Midterm Report

Renewable Energy for Mars Habitat

by

DSE Group 23

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June 3, 2020

TU Delft

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Nomenclature

List of Abbreviations

AWE	Airborne Wind Energy
CAES	Compressed Air Energy Storage
CPV	Concentrator Photovoltaics
EDL	Entry, Descent, and Landing
EZ	Exploration Zone
FTA	Fault Tree Analysis
GPS	Global Positioning System
GS	Ground Station
HMPE	High-Modulus Polyethylene
HW	Hardware
IMU	Inertial Measurement Unit
ISM	In-Space Manufacturing
ISRU	In-Situ Resource Utilisation
KCU	Kite Control Unit
LEI	Leading Edge Inflatable
MBL	Maximum Breaking Load
MCU	Microcontroller Unit
MOLA	Mars Orbiter Laser Altimeter
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OSAM	On-Orbit Servicing, Assembly, and Manufacturing
PDF	Probability Density Function
PV	Photovoltaic
RAMS	Reliability, Availability, Maintainability, and Safety
RBD	Reliability Block Diagram
RFC	Regenerative Fuel Cells
SSL	Safe Service Life
SW	Software
SWL	Safe Working Life
VAWT	Vertical Axis Wind Turbine

List of Symbols

δ	Yearly power degradation [%]
η	Efficiency [-]
γ	Reel velocity coefficient [-]
ρ	Atmospheric density [kg m^{-3}]
ρ_A	Area density [kg m^{-2}]
ρ_l	Linear density [kg m^{-3}]
σ	Stress [Pa]
θ	Kite elevation angle [°]
A	Area [m^2]
C_D	Drag coefficient [-]
C_L	Lift coefficient [-]
d	Diameter [m]
F	Force coefficient [-]
f_c	Normalised force coefficient [-]
g	Gravitational acceleration [m s^{-2}]
g_W	Weibull probability density [-]
I_d	Inherent degradation factor [-]
k	Weibull shape parameter [-]
l	Length [m]
L_s	Solar longitude [$\circ$]
L_d	Life degradation [-]
m	Mass [kg]
P_{sa}	Solar array power output [W]
q	Dynamic pressure [Pa]
S_{in}	Solar irradiance [W m^{-2}]
T	Tether force [N]
t	Time [s]
v	Velocity [m s^{-1}]
W	Weight [N]
x	Solar panel service years [y]

Executive Overview

The Challenge

Interest in the colonisation of Mars has seen a substantial increase in recent years. The main driver behind this is that the space industry is increasingly democratised. Humans have yet to set foot on the Red Planet, but following the technological and investment trends, this might only be a matter of time. Although the interplanetary travel from Earth to Mars is a quite lengthy and costly, the planet still shows great potential for harbouring life. Evidence has shown that the presence of (re)usable resources on Mars could pave the way to enable continuous human presence on an interplanetary scale. Energy is essential for life and its availability will be the key indicator of our success as a species in the colonisation of Mars.

The Solution

The objective is to design a renewable energy system to power the construction and operation of a Mars habitat that can support the livability of humans. The system will consist of a microgrid integrating complementary renewable energy sources *sustainably* harvested from the local Martian environment and resources.

Mission Need Statement: To provide continuous renewable energy supply of 10 kW to a Mars habitat.
Project Objective Statement: Design a renewable energy supply system, primarily focusing on wind energy, which continuously provides 10 kW to a Mars habitat, by 10 students in 10 weeks.

This Design synthesis exercise (DSE) is spearheaded by a team of students and staff from the Aerospace Engineering faculty at the Delft University of Technology in the Netherlands. The DSE will last a total of 10 weeks, beginning on the 20th of April, ending on the 3rd of July, where a final review is awaited during a poster session and symposium.

The DSE is in collaboration with a separate team of Architecture students working on a rhizomatic Mars habitat project for an ESA-ESTEC feasibility study proposal, also part of an ESA competition. This implies that the work and technical insight of the DSE team plays an important role in a multi-disciplinary mission proposal. This lays the foundation for the motivation to produce a complete and verified design as the outcome.

Project Plan

The project plan included in this report is a summarised version of what has been previously reported on in the Project Plan Report. The included items in this report span the work breakdown structure, the work flow diagram and the gantt chart. The organogram has also been included which documents the roles each individual team member is responsible for.

Design Options

Before the trade-offs, a group of design options were taken into consideration based on mission requirements and feasibility. The main items to be traded off are listed below.

Primary Energy System

- Airborne Wind Energy (AWE) system
- Vertical Axis Wind Turbine (VAWT): Buoyant spherically shaped type

Secondary Energy System

- Geothermal energy
- Solar energy

Power Management

- AC Microgrid
- DC Microgrid
- Underground cable infrastructure
- On-ground cable infrastructure
- Overhead cable infrastructure

Storage

- Compressed Air Energy Storage (CAES)
- Gravitational Storage
- Secondary Batteries
- Regenerative Fuel Cells (RFC)
- Latent Heat
- Super Capacitors

Trade-offs

For the trade-offs, the design options of all subsystems were compared following the same systematic approach. They were examined on the following categories: development cost, development risk, mass performance, volume performance, system installation, system operations, maintenance and repairs, system retirement and sustainability. After the trade-off of the first design options, specific trade-offs for the subsystems have been performed, which will be briefly discussed.

For the primary energy unit, the AWE system outperformed the VAWT buoyant type in the trade-off. For the AWE system, a trade-off was done on the power generation principle, the type of wing and the tether. Rigid wing concepts were discarded, followed by the drag-type power generation principle, based on a Mars-specific flight conditions analysis. For the wing type, a tensairity kite was chosen for its aerodynamic performance at low weight and volume. A braided HMPE DM20 tether was further chosen, due to its high strength to weight ratio as well as its creep resistance.

To determine the technology for the secondary energy system, an initial trade-off was performed between geothermal energy generation and solar power. From this it followed that the solar energy unit was best suited for the mission and was therefore chosen as the secondary energy system. From there, trade-offs were performed to determine system aspects for the solar array, choosing a two axis system to increase performance utilising sun simulation to follow the sun. Furthermore, the hydrophobic coating won as the method for preventing dust adhesion due to its passive, low mass functionality. Lastly the cell technology was determined to be thin film, multi-junction, III-V technology on a planer module, due to its high performance efficiency and its property to be customisable to fit a solar spectrum.

With regard to the power management and distribution system, a trade-off between an AC- and DC microgrid was done. The choice for DC was made, mainly because this grid type requires less power converters, which is favourable in terms of mass, volume and efficiency. For the distribution of the power, a proper cable infrastructure is required. Considering the relevance of reliability and safety, the underground cable infrastructure was chosen.

