Design of Power Systems for Extensible Surface Mobility Systems on the Moon and Mars

by

SeungBum Hong

B.S. in Mechanical and Aerospace Engineering,
Seoul National University (2002)

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirement for the Degree of

Master of Science in Aeronautics and Astronautics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2007

Author . . . .
Department of Aeronautics and Astronautics
August 23, 2007

Certified by . . . .
Jeffrey A. Hoffman
Professor of the Practice of Aeronautics and Astronautics
Thesis Supervisor

Accepted by . . . .
David L. Darmofal
Associate Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

Design of Power Systems for Extensible Surface Mobility Systems on the Moon and Mars

by

SeungBum Hong

Submitted to the Department of Aeronautics and Astronautics
on August 23, 2007, in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Aeronautics and Astronautics

Abstract

This thesis presents the power system model description and sample studies for extensible surface mobility systems on the Moon and Mars. The mathematical model of power systems for planetary vehicles was developed in order to estimate power system configuration with given mission parameters and vehicle specifications. The state-of-art power source technologies for space application were used for constructing the model; batteries, fuel cells, and photovoltaic systems were considered in this thesis. The Sequential Quadratic Programming method was used to find the optimal power system configurations based on the concept of a previous MIT study. Several case studies on the Moon and Mars were carried out to show the usefulness of the model and to recommend power system configurations for 7-day off-base exploration missions on the Moon and Mars. For the lunar mission, photovoltaic and fuel cell hybrid power systems were suggested. In addition, vehicles with photovoltaic/fuel cell hybrid systems could be operated without recharging when they were driving in shadowed regions. For the Mars mission, both fuel cell single power systems and photovoltaic/fuel cell hybrid systems were acceptable for short missions of only a few days. However, if long, sustainable missions were considered, photovoltaic/fuel cell hybrid systems were required.

Thesis Supervisor: Jeffrey A. Hoffman
Title: Professor of the Practice of Aeronautics and Astronautics

Acknowledgements

I would like to first and foremost thank my advisor Prof. Jeffrey A. Hoffman for his thorough guidance, encouragement, and support. I would also like to thank my professors for their education in systems engineering and space systems. Finally, I would like to thank my fellow students who were good classmates, and helped my study much.

My work was supported financially by the Samsung Scholarship. I was honored by this opportunity from the Samsung.

Finally I thank my family and friends for their support and concerns. I cannot stand here without their help.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivations

NASA announced a new vision for space exploration (VSE) in 2004 which included human exploration on the Moon no later than 2020, and preparing a human mission to Mars by 2030. NASA's strategic roadmap started with robotic orbital and surface missions while manned missions are developed. Manned missions to the Moon will be executed with multiple EVAs and science excursion from the lander. In addition, permanent base construction will follow. A Mars mission will begin around 2030 to provide 500-600 days surface stay.

Crewed surface mobility systems will have a critical role to generate more value in lunar and Mars surface exploration because they increase the speed of vehicles greatly, provide the capability to move heavy equipment and supplies, and generate the ability to explore more range beyond walking distance. Pressurized surface mobility systems can generate more value for missions on the Moon and Mars because they can extend the reach of crews from 20-30 km to more than 100 km above the duration of regular EVAs.

Several concepts of pressurized vehicles have been developed and suggested since the Apollo program. A concept of a two astronaut pressurized rover called MOLAB (MObile LABoratory) was studied and suggested under a NASA contract to Boeing [1]. Two different pressurized rover concepts were proposed by the reports from the Universities Space Research Association (USRA) operated NASA/USRA University Advanced Design Program. One is a relatively small and low speed rover; whereas the other has two cylindrical pressurized vessels connected by a pressurized passageway [2, 3]. The

University of Texas developed an interesting concept of rover, called Mars Surface Transportation System, equipped with an inflatable habitat contained in parabolic trusses which was different from the common cylindrical habitat [4]. Hoffman and Kaplan suggested a large pressurized rover, which can stay for an 18 to 20 months on the Mars surface [5]. Finley proposed a Daylight Rover equipped with two cylindrical vessels and two manipulating arms for geological sampling and collecting [6]. In addition, Arno developed a concept of lunar pressurized rover model including power and weight requirements for drilling and digging abilities [7].

The MIT Fall 2004 16.981 Advanced Special Project class developed the Moon and Mars exploration mission architecture for NASA's Concept Evaluation and Refinement study (CE&R study [8]). In the MIT CE&R study, a new concept of planetary surface mobility was suggested; the combination of unpressurized rovers and pressurized campers was generally less massive than other combination. This design concept included a pressurized camper and an unpressurized vehicle (UPV). The Camper did not include an independent steering system and provided minimal functions for habitation and science work in order to decrease mass. A UPV had roles to tow a Camper to the destination and explore the sites around the camp site, detached from the Camper. Since pressurized campers provided overnight stay and long-range traverse capability and light unpressurized vehicles enhanced fast exploration capability around the camping site, this architecture provided longer range mobility and larger value of return with less mass than other system architectures did.

MIT Spring 2006 16.89/ESD 352 Space System Engineering class focused on crewed surface mobility systems for the Moon, Mars, and analog sites on Earth [9]. This study considered an in-depth look at surface operations and hardware with an emphasis on achieving commonality of components used for the Moon, Mars and analog exploration and testing on Earth. In the first design phase, four Design Reference Missions (DRMs) were grouped to provide appropriate operational scenarios for all the major functions. DRMs include short-range excursion (DRM-1), long-range excursion for extended exploration (DRM-2), re-supply logistics for a permanent outpost on Earth or the Moon (DRM-3), and infrastructure construction on all three planets (DRM-4). This study conducted a high-level architecture analysis to determine base surface mobility system architecture for the fleet of pressurized and unpressurized vehicles. A simple metric for generating trade space between scientific exploration sites visited and vehicle mass was used and it confirmed that a fleet comprised of pressurized campers and unpressurized vehicles generated more scientific value with less massive architecture. The second phase of the study developed a detailed integrated vehicle model, the Terrain Vehicle Model (TVM). TVM estimated baseline lunar vehicle design parameters such as geometric dimensions, masses of subsystems, and power requirements. In the final phase, an analysis of achievable commonality was conducted with a baseline lunar vehicle design and modified designs for Earth and Mars. Figure 1 is a conceptual drawing of the new mobility system [9]

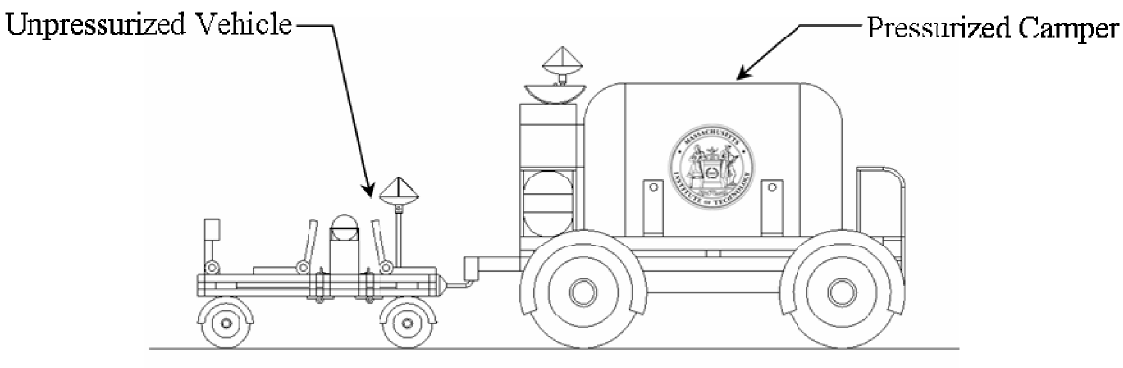

Figure 1. UPV-Camper configuration

However, in the study of the Camper and UPV system, the power system configuration was estimated by assuming the use of fuel cell power source only and average power requirements for the entire mission. In order to minimize the mass of power, more rigorous analysis is needed, such as considering a hybrid power system which includes recharging via photocells. In addition, a new concept of planetary surface mobility system, the combination of a Camper and UPV, will be operated in various short mission scenarios during its lifetime. The vehicles can be operated for several 7-day missions or 14-day missions during a 3-year lifetime, for example. For each short mission, detailed activities might be different: e.g., for 7-day missions, one can have 2-day driving and 5-day doing science activity, while the other has 5-day driving and 2-day science activity. In these cases, energy requirements for two short missions will be different, and it means that power systems should have different configurations. Therefore, a model which considers complex and detailed mission scenarios and power requirements for each operational phase will provide more detailed specification of power systems to system engineers in the conceptual design phase.

1.2 Thesis Objectives

The goal of this thesis is to demonstrate that a power system model of planetary surface mobility systems can be constructed and used for suggesting the primary design with a given lunar or Mars mission in the conceptual design phase.

In this thesis, a model of power system configurations will be provided. The model will estimate the mass of power systems with various power source options and characteristics of power systems for the Camper/UPV system used on the surface of the Moon and Mars. In addition, with this model, case studies will be followed and power system configurations for each case will be recommended.

The objectives of this thesis include:

- To provide the model to estimate the mass of power systems for a given mission scenario.
- To provide the model to compare the mass and size of power systems among two hybrid power options.
- To provide the model to check the feasibility of a given mission scenario.
- To demonstrate case studies for a reference mission scenario.

1.3 Approach Methodology

The characteristics of current power sources, environment data, and specification of the vehicles will be used for the base of the model. Based on these data, the model will optimize the mass of power systems for operation on a given planet and condition. The mass of power systems includes masses of primary power sources, photovoltaic power systems, and secondary power sources: battery or fuel cell systems. Sequential Quadratic

Programming (SQP) will be used for optimization. At each hour during a mission, power balance between consumption and recharge will be calculated, and the net power usage multiplied by time, 1 hour, will be subtracted from the energy stored in secondary power systems. Energy stored in secondary power systems at each hour will be constraints for the optimization; energy stored should be greater than zero at any time.

To achieve the specification of the vehicles and power requirement of each operation phase, the design parameter is entered into the Terrain Vehicle Model (TVM) software. TVM is a MATLAB® [10] program that captures the pertinent physics of the planetary surface mission and generates a specific design of a Camper and UPV. Reference [9] gives a complete account of the physical models used in TVM to compute vehicle specification.

With the power system model, case studies on the Moon and Mars are performed to recommend specific power system option for given mission scenarios. The case studies provide more rigorous concept designs of power systems for the Camper and UPV system.

1.4 Thesis Outline

The reminder of this document develops and demonstrates the model of power systems for extensible planetary surface mobility systems for the conceptual design of the Camper/UPV systems. Chapter 2 will summarize the concept of the Camper and UPV system, developed by the MIT class. Chapter 3 will provide summary of the state-of-art technology of power sources for space applications, which will be used for the model development. Chapter 4 will state the model description including mathematical models of each power system and the optimization procedure. Chapter 5 will illustrate and evaluate the application of the model to lunar and Mars missions. Finally, Chapter 6 states the conclusions from this research and recommendations for future work.

Chapter 2

Concepts of Planetary Campers

Chapter 2 provides the overview of concepts of planetary campers which were proposed by the MIT Spring 2006 16.89/ESD.352 Space System Engineering class. This chapter demonstrates the rationale that Camper/UPV systems are the most reasonable choice in terms of total wet mass and the number of sites visited. In addition, this chapter gives the specifications of Campers and UPVs for lunar excursions. Reference [9] gives a complete description of extensible planetary surface mobility systems.

2.1 Introduction

A combination of pressurized campers and unpressurized vehicles for planetary surface excursion missions was first introduced by the MIT-Draper CE&R study [8]. The new concept of planetary surface mobility systems separated 'habitability' and 'mobility'; pressurized campers provide 'habitability' for the crew, and unpressurized vehicles provide 'mobility' by towing pressurized campers. Figure 2 shows the conceptual drawing of a planetary camper [11]. Since habitats are usually heavy and massive, much energy is required for carrying habitats for entire mission duration. Therefore, energy requirements can be reduced if habitats, e.g., pressurized campers, do not have to be moved and can be partially powered down while astronauts explore around a camp site.

Further study was performed by the MIT Spring 2006 16.89/ESD.352 Space System Engineering class, focusing on developing planetary surface mobility system architectures for the Moon, Mars and Earth analog site excursions, supporting NASA's Vision for Space Exploration, first announced in 2004. The analysis and design approach of the class consisted of: 1) a systematic analysis of the Moon and Mars mobility requirements and architectures, 2) development of subsystem-level design for a single preferred architecture.

Vehicle design concentrated most heavily on the development of lunar vehicles and provided commonality analysis for Mars and Earth analog site vehicles.

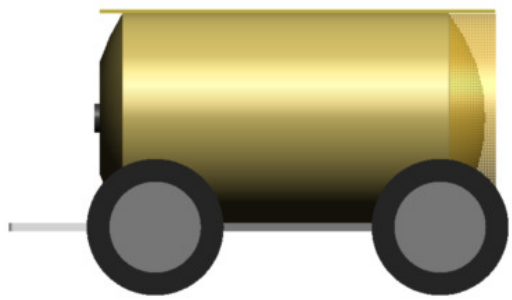

Figure 2. Planetary Camper Concept

2.2 Assumptions

The mobility system is considered separately from the basic outpost; this study does not analyze interfaces between the outpost and surface mobility systems. This assumption enables more detailed analysis of surface mobility systems.

For the Moon, the outpost is landed near a major science site, and the astronauts would travel no farther than the next closest major site. The average distance between the major sites is around 100 km. For the Mars, the outpost is landed near a so-called "National Park." "National Parks" are clusters of science sites with an average spacing of 4500 km. Astronauts operate the mobility system to explore the nearest major site, because no practical surface mobility system is able to traverse from one National Park to another.

2.3 Mobility System Requirements Analysis

2.3.1 Problem Statement

A formal problem statement provides a guideline for further requirements and architecture analysis and design. The goal of the planetary surface mobility system in this study is as follows:

- <u>To</u> extend the capabilities of Moon and Mars surface exploration
- <u>By</u> providing the capabilities to carry out 4 types of design reference missions on

the Moon, Mars, and in analog environments on Earth

  - Short-distance excursions (unpressurized)
  - Long-distance excursions (separate pressurized capability)
  - Base-re-supply excursions (cargo transport)
  - Infrastructure build-up missions (cargo delivery, moving of resources, etc.)

- In a sustainable way (metrics)
  - Affordably
  - Providing continued value delivery
  - With acceptable development and operational risk (especially to human life)
  - Policy robust
- <u>Using</u> a surface transportation system which
  - Is extensible from the Moon to Mars, and can be tested on Earth
  - Can provide short-distance capability for early lunar sortie missions
  - Is reusable for multiple surface missions
  - Can successfully interface with other exploration system elements (such as habitats, communications equipment, electrical power system, etc.)

2.3.2 Design Reference Missions

Four Design Reference Missions (DRMs) are outlined in order to evaluate system architecture choices. The DRMs cover the broad possible range of operational tasks astronauts will perform on the Moon, Mars and in analog environments on Earth. Table 1 summarizes DRM applicability to different operational scenarios.

Sortie missions are short duration missions of up to one week on the lunar surface, and astronauts live in the lunar lander. Due to trajectory constraints between Earth and Mars [12], sortie missions are not performed on Mars. Outpost missions are performed on the Moon and Mars, and astronauts live in the outpost habitat.

The detailed explanation of DRM-1 and DRM-2 will follow. Since a Camper/UPV system was created, focusing on DRM-1 and DRM-2, DRM-3 and DRM-4 will not be described in this thesis. For more detailed explanation of DRM-3 and DRM-4, refer to reference [9].

Table 1. DRM applicability to different operational scenarios

	DRM 1 short traverse	DRM 2 long traverse	DRM 3 re-supply mission	DRM 4 infrastructure mission
Earth Analogue	O	O	O	O
Lunar Sortie	O	X	X	X
Lunar Outpost	O	O	O	O
Mars Outpost	O	O	X	O

DRM-1: Short-Distance Excursion

Short-distance excursions will explore a relatively short range around the lander or outpost, similar to the Apollo program. DRM-1 includes geological surveying, deployment of science instruments, and investigation of primary science sites. Astronauts will operate UPVs, not Campers, when performing DRM-1.

Duration of DRM-1 is limited by space suit life capacity and astronaut fatigue, and is assumed to be 8 hours. Considering the safety of astronauts and using historical data from the Apollo program, the maximum range of a DRM-1 excursion is ~20 km.

DRM-2: Long-Distance Excursion

A pressurized vehicle is used in DRM-2, allowing overnight stays on the surface of the Moon and Mars and increasing the range beyond the range of a single EVA. Astronauts can live inside the pressurized vehicle without spacesuits. DRM-2 includes all activities performed in DRM-1, together with eating, washing, researching, and sleeping inside the pressurized vehicle.

The duration of DRM-2 is dependent on the life support capacity of the pressurized vehicle and the available energy. A detailed specification of DRM-2 duration remains a variable for the architectural selection. The range of DRM-2 excursions is determined by the distribution of interesting sites on the Moon and Mars. For the Moon, the major sites of scientific interest are, on the average, distributed roughly 100 km apart, and the minor sites lie in between the major sites. For Mars, the average distance between the major sites is 200 km and the distance between the National Parks is 4500 km [8].

2.4 Mobility System Architecture Analysis

In order to establish a baseline mobility system architecture for the set of pressurized and unpressurized vehicles, a high-level architecture analysis is conducted. Metrics are the wet mass of systems and science values; mass serves as a proxy for cost, since it drives launch costs and the number of science sites visited serves as a metric for science values based on the assumptions that a constant time is required for science exploration at a single site and a uniform linear distribution of sites exists along the traverse path.

Objectives of the architecture analysis are to minimize mass and maximize the number of science sites visited. Risk, extensibility, and robustness are considered as constraints. The Planetary Surface Vehicle (PSV) model [11], a framework to model mass, power, and dimensional specification of planetary vehicles, is used for computing mass of the mobility system architecture.

Figure 3 shows one example of the Pareto fronts generated by architecture analysis. DRM-1 and DRM-2 architecture analysis and architecture sensitivity analysis lead to selecting a baseline of 2 unpressurized vehicles with 2 crew each for DRM-1 and 2 pressurized "campers" supporting 2 crew each for DRM-2, along with several unpressurized vehicles. Overall baseline architecture selection is summarized in Table 2. The camper architecture reduces energy storage, cockpit, and steering mass compared to traditional concepts of pressurized rovers, with consequent reductions in other subsystems. The architecture analysis results suggest that these reductions are sufficient to make the camper/UPV system a superior architecture for both the Moon and Mars.

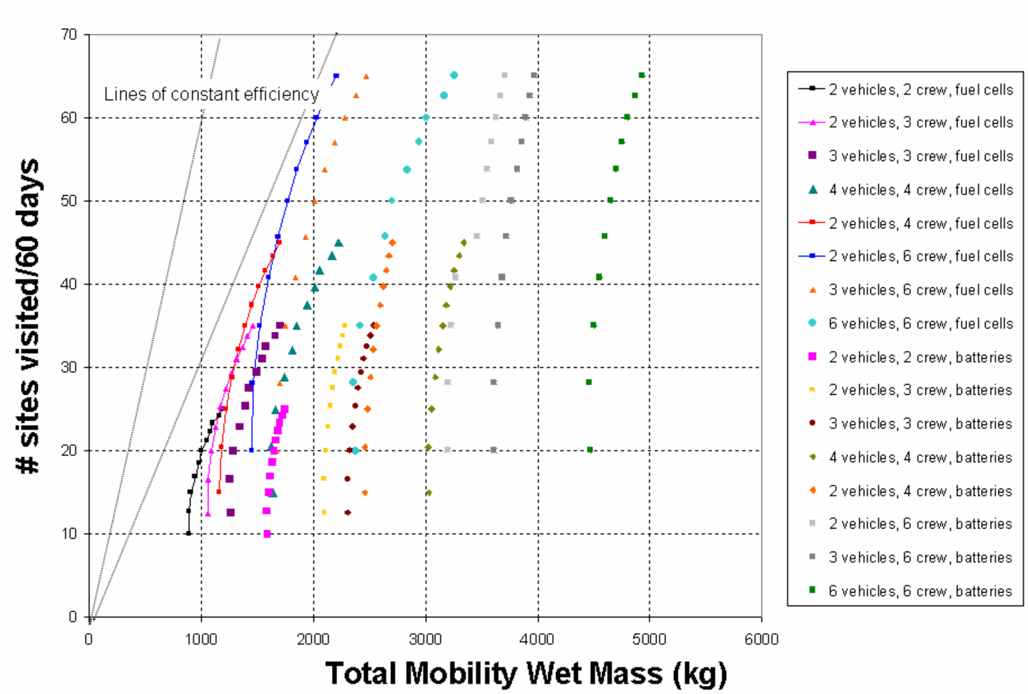

Figure 3. Mars DRM-1 Pareto Front

Table 2. Baseline Architecture Selection

Planet	DRM-1	DRM-2
Moon	2 UPVs with 2 crew each	2 campers (2 crew each) with 3 UPVs
Mars	2 UPVs with 2 crew each	2 campers (2 crew each) with 4 UPVs
Earth	2 UPVs with 2 crew each	2 campers (2 crew each) with 4 UPVs

2.5 Mobility System Design

2.5.1 Approach

The objective of the vehicle design study is to model mass, power, and dimensional requirements for the each of the two vehicles (camper and UPV) in each of the three environments of interest (Moon, Mars, and Earth). The design effort is concentrated on the design of the lunar camper and lunar UPV. After that, a commonality analysis is performed in order to assess the penalties and benefits of adapting the lunar vehicle design to different environments. This analysis estimates the mass of the Mars and Earth analog site vehicles.

The Terrain Vehicle Model (TVM) has been developed in MATLAB® [10] to model mass, power, and dimensional requirements for the planetary vehicles. Each subsystem module is coded and run iteratively until the system converges to a specific design. Then the Mission Utility Simulation Environment (MUSE [13]) analyzes the vehicles' dynamic capabilities by taking the resulting design parameters of lunar vehicles as inputs. MUSE is a simulation tool that takes the vehicle design parameters as an input and evaluates the performance of the design on certain terrain on the planetary surface. The result from MUSE provides valuable feedback to the vehicle team; MUSE evaluates whether the vehicles can perform a certain mission on representative terrain or not. The result from MUSE is then used to adjust inputs to the TVM manually, and this process is performed iteratively. After the iteration between MUSE and TVM, the PSV [11] is used for a commonality analysis for estimating vehicles on the Earth and Mars. The vehicle design process is shown in Figure 4.

