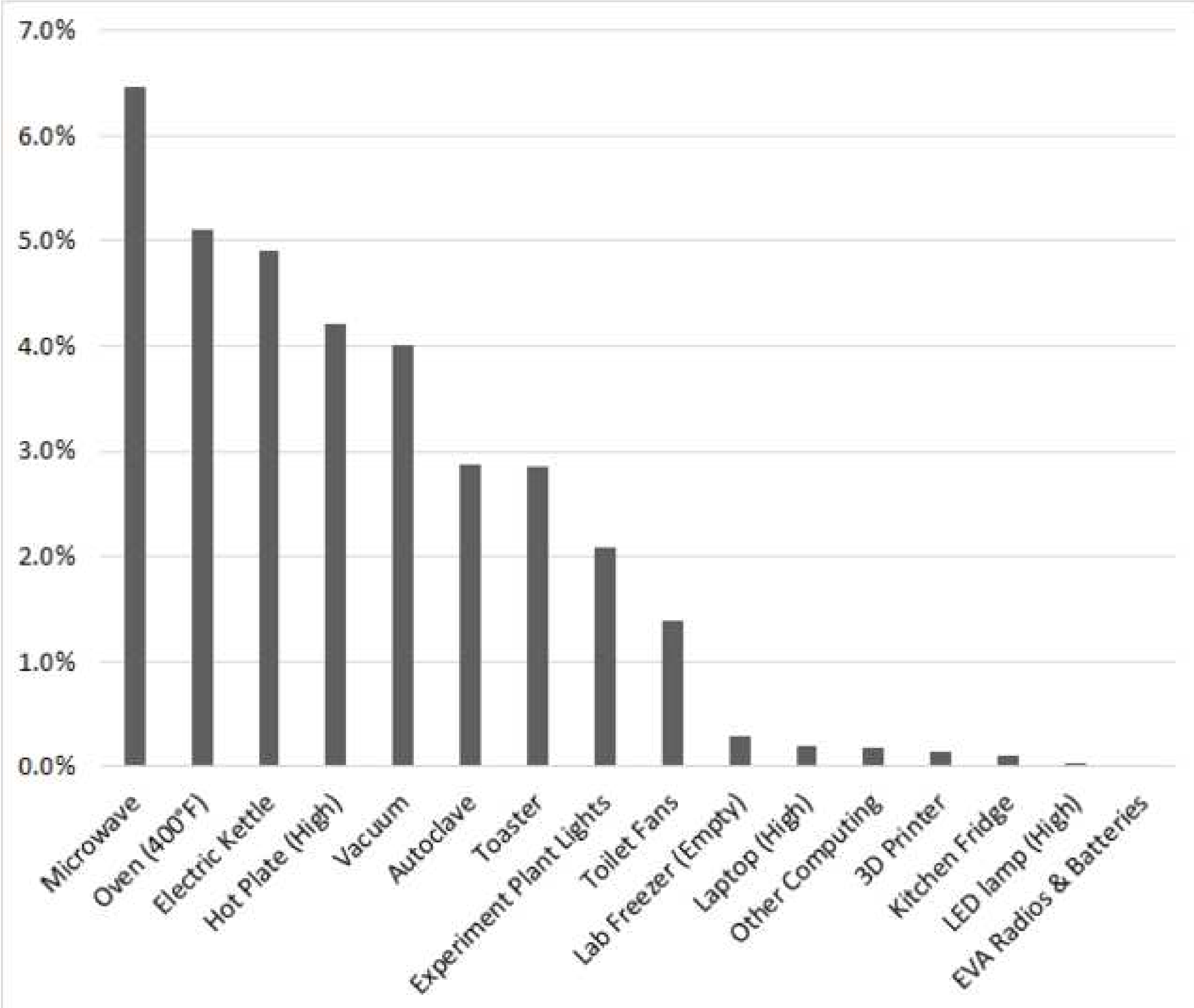
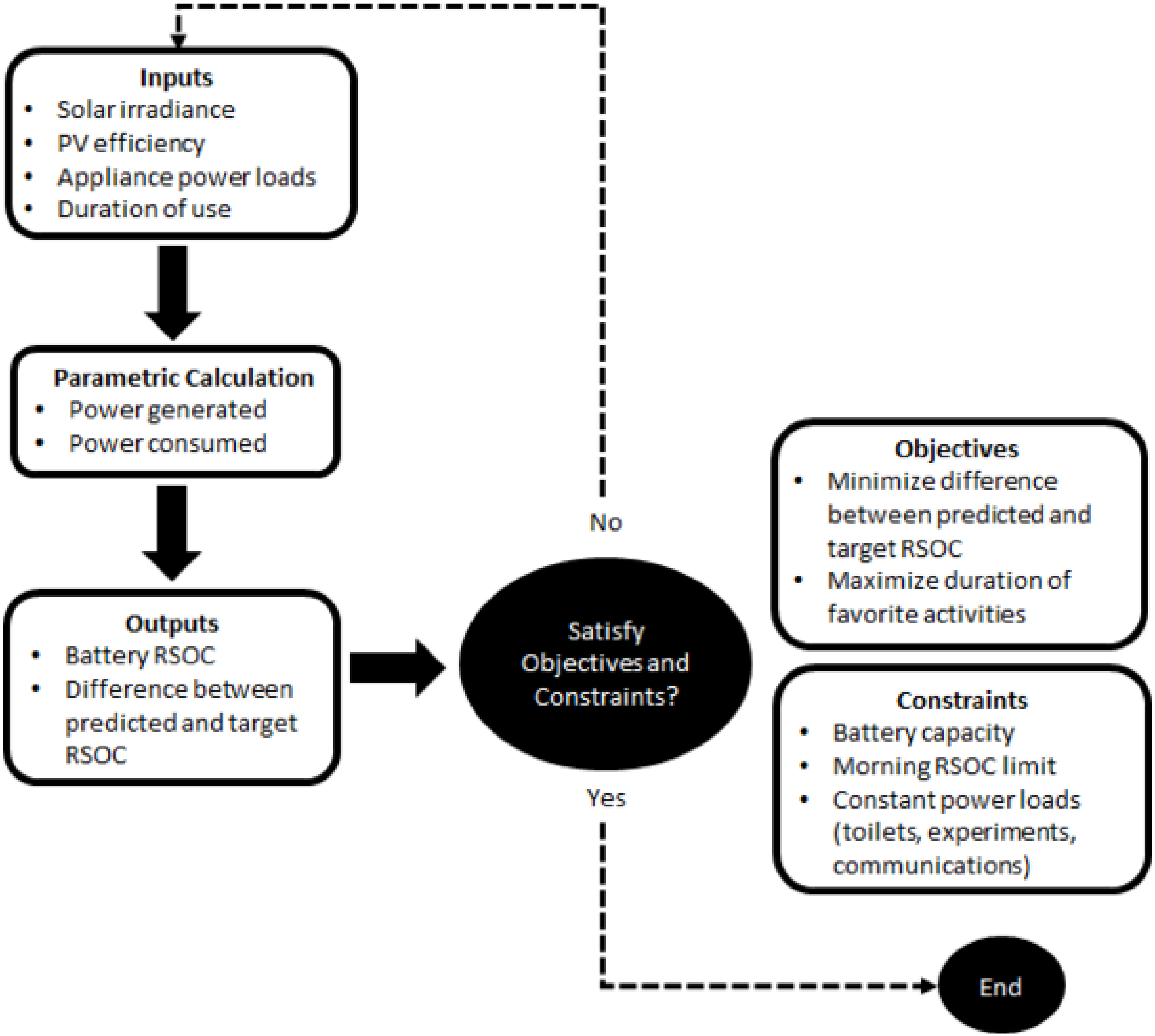