Finally, for the energy storage system a distinction had to be made between seasonal and day-to-day storage. For the seasonal storage gravitational storage and CAES were initially considered. However, due to its extremely low energy density, gravitational was disregarded before the trade-off. Then for day-to-day storage, the CAES was considered together with secondary batteries and regenerative fuel cells, where secondary batteries won the trade-off.

The final design for each subsystem is consolidated below.

- **Primary Energy System**: A pumping kite power system utilising a tensairity kite and a HMPE DM20 braided tether.
- **Secondary Energy System**: Solar Panels with a 2-axis, multi-junction cells, III-V semiconductor materials, planar module and hydrophobic coating system.
- **Power Management**: DC Microgrid with underground distribution cables.
- **Storage System**: Compressed-air energy storage with secondary batteries.

Site Selection and Energy Resources

The DSE team has investigated seven sites from the NASA site selection workshop and the one considered for the Starship mission of SpaceX. In the initial stage, three clearly unfeasible sites were eliminated after which the remaining four were evaluated on several criteria. The two most important groups of criteria were the availability of water and presence of wind. Based on these Deuteronilus Mensae, one of the SpaceX sites was chosen.

At this site, the Weibull distribution of wind per season has been established based on the Viking 2 measurement, which were modified with the mean velocities observed from the Martian General Circulation Model. Furthermore, in order to evaluate the available solar energy, first the change in solar irradiance was calculated, which is the result of the eccentricity of the Martian orbit. Changing incidence angle was not taken into account as the solar panel can be rotated to face the Sun. Another important parameter is optical depth, which is the opacity of the Martian atmosphere and is greatly influenced by the concentration of dust particle. Thus, during dust storms for example, solar irradiance is immensely reduced. Considering all of these aspects, a year-long prediction was made for solar irradiance.

Preliminary Design and Analysis

After trade-off and investigation in the site selection and energy resources, a preliminary system design is made. This is done based on a system performance analysis, estimating the required power generation per month for the wind and solar energy system. In table 1 the nominal generated power per month for the wind

(W) and solar (S) system are showed, supplemented by the power mix values for that season. This results in a total yearly power supply and generation from which 52% is wind and 48% is solar energy. Based on these values, a preliminary design for the renewable energy system on Mars is made.

Table 1: Monthly generated nominal power for wind (W) and solar (S) and seasonal supplied energy mix to the habitat

		Generated Nominal Power [kW]	Supplied Energy			
			Wind	Solar	Battery	CAES
L_s=0°	1 2 3	W:15.7 W:10.0 S:15.7	0.24	0.17	0.17	0.42
L_s=90°	4 5 6	S:41.9 S:49.9 S:31.8	0	0.50	0.50	0
L_s=180°	7 8 9	S:10.0 W:10.0 W:15.7	0.24	0.17	0.08	0.50
L_s=270°	10 11 12	W:46.4 W:54.6 W:42.7	0.50	0	0.50	0
Yearly			0.24	0.22	0.31	0.48

Table 2: AWE Preliminary System Parameters

Parameter	Parameter symbol	Value	Unit
Kite area	A	900	[m^2]
Kite lift coefficient	C_L	0.6	[-]
Kite drag coefficient	C_D	0.06	[-]
Kite area density	ρ_A	0.1	[kg m^{-2}]
Cut-in speed	$v_{cut_{in}}$	5	[m s^{-1}]
Cut-out speed	$v_{cut_{out}}$	25	[m s^{-1}]
Kite mass	m_{kite}	90	[kg]
Tether length	l	400	[m]
Tether mass per 100 m	m_t	19.7	[kg 100 m^{-1}]
Tether mass	m_{tether}	78.9	[kg]
Tether diameter	d	1.65	[cm]
Tether SSL creep	SSL	29	[yrs]
Ground Station (GS) mass	m_{gs}	100	[kg]
GS conversion efficiency	η_{gs}	0.8	[-]

In sizing the energy supply systems, it is crucial to first account for transmission and power conversion efficiencies resulting from the power management and distribution system. The relevant components that are needed to integrate the various energy resources and storage solutions into the microgrid were researched, and their efficiencies were determined. These were then used in the preliminary design of the primary and secondary energy systems.

Secondly, for the preliminary sizing of the kite, the physical AWE system model from Luchsinger was implemented in code. This was complemented by the tether sizing model from Bosman et al. Based on the parameters provided in table 2, a preliminary primary energy system was made. This results in a primary energy system providing 52% of the annual energy capacity, with a mass of 268.9 kg.

Next, for the secondary energy unit a preliminary estimation was made to determine the approximate area required for the solar array to generate the required peak nominal power. This was done while considering the grid and storage efficiencies using the aforementioned performance analysis data and PV cell degradation. From this it followed, to have 49.9 kW available for the habitat, 57.1 kW would have to be generated. This is due to the losses during energy transfer. From this power requirement a surface area of 934.8 m^2 could be determined.

Lastly, a literature study for the CAES approximated the compressive, expansion and storage efficiencies to be 0.7, 0.6 and 0.95 respectively. This lead to a preliminary estimation of the CAES volume; 10^2m^3. A similar approach was used to determine a mass estimation for the secondary battery. Again, from literature the performance of a promising Lithium-ion battery with efficiency of 0.88 was examined using the longest night duration, which lead to a mass approximation of 10^3 kg.

Operations and Logistics

To summarise the system operations and logistics of the mission, it is most straightforward to include the diagram in figure 1. It shows the steps of the mission in its larger scope from the launch of the first robotics and equipment to the operation of the habitat with people living in it. A few items to remark about the mission, are that the habitat and energy system will be up and running when the astronauts arrive at the base. This means that the construction period will need to be automated. Additionally, the maintenance part of the mission will be supported by a servicing module and a Mars Ascent Vehicle. Naturally this mission configuration is not yet set and is still subject to change if necessary in the final design.