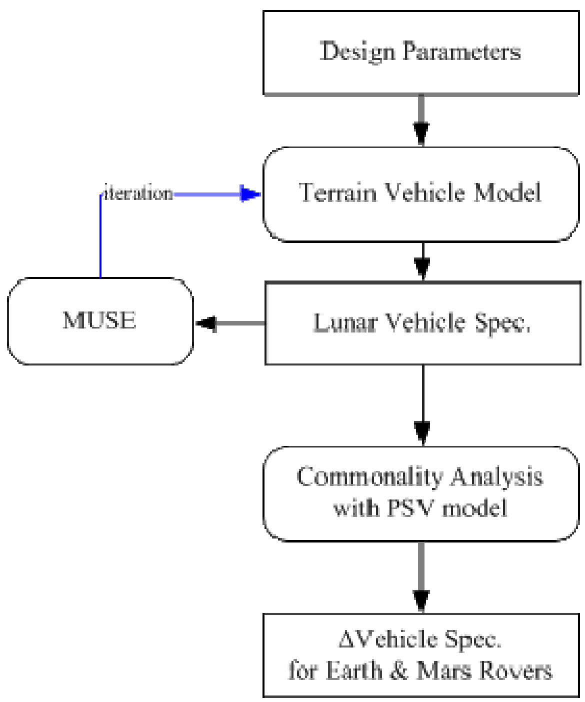

Figure 4. Block diagram of the vehicle design process

2.5.2 Assumptions

Several assumptions are made for simplifying the vehicle model:

- Both the camper and UPV carry 2 crew members.
- Both the camper and UPV have 4 wheels.
- Both the camper and UPV have an aluminum structure and chassis.
- The camper ECLSS is able to regenerate water.
- The camper can perform 125 excursions, and each excursion has a 7-day duration.
- Up to 4 of the 7 camper excursion days are spent driving, while at least 3 are spent performing DRM-1 types of operations.
- The vehicles drive up to 8 hours per day, and 12 hours in case of an emergency.
- The camper does not have its own steering system.
- The camper has its own propulsion system.

2.5.3 Subsystems

The Terrain Vehicle Model (TVM) consists of 13 subsystem modules: avionics, payload, communication, ECLS, human activities, structure, radiation, chassis, thermal, steering, propulsion, power, and suspension modules. Each subsystem module has its own input and output variables, and that information flow affects other subsystem modules. Figure 5 represents the N2 diagram associated with TVM. The feedback loops are handled by running the main code several times until the design converges.

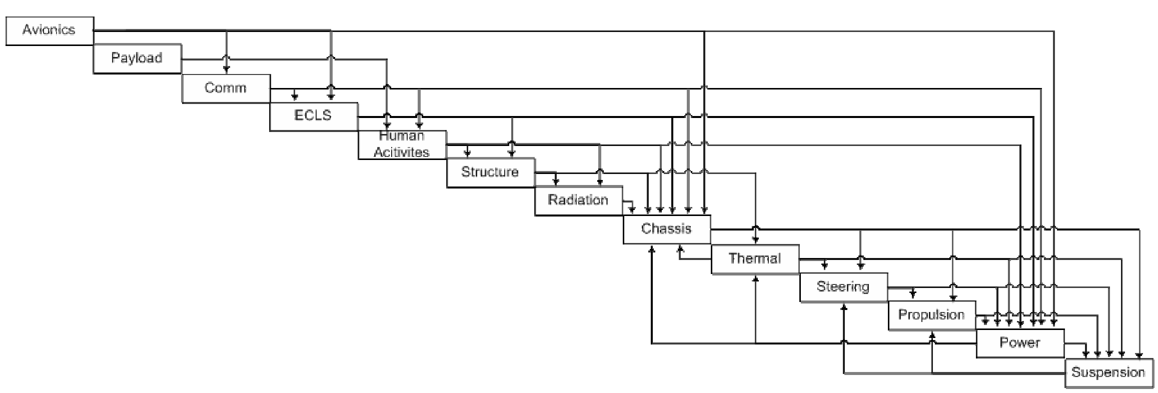

Figure 5. N^2 Diagram of TVM

2.5.4 Vehicle Selection

The vehicle specifications of the camper and UPV on the Moon are fixed from running TVM. Table 3 and Table 4 show the dimensional requirements and mass distribution of the lunar camper and UPV.

Table 3. Lunar Camper Mass and Dimension Specification

	dimensions [m]		volume [m^3]	mass [kg]
Crew compartment	radius	1.63		275
	length	3.11		
Communication	antenna height	1		10
Chassis	wheel base	3.64		321
	wheel track	3.49		
	height	0.0755		
Avionics			0.248	200
ECLSS	O_2-N_2 tanks		0.0966	358
	H_2O tanks		0.1428	
Payload	equipment		0.53	482
Propulsion	wheel diameter	1.6		229
	wheel width	0.5		
Radiation	around shell			840
Suspension				355
Power	total		0.27	364
	water		0.151	
Thermal	vert. radiator		0.5281	226
	MLI		0.55	
	pump		0.06	
Samples			1	150
			Total Mass [kg]	**3810**

Table 4. Lunar UPV Mass and Dimension Specification

	dimensions [m]		volume [m^3]	mass [kg]
Chassis	wheel base	2.6		58
	wheel track	1.7		
	height	1.4		
Avionics			0.248	20
Payload	equipment		0.21	90
Propulsion	wheel diameter	0.7		48
	wheel width	0.23		
Steering				15
Suspension				69
Power	total	0.27		44
Thermal	total			12
Samples			0.1	30
			Total Mass (kg)	**386**

Table 5 and Table 6 show power requirements of the vehicles for each operation phase. The avionics, communication, and ECLS systems always require power. When the astronauts drive a camper, propulsion, thermal, avionics, communication, and ECLS systems require power, but the human activities module does not require power, because every astronaut is performing EVA. When the astronauts do science work in the camper, thermal, avionics, communication, human activities, ECLS, and payload modules require power, but the propulsion module does not need power because the camper is not moving. At night, only thermal, communication, human activities, and ECLS systems are operated.

Table 5. Power Distribution of the Camper

Camper [W]	always	driving	science	night
Propulsion		1205		
Thermal		73	87	87
Avionics	300	300	400	
Communication	96	96	96	96
Human Activity			150	150
ECLS	80	80	900	900
Payload (Science)			100	
Steering				
sub Total	476	1754	1733	1233
Total with 15% margin	547.4	2017.1	1992.95	1417.95

Table 6. Power Distribution of the UPV

UPV [W]	driving
Total with 15% margin	852

Conceptual Drawing of the Vehicles

Based on the information about the dimensional requirement of both vehicles, 2-D conceptual drawings of the vehicles were created. Geometric design provides a baseline concept for the geometrical arrangement of vehicle systems, and demonstration of interface between the camper and UPV. Figure 6 and Figure 7 show the conceptual drawing of the UPV and camper, respectively. Figure 8 shows the connected configuration for DRM-2 missions.

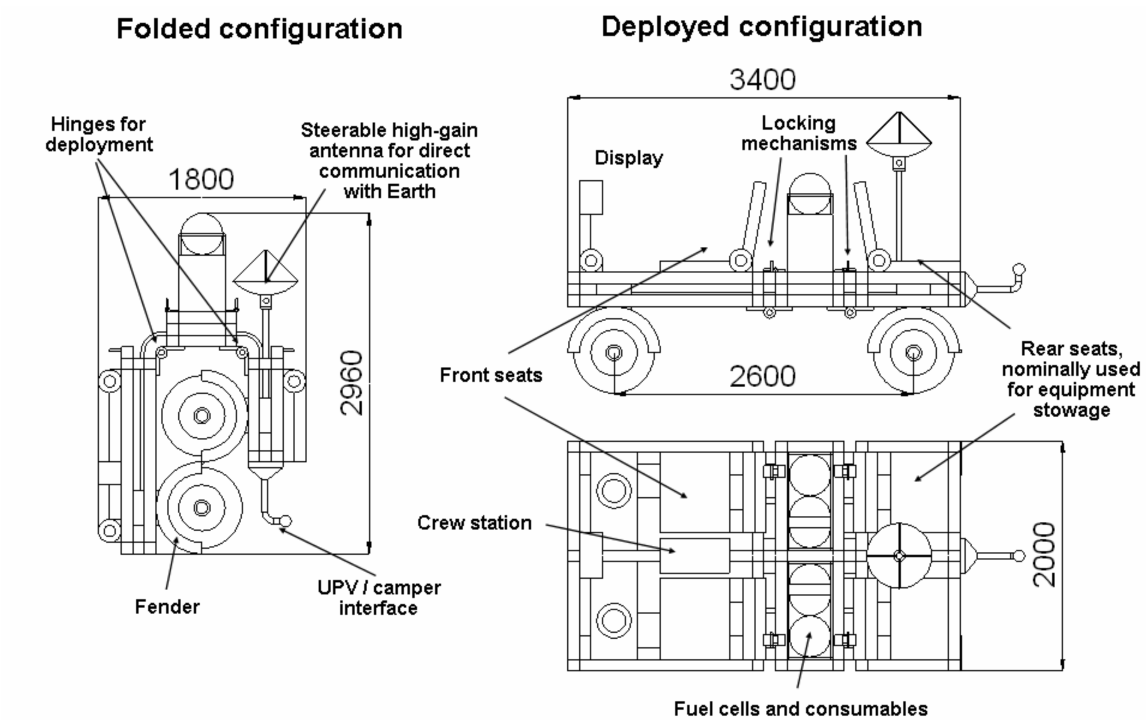

Figure 6. Conceptual Drawing of the UPV

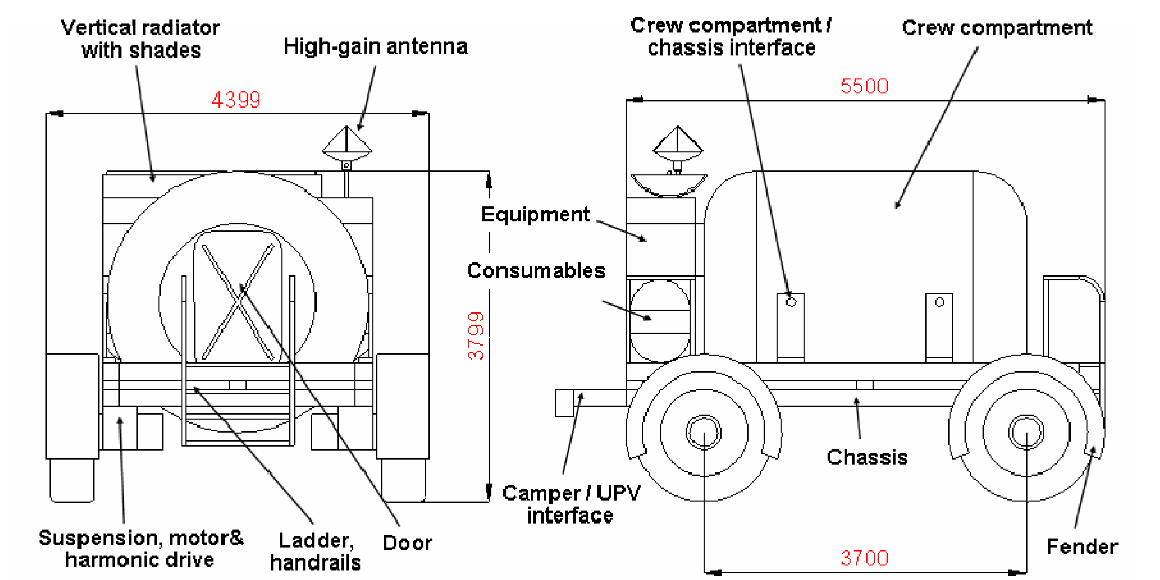

Figure 7. Conceptual Drawing of the Camper

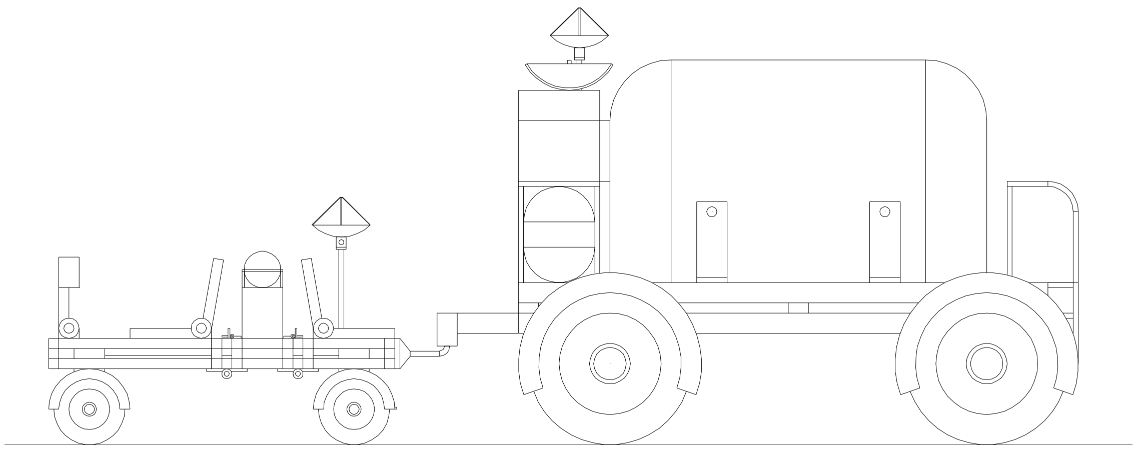

Figure 8. Configuration for DRM-2 Missions

Chapter 3

Power Source Technologies Today for Space Operations

Chapter 3 provides a summary of current power source technologies which will be applied for developing the power system model for a Camper/UPV system. Photovoltaic power generation will be considered as the primary power system, which is able to generate energy for operating the vehicles and recharging the secondary power systems. Fuel cell or battery systems will be considered as secondary power systems, which are able to operate UPVs, provide energy during dark periods, and manage peak power. In addition, the performance characteristics of state-of-art photovoltaic, fuel cell, and battery systems will be presented.

3.1 Overview of Power Systems on the Camper and UPV

The Camper/UPV combination has two power systems, primary and secondary. Primary power systems have the role of providing energy to operate vehicles and recharge secondary power systems. For primary power, photovoltaic, solar dynamic, and nuclear systems can be used. However, nuclear systems require heavy radiation shielding, and have safety issues. Solar dynamic systems have lower specific mass and lifecycle cost, but they also have very strict pointing requirements: it is hard to implement solar dynamic systems on 'moving' vehicles.

In addition, because of the lack of a primary power system on UPVs and the lack of sunlight during some periods of the operation, additional energy storage systems are required. When the UPV is moving, deploying large solar panels is impractical. Moreover, the UPV can be plugged into the Camper for recharging at the end of UPV solo missions.

Therefore, equipping primary power systems (photovoltaic power systems) on the UPV is not necessary. Secondary power systems (energy storage systems) will provide energy during dark periods, operate UPVs, which are not equipped with photovoltaic systems, and manage peak power issues. Fuel cells and batteries are commonly used as energy storage systems, so those two options will be considered as secondary power systems for the Camper/UPV.

3.2 Primary Power System - Photovoltaic Systems

Photovoltaic (PV) arrays have been used to provide primary power for space systems for 40 years. Photovoltaic systems have the advantages of modularity and light weight, but they also have disadvantages of requiring energy storage system for use at night or in shadow. A photovoltaic array consists of solar cells with transparent covers to protect the cells from radiation, electrical interfaces between cells, bypass diodes, substrate, boom and deployment mechanisms, and a pointing mechanism [14].

There are several kinds of solar cell technologies. Silicon (Si) cells haves been the most widely used type of solar cell in space applications because of their low price per unit power, but they have disadvantages of the relatively large degradation in efficiency with environment temperature and sensitivity to radiation damage. Multi-junction cells have more resistance to radiation and higher efficiency compared to Si-type cells, but they are heavier and more expensive than Si-type cells. More options can be found in reference [14].

EMCORE is one of the leading suppliers of highly efficient radiation hard solar cells for space power applications. In this thesis, three types of EMCORE solar cells are considered: state-of-art 3-mil high-efficiency Si, InGaP/GaAs-on-Ge dual-junction (2J), and InGaP/GaAs/Ge-on-Ge triple-junction (3J) solar cells. They are currently in volume production and are available for space applications. 3-mil high-efficiency Si solar cells have beginning-of-life (BOL) efficiencies averaging about 17.0%, under one Sun and air mass zero illumination conditions[†]. On the other hand, 2J and 3J solar cells have BOL efficiencies averaging about 23.5% and 26.0%, respectively. Temperature coefficients describe the effect of changing temperature environments on solar cells efficiency. BOL efficiencies and the temperature coefficients of 2J and 3J solar cells are significantly better than those of Si solar cells, but it should be noted that Si solar cells are lighter than 2J and 3J solar cells when considering area densities. Therefore, a tradeoff between mass and efficiency exists. In addition, since 3J solar cells are better than 2J solar cells in three characteristics, Si and 3J solar cells will be considered as the two possible options for photovoltaic systems. The characteristics of the three types of solar cells are presented in Table 7 [16].

Table 7. Electrical Performance and Area Density Comparison for Three Types of Solar Cells

Solar Cell Technology	BOL Minimum Average Efficiency (%)	Temperature Coefficient (abs.%/K)	Area Density (kg/m^2)
3-mil High-Efficiency Si	17.0	-0.053	0.23
2J	23.5	-0.030	0.85
3J	26.0	-0.045	0.85

3.3 Secondary Power Systems

Since the UPV does not carry photovoltaic arrays and photovoltaic power systems cannot generate power during some periods of the operation, an energy storage system is needed. Energy storage systems are required for following cases:

- Photovoltaic power systems have dark periods with the diurnal motion of the sun.
- Photovoltaic power systems cannot provide power during some periods of the operation such as the operation at night time or in shadowed regions.
- Photovoltaic power systems cannot produce enough peak power.

[†] Air mass is the optical path length through Earth's atmosphere for light from a celestial source, normally indicating the path length relative to that at the zenith. Therefore, the air mass zero illumination condition means the extra-terrestrial solar spectrum condition [15].

- Photovoltaic arrays are not installed on the UPV: The UPV uses its own secondary power system.

Fuel cells and batteries will be considered as secondary power systems. They have been used as energy storage systems for space applications for several decades and have proved their reliability.

3.3.1 Fuel Cells

One option for a secondary power system is fuel cells. Fuel cells are an attractive energy storage system, especially for human space missions that require high power for long periods. Fuel cells have higher specific energy, but they are generally less compact and more complex than batteries. The reaction cell's mass is proportional to the power level required, and the reactants' mass is directly proportional to the energy.

Recently, a new type of fuel cells is being investigated for space application [17]. This fuel cell uses $NaBH_4$ as fuel and H_2O_2 as oxidizer. There are several benefits of direct H_2O_2 fuel cells compared to other types of fuel cells using gaseous O_2 as oxidizer:

- **Higher current density due to larger oxidizer density** – A conventional fuel cell uses a gaseous form of oxidizer, and the mass density of a gaseous oxidizer is much less than that of a liquid oxidizer. Since peroxide fuel cells use liquid H_2O_2 as an oxidizer, they have the potential for a higher area current density.
- **Single-phase transport on the cathode side of fuel cells** – In a conventional fuel cell, the mass transport of reactants is a two-phase process. Proton exchange membrane fuel cells are limited by two-phase transport of reactants [18], while single-phase transport of liquid H_2O_2 fuel cell is free from this phenomenon.
- **Eliminating the O2 reduction** – The oxygen reduction is known to be the limiting factor for current density, power density, and the overall energy conversion efficiency of an oxygen fuel cell. Typical reaction of oxygen fuel cells involves 4-electron exchange ($O_2+4H^++4e \rightarrow 2H_2O$) but, the reaction of $NaBH_4/H_2O_2$ fuel cells involves only 2-electron exchange ($H_2O_2+2e \rightarrow 2OH^-$), which means the activation barrier of the $NaBH_4/H_2O_2$ fuel cells is lower than that of typical oxygen fuel cells.

The advantages described above result in improved capabilities of $NaBH_4/H_2O_2$ fuel cells compared to conventional fuel cells using oxygen as oxidizer: 1) very high energy density (over 2580 W·hr/kg), 2) very high volume power density, 3) the ability to load for a short period of time by concentrating H_2O_2, and 4) a very high efficiency (currently 55%, and the potential for over 60%). Table 8 summarizes the performance of $NaBH_4/H_2O_2$ fuel cells.

Table 8. Performance of UIUC/NPL Peroxide Fuel Cells at 1 atm. and 300K

Ideal Energy Density	Voltage (Open Circuit)	Current (Short Circuit)	Max. Power Density	Efficiency at 100 mA/cm^2
2580 [W·hr/kg]	>1.40 [V]	>3.0 [A/cm^2]	>0.7 [W/cm^2]	~55 [%]

3.3.2 Batteries

Rechargeable batteries are electrochemical devices that convert chemical energy to electrical energy, and vice versa. Rechargeable batteries have been used in space missions with photovoltaic systems for managing peak power and providing energy during dark periods.

There are many kinds of rechargeable batteries which are currently used in space missions such as NiCd, NiH_2, NiMH, NaS, and Li-Ion batteries [14]. In this thesis, Lithium-Ion batteries will be considered because Li-ion batteries have several advantages compared to other forms of batteries [19]: higher specific energy [W·hr/kg], higher energy density [W·hr/L], and smaller self-discharge.

Li-Ion batteries have been more widely used in aerospace applications recently for several reasons. Li-Ion batteries provide higher specific energy and energy density compared to the state-of-art technology of other batteries; Li-Ion batteries are lighter and less voluminous than other batteries under the same energy requirements. However, limited cycle life and safety under severe conditions are disadvantages of Li-Ion batteries. Nevertheless, since much research on improving Li-Ion batteries is on-going, Li-Ion batteries are a good option for a secondary power system. Yardney Technical Products Inc. installed their batteries in NASA's Mars Exploration Rovers, and the mission has been extremely successful. The state-of-art characteristics of Li-Ion batteries of Yardney are presented in Table 9 [20].