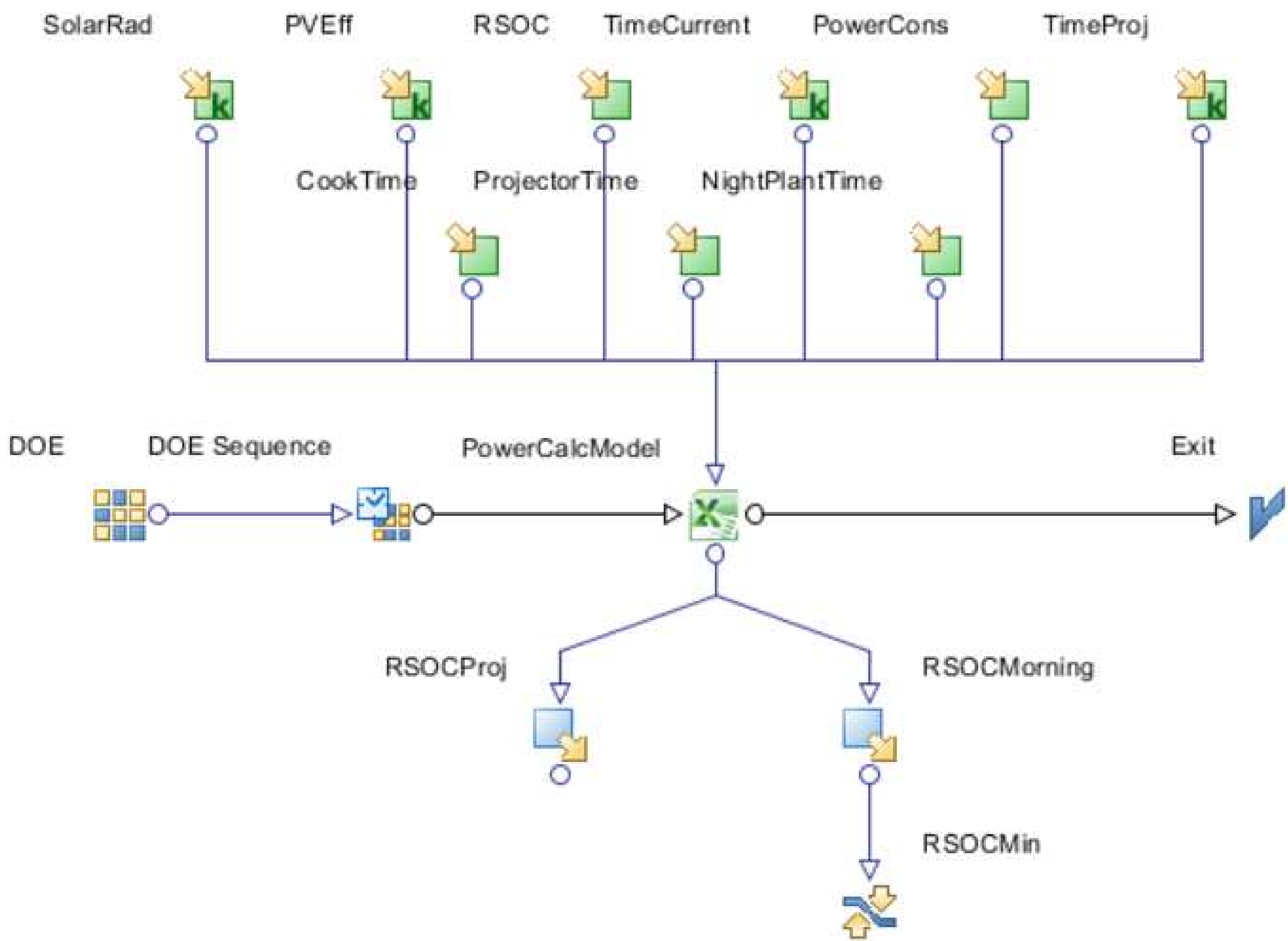