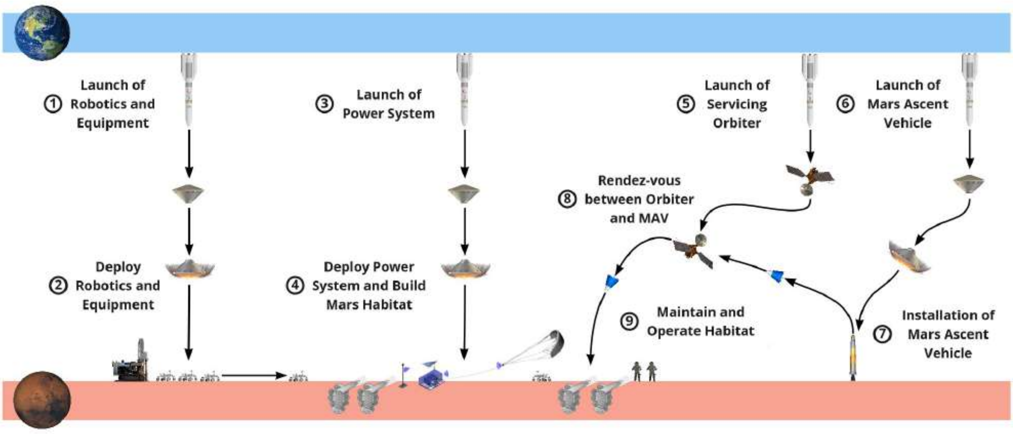

Figure 1: Simplified schematic of the mission configuration

Risk assessment, Reliability and Availability

At this stage of the process, the failure modes of each subsystem described above are examined as well as the risks associated with site selection. The analysis of the wind energy system was the most detailed, as this is the primary source of power. Two mitigation measure were distinguished: *mitigate* to reduce the impact and *research* to reduce the likelihood of the risk happening. The five highest risks are: **SS-03:** Low mean wind speed, **WE-01:** Tether(s) brake, **WE-15:** Left motor HW failure, **WE-16:** Right motor HW failure, and **SO-07:** Glass breakage.

Furthermore, on Mars accurate wind measurement are only available at rover locations, which are not abundant. Global wind maps are only available from the General Circulation Model, which are rather qualitative than quantitative. This implies that there is a high risk associated with encountering a lower mean wind speed (**SS-03**) than anticipated. Moreover, the risk associated with **WE-01**, **WE-15** and **WE-16** are twofold. On one hand, any of these components failing would lead to not being able to steer the kite, thus not being able to generate electricity, which would be detrimental to the habitat. On the other hand, the kite being unsteerable can also pose risk on the safety of personnel as it can even lead to death.

In such a hazardous environment, solar panels being exposed to UV and other types of radiation can make the panel prone to glass breakage (**SO-07**). This crack would open the panel and make it possible for dust to enter. This would mean the failure of the whole panel, this thus has to be avoided.

Reliability is the measure of non-repairable parts. It is modelled by an exponential function and the main indicator is the Mean Time To Failure, which is to be maximised. One of the methods to conduct the analysis is a Reliability Block Diagram, which consists of functional blocks of each part. These are connected in either parallel or series. The reliability of the system can be calculated from the reliability of the individual parts. Furthermore, the main focus of availability is on repairable parts; it is defined as the quotient of the downtime and the total time a part is used. This is also aimed to be maximised.

Verification and Validation

The verification and validation is described in three disparate parts:

- Preliminary AWE model: To perform a preliminary sizing of the AWE system (weights and dimensions), a physical model was implemented, which was verified. The methodology included using (aerodynamic) parameters from previous research, sensitivity analysis, syntax errors tests, and system tests.
- Future design activities: The detailed design and sizing of other subsystems need to be verified in their own right as well as an integrated system design. Several key unit, integration and system tests are described below to prepare for the next phase of design.
  - Unit test 1: Martian conditions - to verify the parameters of Martian conditions including resource availability.
  - Unit test 2: Battery sizing: To validate the reliability of secondary battery's manufacturing source specifications.
  - Unit test 3: Solar radiation model: To validate solar resource availability
  - Integration test 1: Computer calibration to verify proper communication of units, dimensions, vectors between disparate models, as well as implementation and sensitivity checks.
  - System test 1: Wind energy: to verify the wind simulation model for Martian conditions.
  - System test 2: Solar energy: to verify sizing of secondary energy in meeting requirements.
  - System test 3: Microgrid design: to validate the microgrid acts as a functional closed circuit.
- Final Product: The four key validation methods are described below. These methods are planned to be applied for the validation of assembly and the final product, as well as during the mission operations of the system.
  - Test: performed in dedicated test facilities, such as the wind tunnel and/or Spectrolab.
  - Analysis: using well-validated models to predict the performance of the design.
  - Inspection: physical visual examination of a realised component or end product.
  - Demonstration: to establish compliance of the product with its requirements by operation of the product.

Sustainability

During the design trade-off process, sustainability aspects are taken into account. The sustainability of the subsystem design is scored on three fronts: production, life-time and retirement of the system. After the preliminary design concept, an overview of the material discovery is presented and the potential waste production is estimated. As part of the next design phase, the Final Report will produce a more detailed material and resource breakdown for each subsystem. In addition, documentation of the processes that each subsystem goes through during production phase will also be produced. This to ensure minimal production inefficiencies and material wastage, and is an integral part of the sustainability development strategy of the DSE.

1 Introduction

Throughout history, one of the main catalysts for human progress has been the ambition to seek and explore new frontiers. Since the beginning of the space age in the second half of the twentieth century, Mars has been a centre of attraction for human exploration for several reasons: the first, and perhaps the most obvious reason, is that it is a planet close by in the Solar System where the current state-of-the-art technology for space exploration can be launched and operated. Humanity's desire to know and understand the Red Planet has prompted enormous efforts to study its history and characteristics. The scientific evidence has shown that Mars shares many similarities with Earth, which has led to the question whether life could have ever existed on Mars. Moreover, the discovery of the presence of water in the Martian surface gave rise to a whole new set of reasons to support the premise that Mars could be a suitable place for harbouring life.

However, many challenges must be overcome first in order to be able to accommodate a sustained human presence on the Martian surface. One of the most limiting factors in the definition of any space mission is the availability of energy to ensure a correct operation of the payload. Additional to this, the hostility of the Martian environment, the lack of in-depth knowledge of the available resources, as well as the high transportation and operation costs result in additional layers of complexity. Furthermore, the expected level of complexity for a mission to colonise Mars implies a need for a high level of automation and Earth-independence to ensure a smooth, affordable, and nominal operation. Although some efforts have been made to overcome some of these challenges, only a limited amount of progress has been made to alleviate the constraints resulting from the lack of available energy resources. A key enabling factor to close the gap between concept and reality will strongly depend on the optimal utilisation of the local resources to generate sustainable energy to power humanity's plan for the Red Planet.

The objective of DSE team 23 is to design a renewable energy system to power the construction and operation of a rhizomatic Mars habitat as developed in the ESA-ESTEC feasibility study proposal led by an external team of Architecture students. Furthermore, this report will delve into the potential of different types of renewable energy generation based on the available resources on Mars, with special focus put on the plausibility of wind energy generation. The objective of this report in particular is to finalise a design concept selection, as well as to describe the preliminary design of the system in its first iteration.

To do this, the report is divided in several chapters that outline the methodology, analysis, and results of the design synthesis so far: chapter 2 outlines the project objectives and planning as specified in the project plan and baseline report of DSE team 23. Next, the design options and trade-off methodology is described in chapter 3, which is used in chapters 4-6 to finalise a design selection. Chapter 7 then describes the selection of the landing site on Mars in which the mission will be developed. Based on this, the preliminary design and analysis is developed and documented in chapter 8. Next, a general outline of the mission operations and logistics is introduced in chapter 9. The risk assessment, verification and validation, and sustainability approach are then introduced in chapters 10, 11 and 12 respectively. Finally, the conclusions and recommendations for the final stage of the design synthesis are included in chapter 13.