Table 9. Charateristics of Yardney's Li-Ion Batteries

Energy Density	Specific Energy	Cycle Life	Discharge Capability		Operating Temp. Range
			Continuous	Pulse	
358 [W·hr/L]	145 [W·hr/kg]	2100	10C	50C	-40 to +65 °C

Chapter 4

Methodology

In this chapter, the optimal model of power system configuration for integrated planetary mobility system and the model validation are presented. The model consists of the mass calculation module, vehicle power consumption calculation module, power generating calculation module, and remaining energy in secondary power systems calculation module. Based on information from those modules, the model poses the optimization problem with one objective function.

4.1 Model Description

4.1.1 Operation phases

The planetary mission is composed of five operation phases. At each phase, the vehicles consume different levels of power. The summary of each operation phase is shown in Table 10.

Exploration Phase

The exploration phase is the operation phase in which the astronauts explore around the Camper, driving the UPV. Since no astronaut stays inside the Camper, the avionics, communication, and ECLSS systems require power but the propulsion, thermal, habitat, and science equipment systems are not operated on the Camper. The UPV is operated in this phase, so it requires power. Since the Camper and UPV are detached, the secondary power system on the UPV cannot be recharged: the UPV must use its own power system.

Driving Phase

The driving phase is the operation phase in which the UPV guides the Camper. In this phase, the Camper operates the propulsion, thermal, avionics, communication, ECLSS systems, but the habitat and science equipment system are not used, since the astronauts are in the

UPVs. The UPV is operated at this phase. Since the Camper and UPV are attached to each other, energy can be transferred during this phase.

Science Phase

The science phase is the operation phase in which the astronauts do science or housework in the Camper. In this phase, the thermal, avionics, communication, habitat, ECLSS, and science equipment systems are operated on the Camper, but not the propulsion system. The UPV is not operated and is attached to the Camper during this phase.

Inactivity Phase

The inactivity phase is the operation phase in which the astronauts take a rest in the Camper; usually this is a sleep period. In this phase, the thermal, communication, habitat, and ECLSS systems are operated in the Camper, but not the propulsion and avionics systems. The UPV is not operated and is attached to the Camper at this phase.

Base Phase

The base phase is the operation phase in which the Camper and UPV parks at the base. The base supplies power for maintaining the mobility system, so power systems on the vehicles are not activated.

Table 10. The description of operation phases

Activity Phase	Description	Vehicle Connection
Exploration	the operation phase in which the astronauts explore around the Camper, driving the UPV, and no astronaut is left in the Camper	X
Driving	the operation phase in which the UPV tows the Camper	O
Science	the operation phase in which the astronauts do science or housework in the Camper	O
Inactivity	the operation phase in which the astronauts take a rest in the Camper	O
Base	the operation phase in which the Camper and UPV park at the base. No astronaut is in the vehicles	O

4.1.2 Module Description

Photovoltaic Systems

A photovoltaic system is the primary power system for the vehicles and it generates power in order to run both vehicles and recharge their secondary power systems. This module calculates the mass of the entire solar power system from the characteristics of solar panels and empirical data.

The mass of the solar cells themselves does not contribute significantly to the total mass of the array. Therefore, the blanket mass of solar array is the mass of the solar cells including cover glass, interconnects, and the substrate. The blanket mass is typically 55% of the total mass of the array, where the other 45% of the array's mass includes the structure. The mass of the tracking drive mechanism, m_{drive} [kg], is estimated from a function of the array's mass, m_{array} [kg];

$$m_{drive} = (-0.014 m_{array} + 20.6) m_{array} / 100 \tag{1}$$

Based on the mass breakdown data of a solar array in International Space Station's photovoltaic power module, the mass of the electrical equipment and thermal control is estimated as 41% and 35% of the array's mass, respectively.

Solar Power Generation

This module computes power generated from solar cells based on the overall efficiency and solar flux at the specific location on the Moon or Mars. The efficiency of the solar panels is computed with several corrections in Table 11.

Table 11. Correction Table for Solar Array

Corrections for solar array	
Cell packing factor	85%
Tracking cosine loss (±5° error band)	99.6%
Shadowing losses	100%
Radiation damage	96.02% (at 1 year operation)
UV darkening	99.5% (at 1 year operation)
Micrometeoroid damage	98.98% (at 1 year operation)
Contamination and dust obscuration	99.72% (at 1 day operation)
Array resistance and diode losses	95.8%
Temperature correction	Standard Efficiency
Corrections for power management and distribution system	
Distribution resistance losses	98%
Power management and distribution losses	91.7%
Other corrections	
Contingency	90%

For example, for the 7 day lunar surface exploration, average power generated is 64.25% of the power generated by a 100% efficient Sun-pointing array without considering temperature correction.

Solar power generated from the solar panels is calculated from a given area of solar array, the flux of sunlight, and the conversion efficiency:

$$P = \varphi_{sun} \eta_S A_S \tag{2}$$

where φ_{sun} is the flux of sunlight, η_S the conversion efficiency, A_S the area.

Battery System

In this module, the mass of the battery systems is computed. Inputs are the characteristics of a given battery, energy required, battery losses, and the depth of discharge, which is the fraction of the energy that is used.

The mass of batteries is calculated as follows:

$$M_{batt} = E_b / (DOD \times \eta_b \times \rho_b) \tag{3}$$

where, E_b is the capacity of battery, DOD the depth of discharge, η_b battery losses, and ρ_b specific energy per mass. The depth of discharge and battery losses are assumed to be 80% and 93%, respectively.

Fuel Cell System

In this module, the mass of the fuel cell system is computed, including the mass of the stack and fuel. Other smaller subsystems such as fuel tanks and hydraulic machinery are neglected in this analysis.

The mass of the fuel cell systems, M, is given by:

$$M = M_F + M_S \tag{4}$$

where M_F is the mass of the fuel, M_S the mass of the stack.

At 100% efficiency, the theoretical energy generated from hydrogen peroxide/sodium borohydride is 2580 W·hr per kg of reactants. Therefore, in reality, if the solution concentrations α, and the discharge energy conversion efficiency η_d are considered, the fuel specific power density can be characterized by:

$$\rho_F = \frac{2580\eta_d\alpha}{t_d} \tag{5}$$

where t_d is the fuel cell discharge time.

From the definition of the fuel specific power density, the mass of fuel is given as follows:

$$\rho_F = \frac{P}{M_F} \tag{6}$$

Therefore, M_F can be re-written as,

$$M_F = \frac{P}{\rho_F} = \frac{P}{2580\eta_d \alpha / t_d} = \frac{Pt_d}{2580\eta_d \alpha} = \frac{E}{2580\eta_d \alpha} \tag{7}$$

where, E represents the total energy output.

From the definition of the stack specific power density, the specific power density of the stack is given as follows:

$$\rho_S = \frac{P}{M_S} \tag{8}$$

The specific power density of the stack is also given with voltage V, discharge current density I, and active area per unit mass A:

$$\rho_S = VIA \tag{9}$$

Considering the ratio of reactants which is consumed during discharge, the discharge energy conversion efficiency can be rewritten as:

$$\eta_d = \mu_f \frac{V}{E_v} \tag{10}$$

where μ_f is the reacted fuel coefficient, V the discharge voltage, and E_v is the reversible open-circuit voltage. Therefore, rewriting Eqn.(10), the discharge voltage is obtained in terms of the discharge energy conversion efficiency, the reacted fuel coefficient, and the reversible open-circuit voltage:

$$V = \frac{\eta_d E_v}{\mu_f} \tag{11}$$

Since the reversible open-circuit voltage of $NaBH_4/H_2O_2$ fuel cell is 2.25V, Eqn.(11) can be rewritten as:

$$V = \frac{2.25\eta_d}{\mu_f} \tag{12}$$

Now, in order to obtain the discharge current density, I, the experimental data is used. From the experimental performance of the UIUC/NPL $NaBH_4/H_2O_2$ fuel cell, the relationship between voltages (V) and current (I) is obtained as follows:

$$I = (V - 1.267) / -6.48 \times 10^{-5} \tag{13}$$

Based on the state-of-art technology, the solution concentrations α is in the range of 50 to 55%. In this study, the solution concentrations are assumed to be 52%, but in the future, it could reach the range of 65 to 70%. From the performance experiment of the UIUC/NPL peroxide fuel cell at 1 atm. and 300K, the efficiency η_d is approximately 55%. In addition, the active are per unit mass A and the reacted fuel coefficient μ_f are assumed to be 0.2 and 0.95, respectively.

Combining Eqn.(12) and (13) to Eqn.(9), the specific density of the stack can be rewritten as:

$$\rho_S = \frac{2.25\eta_d}{\mu_f} \times \left(\frac{2.25\eta_d}{\mu_f} - 1.267 \right) \times \frac{1}{-6.48 \times 10^{-5}} \tag{14}$$

From Eqn.(8) and (14), M_S can be obtained as:

$$M_S = \frac{1}{-6.48 \times 10^{-5}} \times \frac{2.25\eta_d}{\mu_f} \times (\frac{2.25\eta_d}{\mu_f} - 1.267) \times A \tag{15}$$

4.2 Optimization Methodology

4.2.1 Premises and Assumptions

In this thesis, several premises and assumptions are introduced in order to build the model. These premises and assumptions relate to the mission scenario, power flow, constraints, and other basic concerns.

- Solar panels can provide power to the UPV during the 'Driving' phase.
- If sufficient time to regenerate energy to the UPV is allowed before the 'Exploration' phase starts, a secondary power system on the UPV provides power during the 'Driving' phase.
- The solar panel area is limited by the Camper geometry during the 'Driving' phase.
- If one of secondary power systems (either UPV or Camper) is fully charged, power from the solar panels goes to the other system, when they are attached.
- Energy is generated only on the Camper.

- The UPV is not equipped with solar panels.
- Solar panels can track the Sun during the 'Exploration,' 'Inactivity,' and 'Science' phases, but not during the 'Driving' phase.
- Stored energy can be transferred from the UPV to the Camper, and vice-versa.
- Secondary power systems are fully charged when the vehicles leave the main base or outposts.
- Energy regenerating rates are determined by power provided to regeneration utilities.
- Dust on solar panels is cleaned after a mission.

4.2.2 Problem Statement

This work poses the following optimization problem:

$$\min_{\mathbf{x}} J = M_1 + M_2$$

$$\text{subject to } \mathbf{g}(\mathbf{x},\mathbf{p}) \le \mathbf{0}$$

where,

$$\mathbf{x} = [x_1 \quad x_2 \quad x_3]^T$$

$$\mathbf{g} = \left[\mathbf{g}_1 \quad \mathbf{g}_2 \quad g_3\right]^T \text{ with}$$

$$\mathbf{g}_1 = -\mathbf{E}_{rC}(t),\ \mathbf{g}_2 = -\mathbf{E}_{rU}(t),\ \ g_3 = x_3 - \overline{A}_S$$

where,

J: The total mass of power systems on the Camper and UPV [kg]

M_1: The total mass of a primary power system on the Camper [kg]

M_2: The total mass of a secondary power system on the Camper and UPV [kg]

x: Design variable vector

p: Parameter vector

g: Constraint vector

$\mathbf{E}_{rC}$: Energy remaining on the Camper with time [W·hr or kg]

$\mathbf{E}_{rU}$: Energy remaining on the Camper with time [W·hr or kg]

$\overline{A}_S$: Upper limit on solar panel area [m^2]

The objective is to minimize the total mass of the power system including the primary power source on the Camper and secondary power sources on the Camper and UPV, J. The design variable vector, **x**, contains the area of the solar panel on the Camper, x_1, the capacity of the secondary power system on the Camper, x_2, and the fraction of power used to regenerate energy on the Camper, x_3. The capacity of the secondary power system on the UPV is not a design variable because it can be computed based on the maximum 'Exploration' phase in the mission. Since the UPV has no solar panel and it is detached from the Camper during the 'Exploration' phase, the UPV should use its own power source when it is being operated in the 'Exploration' phase. Therefore, if the secondary power system on the UPV is fully recharged at the beginning of the 'Exploration' phase, the UPV does not need to carry more capacity in its power system than what will support the maximum 'Exploration' phase.

The parameter vector, **p**, includes mission characteristic parameters and environment parameters. Mission characteristic parameters include mission scenarios and power requirements for each operation phase. Users can change these parameters to find vehicle specifications for a given mission which users want to evaluate. In addition, users can change environment parameters in order to simulate environment of a possible mission site.

The inequality constraints state energy remaining at each hour. For a feasible mission, energy remaining in secondary systems should always be greater than zero. In addition, the solar panel area on the Camper might be limited due to the Camper geometry. However, users can remove the area constraint if it is necessary. The detailed description of design variables, parameters, and constraints will be followed.

Since, the gradient-based optimization method is sensitive to the initial point, evaluating only one initial point might not find a 'good enough' solution because a solution could be trapped on a local optimum. Therefore, users can set minimum and maximum value of each design variable and choose the number of steps in order to increase the number of initial start points. Then, the program divides the range of each design variable by the number of steps and optimizes the objective with those multiple initial start points. After that, the program chooses the best solutions among solutions from the optimization with multiple initial points. This process can help users find a good solution close to the global optimal solution. Users can increase the number of steps to evaluate more initial start points, but it takes more computational effort.

The scheme of the optimization procedure is shown in Figure 9.

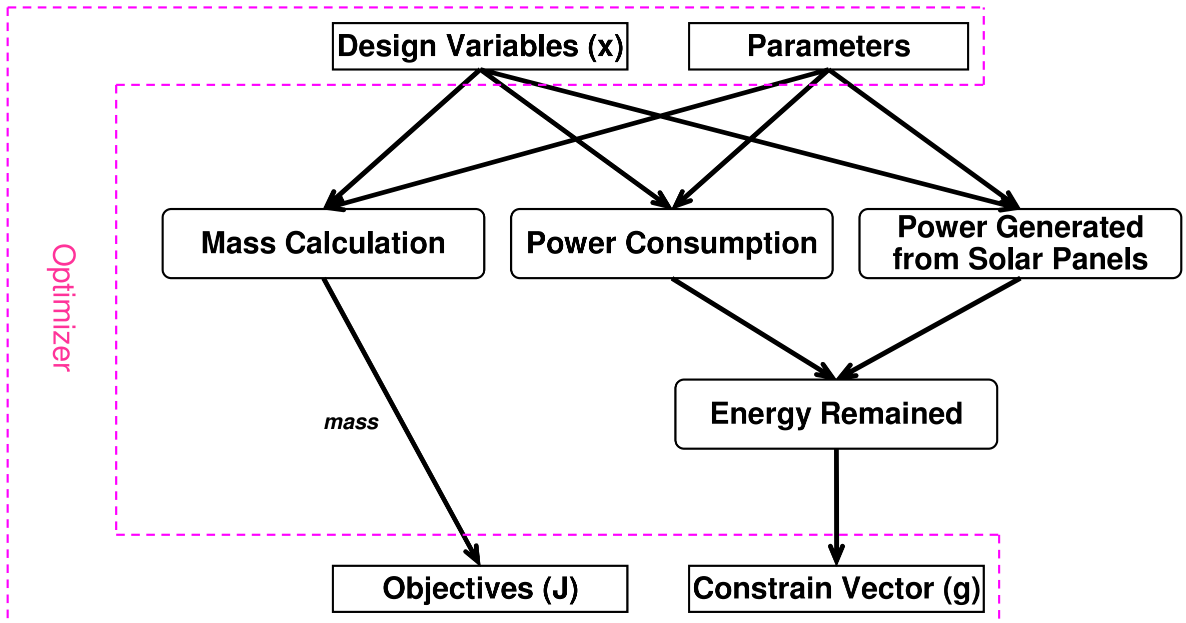

Figure 9. The scheme of the optimization procedure

Design Variables

Design variables are shown in Table 12. The capacity of the secondary power system on the UPV is determined by the maximum 'Exploration' phase.

Table 12. Design variables

Design Variables	Description	Unit	Range
x_1	The area of solar panels on the Camper	m^2	$[0,\infty)$
x_2	The capacity of the secondary power system on the Camper	W·hr (for batteries) kg (for fuel cells)	$[0, \infty)$
x_3	The fraction of power used to regenerate energy on the Camper	-	[0, 1]

Parameters

The amount of solar flux is determined by the parameter ‘planet:’ ‘Moon’ indicates the vehicles are operated on the South Pole of the Moon while ‘Mars’ indicates the vehicles are operated on the landing spot of the Viking 1 (VL1) on Mars. VL1 is located at 22.3'N latitude and 47.9 'W longitude. Life time of the vehicles is used for determining the efficiency of the solar arrays. The mission scenario is put into the ‘missionProfile.’ Users can run any kind of mission scenarios with the ‘missionProfile’ parameter. In addition, users can change power requirements for the Camper and UPV in the ‘powerRequiredCamper’ and ‘powerRequiredUPV’ parameter matrix. The geometry of the Camper determines the solar panel area limit and users can change the ‘areaLimit’ parameter for this purpose. The parameter ‘sysType’ indicates whether the mobility system uses a hybrid or single power system: the hybrid system means that both primary power system and secondary power system are used, while the single power system means that the primary power system (photovoltaic system) is not used. The parameter ‘rechargable’ indicates whether the solar arrays of the Camper can generate power during the ‘Driving’ phase: 0 for non-rechargeable and 1 for rechargeable. Parameters are shown in Table 13.

Constraints

Energy remaining in the secondary power systems on the Camper and UPV is the one of the constraints, which gives $\mathbf{g}_1$, and $\mathbf{g}_2$. In the secondary power system, energy can be used or recharged, but energy remained in batteries or fuel cells should be greater than zero at all times. The constraint vector $\mathbf{g}_1$ represents the energy remaining on the Camper with time. It is obtained by adding the energy balance between recharging and consumption to the energy remaining of one time sample ago. The constraint vector $\mathbf{g}_2$ is the energy remaining on the UPV with time. In addition, the geometry of the Camper limits the maximum area of solar panels, which gives g_3.

Table 13. Parameters

Parameters	Description	Unit	Range
planet	Determines amount of solar flux	-	'Moon' 'Mars'
lifetime	Whole life time of the vehicles	days	[0, ∞)
missionProfile	Mission scenario composed of the operation phases with time (hr)	-	
powerRequiredCamper[4]	Power requirement for each operation phase for the Camper 1: Power for the 'Driving' phase 2: Power for the 'Science' phase 3: Power for the 'Inactivity' phase 4: Power for the 'Exploration' phase	W	[0, ∞)
powerRequiredUPV[4]	Power requirement for each operation phase for the UPV 1: Power for the 'Driving' phase 2: Power for the 'Science' phase 3: Power for the 'Inactivity' phase 4: Power for the 'Exploration' phase	W	[0, ∞)
areaLimit	Solar panel area limitation in the 'Driving' phase	m^2	[0, ∞)
sysType	Indicator of whether the power system is a hybrid or single system	-	'single' 'hybrid'
rechargeable	Indicator of whether the solar arrays can generate power during the 'Driving' phase or not	-	0 or 1 (
rechargeHour	The mission hour the energy storage system should be fully recharged by.	hour	[0, ∞)

4.2.3 Optimization Method

For this model, the sequential quadratic programming (SQP), which is implemented with the MATLAB® function 'fmincon [10],' is used. SQP has following procedure: 1) applies a quadratic approximation to the Lagrangian for the objective function, 2) applies linear approximation to the constraints, 3) solves the quadratic problem to find the searching direction, 4) performs a 1-D search, and 5) updates the approximation to the Lagrangian. SQP is known as the best gradient-based optimization method.

Since design variables are continuous, heuristic optimization methods, such as the genetic algorithm, simulated annealing, particle swarm analysis, and taboo search, are not used. For avoiding the convergence to the local optimum, the optimization is performed for several initial points, which users can set.

4.3 User Manual

The user guide can be found in Appendix A and the optimization program can be found in the attached CD in this thesis.

Chapter 5

Case Studies

In this chapter, the case studies for 7-day sample mission scenario are presented. The case studies include lunar and Mars missions and six different types of power system configurations are examined for each mission. Based on information from those case studies, a power system configuration for the lunar or Mars mission is proposed.

5.1 Model Parameters

5.1.1 Vehicle Specification

In the case studies, the Camper/UPV systems proposed by the MIT Spring 2006 16.89/ESD.352 Space System Engineering class are selected as a planetary surface mobility system. A detailed description about the Camper/UPV systems can be found in Chapter 3. As it shown in Figure 7, the height of the Camper is 3799 (mm) and the length of the Camper is 5500 (mm). In this study, it is assumed that at most 34 m^2 ($3\times4\times\sqrt{2}$ m^2) of A-shaped solar array will be attached outside of the Camper.

5.1.2 Environmental Parameters

Moon

It is assumed that the astronauts will explore the South Pole of the Moon, and the campaign will be conducted during the daytime on the Moon. The solar flux per unit area has an average value of 1368 W/m^2 at one astronomical unit, and the solar flux decreases as inverse square of the distance from the Sun [21]. Since the Moon is relatively close to the Earth compared to the distance between the Earth and the Sun, it can be assumed that the solar flux on the lunar surface is constant for all day, 1368 W/m^2.

Mars

It is assumed that the astronauts will explore around the Viking Lander location 1 (VL1) which is located at 22.3°N latitude and 47.9°W longitude on Mars. Appelbaum and Landis developed the solar radiation model on Mars which models solar radiation related data from which the daily variation of the global, direct beam and diffuse insolation was calculated [22]. The diurnal variation of the solar flux on a horizontal surface for L_s = 141° for VL1 is shown in Figure 10. Areocentric longitude L_s = 141° corresponds to the lowest opacity of 0.35, which means it is the worst case for the amount of the solar flux.