Inputs
Solar irradiance
PV efficiency
Appliance power loads
Duration of use
Parametric Calculation
Power generated
Power consumed
Outputs
Battery RSOC
Difference between predicted and target RSOC
No
Satisfy Objectives and Constraints?
Yes
Objectives
Minimize difference between predicted and target RSOC
Maximize duration of favorite activities
Constraints
Battery capacity
Morning RSOC limit
Constant power loads (toilets, experiments, communications)
End


SolarRad
PVEff
RSOC
TimeCurrent
PowerCons
TimeProj
CookTime
ProjectorTime
NightPlantTime
DOE
DOE Sequence
PowerCalcModel
Exit
RSOCProj
RSOCMorning
RSOCMin

20th Oct. 2019

M.T. Kezirian
Editor-In-Chief
Journal of Space Safety Engineering

Dear Editor:

Conflict of interest statement:

I wish to submit an article for publication in the *Journal of Space Safety Engineering* titled "Mars Habitat Power Consumption Constraints, Prioritization, and Optimization." The paper was coauthored by Ansley Barnard, and Kim Binsted.

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. All study participants provided informed consent, and the study design was approved by the appropriate ethics review board. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

Thank you for your consideration. I look forward to hearing from you.

Sincerely,

Simon Engler

Simon T. Engler
Department of Information and Computer Science,
University of Hawai'i, POST Building,
Rm 317, 680 East-West Road, Honolulu, HI,
E-mail: simon.engler@hawaii.edu