2
Project Objectives and Planning

This chapter summarises the project objectives and some important project planning aspects. First the project objectives are discussed in section 2.1. Following this, the project planning is discussed in section 2.2 which contains the work breakdown structure and flow diagram (2.2.1), the Gantt chart (2.2.2), and finally the organogram (2.2.3).

2.1. Project Objectives

For the project, the following Mission Needs Statement and Project Objective Statement are determined:

Mission Need Statement
To provide continuous renewable energy supply of 10 kW to a Mars habitat.

Project Objective Statement
Design a renewable energy supply system, primarily focusing on wind energy, which continuously provides 10 kW to a Mars habitat, by 10 students in 10 weeks.

The DSE team 23 has been tasked with designing a renewable energy system for a Mars habit. This project is performed in collaboration with a group of architecture students and staff who have designed the underground Mars habitat structure. Together with this group, the DSE team will suggest a selection of suitable sites on Mars to be able to set up the habitat. The renewable energy system is required to provide a continuous 10 kW of energy and about 50% of the annual energy production should be sourced from wind energy. Along with the primary energy source, a secondary energy source will be considered to be either solar or geothermal energy to provide power when wind energy is not available.

2.2. Project Planning

Now that the project objectives have been discussed, the project planning is summarised below:

2.2.1. Work Breakdown Structure and Flow Diagram

The work breakdown structure and flow diagram are presented in figures 2.1 and 2.2.2 respectively. The two diagrams are directly related as the numbers of tasks confer with each other. The work breakdown structure details all of the tasks and sub-tasks that need to be done per topic. Not all tasks are always necessary for the same report even when they are listed in the same section. The tasks from the work breakdown structure can be found again in the work flow diagram. Here they are chronologically ordered such that the tasks are done at the right moment in time. Many tasks can be completed in parallel, however there is a critical path which needs to be followed to make the final design possible.

2.2.2. Gantt Chart

The Gantt chart is a living planning document in which all the team's tasks are summarised on a timeline. The length and dates of many activities have been changed since the chart was first made, and many more tasks have been assigned to team members as the group progressed. The online software used to create the Gantt chart (Wrike) accommodates for the regular changes, as every team member has access to the site and can also view their personalised to-do list. The collapsed Gantt chart is visible in figure 2.2.2.