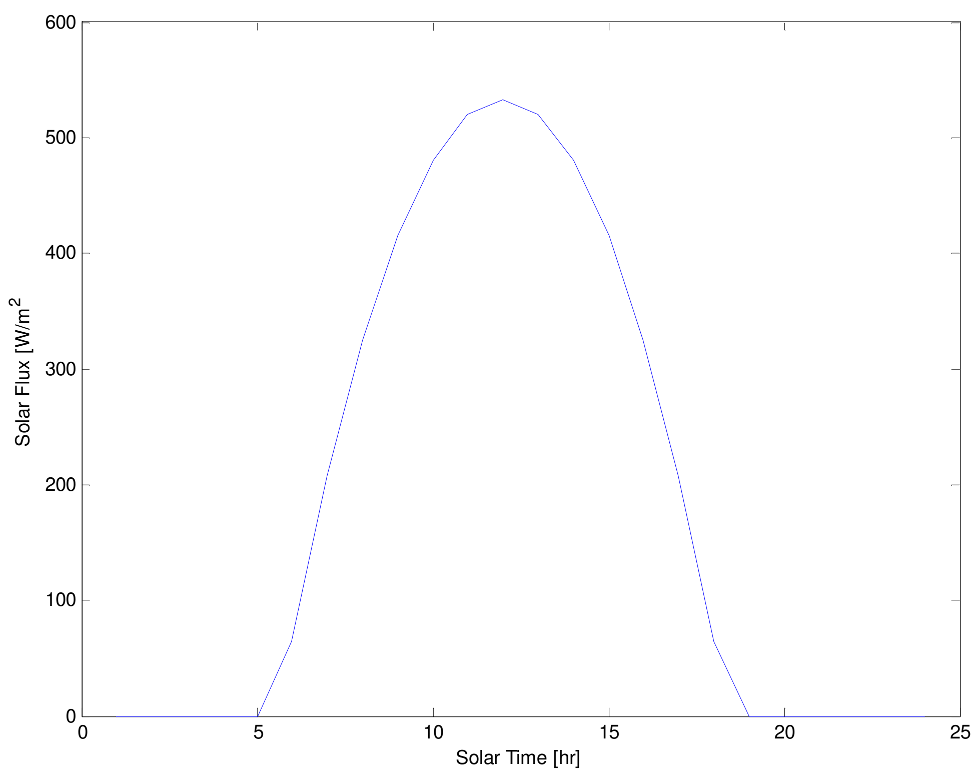

Figure 10. The Diurnal Variation of the Solar Flux at VL1 for L_s = 141°

5.1.3 Power Requirements

Power requirements of each operation phase were computed based on the vehicle specification by the MIT Spring 2006 16.89/ESD.352 Space System Engineering class for lunar missions. However, the environmental parameters of the Moon and Mars are different from each other; power requirements for Mars mission should be estimated again.

Besides the duration of daylight, a major difference between the Moon and Mars environment is gravity. Moon gravity is 1.62 m/s^2 and Mars gravity is 3.71 m/s^2. High gravity induces high wheel load, and high wheel load requires more power to overcome friction between wheel and terrain. Increased gravitational force also requires more power when the vehicles climb up the slopes. Power requirements on the Moon are directly from the study of the MIT class. However, since the MIT class concentrated on the lunar mission, TVM was executed with new gravitational coefficient, 3.71 m/s^2 to achieve power requirements on Mars. Power requirements for each operational phase on the Moon and Mars can be found in Table 14. Note that the power consumption of each phase includes 15% margin.

Table 14. Power Requirements for the Vehicles on the Surface of the Planets

Phase	Vehicle	Mars [W]	Moon [W]
Driving	Camper	10718	6174
	UPV	1108	852
Science	Camper	1993	1993
	UPV	0	0
Inactivity	Camper	1418	1418
	UPV	0	0
Exploration	Camper	547	547
	UPV	1108	852
Base	Camper	0	0
	UPV	0	0

5.2 Mission Scenario

In the basic mission scenario used for analysis, the Camper and UPV will be driven to the destination for two days. The Camper will then be parked, and the UPV will travel on its own, exploring around the destination for three days. After exploration, the Camper and UPV will be driven back to the main base for two days. The detailed mission scenario is in Table 15. Note that 1 Martian day is converted to 1 Earth day. Also note that an 8-hour period at the base camp is included in the scenario before the driving begins.

The duration of each EVA is limited by space suit life support capacity and astronaut fatigue, nominally assumed to be 8 hours based on current space suit technology. During the 'Driving' and 'Exploration' phases, astronauts perform EVAs. Since the UPV is an unpressurized vehicle, astronauts should wear space suits when driving the UPV. Therefore, in 1st, 2nd, 6th, and 7th days, the 'Driving' phase is limited to 8 hours.

Table 15. Mission Scenario on the Moon and Mars

Day 1	Base (8 hr)	Driving (8 hr)	Inactivity (8 hr)	
Day 2	Inactivity (8 hr)	Driving (8 hr)	Inactivity (8 hr)	
Day 3	Inactivity (8 hr)	Exploration (6 hr)	Science (2 hr)	Inactivity (8 hr)
Day 4	Inactivity (8 hr)	Exploration (6 hr)	Science (2 hr)	Inactivity (8 hr)
Day 5	Inactivity (8 hr)	Exploration (6 hr)	Science (2 hr)	Inactivity (8 hr)
Day 6	Inactivity (8 hr)	Driving (8 hr)	Inactivity (8 hr)	
Day 7	Inactivity (8 hr)	Driving (8 hr)	Base (8 hr)	

5.3 Lunar Mission

5.3.1 Single Source

The planetary surface mobility systems can be operated without primary power systems if enough energy is stored in secondary power systems. Using only energy storage systems can reduce the degree of the system complexity and the development cost because charge control systems and interfaces between primary and secondary power systems are not necessary.

Moreover, the result of single power source missions is a good reference for determining whether to equip single source systems or hybrid systems. If the mass of single power source systems is not much heavier than one of hybrid systems, then single power systems are reasonable options in order to avoid the complexity of hybrid power systems.

Initial start points for the optimization are summarized in Table 16. Since there are no solar panels in this scenario, each combination of power systems has two design variables: x_2 and x_3, each of which has 5 initial start points. Therefore, a total of 25 initial start points will be examined and the best solution will be taken amongst results of 25 runs. However, since there is no solar power in this scenario, x_3 does not affect the result of this optimization.

Table 16. Initial Points for Lunar Single Mission Optimization

	Variables	Range	# of steps
Battery Hybrid System	x_1: The area of solar panels on the Camper [m^2]	fixed as 0	-
	x_2: The energy capacity of battery systems on the Camper [W·hr]	[0, 800000]	5
	x_3: The fraction of solar power used to recharge a Camper battery [-]	[0, 1]	5
Fuel Cell Hybrid System	x_1: The area of solar panels on the Camper [m^2]	fixed as 0	-
	x_2: The fuel mass of fuel cell systems on the Camper [kg]	[0, 1200]	5
	x_3: The fraction of solar power used to recharge Camper fuel [-]	[0, 1]	5

Table 17 shows the power system specification obtained by the optimization for the lunar single source mission. Once the design variables are obtained, the power system specification can be calculated by the model. The detailed process can be found in Chapter 4. The total mass of battery systems is 3904 kg, while the total mass of fuel cell systems is 647 kg. The total mass of battery systems is five times as heavy as the one of fuel cell systems. It is because specific mass energy density of Li-Ion batteries is much heavier than one of $NaBH_4$ fuel cells. Obviously, for the single power source mission on the Moon, fuel cell power systems are more reasonable option rather than battery system in terms of total wet mass.

Table 17. Power System Specification for Lunar Single Source Missions

Battery Systems		Fuel Cell Systems	
Battery Type	Li-Ion	Fuel Cell Type	$NaBH_4$
Mass of Camper Battery	3509 (kg)	Mass of Camper Stack	28 (kg)
Mass of UPV Battery	395 (kg)	Mass of Camper Fuel	553 (kg)
Volume of Camper Battery	1421 (m^3)	Mass of UPV Stack	4 (kg)
Volume of UPV Battery	160 (m^3)	Mass of UPV Fuel	62 (kg)
Total Mass	3904 (kg)	Total Mass	647 (kg)

Figure 11 and Figure 12 show the energy remaining in battery systems and fuel remaining in fuel cell systems, respectively. Figure 13 and Figure 14 show the battery recharging rate and fuel reforming rate. Since there is no photovoltaic system on the Camper and the surface mobility system cannot generate energy from external sources, energy recharging rates in both battery and fuel cell system are always negative.

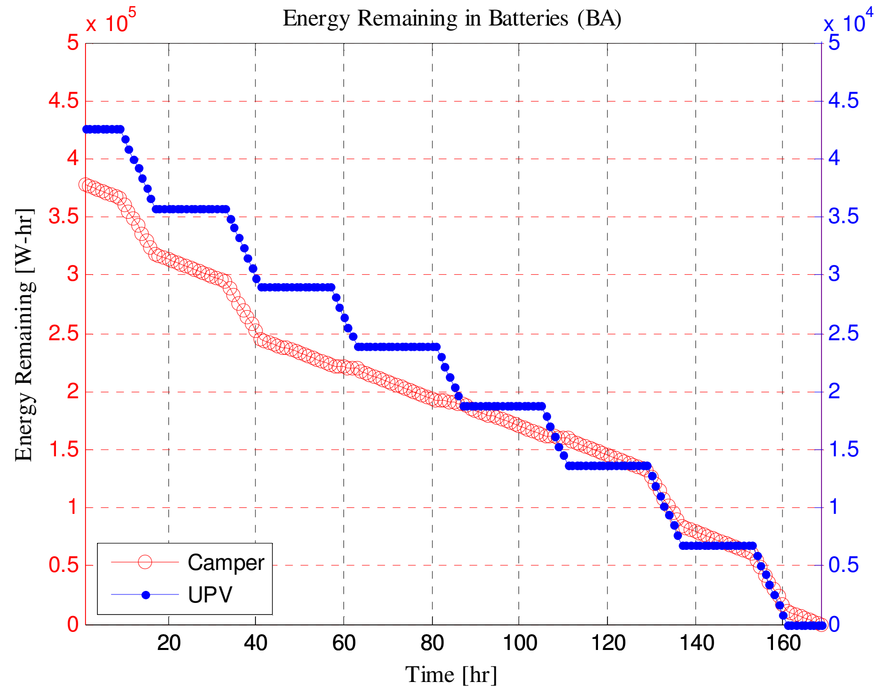

Figure 11. Energy Remaining in Batteries on the Moon

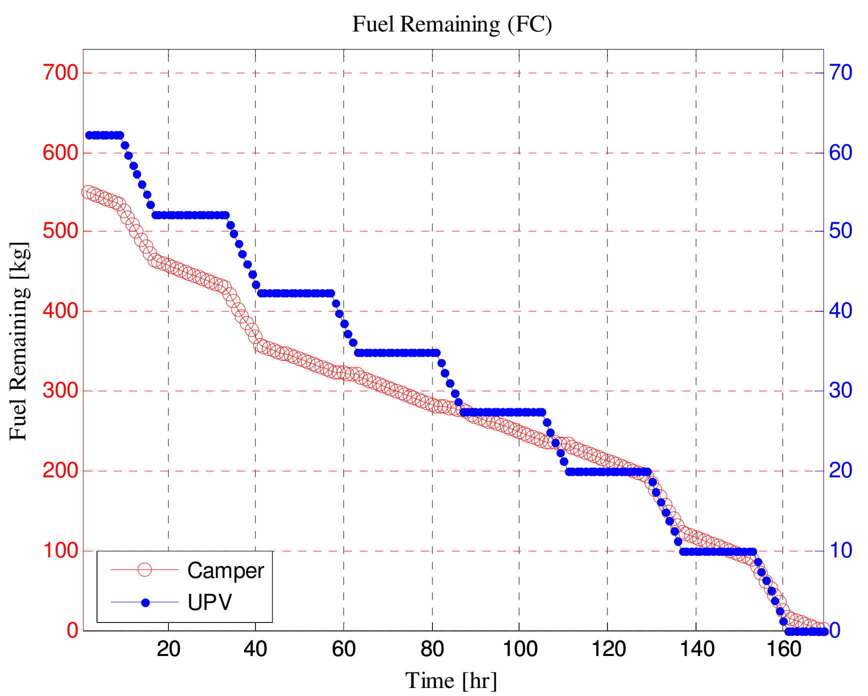

Figure 12. Fuel Remaining in Fuel Cells on the Moon

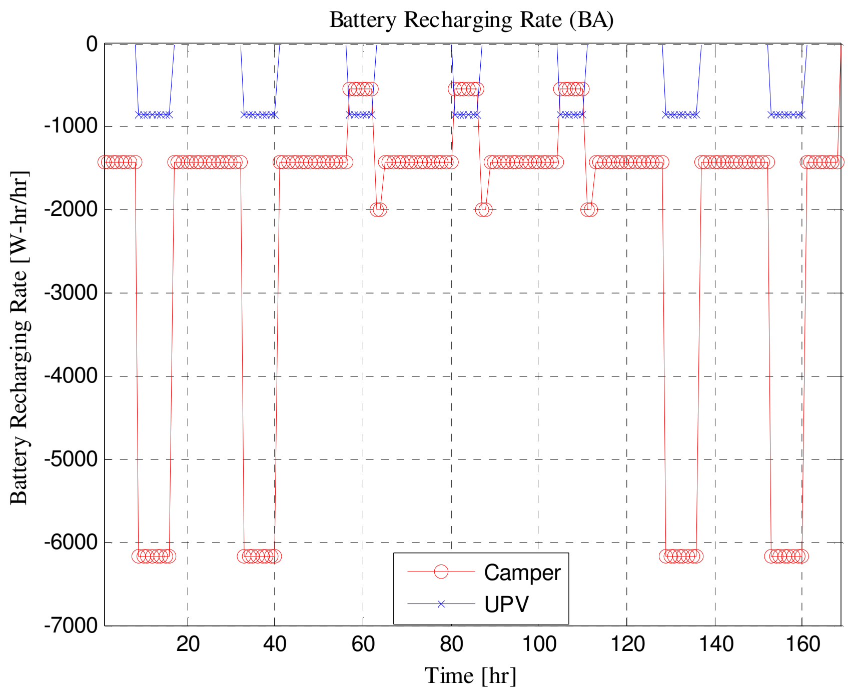

Figure 13. Battery Recharging Rate on the Moon

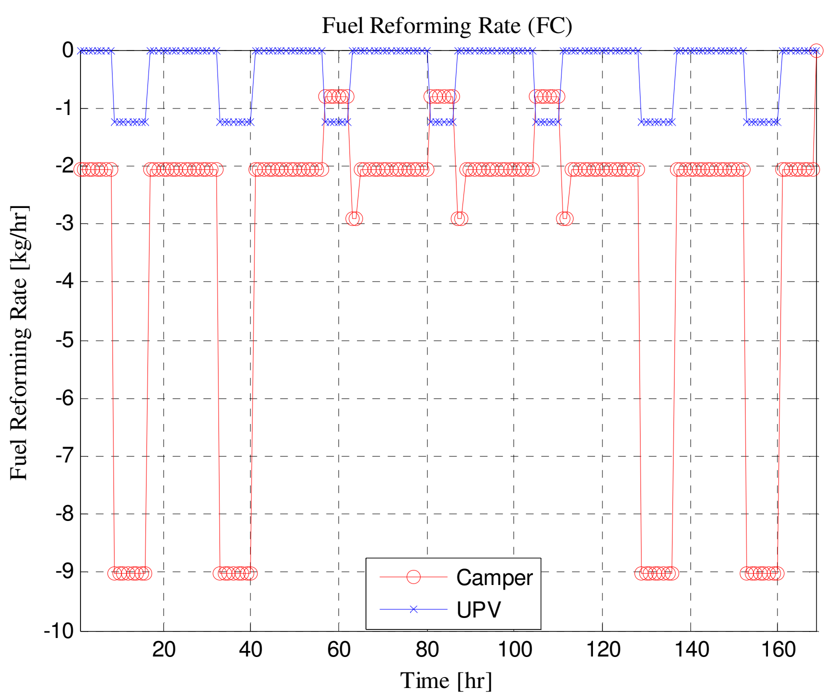

Figure 14. Fuel Reforming Rate on the Moon

5.3.2 Hybrid Power Source

Energy regeneration by primary power systems can reduce the total mass of the system. Primary power systems can generate energy from out of the system and energy generated by primary power systems can take a part of the energy consumption of the vehicles. Therefore, energy which should be stored in secondary power systems is relatively low compared to energy stored for the single power source mission with the same mission scenario.

Initial start points for the optimization are summarized in Table 18. Each design variable has 5 initial start points and each combination of power systems has three design variables: x_1, x_2, and x_3. Therefore, total 125 of initial start points will be examined and the best solution will be taken amongst results of 125 runs.

Table 18. Initial Points for Lunar Mission Optimization

	Variables	Range	# of steps
Battery Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 33]	5
	x_2: The energy capacity of battery systems on the Camper [W·hr]	[0, 800000]	5
	x_3: The fraction of solar power used to recharge a Camper battery [-]	[0, 1]	5
Fuel Cell Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 33]	5
	x_2: The fuel mass of fuel cell systems on the Camper [kg]	[0, 1200]	5
	x_3: The fraction of solar power used to recharge Camper fuel [-]	[0, 1]	5

Table 19 shows the power system specification obtained by the optimization. Once the design variables are obtained, the power system specification can be calculated by the model. The detailed process can be found in Chapter 4. For battery hybrid systems, the optimized masses of the Camper Li-Ion battery and UPV battery are 269 kg and 59 kg, respectively. For fuel cell hybrid systems, the mass of the Camper fuel cell stack and Camper fuel is 28 kg and 78 kg, respectively, while the mass of the UPV fuel cell stack and UPV fuel is 4 kg and 1 kg, respectively. Generally, since the specific mass power density of photovoltaic systems is lower than those of battery and fuel cell systems, the area of solar panel tends to increase until it reaches the solar panel area constraint. In this case study, the upper limit of the solar panel area is 34 m^2, so the area of solar panels is 34 m^2 for both options. However, the panel types are different: triple-junction cells for battery hybrid systems and Si cells for fuel cell hybrid systems. It is because of the specific mass power densities that the power options are very different from each other. The area density of Si solar cells (0.23 kg/m^2) is smaller than the density of triple-junction cells (0.85 kg/m^2), so Si solar cells are the best option for photovoltaic systems in terms of the mass with the area limitation. However, the efficiency of Si cells is also smaller than the efficiency of triple-junction cells. With the same panel areas, power generated from Si solar cells is lower than power from triple-junction solar cells (Figure 15 and Figure 16). It means that the capacity of energy storage systems should become larger when Si solar cells are used in order to meet energy requirements, compared to when triple-junction cells are used with same areas. The specific mass power density of Li-Ion batteries is relatively very high, so using heavy solar cells (triple-junction cells) and a small battery is more beneficial than using light solar cells (Si cells) and a large battery. In contrast, for fuel cell hybrid systems, using light solar cells (Si cells) and loading more fuel are more beneficial than using heavy solar cells (triple-junction cells) and loading less fuel. The mass of photovoltaic systems in battery hybrid systems is 103 kg, and the mass of photovoltaic systems in fuel cell hybrid systems is 28 kg. Total wet masses of battery hybrid systems and fuel cell hybrid systems are 431 kg and 139 kg, respectively.

Obviously, fuel cell hybrid systems are more reasonable option rather than battery hybrid systems in terms of total mass. However, regenerative fuel cell systems are complex and sensitive systems, so a battery hybrid system can be a reasonable option if considering the complexity of power systems.

Table 19. Power System Specification for Lunar Missions

Battery Hybrid Systems		Fuel Cell Hybrid Systems	
Battery Systems		Fuel Cell Systems	
Battery Type	Li-Ion	Fuel Cell Type	$NaBH_4$
Mass of Camper Battery	269 (kg)	Mass of Camper Stack	28 (kg)
Mass of UPV Battery	59 (kg)	Mass of Camper Fuel	78 (kg)
Volume of Camper Battery	109 (m^3)	Mass of UPV Stack	4 (kg)
Volume of UPV Battery	24 (m^3)	Mass of UPV Fuel	1 (kg)
Photovoltaic Systems		Photovoltaic Systems	
Solar Panel Type	3J	Solar Panel Type	Si
Mass of Photovoltaic Sys.	103 (kg)	Mass of Photovoltaic Sys.	28 (kg)
Panel Area	34 (m^2)	Panel Area	34 (m^2)
Fraction of solar power used to recharge a Camper battery	98 (%)	Fraction of solar power used to recharge Camper fuel	91 (%)
Total Mass	431 (kg)	Total Mass	139 (kg)

Figure 15 and Figure 16 represents the solar flux on the Moon and power generated from secondary power systems. The solar flux on the Moon is constant, 1368 W/m^2. During the ‘Driving’ phase, solar panels do not track the Sun, so power generated from solar panels during the ‘Driving’ phase is only about 46% of power generated during other phases. As described before, power generated in battery hybrid systems is higher than power generated in fuel cell hybrid systems.

Figure 17 and Figure 18 show energy remaining in secondary systems of both the Camper and UPV. Figure 19 and Figure 20 show energy recharging rates in secondary systems of both the Camper and UPV. Since the solar flux on the Moon is sufficient enough to fully recharge energy in secondary power systems at the end of 5th day (120hr), the lunar mission can be continued beyond the 7-day mission scenario if astronauts spend the 6th and 7th days to drive to another interesting site, and other supplies are provided.

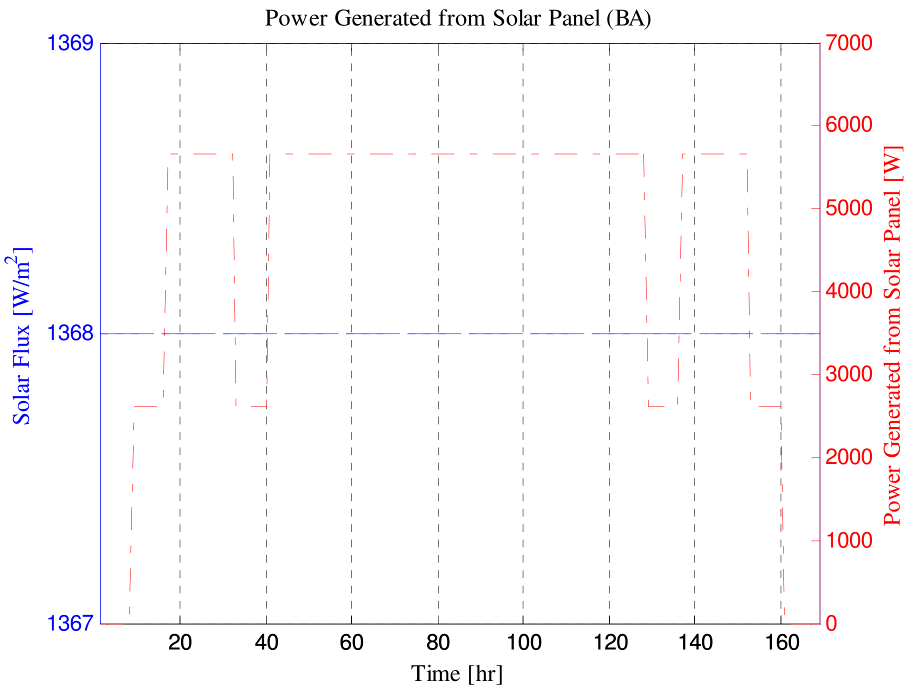

Figure 15. Power Generated from Solar Panel in Battery Systems

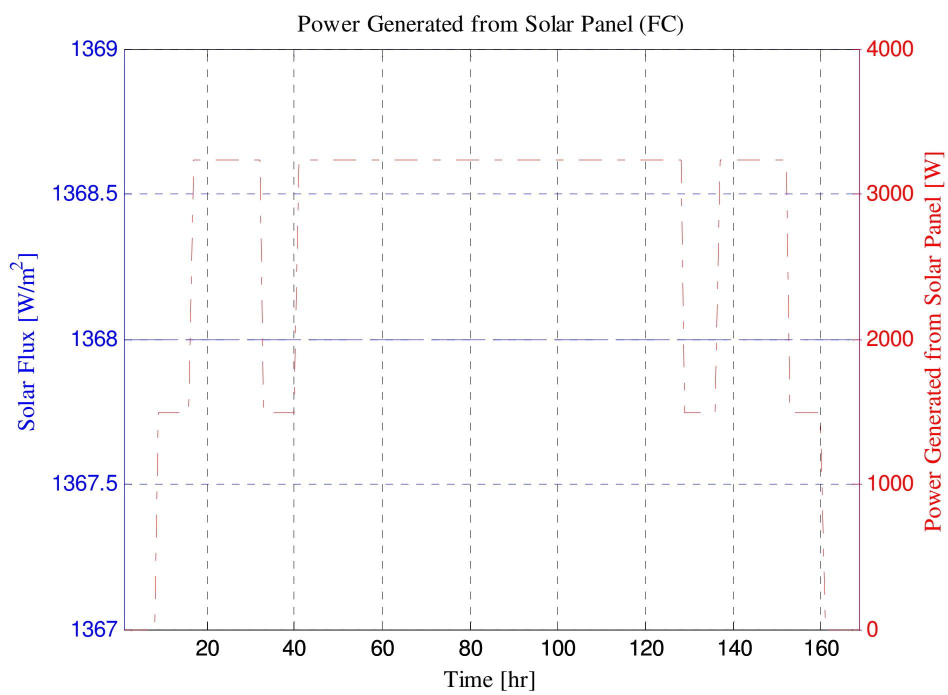

Figure 16. Power Generated from Solar Panel in Fuel Cell Systems

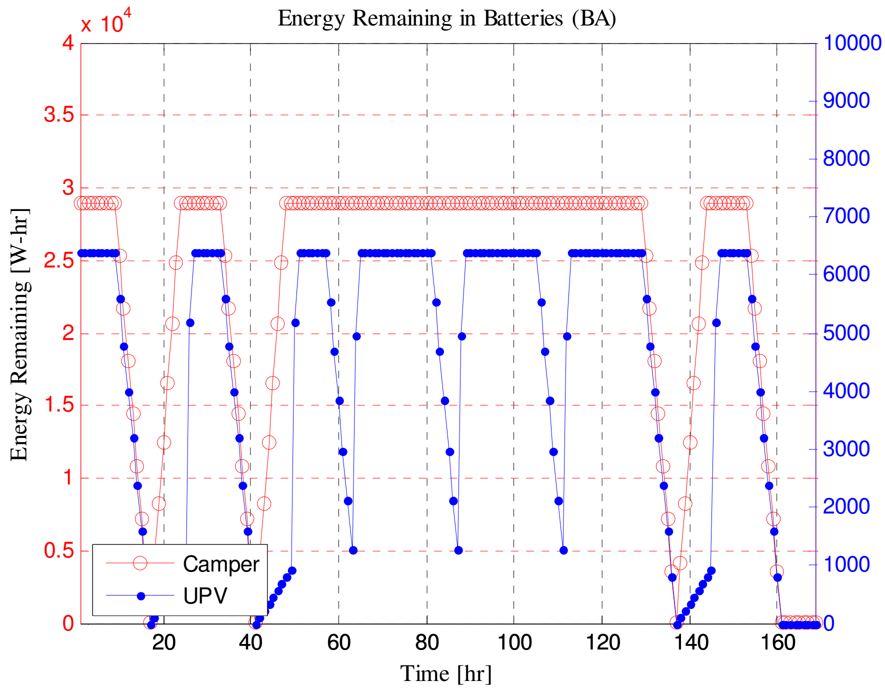

Figure 17. Energy Remaining in Batteries

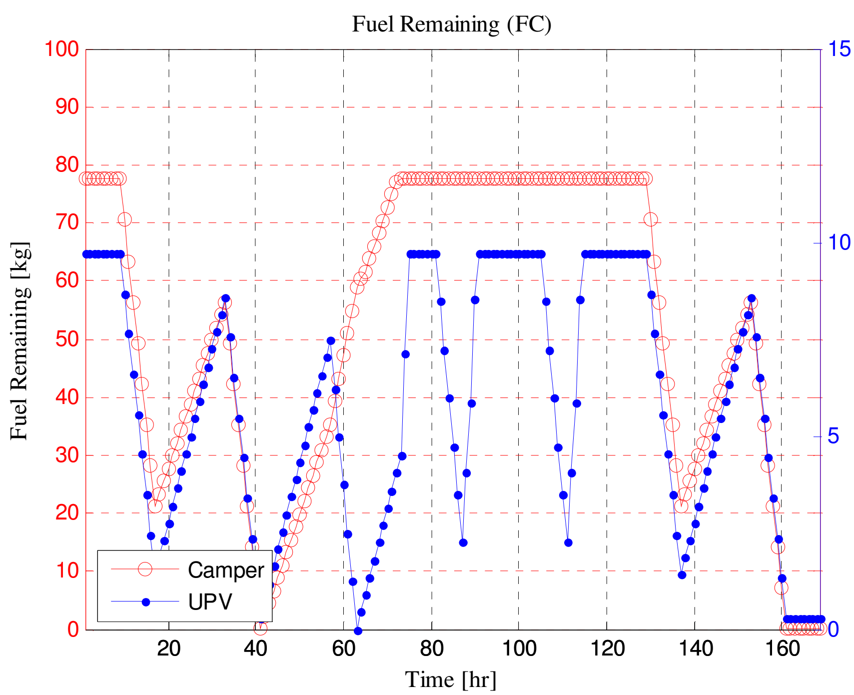

Figure 18. Fuel Remaining in Fuel Cells

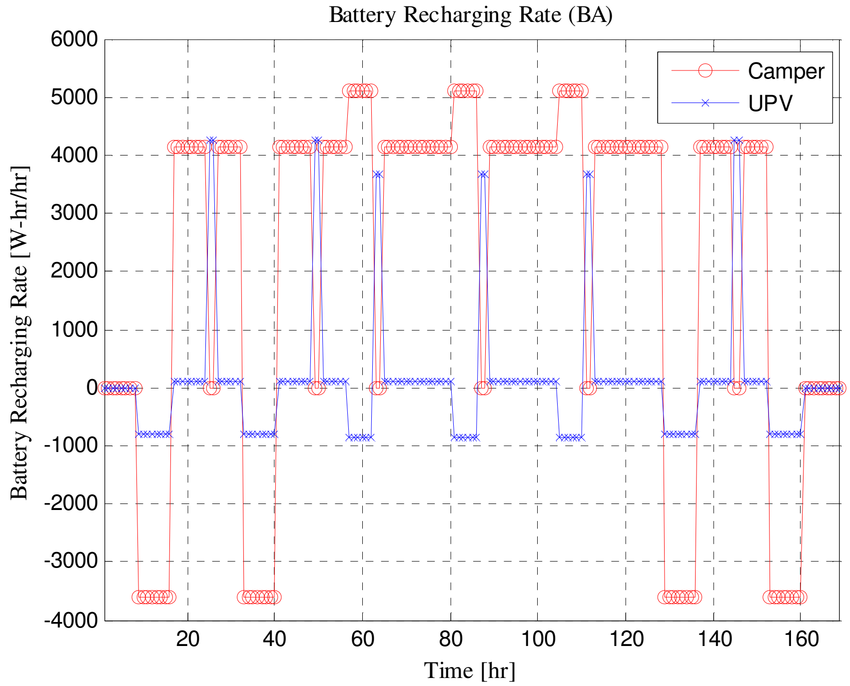

Figure 19. Battery Recharging Rate

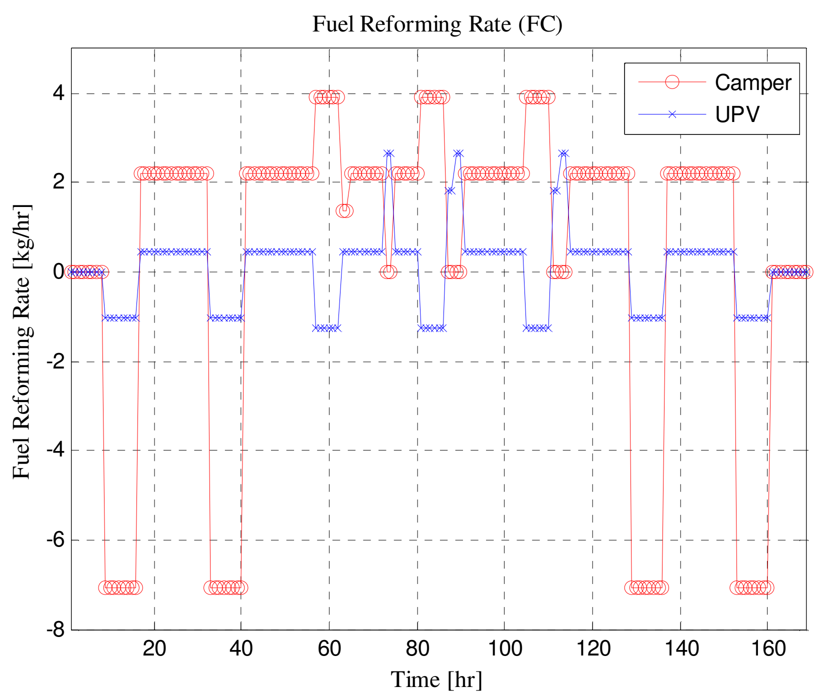

Figure 20. Fuel Reforming Rate

No Recharging during the 'Driving' Phase

The Moon's axis of rotation is almost perpendicular to the solar ecliptic, so there are permanently shadowed regions near some craters in the polar regions [23]. Therefore, even if the Camper can be parked in illuminated sites for recharging secondary power systems, the Camper might go through shadowed regions during the 'Driving' phase. When astronauts drive the Camper and UPV through shadowed regions, photovoltaic systems cannot generate power from the Sun. Before running the program, users should set the parameter 'rechargeable' as 0.

Initial start points for the optimization are summarized in Table 20. Each design variable has 5 initial start points and each combination of power systems has three design variables: x_1, x_2, and x_3. Therefore, total 125 of initial start points will be examined and the best solution will be taken amongst results of 125 runs.

Table 20. Initial Points for Lunar Mission Optimization without Recharging during the 'Driving' Phase

	Variables	Range	# of steps
Battery Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 33]	5
	x_2: The energy capacity of battery systems on the Camper [W·hr]	[0, 800000]	5
	x_3: The fraction of solar power used to recharge a Camper battery [-]	[0, 1]	5
Fuel Cell Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 33]	5
	x_2: The fuel mass of fuel cell systems on the Camper [kg]	[0, 300]	5
	x_3: The fraction of solar power used to recharge Camper fuel [-]	[0, 1]	5

Table 21 shows the power system specification obtained by the optimization. Once the design variables are obtained, the power system specification can be calculated by the model. The detailed process can be found in Chapter 4. For battery hybrid systems, the masses of the Camper Li-Ion battery and UPV battery are 458 kg and 79 kg, respectively. For fuel cell hybrid systems, the mass of the Camper fuel cell stack and Camper fuel is 28 kg and 109 kg, respectively, while the mass of the UPV fuel cell stack and UPV fuel are 4 kg and 1 kg, respectively. For photovoltaic systems of battery hybrid systems, the solar panel area did not reach the maximum area constraint (34 m^2). Batteries cannot be recharged during the 'Driving' phase, so batteries should be large enough to store energy which is needed for the eight-hour drive without recharging. Therefore, the capacity of batteries is sufficient, and enough time to fully recharge batteries is allowed in the 3rd, 4th, and 5th days for driving back to the base; therefore, the maximum area of solar panels is not necessary. For photovoltaic - fuel cell hybrid systems, the solar panel area reached 34 m^2 because Si solar cells were used. If we use 3J solar cells, which are more efficient than Si solar cells, the fuel mass would decrease. However, the mass of solar panels increases more than the fuel mass decreases because the specific mass power density of fuel cells is lower than the specific density of solar cells. The mass of photovoltaic systems in battery hybrid systems is 88 kg, and the mass of photovoltaic systems in fuel cell hybrid systems is 28 kg. Total wet masses of battery hybrid systems and fuel cell hybrid systems are 625 kg and 171 kg, respectively.

The masses of both battery and fuel cell systems for lunar missions without recharging at the 'Driving' phase are heavier than those of both systems for lunar regular missions. For battery hybrid systems, the total mass increases by 194 kg (625 – 431 kg), while total mass of fuel cell hybrid systems increases only by 32 kg (171 – 139 kg). Therefore, even if fuel cannot be reformed during the 'Driving' phase, the mission can be performed with little mass increase when fuel cell hybrid systems are used.

Table 21. Power System Specification for Lunar Mission without Recharging during the 'Drive' Phase

Battery Hybrid Systems		Fuel Cell Hybrid Systems	
Battery Systems		Fuel Cell Systems	
Battery Type	Li-Ion	Fuel Cell Type	$NaBH_4$
Mass of Camper Battery	458 (kg)	Mass of Camper Stack	28 (kg)
Mass of UPV Battery	79 (kg)	Mass of Camper Fuel	109 (kg)
Volume of Camper Battery	186 (m^3)	Mass of UPV Stack	4 (kg)
Volume of UPV Battery	32 (m^3)	Mass of UPV Fuel	1 (kg)
Photovoltaic Systems		Photovoltaic Systems	
Solar Panel Type	3J	Solar Panel Type	Si
Mass of Photovoltaic Sys.	88 (kg)	Mass of Photovoltaic Sys.	28 (kg)
Panel Area	29 (m^2)	Panel Area	34 (m^2)
Fraction of solar power used to recharge a Camper battery	93 (%)	Fraction of solar power used to recharge Camper fuel	90 (%)
Total Mass	625 (kg)	Total Mass	171 (kg)

Figure 21 and Figure 22 represents the solar flux on the Moon and power generated from secondary power systems without recharging during the ‘Driving’ phase. The solar flux on the Moon is constant, 1368 W/m^2. During the ‘Driving’ phase, solar panels do not generate energy, so power generated from solar panels during the ‘Driving’ phase is zero. As described before, power generated in battery hybrid systems is higher than power generated in fuel cell hybrid systems.

Figure 23 and Figure 24 show energy remaining in secondary systems of both the Camper and UPV. Figure 25 and Figure 26 show energy recharging rates in secondary systems of both the Camper and UPV. Since the solar flux on the Moon is sufficient to fully recharge energy in secondary power systems at the end of 5th day (120hr), the lunar mission can be continued beyond the 7-day mission scenario if astronauts spend 6th and 7th days to drive another interesting site, and other supplies are provided.