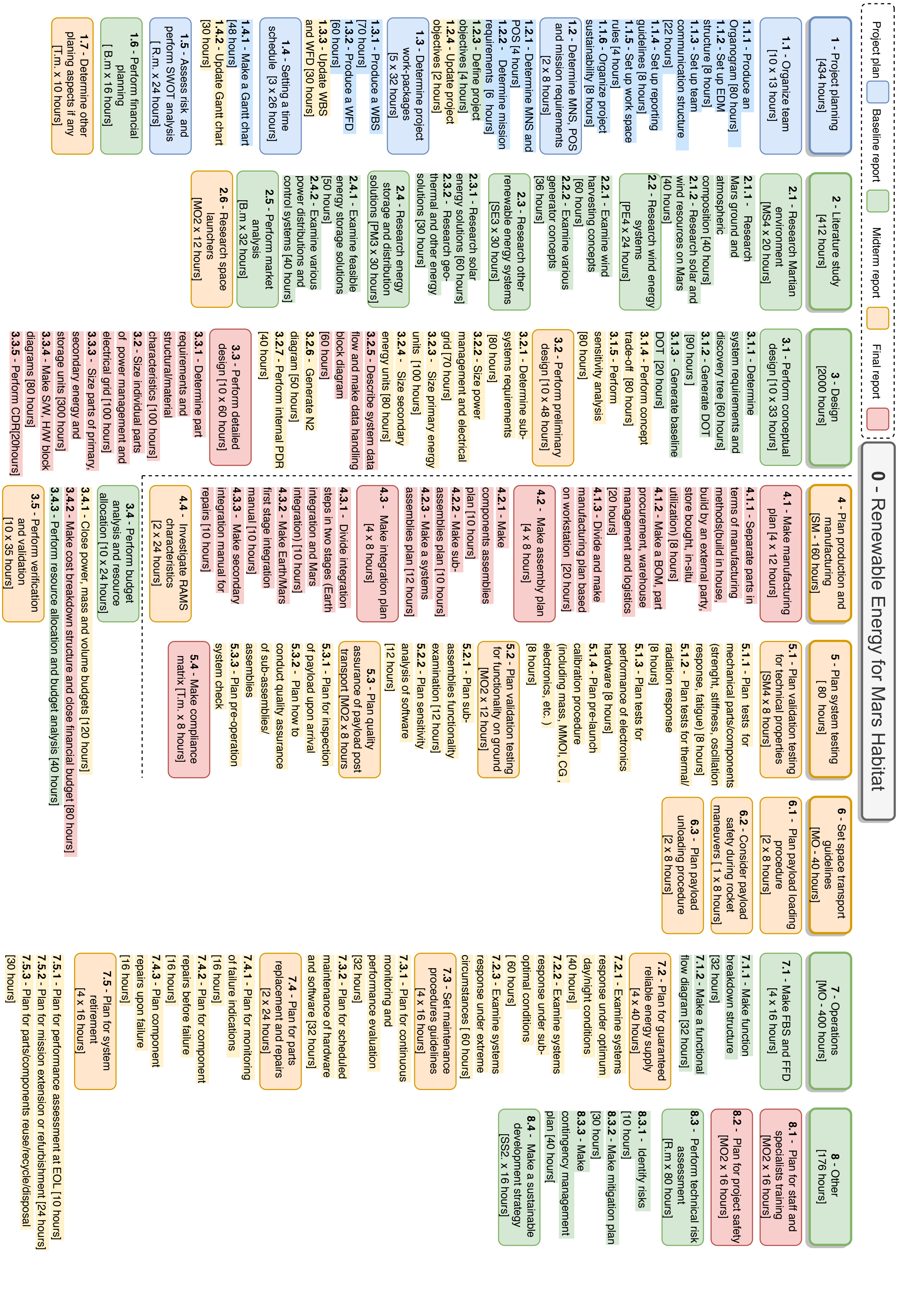

Figure 2.1: Work Breakdown Structure

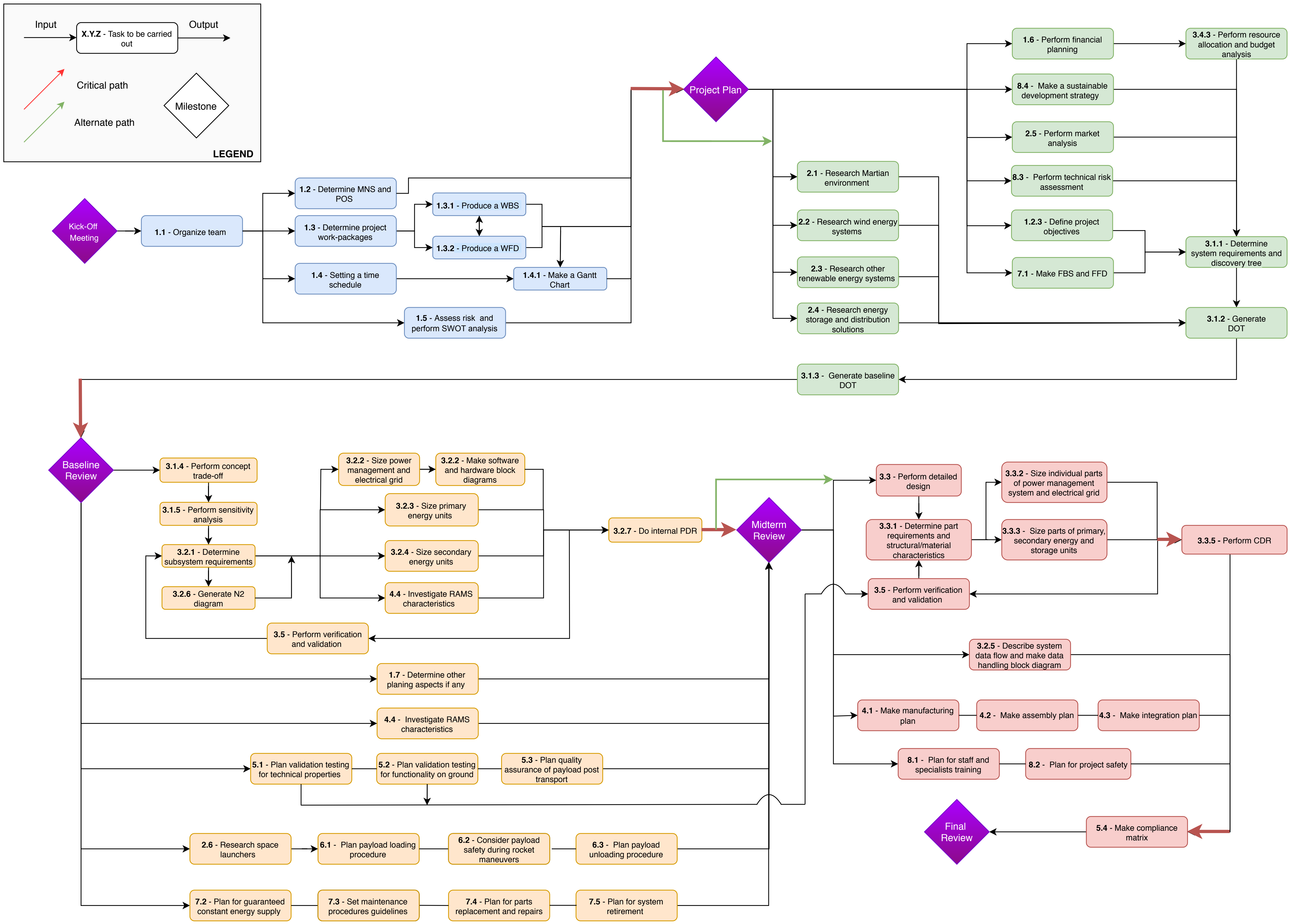

Figure 2.2: Work Flow Diagram.

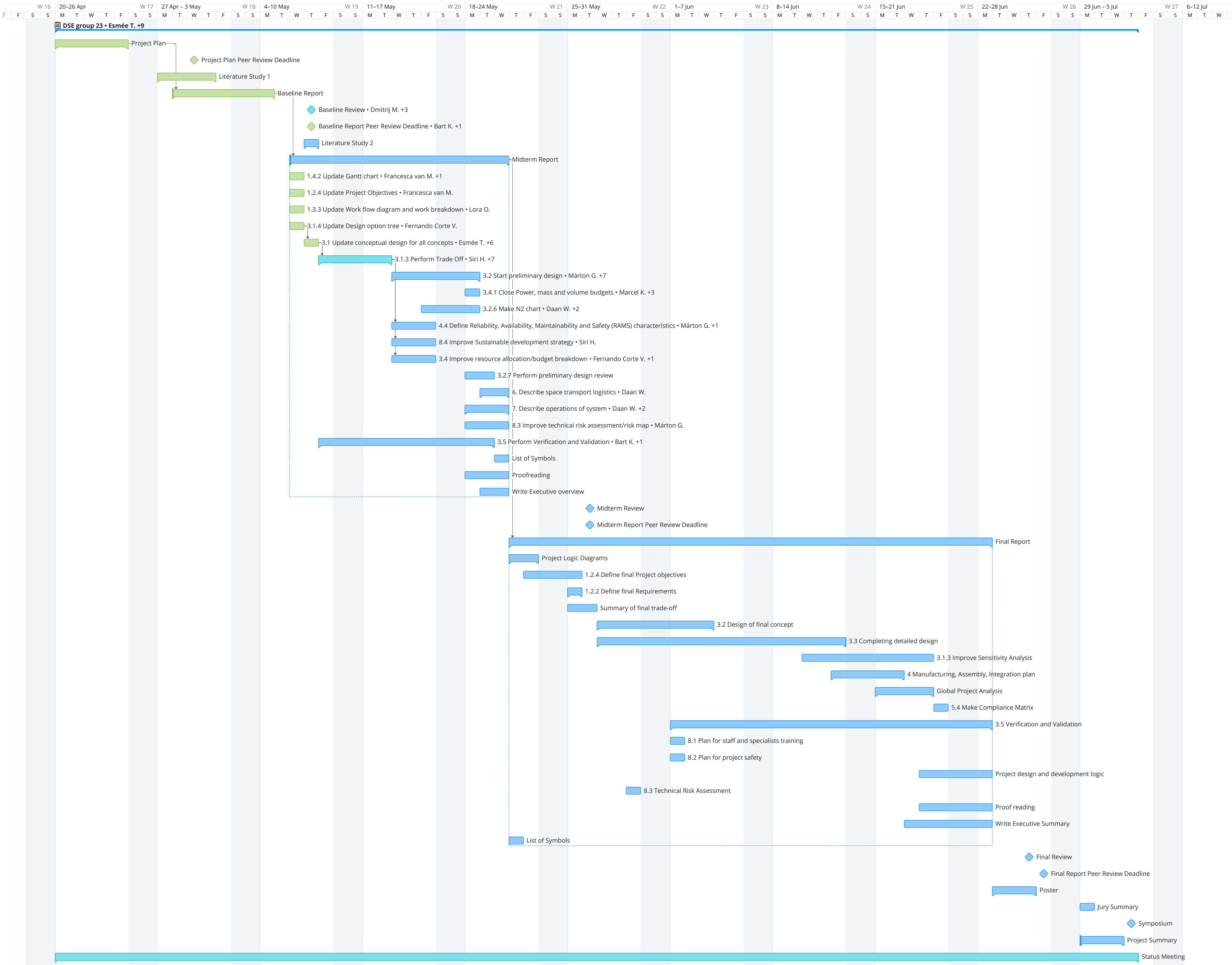

Figure 2.3: Gantt Chart.

2.2.3. Organogram

Figure 2.4 illustrates the positions and technical sub-groups the team is divided in. Each member has an organisational role and a technical role. This diagram does not intend to show a hierarchical structure, it was rather geared towards showing the flow of communication within the group. All communication to external parties must go through the communications officer.

Each of the sub-groups in the technical area of the diagram have a chief, i.e. a person responsible of keeping an overview of the tasks to be done and of playing as an “expert” in that particular area. Each sub-group has other members assigned to help with the tasks. This team structure has been complied with for the most part, however when someone needs extra help, some flexibility must be allowed to enhance the collaboration.

One element in the organisational structure that has not been portrayed in this section, is the table defining the back-up positions. This was constructed together by the group to ensure that there would always be a backup in case someone was unavailable for any reason. This table can be found on page 5 of the project plan [16].

Finally, the team roles have already been extensively described in the project plan report [16].

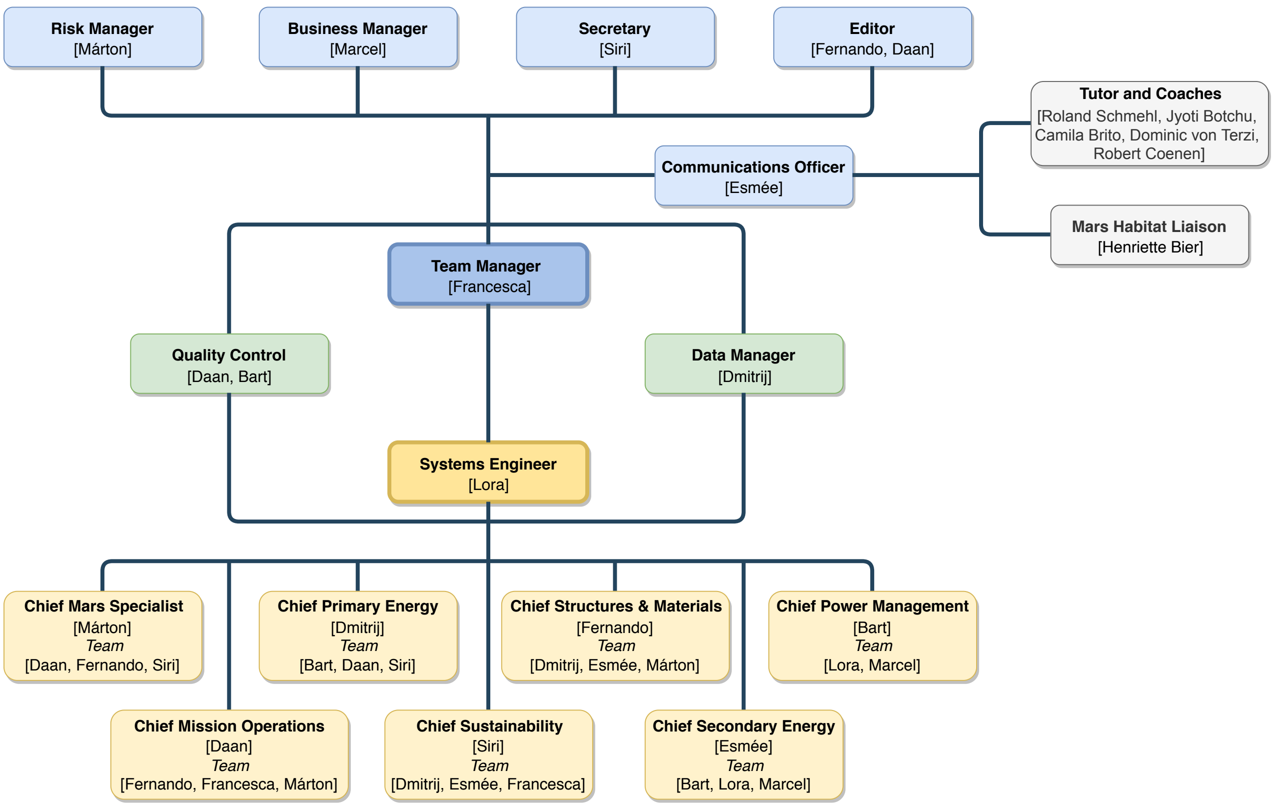

Figure 2.4: Organisational structure

3
Design Options and Trade-Off Method

This chapter discusses both the updated design option trees (DOTs) as well as the method used to do the trade-off on the remaining design options. Section 3.1 explains the new design option tree with the remaining options and section 3.2 elaborates on the trade-off method, things like trade-off categories, computation method and sensitivity analysis method are discussed here.

3.1. Design Option Trees and Selected Concepts

To continue the design trade-off process, the design option trees resulting from the initial design option elimination done in the baseline report are included. The grey blocks included in the diagrams of the previous report were discarded due to feasibility issues or by simple failure of meeting top requirements, and are not shown in this report for the sake of compactness.

Hence, figure 3.1 has been created to summarise all the options selected from the baseline report to go into the trade-off in the upcoming sections. These figures include several options that still need to be fully conceptualised before they can go through the trade-off selection. The detailed description of these concepts is discussed in chapters 4, 5, and 6, with their corresponding trade-off results.

3.2. Trade-Off Method

To have a consistent, systematic approach for the trade-off of the selected design options, a general method for the trade-off and the sensitivity analysis must be documented. This will be elaborated on below.

3.2.1. Trade-Off Weights and Scores

The aim of the trade-off is to identify the most favourable design options based on quantitative parameters. In order to evaluate the performance of a certain design concepts, a weight and a score must be assigned to the contributing aspects. The weights represent the importance of a given aspect to the overall design, while the scores evaluate the quality of the performance of a solution with respect to the criteria.

The rationale behind the different weights and scores is explained in table 3.1. Important to note is the final jump from 7 directly to 10 in the definition of the scoring. This was implemented in order to clearly distinguish numerically between a good performance and a great one. Hence, if a certain design choice is beneficial for the overall system performance, it gets a high score and if it is not beneficial, it is assigned a low score. This gives the team a frame of reference to finalise the concept selection that will be incorporated in the design of the energy system.