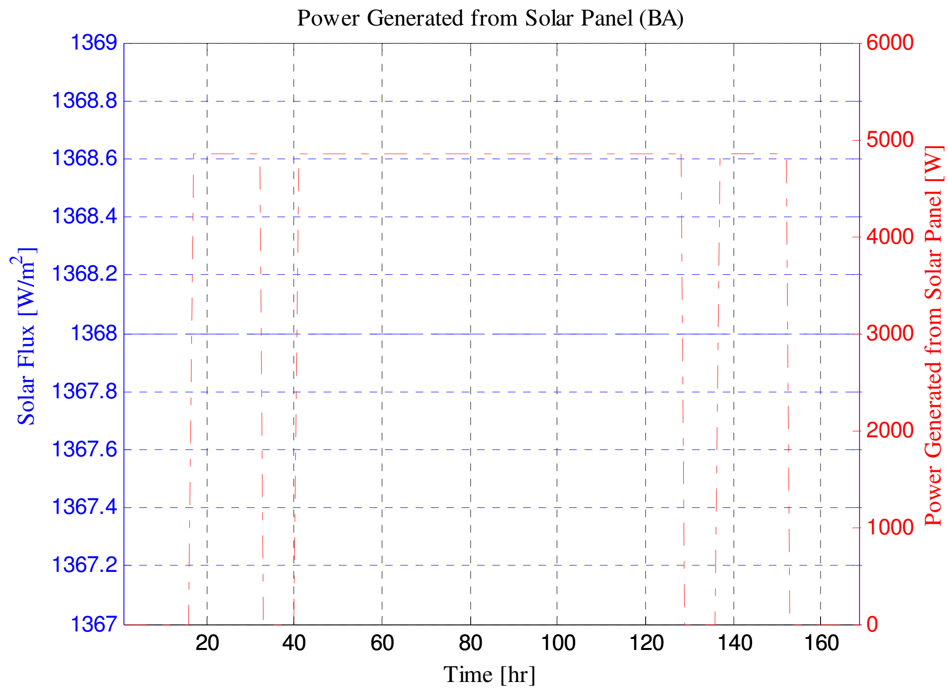

Figure 21. Power Generated from Solar Panel in Battery Systems on the Moon

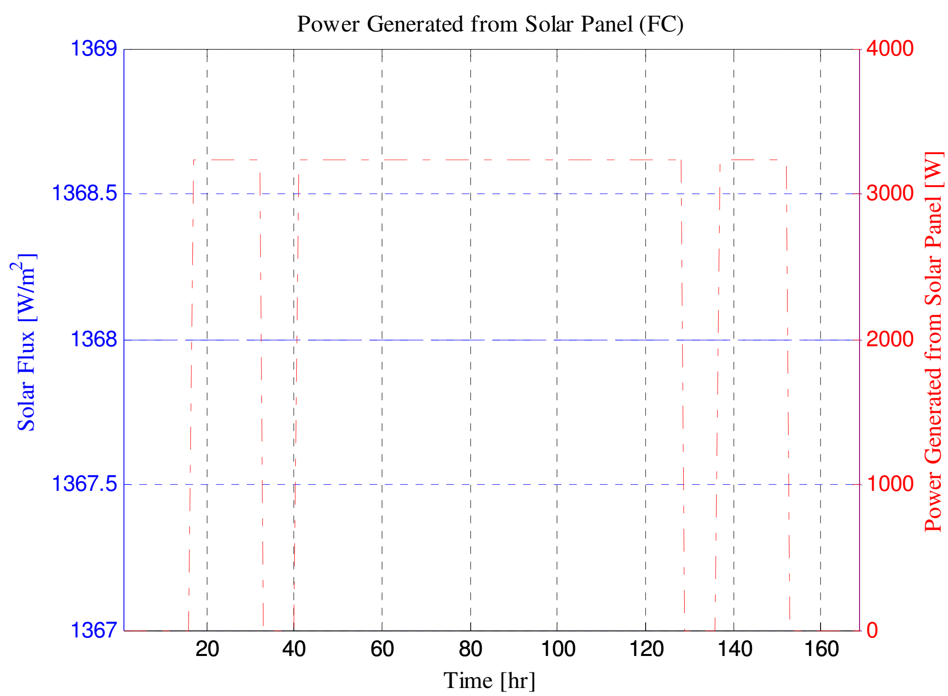

Figure 22. Power Generated form Solar Panel in Fuel Cell Systems on the Moon

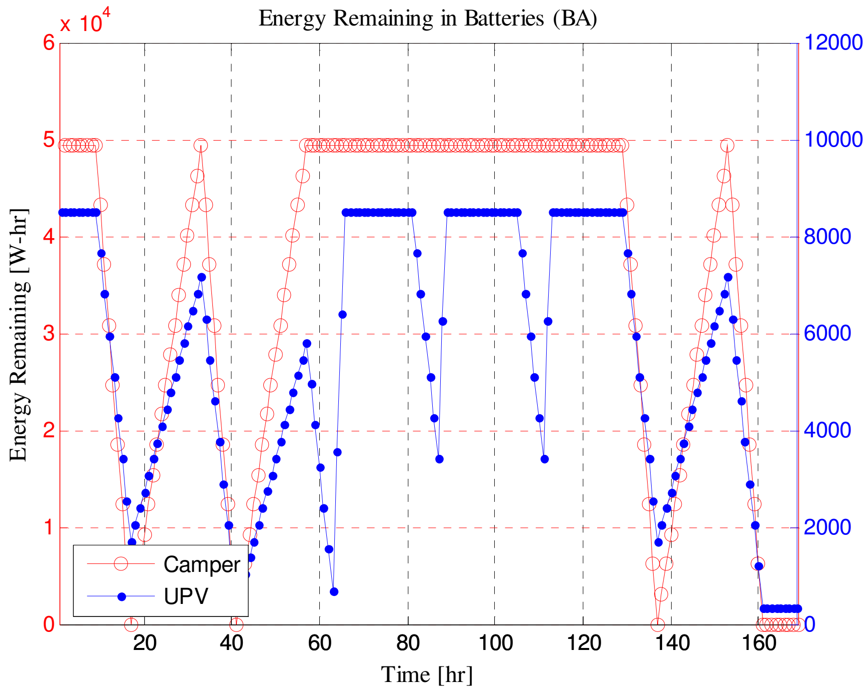

Figure 23. Energy Remaining in Batteries

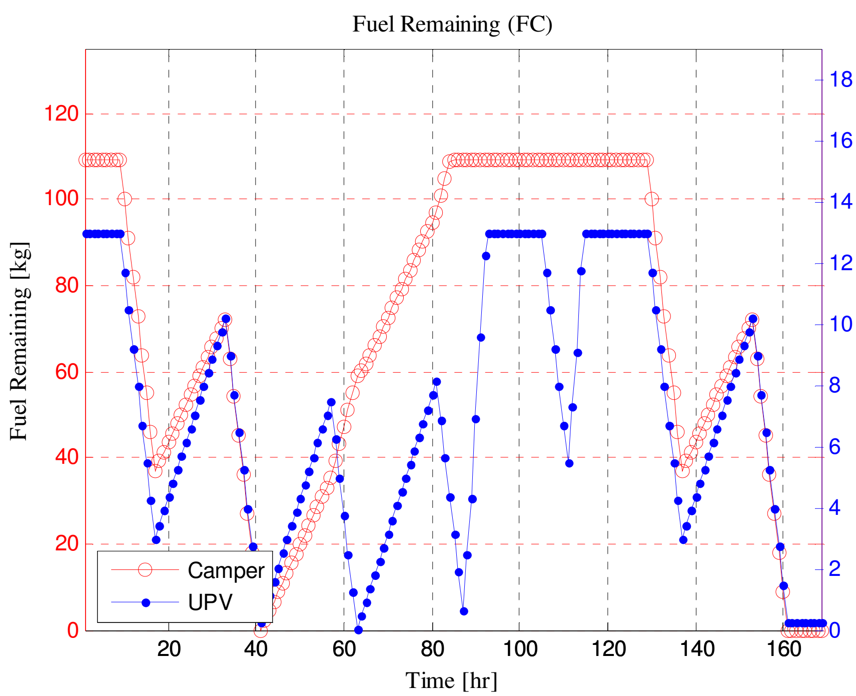

Figure 24. Fuel Remaining in Fuel Cells

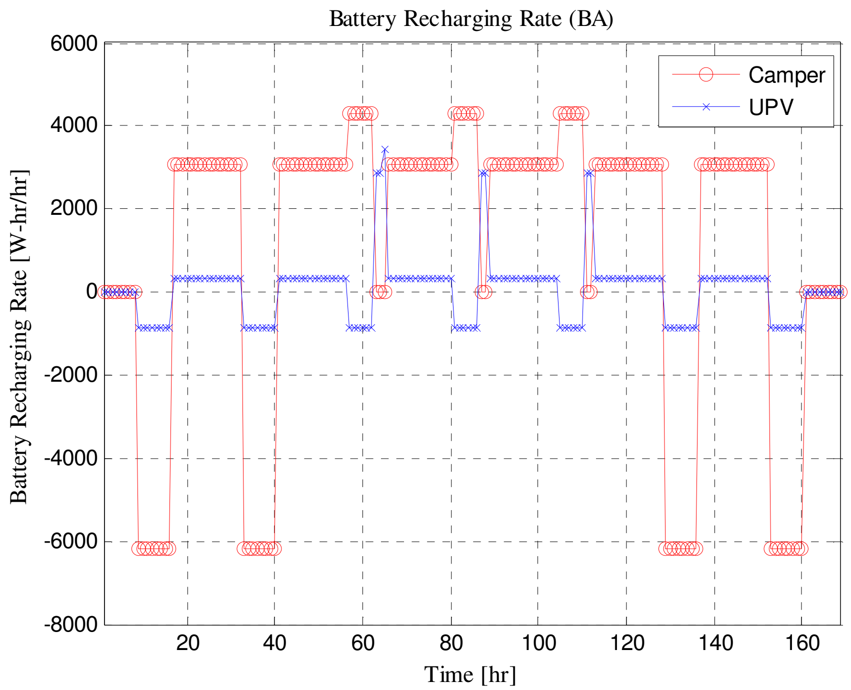

Figure 25. Energy Recharging Rates

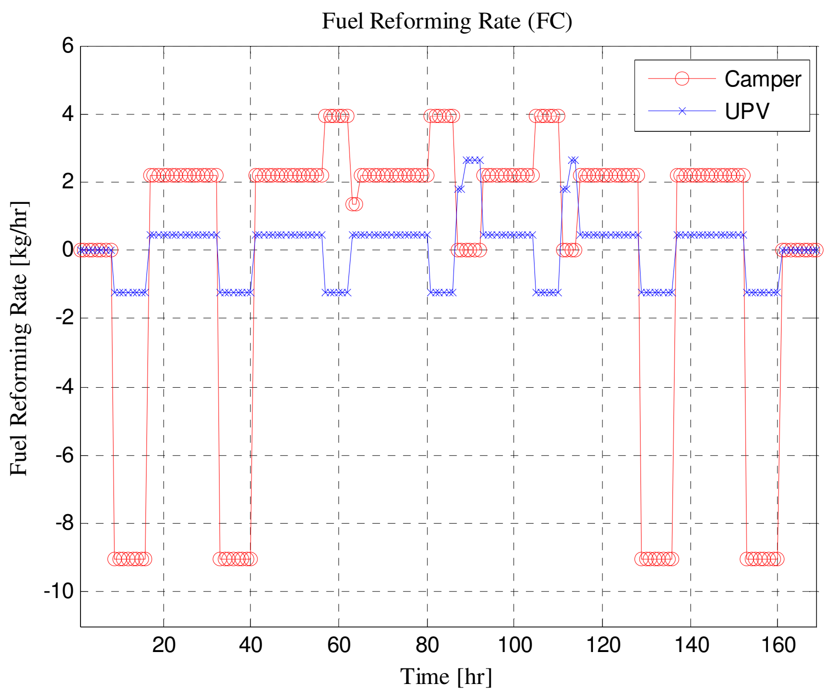

Figure 26. Fuel Reforming Rates

5.4 Mars Mission

Mars has a higher surface gravity (3.71 m/s^2) than the Moon. In addition, Mars has very short daytime compared to the Moon. Because of this environmental difference, power systems optimized for the lunar mission will not be optimum for Mars.

5.4.1 Single Source

Similar to the lunar single power source mission, using only energy storage systems can reduce the degree of the system complexity and the development cost. In addition, the result of single power source missions is a good reference for determining whether to equip single source systems or hybrid systems.

Initial start points for the optimization are summarized in Table 22. Since there is no solar panel in this scenario, each combination of power systems has two design variables: x_2 and x_3. Each design variable has 5 initial start points except x_1. Therefore, total 25 of initial start points will be examined and the best solution will be taken amongst results of 25 runs. However, since there is no solar power in this scenario, x_3 does not affect the result of this optimization.

Table 22. Initial Points for Mars Single Mission Optimization

	Variables	Range	# of steps
Battery Hybrid System	x_1: The area of solar panels on the Camper [m^2]	fixed as 0	-
	x_2: The energy capacity of battery systems on the Camper [W·hr]	[0, 800000]	5
	x_3: The fraction of solar power used to recharge a Camper battery [-]	[0, 1]	5
Fuel Cell Hybrid System	x_1: The area of solar panels on the Camper [m^2]	fixed as 0	-
	x_2: The fuel mass of fuel cell systems on the Camper [kg]	[0, 1200]	5
	x_3: The fraction of solar power used to recharge Camper fuel [-]	[0, 1]	5

Table 23 shows the power system specification obtained by the optimization for Mars single power missions. Once the design variables are obtained, the power system specification can be calculated by the model. The detailed process can be found in Chapter 4. The total mass of battery systems is 4695 kg, while the total mass of fuel cell systems is 871 kg. The total mass of battery systems is approximately five times as heavy as the one of fuel cell systems. It is because specific mass energy density of Li-Ion batteries is much heavier than one of $NaBH_4$ fuel cells. Obviously, for the single power source mission on Mars, fuel cell power systems are a more reasonable option rather than battery system in terms of total wet mass.

Table 23. Power System Specification for Mars Single Source Missions

Battery Systems		Fuel Cell Systems	
Battery Type	Li-Ion	Fuel Cell Type	$NaBH_4$
Mass of Camper Battery	4695 (kg)	Mass of Camper Stack	46 (kg)
Mass of UPV Battery	514 (kg)	Mass of Camper Fuel	739 (kg)
Volume of Camper Battery	1902 (m^3)	Mass of UPV Stack	5 (kg)
Volume of UPV Battery	208 (m^3)	Mass of UPV Fuel	81 (kg)
Total Mass	5209 (kg)	Total Mass	871 (kg)

Figure 27 and Figure 28 show the energy remaining in battery systems and fuel remaining in fuel cell systems, respectively. Figure 29 and Figure 30 show the battery recharging rate and fuel reforming rate. Since there is no photovoltaic system on the Camper and the surface mobility system cannot generate energy from external sources, energy recharging rates in both battery and fuel cell system are always negative.

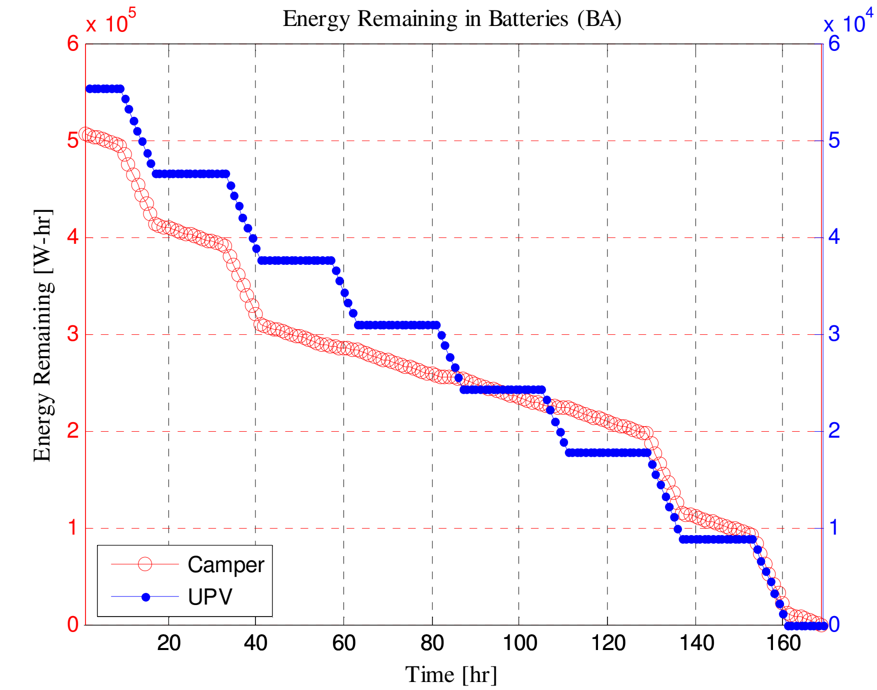

Figure 27. Energy Remaining in Batteries on Mars

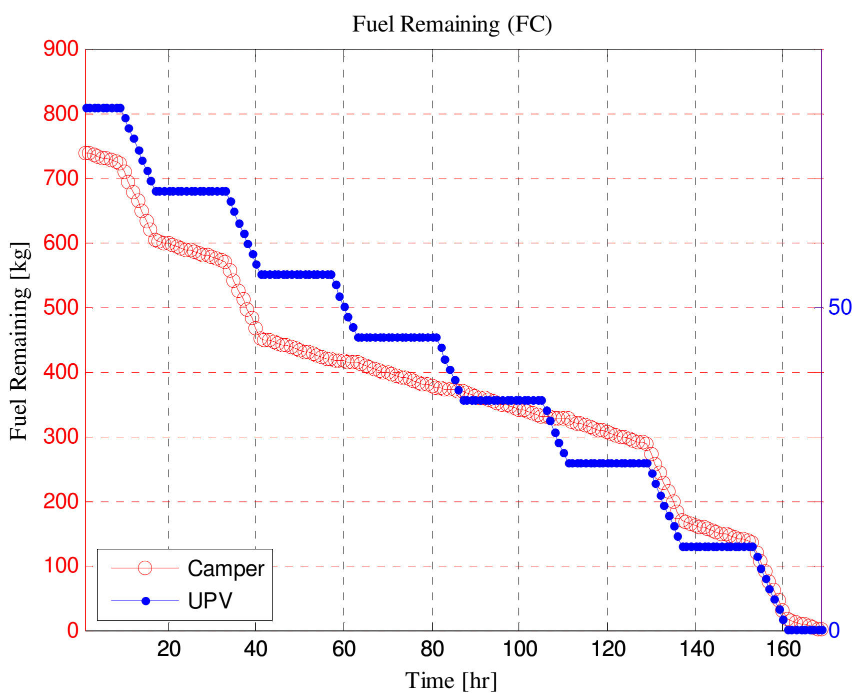

Figure 28. Fuel Remaining in Fuel Cells on Mars

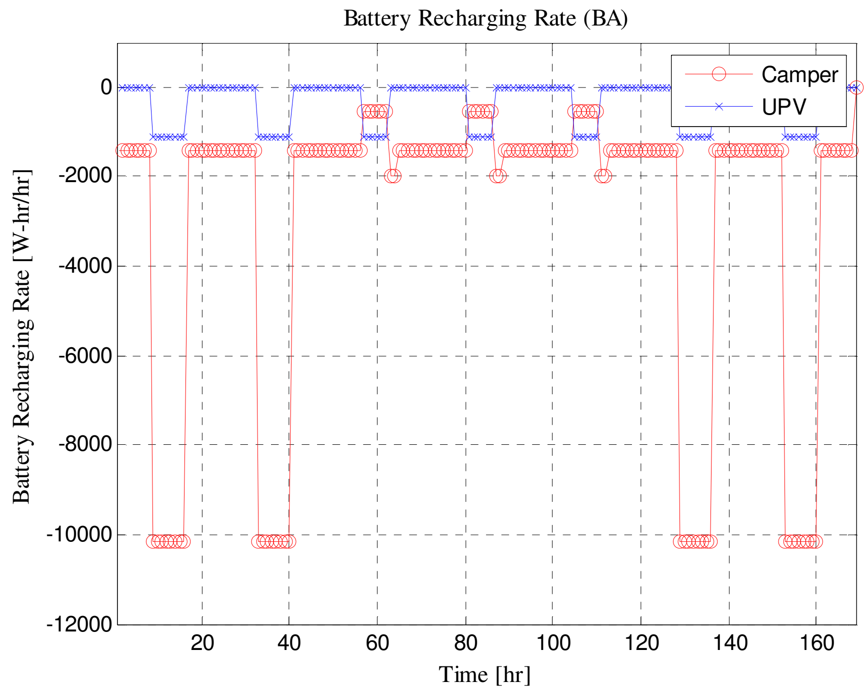

Figure 29. Battery Recharging Rate on Mars

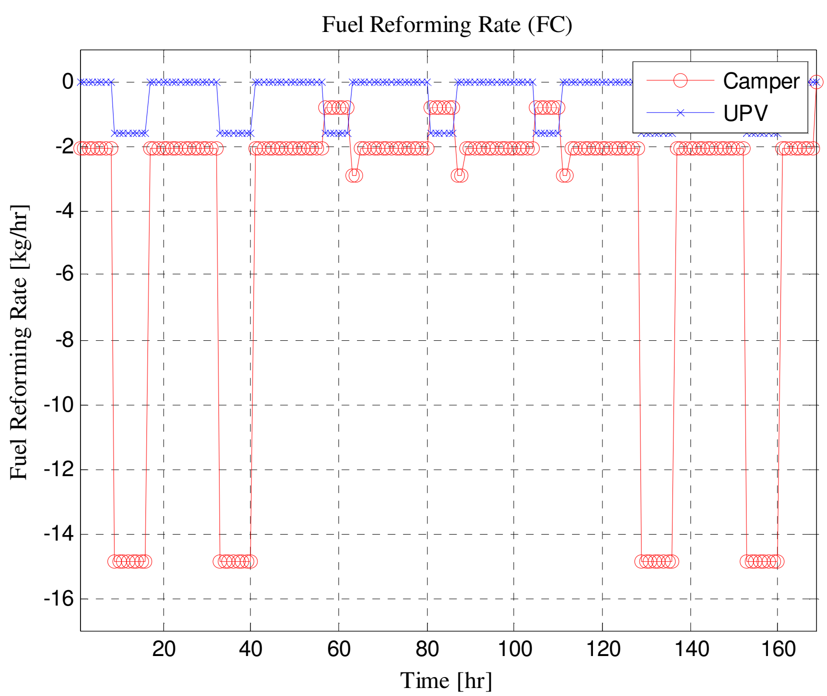

Figure 30. Fuel Reforming Rate on Mars

5.4.2 Hybrid Power Source

Energy regeneration by primary power systems can reduce the total mass of the system. Primary power systems can generate energy from out of the system and energy generated by primary power systems can provide for a part of the energy consumption of the vehicles. Therefore, energy which should be stored in secondary power systems is relatively low compared to energy stored for the single power source mission with the same mission scenario.

Initial start points for the optimization are summarized in Table 24. Each design variable has 5 initial start points and each combination of power systems has three design variables: x_1, x_2, and x_3. Therefore, total 125 of initial start points will be examined and the best solution will be taken amongst results of 125 runs.

Table 24. Initial Points for Mars Mission Optimization

	Variables	Range	# of steps
Battery Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 50]	5
	x_2: The energy capacity of battery systems on the Camper [W·hr]	[0, 800000]	5
	x_3: The fraction of power used to recharge a Camper battery [-]	[0, 1]	5
Fuel Cell Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 50]	5
	x_2: The fuel mass of fuel cell systems on the Camper [kg]	[0, 1200]	5
	x_3: The fraction of power used to recharge Camper fuel [-]	[0, 1]	5

Table 25 shows the power system specification obtained by the optimization. Once the design variables are obtained, the power system specification can be calculated by the model. The detailed process can be found in Chapter 4. For battery hybrid systems, the masses of the Camper Li-Ion battery and UPV battery are 4073 kg and 77 kg, respectively. For fuel cell hybrid systems, the mass of the Camper fuel cell stack and Camper fuel is 46 kg and 639 kg, respectively, while the mass of the UPV fuel cell stack and UPV fuel is 5 kg and 2 kg, respectively. Note that the mass of the fuel cell stack is proportional to the maximum power required, which is 852 W for the UPV. In addition, the specific energy density of th e $NaBH_4$ fuel cell is about 1 kW·hr/kg, so the UPV can perform its mission with small a amount of fuel. The detailed description of the $NaBH_4$ fuel cells can be found in Chapter 4. Photovoltaic systems cannot generate energy during Martian night, and the maximum solar flux is only 580 W/m^2, which is almost half of the solar flux on the Moon. Moreover, energy required on Mars is much higher than on the Moon because of high gravity on Mars. Therefore, a heavy energy storage system is required in order to meet the energy requirement.

The solar panel areas reach to the maximum geometry limit (34 m^2), and 3J solar cells are used for both battery and fuel cell hybrid systems in order to generate power as high as possible because of the lack of solar energy. The masses of photovoltaic systems in both battery and fuel cell hybrid systems are 103 kg, and the areas are 34 m^2.

Total wet masses of battery hybrid systems and fuel cell hybrid systems are 4253 kg and 795 kg, respectively. Since fuel cell hybrid systems are much lighter than battery hybrid systems, fuel cell hybrid systems are reasonable option for Mars missions.

Table 25. Power System Specification for Mars Missions

Battery Hybrid Systems		Fuel Cell Hybrid Systems	
Battery Systems		Fuel Cell Systems	
Battery Type	Li-Ion	Fuel Cell Type	$NaBH_4$
Mass of Camper Battery	4073 (kg)	Mass of Camper Stack	46 (kg)
Mass of UPV Battery	77 (kg)	Mass of Camper Fuel	639 (kg)
Volume of Camper Battery	1650 (m^3)	Mass of UPV Stack	5 (kg)
Volume of UPV Battery	31 (m^3)	Mass of UPV Fuel	2 (kg)
Photovoltaic Systems		Photovoltaic Systems	
Solar Panel Type	3J	Solar Panel Type	3J
Mass of Photovoltaic Sys.	103 (kg)	Mass of Photovoltaic Sys.	103 (kg)
Panel Area	34 (m^2)	Panel Area	34 (m^2)
Fraction of solar power used to recharge a Camper battery	13 (%)	Fraction of solar power used to recharge Camper fuel	15 (%)
Total Mass	4253 (kg)	Total Mass	795 (kg)

Figure 31 and Figure 32 represents the solar flux on Mars and power generated from secondary power systems. As it seen in those figures, photovoltaic systems cannot generate energy when the Sun is down. Moreover, even if the Sun is up in the sky, the solar flux is much less than on the Moon. Therefore, the power generated from solar panels is quite small, compared to the power generated on the Moon.

Figure 33 and Figure 34 show energy remaining in secondary systems of both the Camper and UPV. Figure 35 and Figure 36 show energy recharging rates in secondary systems of both the Camper and UPV. Since the solar flux on Mars insufficient to fully recharge secondary power systems at the end of 5th day (120hr), the Mars mission cannot be continued beyond the 7-day mission scenario even if other supplies are provided. Generally, power generated from solar panels has an effect to slow down the energy consumption of secondary power systems but cannot fully recharge secondary power systems.