Table 3.1: Weights and scores for the design trade-off

Weight	Interpretation	Score	Interpretation
1	Negligible	1	Poor
2	Minor	3	Marginal
3	Moderate	5	Sufficient
4	Significant	7	Good
5	Severe	10	Great

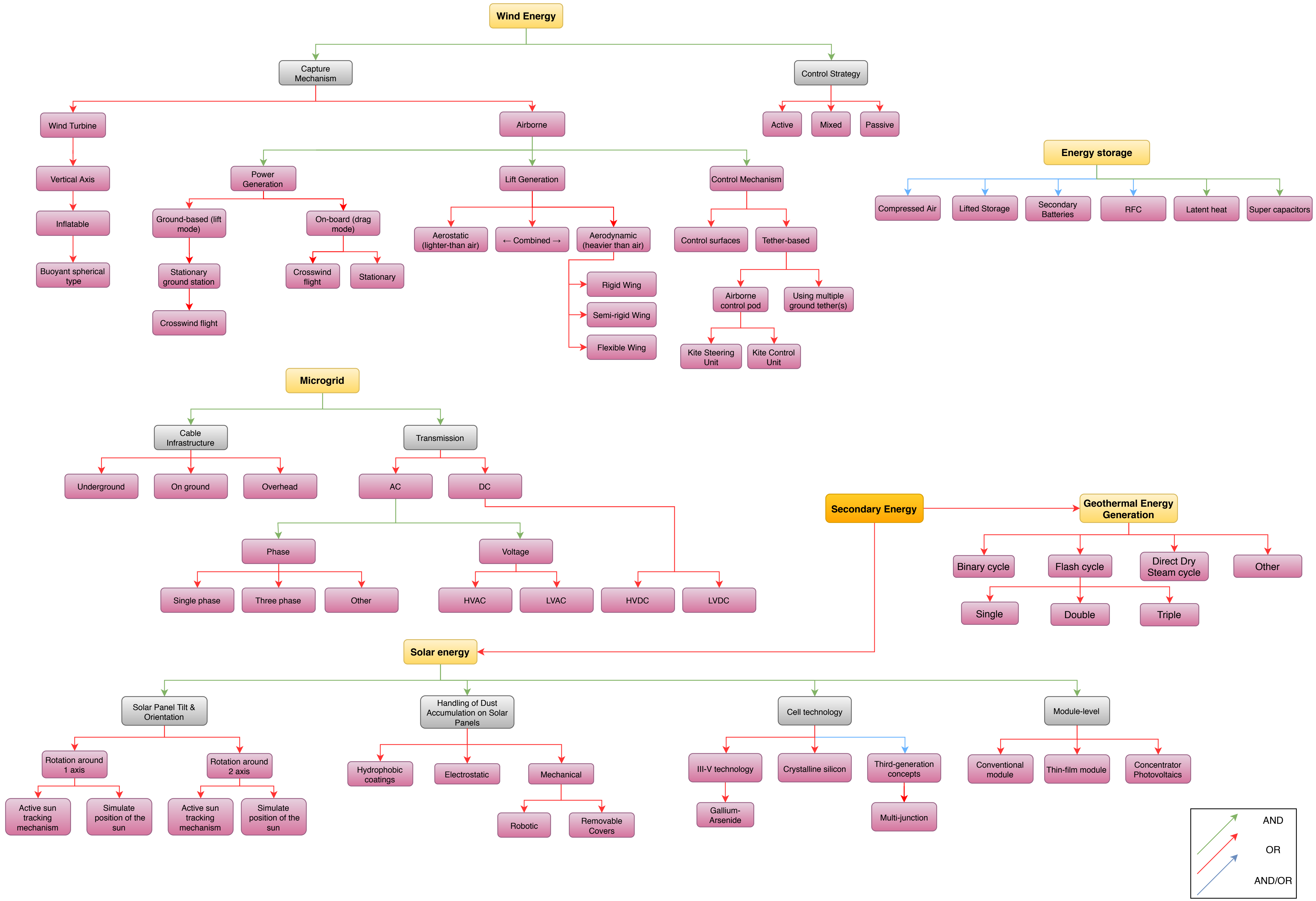

Figure 3.1: Selected options for trade-off

3.2.2. Trade-Off Categories

In order to generate well-defined trading categories, it is important that the key requirements are properly considered. To maintain the influence of the key requirements, nine main categories were defined. Each category is furthermore broken up into aspects. The categories and their respective aspects are described below. Furthermore, the relevant identifiers of the key requirements as documented in the baseline report [15] have been included in the description of the categories. It should be noted that the system trade off will be susceptible to a few system-specific categories. For example, the primary energy system will have different considerations for a trade-off than a geothermal energy system (e.g. a borehole cannot fall out of the sky). In light of this, the aspects of the system level trade-offs might differ slightly as they are determined by how important it is to the system in question.

Development cost: This category aims to represent the time and money resources that are necessary to fully develop the design. It is split into five aspects: research cost, design cost, production cost, verification cost and validation cost. Low cost is favourable for the design, since there is a budget restraint by **REM-COST-01**. For this reason, high scores are assigned to relatively cheaper solutions. Moreover, the distinction between research cost and design cost must be noted: research cost is the time and effort necessary to obtain the necessary information on the system, so that the desired accuracy and detail can be achieved. On the other hand, the design cost reflects the cost that is needed to finalise the design. Production cost, verification cost and validation cost are the costs required for the physical production, the testing of the design, and to evaluate the correctness of the system respectively.

Development risk: This category aims to incorporate the likelihood of occurrence of the most critical risks that could potentially endanger the development of the mission. The first aspect of this category relates to the power requirement, as specified by requirement **REM-NRG-01**. Another aspect relates to the risk that the designed system cannot be manufactured due to e.g. material requirements, size or available technologies. Finally, another important aspect is that, due to a lack of knowledge on the exact behaviour of the design on Mars, the reliability of the design would be insufficient.

Mass performance: There are two requirements that specify the upper limit of the payload mass for each launch: **REM-LD-02** specifies that the mass of the entire system shall not exceed 800 kg per launch, and **REM-Sys-N02-01** constrains the mass of the primary energy unit to 200 kg per launch. As the number of launches should be limited, it is very important to consider the expected mass of the system in the trade-off.

Volume performance: For the volume of the system there are analogous considerations as for the mass. **REM-LD-01** states that for every launch a maximum of 3 m^3 is available for the transportation of the system. Therefore careful consideration must be taken with respect to the volume of the payload and the power density of the system as to keep the volume to a minimum.