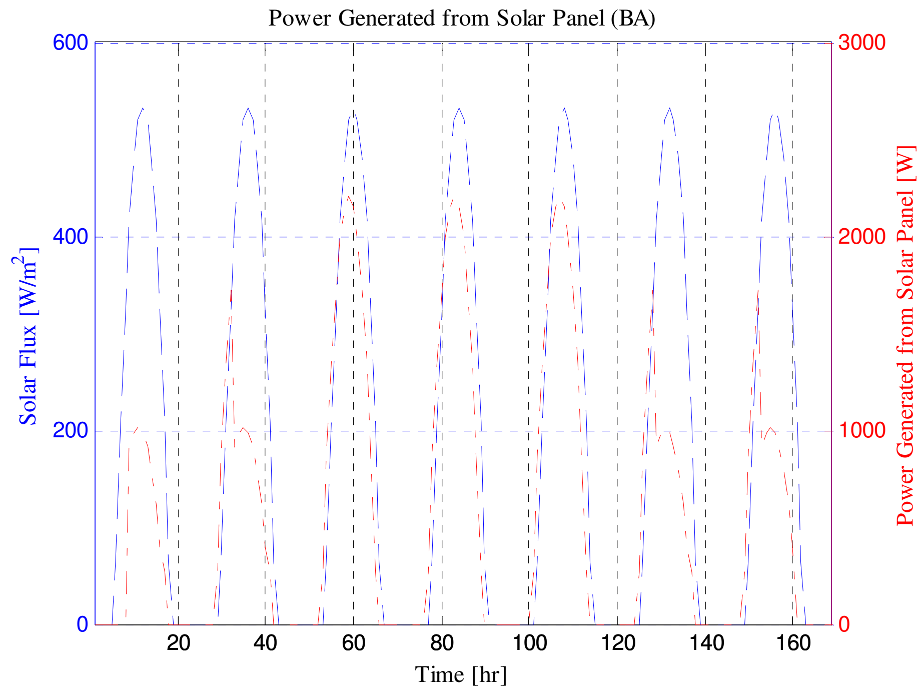

Figure 31. Power Generated from Solar Panels in Battery Systems on Mars

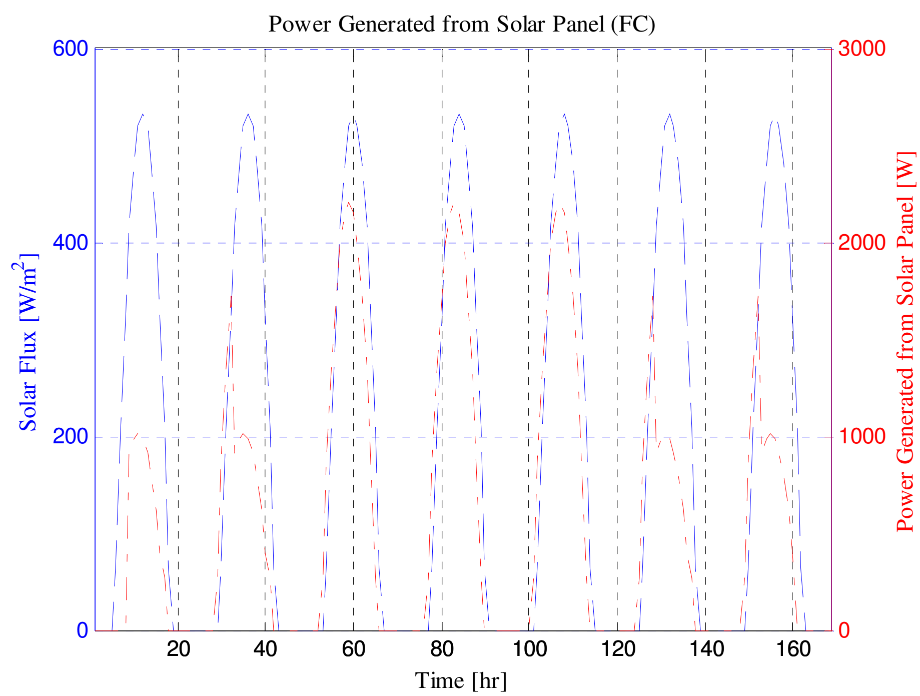

Figure 32. Power Generated from Solar Panels in Fuel Cell Systems on Mars

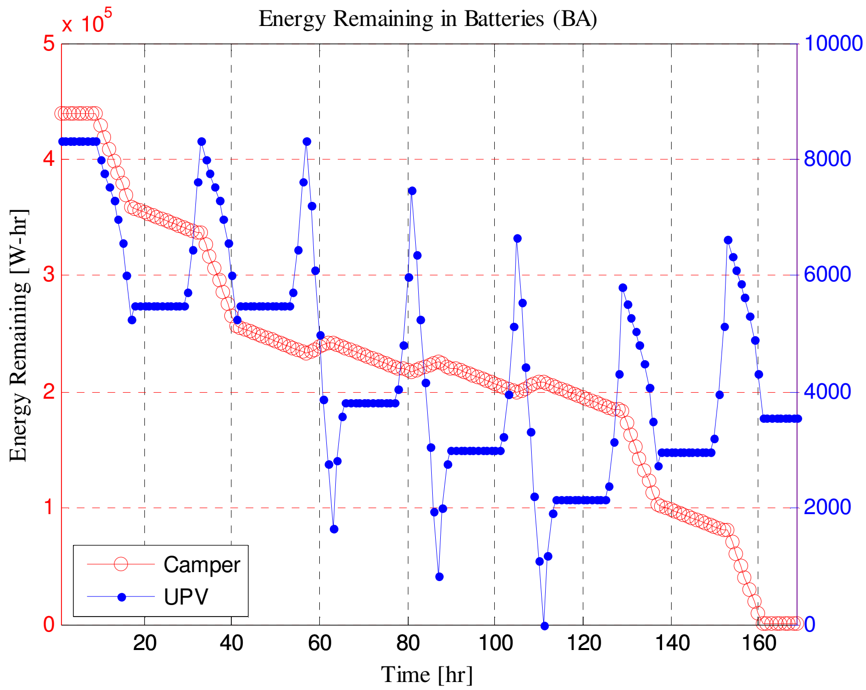

Figure 33. Energy Remaining in Batteries on Mars

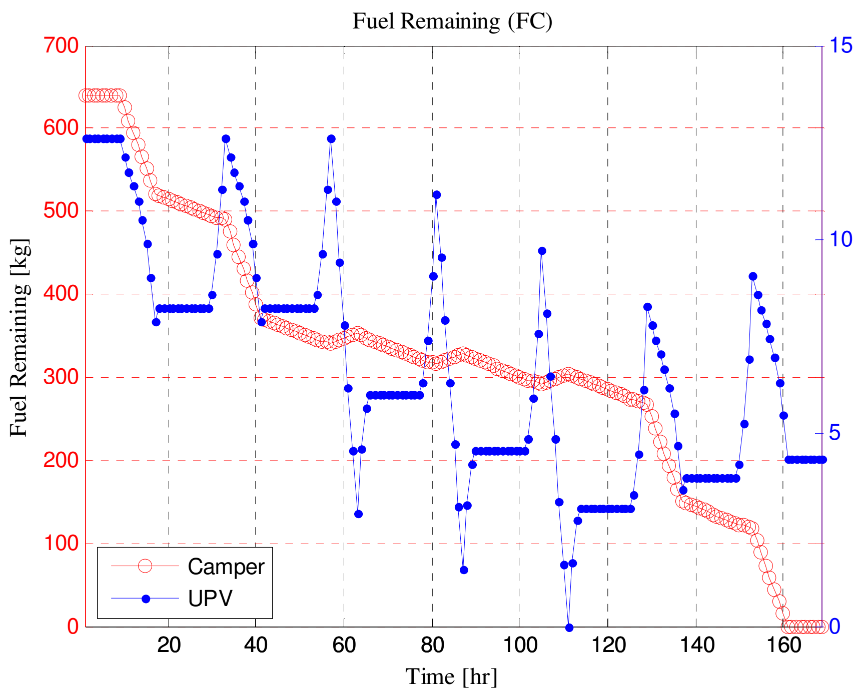

Figure 34. Fuel Remaining in Fuel Cells on Mars

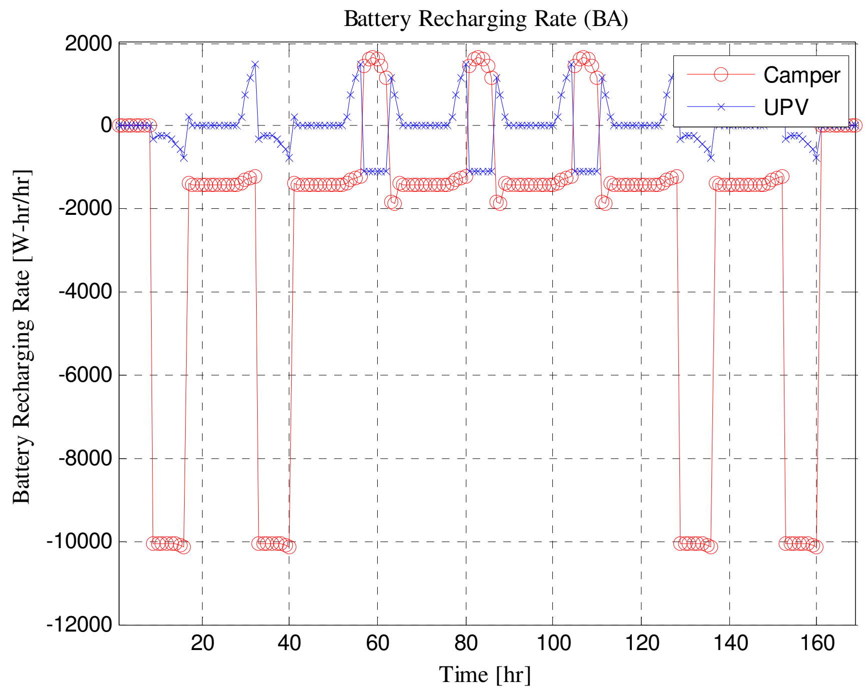

Figure 35. Battery Recharging Rates on Mars

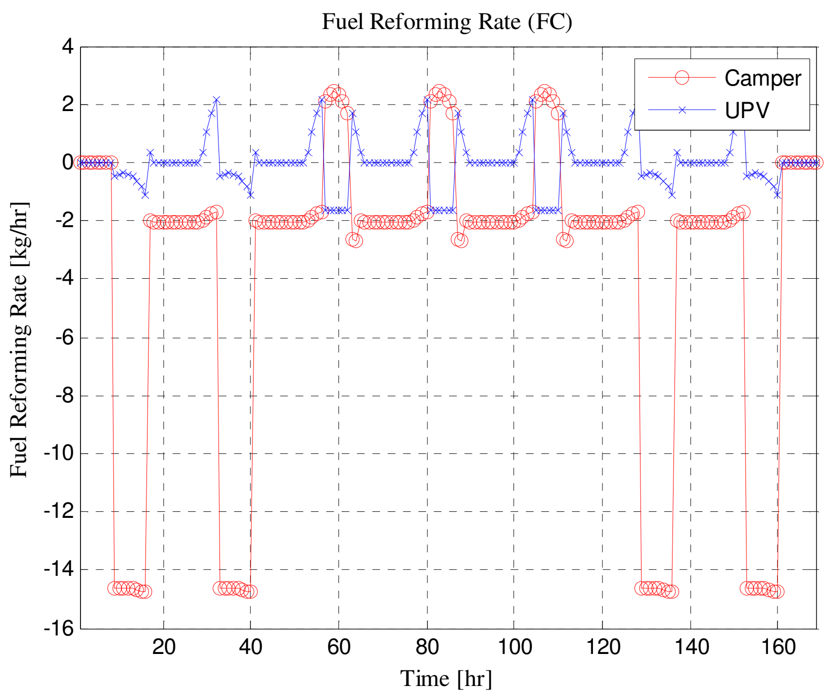

Figure 36. Fuel Reforming Rates on Mars

Sustainable missions on Mars

With the limitation on the solar panel area, Mars missions cannot be sustainable unless fully recharged fuel or battery is re-supplied. However, if astronauts can unfold additional extended solar panels beyond the area geometry limitation when the Camper stops, the system can generate enough power to make the mission sustainable.

Initial start points for the optimization are summarized in Table 26. Each design variable has 5 initial start points and each combination of power systems has three design variables: x_1, x_2, and x_3. Therefore, total 125 of initial start points will be examined and the best solution will be taken amongst results of 125 runs. The optimization will be performed without the area limitation constraint. In addition, the parameter 'rechargeHour' is set as 113 hours, which is the end of the 5th day.

Table 26. Initial Points for Mars Sustainable Mission Optimization

	Variables	Range	# of steps
Battery Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 200]	5
	x_2: The energy capacity of battery systems on the Camper [W·hr]	[0, 800000]	5
	x_3: The fraction of power used to recharge a Camper battery [-]	[0, 1]	5
Fuel Cell Hybrid System	x_1: The area of solar panels on the Camper [m^2]	[0, 200]	5
	x_2: The fuel mass of fuel cell systems on the Camper [kg]	[0, 300]	5
	x_3: The fraction of power used to recharge Camper fuel [-]	[0, 1]	5

Table 27 shows the power system specification obtained by the optimization. Once the design variables are obtained, the power system specification can be calculated by the model. The detailed process can be found in Chapter 4. For battery hybrid systems, the masses of the Camper Li-Ion battery and UPV battery are 1625 kg and 77 kg, respectively. For fuel cell hybrid systems, the mass of the Camper fuel cell stack and Camper fuel is 46 kg and 258 kg, respectively, while the mass of the UPV fuel cell stack and UPV fuel is 5 kg and 2 kg, respectively. Removing the area constraint decreases the mass of energy storage systems significantly, but photovoltaic systems of both options increases significantly because of the large area of solar panels. For battery hybrid systems, the area of solar panels is 183 m^2, and its mass is 546 kg, while the area of solar panels of fuel cell hybrid systems is 164 m^2, and its mass is 490 kg. Since the specific mass power of $NaBH_4$ fuel is relatively small, fuel cell hybrid systems require relatively small area which can only generate energy to fully recharge the fuel at the end of the 5th day. It is not necessary to have wider solar panels in order to reduce the fuel mass. However, in contrast to fuel cells, Li-Ion batteries are heavy. Therefore, wider solar panels and minimum battery capacity is reasonable for battery hybrid systems, but batteries should contain energy which is required for night use and operation when the solar flux is not enough (morning and evening).

Total wet masses of battery hybrid systems and fuel cell hybrid systems are 2249 kg and 801 kg, respectively. The reason the total mass of battery hybrid systems decreases significantly is that the capacity of batteries decreases. However, even though the total mass of battery hybrid systems for sustainable missions decreases by half, fuel cell hybrid systems are still more reasonable option for Mars sustainable missions.

Table 27. Power System Specification for Mars Sustainable Mission

Battery Hybrid Systems		Fuel Cell Hybrid Systems	
Battery Systems		Fuel Cell Systems	
Battery Type	Li-Ion	Fuel Cell Type	$NaBH_4$
Mass of Camper Battery	1625 (kg)	Mass of Camper Stack	46 (kg)
Mass of UPV Battery	77 (kg)	Mass of Camper Fuel	258 (kg)
Volume of Camper Battery	658 (m^3)	Mass of UPV Stack	5 (kg)
Volume of UPV Battery	31 (m^3)	Mass of UPV Fuel	2 (kg)
Photovoltaic Systems		Photovoltaic Systems	
Solar Panel Type	3J	Solar Panel Type	3J
Mass of Photovoltaic Sys.	546 (kg)	Mass of Photovoltaic Sys.	490 (kg)
Panel Area	183 (m^2)	Panel Area	164 (m^2)
Fraction of solar power used to recharge a Camper battery	71 (%)	Fraction of solar power used to recharge Camper fuel	72 (%)
Total Mass	2249 (kg)	Total Mass	801 (kg)

Figure 37 and Figure 38 represents the solar flux on Mars and power generated from secondary power systems. As it seen in the figures, photovoltaic systems generate very high energy when the solar panels are fully unfolded and deployed on the ground.

Figure 39 and Figure 40 show energy remaining in secondary systems of both the Camper and UPV. Figure 41 and Figure 42 show energy recharging rates in secondary systems of both the Camper and UPV. Since the energy generated from solar panels is sufficient to fully recharge secondary power systems at the end of 5th day (130hr), the mission can be continued beyond the 7-day mission scenario if astronauts spend the 6th and 7th days to drive to another interesting site, and other supplies are provided.

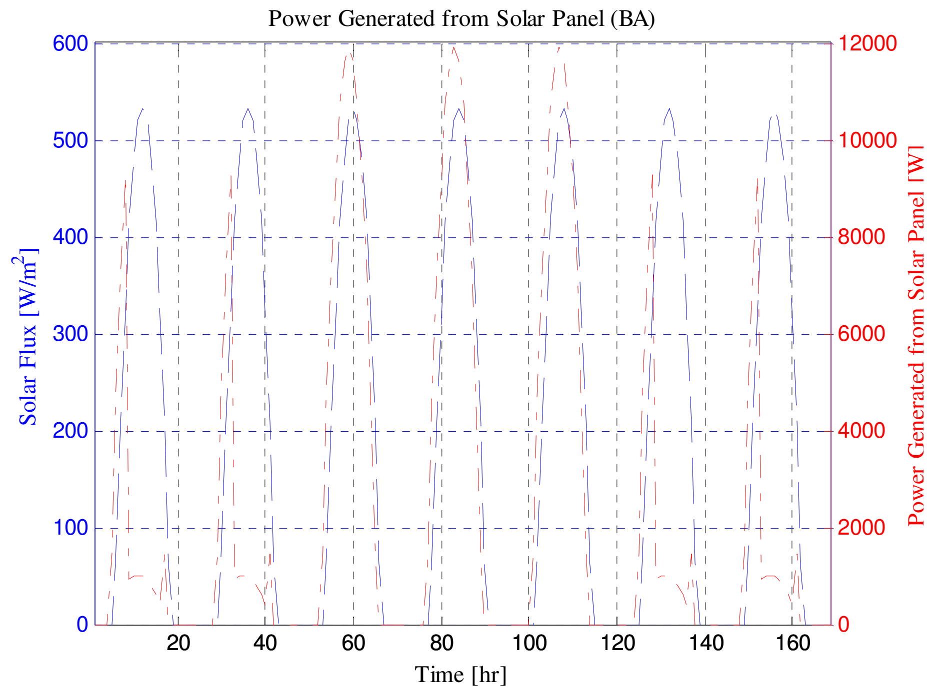

Figure 37. Power Generated from Solar Panels in Battery Systems for Mars Sustainable Missions

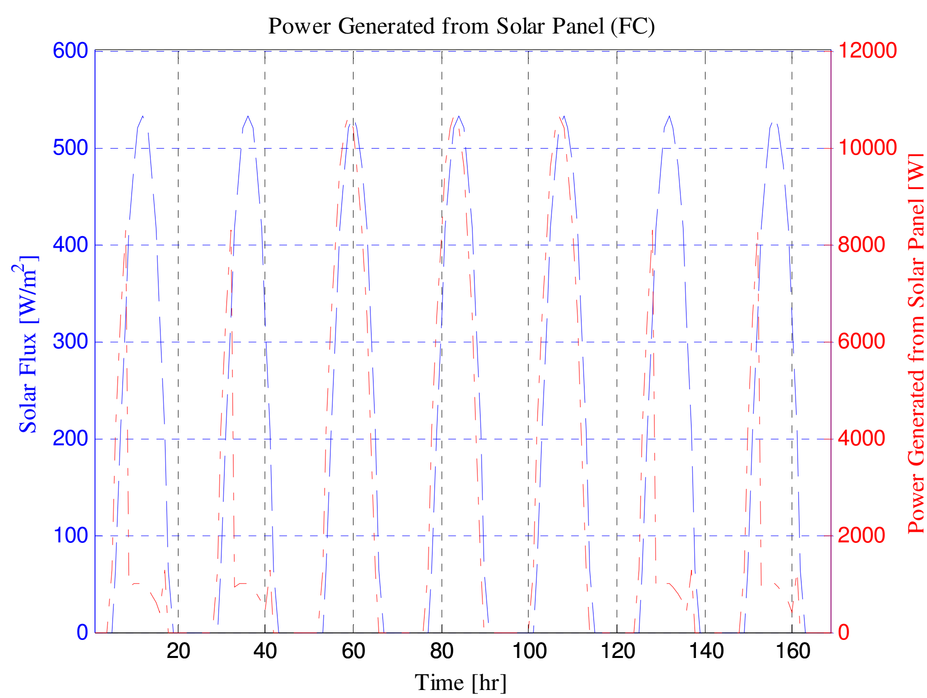

Figure 38. Power Generated from Solar Panels in Fuel Cell Systems for Mars Sustainable Missions

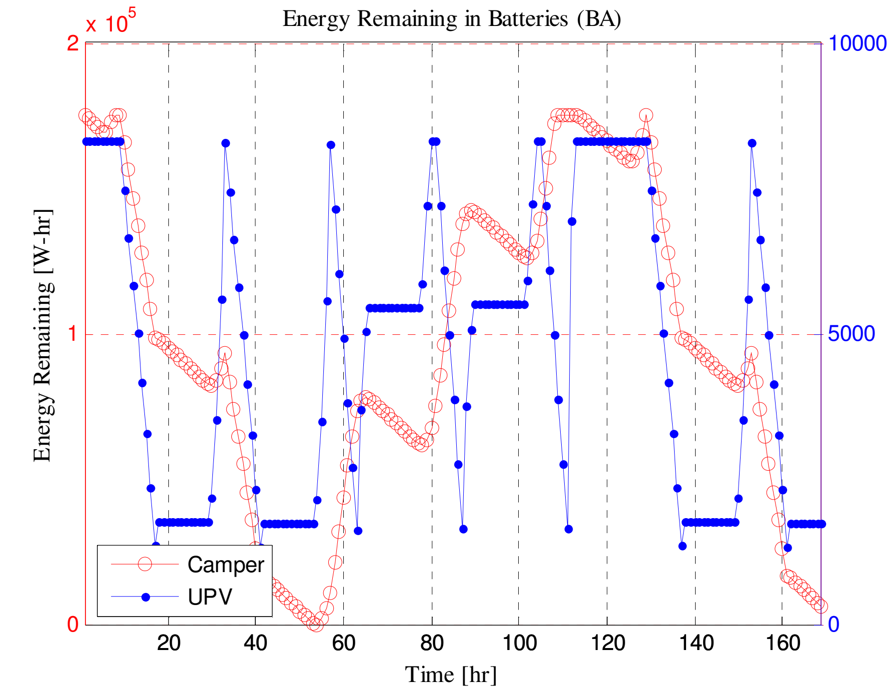

Figure 39. Energy Remaining in Batteries for Mars Sustainable Missions

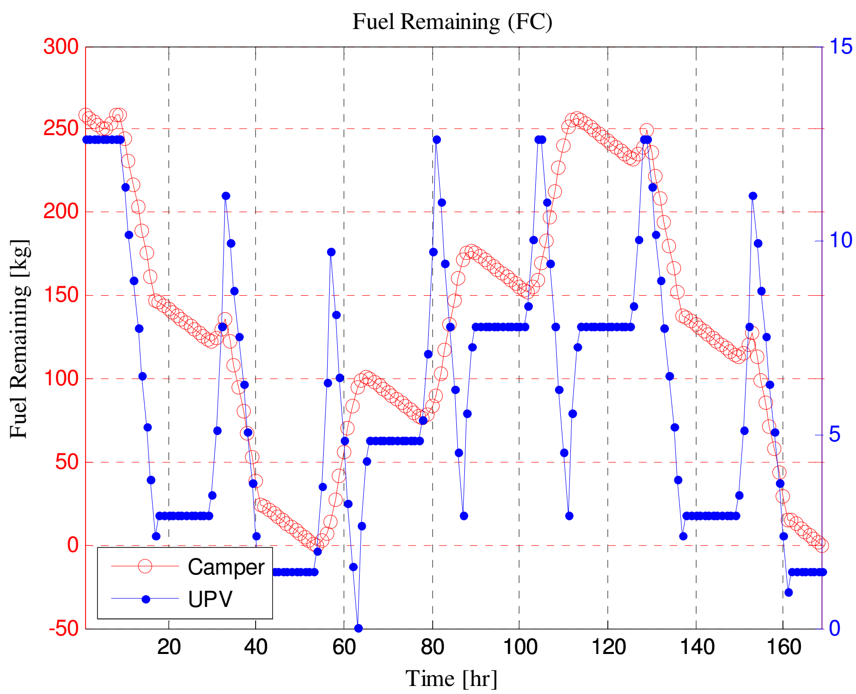

Figure 40. Fuel Remaining in Fuel Cells for Mars Sustainable Missions

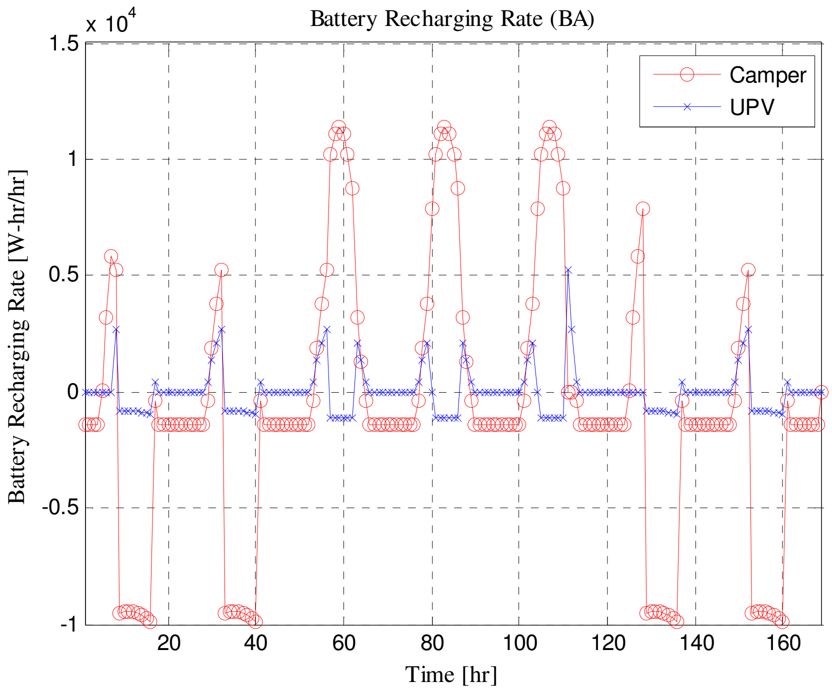

Figure 41. Battery Recharging Rates for Mars Sustainable Missions

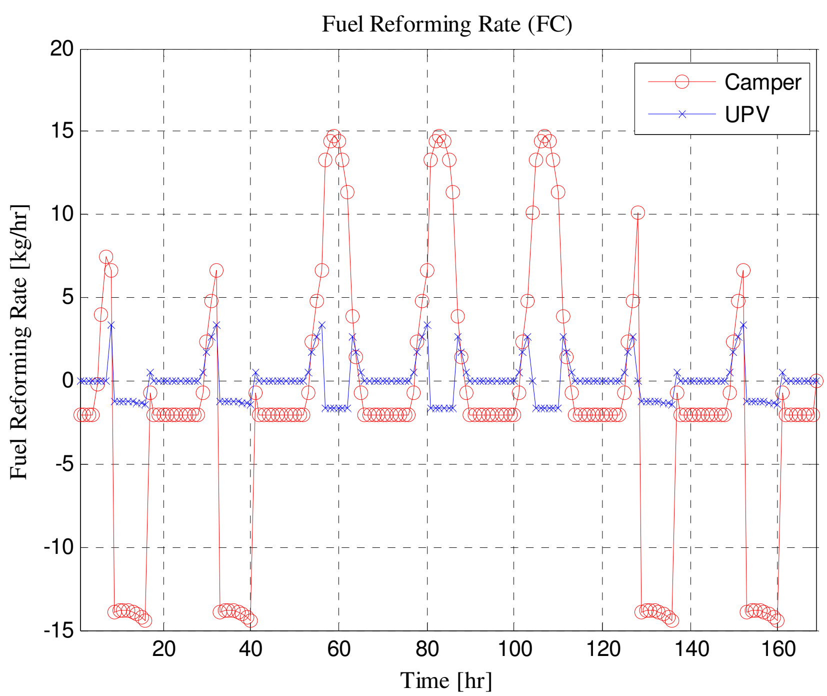

Figure 42. Fuel Reforming Rates for Mars Sustainable Missions

5.5 Conclusions

This chapter has illustrated the application of the model to the sample case studies on both the Moon and Mars. First, the environmental parameters of landing spots, the power requirement of each operational phase from TVM, and the sample mission scenario on the Moon and Mars were stated. Next, the power system specifications for lunar and Mars missions were computed with various power system options. With this information in hand, the best power system option was suggested for the lunar and Mars missions.

Table 28 summarizes the total wet masses of each power source option on the Moon. Based on this information, fuel cell hybrid systems are recommended with the assumption that the vehicles cannot generate energy during the 'Driving' phase. Obviously, fuel cell systems are much lighter than battery systems. Though battery systems are less complex systems, the mass difference is big. Therefore, fuel cell systems are recommended for the lunar mission. Between the single and hybrid source systems, hybrid source systems are more reasonable. Though a single power source for a lunar mission is a feasible option, the total mass of power systems is very heavy compared to the mass of hybrid power source systems. Therefore, using single power sources is not reasonable in terms of the total wet mass. It is evident that the system becomes heavier when photovoltaic systems cannot generate energy during the 'Driving' phase due to operation through shadowed regions. However, the mass difference is only 32 kg (171 – 139 kg). If 32 kg difference is acceptable, it is recommended to design power systems based on the assumption that fuel cell hybrid power systems cannot generate energy during the 'Driving' phase.

Table 28. Total Wet Mass Comparison for Lunar Missions

	Single Source	Hybrid Source	Hybrid Source without Recharging during the 'Driving' phase
Battery Hybrid Systems			
Battery Systems			
Battery Type	Li-Ion	Li-Ion	Li-Ion
Mass of Camper Battery	3509 (kg)	269 (kg)	458 (kg)
Mass of UPV Battery	395 (kg)	59 (kg)	79 (kg)
Volume of Camper Battery	1421 (m^3)	109 (m^3)	186 (m^3)
Volume of UPV Battery	160 (m^3)	24 (m^3)	32 (m^3)
Photovoltaic Systems			
Solar Panel Type	N/A	3J	3J
Mass of Photovoltaic Sys.	N/A	103 (kg)	88 (kg)
Panel Area	N/A	34 (m^2)	29 (m^2)
Fraction of solar power used to recharge a Camper battery	N/A	98 (%)	93 (%)
Total Mass	**3904** (kg)	**431** (kg)	**625** (kg)
Fuel Cell Hybrid Systems			
Fuel Cell Systems			
Fuel Cell Type	$NaBH_4$	$NaBH_4$	$NaBH_4$
Mass of Camper Stack	28 (kg)	28 (kg)	28 (kg)
Mass of Camper Fuel	553 (kg)	78 (kg)	109 (kg)
Mass of UPV Stack	4 (kg)	4 (kg)	4 (kg)
Mass of UPV Fuel	62 (kg)	1 (kg)	1 (kg)
Photovoltaic Systems			
Solar Panel Type	N/A	Si	Si
Mass of Photovoltaic Sys.	N/A	28 (kg)	28 (kg)
Panel Area	N/A	34 (m^2)	34 (m^2)
Fraction of solar power used to recharge Camper fuel	N/A	91 (%)	90 (%)
Total Mass	**647** (kg)	**139** (kg)	**171** (kg)

Table 29 summarizes the total wet masses of each power source option on Mars. Due to the higher gravity, the power requirement on Mars is higher than on the Moon. Moreover, the smaller solar flux makes the energy system heavier. Between battery and fuel cell systems, definitely fuel cell systems are a better option in terms of the total wet mass. Unlike on the Moon, single power source options are not much heavier than hybrid source options for short, unsustainable missions; the difference is 76 kg (871 – 795 kg). Therefore, if 76 kg difference is acceptable and sustainable missions are not required, single power source missions can be a good solution for Mars missions. The total mass of fuel cell hybrid systems for sustainable systems is almost same as the system for unsustainable missions. Therefore, the mass penalty is not big if sustainable missions on Mars are needed. If there is enough space to store extended solar panels and technology to deploy and fold solar panels, the sustainable configurations can be a good option for Mars missions.

Table 29. Total Wet Mass Comparison for Mars Missions

	Single Source	Hybrid Source, Unsustainable Mission	Hybrid Source, Sustainable Mission
Battery Hybrid Systems			
Battery Systems			
Battery Type	Li-Ion	Li-Ion	Li-Ion
Mass of Camper Battery	4695 (kg)	4073 (kg)	1625 (kg)
Mass of UPV Battery	514 (kg)	77 (kg)	77 (kg)
Volume of Camper Battery	1902 (m^3)	1650 (m^3)	658 (m^3)
Volume of UPV Battery	208 (m^3)	31 (m^3)	31 (m^3)
Photovoltaic Systems			
Solar Panel Type	N/A	3J	3J
Mass of Photovoltaic Sys.	N/A	103 (kg)	546 (kg)
Panel Area	N/A	34 (m^2)	183 (m^2)
Fraction of solar power used to recharge a Camper battery	N/A	13 (%)	71 (%)
Total Mass	**5209** (kg)	**4253** (kg)	**2249** (kg)
Fuel Cell Hybrid Systems			
Fuel Cell Systems			
Fuel Cell Type	$NaBH_4$	$NaBH_4$	$NaBH_4$
Mass of Camper Stack	46 (kg)	46 (kg)	46 (kg)
Mass of Camper Fuel	739 (kg)	639 (kg)	258 (kg)
Mass of UPV Stack	5 (kg)	5 (kg)	5 (kg)
Mass of UPV Fuel	81 (kg)	2 (kg)	2 (kg)
Photovoltaic Systems			
Solar Panel Type	N/A	3J	3J
Mass of Photovoltaic Sys.	N/A	103 (kg)	490 (kg)
Panel Area	N/A	34 (m^2)	164 (m^2)
Fraction of solar power used to recharge Camper fuel	N/A	15 (%)	72 (%)
Total Mass	**871** (kg)	**795** (kg)	**801** (kg)

Chapter 6

Conclusions and Recommendations

6.1 Thesis Summary

This thesis developed a model for comparing several power system options for planetary surface mobility systems. The target mobility systems were suggested by the architecture analysis from the MIT Spring 2006 16.89/ESD 352 Space System Engineering class – the Camper/UPV system. The state-of-art technology of energy storage systems and photovoltaic power systems was applied for estimating the specific power density and energy density. In order to estimate the power system mass which meets the energy requirement of a given mission scenario, the sequential quadratic programming method was applied to the model.

With the model developed in Chapter 4, the 7-day sample mission was analyzed for the lunar and Mars missions. For the lunar mission, the single power source configuration and hybrid power source configurations were analyzed. In addition, the case where the power system cannot generate energy during the 'Driving' phase was considered. For the Mars mission, the single power source configuration was analyzed. For the hybrid power source configurations, the power system configurations for unsustainable and sustainable missions were considered.

From the case study analysis, fuel cell hybrid systems were recommended for the lunar mission. Even if the system cannot generate energy during the 'Driving' phase, fuel cell hybrid systems were a reasonable option. For the Mars mission, the fuel cell single power source can be applied to the short, unsustainable mission though its mass was slightly heavier than the hybrid fuel cell systems. In addition, for the sustainable mission on Mars, the hybrid fuel cell system was required.

6.2 Future Work

Specific recommendations to further develop and extend this work include:

- Extension of target mobility systems from the Camper/UPV systems to other types of surface mobility platforms, such as unmanned vehicles, pressurized rovers, and unmanned aerial vehicles
- Extension of power source options from photovoltaic, battery, and fuel cell options to other types of power source options, such as internal combustion engines, dynamic isotope propulsion systems, and solar dynamic systems
- Investigation of other sample mission scenarios for the operation on other Mars sites – the solar flux variation of Mars with latitudes and seasons
- Incorporation of the Terrain Vehicle Model to estimate the total mass of entire surface mobility systems
- Incorporation of fuel supplement model from the main base, Earth, or supply depots in orbit

Appendix A

User Guide for Power System Selection Model

This appendix presents the user guide for the power system selection model which was described in Chapter 4 and used in Chapter 5. Users can use the program attached in this thesis to evaluate their own mission scenarios. When users execute the main file, 'pss.m,' users can see the main Graphical User Interface.

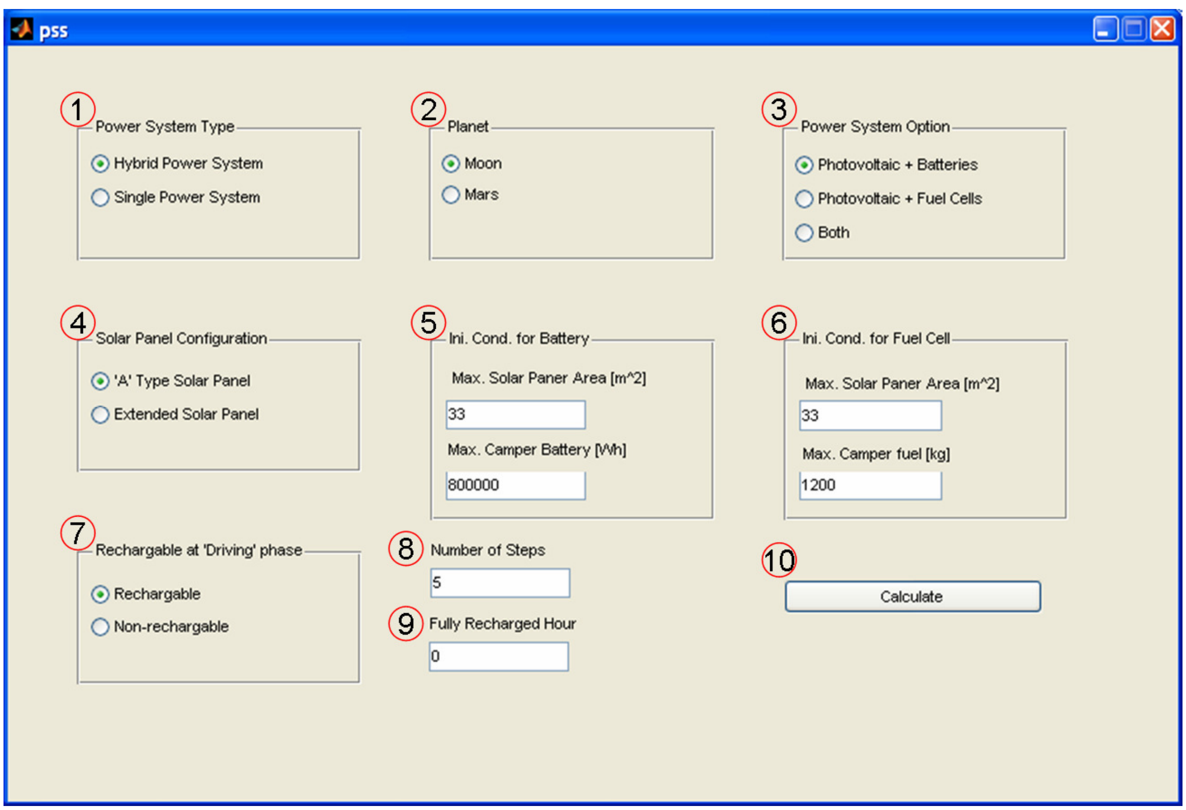

Figure 43. GUI of Power System Selection Program

① Power System Type

- Hybrid Power System: The program computes the power system configuration for hybrid power source systems. Users can choose battery/photovoltaic systems, fuel cell/photovoltaic systems, or both in Power System Option (see ③)
- Single Power System: The program computes the power system configuration for single power source systems. The program shows the result of both battery and fuel cell systems.

② Planet

- Moon: The program computes the power system configuration for a lunar mission.
- Mars: The program computes the power system configuration for a Mars mission

③ Power System Option

- Photovoltaic + Batteries: The program computes the photovoltaic/battery system configuration.
- Photovoltaic + Fuel Cell: The program computes the photovoltaic/fuel cell system configuration
- Both: The program computes both power options: photovoltaic/battery systems and photovoltaic/fuel cell systems.

④ Solar Panel Configuration

- 'A' Type Solar Panel: The program adds the area limit constraint.
- Extended Solar Panel: The program removes the area limit constraint.

⑤ Initial Condition for Battery Systems

- Max. Solar Panel Area: Set maximum range of initial conditions corresponding to the solar panel area (x_1) for battery systems.
- Max. Camper Battery: Set maximum range of initial conditions corresponding to the Camper battery capacity (x_2) for battery systems.

⑥ Initial Condition for Fuel Cell Systems

- Max. Solar Panel Area: Set maximum range of initial conditions corresponding to the solar panel area (x_1) for fuel cell systems.

- Max. Camper Fuel: Set maximum range of initial conditions corresponding to the Camper fuel mass (x_2) for fuel systems.

⑦ Rechargeable during the ‘Driving’ phase
- Rechargeable: The vehicles can generate solar energy during the ‘Driving’ phase.
- Non-Rechargeable: The vehicles cannot generate solar energy during the ‘Driving’ phase.

⑧ Number of Steps: Set the number of steps for dividing initial start points in order to optimize the power system with multiple initial start points.

⑨ Fully Recharged Hour: The mission hour when the energy storage system on the Camper should be fully recharged.

⑩ Calculate: Execute the program.

References

[1] Griffin, B., Thrasher, D., and Wallce, B., "A Pressurized Rover for Early Lunar Exploration," *Space Program and Technologies Conference*, AIAA-1992-1488, AIAA, Huntsville, AL, 1992.

[2] Creel, K., Frampton, J., Honaker, D., McClure, K., and Zeinali, M., "Pressurized Lunar Rover," NASA CR-192034, 1992.

[3] Bhardwaj, M., Bulsara, V., Kokan, D., Shariff, S., Svarverud, E., and Wirz, R., "Design of a Pressurized Lunar Rover," NASA CR-192033, 1992.

[4] Collins, C., Gomez, A., Muniz, R., Musson, D., and Fowler, W. T., "Conceptual Design of a Mars Surface Transportation System (MSTS)," *Annual HEDS-UP Forum Forum, 2nd, Proceedings*, 1999, pp. 201-225.

[5] Hoffman, S. J. and Kaplan, D. I., "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team," NASA SP-6107, 1997.

[6] Zakrajsek, J. J., McKissock, D. B., Woytach, J. M., Zakrajsek, J. F., Oswald, F. B., McEntire, K. J., Hill, G. M., Abel, P., Eichenberg, D. J., and Goodnight, T. W., "Exploration Rover Concepts and Development Challenges," *1st Space Exploration Conference: Continuing the Voyage of Discovery*, AIAA-2005-2525, AIAA, Orlando, FL, Jan. 30-1 2005.

[7] Arno, R., "Planetary Surface Vehicles," *Human Spaceflight Mission Analysis and Design*, edited by Larson, W. J. and Pranke, L. K., Space Technology Series, 2000, Chap. 14.

[8] Project, A. S., "NASA Concept Evaluation and Refinement Study," Massachusetts Institute of Technology, Cambridge, MA, 2005.

[9] Bairstow, B., Baldesarra, M., Coffee, T., Fong, A., Hofstetter, W., Hong, S., Judnick, D., McCloskey, S., Mellein, J., and Underwood, J., "Extensible Planetary Surface Mobility Systems," Massachusetts Institute of Technology, Cambridge, MA, May 2006.

[10] MATLAB, Ver. 7.1.0.246 (R14) Service Pack 3, The MathWorks, Inc., 2005.

[11] Siddiqi, A. and Hong, S., Planetary Surface Vehicle, Massachsetts Institute of Technology, 2005.

[12] Landau, D. F. and Longuski, J. M., "Trajectories for Human Mission to Mars, Part 1: Impulsive Transfers," *Journal of Spacecraft and Rockets*, Vol. 45, No. 5, Sep.-Oct. 2006, pp. 1035-1042.

[13] Underwood, J. and Baldesarra, M., "Operations Simulation Framework to Evaluate Vehicle Designs for Planetary Surface Exploration," *AIAA Space 2007*, AIAA, Long Beach, CA, Sep. 18-20 2007.

[14] Landis, G. A., McKissock, B. I., and Bailey, S. G., "Designing Power Systems," *Human Spaceflight Mission Analysis and Design*, edited by Larson, W. J. and Pranke, L. K., Space Technology Series, 2000, Chap. 20.

[15] Nelson, J., *The Physics of Solar Cells*, Imperial College Press, London, UK, 2003, p. 20.

[16] Fatemi, N. S., Pollard, H. E., Hou, H. Q., and Sharps, P. R., "Solar Array Trades between Very High-Efficiency Multi-Junction and Si Space Solar Cells," *28th IEEE Photovoltaic Specialists Conference*, 7027956, Anchorage, AK, Sep. 17-22 2000.

[17] Luo, N., Miley, G. H., Shrestha, P. J., Gimlin, R., Burton, R., Rusek, J., and Holcomb, F., "H_2O_2-Based Fuel Cells for Space Power Systems," *3rd International Energy Conversion Engineering Conference*, AIAA-2005-5755, AIAA, San Francisco, CA, Aug. 15-18 2005.

[18] Wang, C. Y., "Two-Phase Flow and Transport," *Handbook of Fuel Cells - Fundaentals, Technology, and Applications*, edited by Vielstich, W., Lamm, A., and Gasteiger, H., 2003, pp. 337-347.

[19] Surampudi, R., Bugga, R., Smart, M. C., Narayanan, S. R., Frank, H. A., and Halpert, G., "Overview of Energy Storage Technologies for Space Applications," Jet Propulsion Laboratory, NASA, Pasadena, CA, 2006.

[20] Yardney, URL: http://www.yardney.com/lithion/index.html [cited July 10 2007].

[21] Tribble, A. C., "The Space Environment - Hazards and Effects," *Human Spaceflight Mission Analysis and Design*, edited by Larson, W. J. and Pranke, L. K., Space Technology Series, 2000, Chap. 3.

[22] Appelbaum, J. and Landis, G. A., "Solar Radiation on Mars - Update 1991," NASA TM 105216, 1991.

[23] Mendell, W., Plescia, J., and Tribble, A. C., "Surface Environments," *Human Spaceflight Mission Analysis and Design*, edited by Larson, W. J. and Pranke, L. K., Space Technology Series, 2000, Chap. 4.