System installation: Although complex systems can provide a high performance, they are also generally harder to set up. This could mean more set up equipment is required, increasing the number of launches. Furthermore, more support infrastructure might be required. As one of the key requirements asks for using using local resources (**REM-Sys-M02-01**), the system and its installation equipment should be able to support this. Furthermore, if a system is more complex, there are more opportunities for damage to occur. Therefore, it is favourable to have a system that is not complicated to install.

System operations: System operations entail the functionality of the system after set-up on Mars. As the system is designed on Earth, there is the possibility that the system will not work as intended in Mar's hostile environment. As the system will rely on automation to a high degree, there is a chance of it not performing as planned. Furthermore, this could potentially pose a threat to the habitat or its inhabitants. There is also the possibility of the system working as intended, but having an insufficient performance; the power is susceptible to the seasonal fluctuations in the energy supply, for example. The system should be able to account for this.

Maintenance and repairs: The system has to be maintained through its five martian year lifespan to ensure optimal performance. There are two things that need extra consideration, namely the ease and cost of maintenance. The cost incorporates the time and effort required to maintain the system by detecting problems and repairing them. The ease of maintenance is important as there is no use for a system that cannot be repaired when problems occur during the mission, considering that it needs to last five Martian years (**REM-NRG-04**).

System retirement: When the mission is completed, the system needs to be decommissioned such that the mission impact on Mars is minimum, as specified by **REM-MENV-02**. The logistics for this need to be considered in the sense of how complicated is the decommissioning, as this could entail more time and cost necessary for the deconstruction.

Sustainability: Sustainability is at the core of the design of a renewable energy system. There are three separate aspects in which this can be implemented. The first being the availability of using environmentally friendly processes during the production of the system. Next, in terms of the system operations, as the aim is to have a system that generates as little waste as possible while operating. And lastly, the retirement stage. Not only the logistics of system retirement need to be considered, also the possibility of recycling or reusing the parts of the system must be taken into account.

3.2.3. Computation Method

Once, the weights and scoring have been defined, along with the relevant categories and their contributing aspects, the performance of a design option can be evaluated. This is achieved as specified by the following steps:

1. Assign weights to the trading categories and the relevant aspects within the category.
2. Evaluate the performance of a design option with respect to an aspect qualitatively and assign it a numerical score from table 3.1.
3. Compute the weighted mean ($\bar{x}$) using the equation below for all aspects in a category and document these values as the performance score for that category. In the equation, x_i denotes the aspect's score and w_i is the aspect's weight. This result corresponds to the final score of a single category.

$$\bar{x} = \frac{\sum x_i w_i}{\sum w_i}$$

4. Compute the weighted mean for all categories: in the equation above x_i now denotes the category's score and w_i is the category's weight. Analogically, $\bar{x}$ would then be the final score of a given design option.
5. Identify the highest scoring design option.
6. Perform sensitivity analysis and re-evaluate the final scores. Repeat until trade-off is conclusive.

Through the steps above a final conclusive trade-off is performed and a design option is selected. Nevertheless, as mentioned in the before, the sensitivity of the trade-off with respect to the criteria, weights, and scores must be analysed. This implementation is described in the following subsection.

3.2.4. Sensitivity Analysis Method

Through sensitivity analysis, the variability of the outcomes depending on certain trade-off criteria is evaluated. First a general sensitivity analysis of the trade-off method, is performed as explain above, followed by suggestions for implementing the sensitivity analysis for the design trade-offs.

Due to the multidisciplinary nature of the system at hand and the necessity to perform several engineering trade-offs, plenty of design specifications have to be considered. If a single level trade-off method contains too many design features, the outcome would become less sensitive to drastic weight and score changes. Therefore, a two levelled trade-off method is incorporated for the purposes of this project, so that desirable sensitivity could be achieved while all the contributing factors are still considered. The two-levelled weighing and scoring method allows for evaluating the aspects within a single category with respect to each other. Then, the weighing of the categories once again allows for evaluating their importance relative to the other categories. Nevertheless, the overall sensitivity of the trade-offs vary as so does the number, relevance, and performance of their defining parameters. Thus, individual sensitivity analysis for all of the following trade-offs shall be performed and presented along with the results and conclusion discussions.

In order to analyse the sensitivity of a trade-off, several points of action can be executed. As the goal of the sensitivity analysis is to evaluate if the outcome is biased or if several minor changes could deem it inconclusive, the following steps are suggested:

- The trade-off tables should be filled in by more than one person. This could be done either through discussions between group members or them working independently and comparing results afterwards. If that is not possible, the trade-offs performed by single members should be thoroughly proofread.
- If all examined design solutions have similar performance levels with respect to an aspect or category, that parameter should be removed.
- Once the individual weight and score of a parameter are assigned, it should be evaluated whether these are in accordance with the weights and scores of other parameters and design options.
- Examine how the outcome behaves if small changes are imposed on the weights and scores of the defining parameters.
- Add or remove aspects from certain categories and observe if the trade-off result changes.

4
Primary Energy Trade-Offs

In this chapter, the design trade-off for the primary energy system based on wind energy is discussed. First, a trade off between a Vertical Axis Turbine (VAWT) of the inflatable buoyant type and an Airborne Wind Energy (AWE) system is performed, following from the resulting options from the Design Option Tree (DOT) in figure 3.1. After the trade-off between VAWT and AWE, a trade-off is performed on specific design options of the AWE, since this system came out best suitable for the mission. This trade-off can be found in the section 4.2.

4.1. VAWT vs. AWE

The weights of categories and aspects of the first trade-off are discussed in subsection 4.1.1. The scores given to VAWT and AWE are explained respectively in subsection 4.1.2 and 4.1.3. Its conclusions are summarised in table 4.1.

4.1.1. Weights of Categories and Aspects

For the trade-off between the VAWT and AWE, the same trade-off categories are used as explained in section 3.2. Some aspects are adjusted to the specific requirements of the the wind energy system. A discussion of the categories, their aspects, and weights follows.

Development cost: The development cost is scored over five aspects: the cost for research, design, production, verification and validation. Due to the specified duration of the project, the research and design costs are of moderate importance for the design. The production cost are of severe importance, following the key requirement of €500,000 per primary unit. The validation and verification are respectively valued as minor and negligible for the trade-off, since the possibilities for validation and verification are quite similar to both designs.

Development risk: Development risk has a significant impact on the design of the system, considering the catastrophic events a critical failure could entail. The development risk is split up in three factors: power requirement compliance, achievable manufacturability, and design reliability. The first two are considered of significant importance, since the main goal of the mission is to provide a continuous power supply of 10kW for a Mars habitat. The achievable manufacturability of the design has moderate influence on the design.

Mass performance: Due to the strict stakeholders requirement on the mass of the primary energy unit, as mentioned in subsection 3.2.2, the mass of the wind energy system is of severe importance to the execution of the mission.

Volume performance: The volume performance is of significant importance to the primary energy unit, due to the restrictions on the transport volume in the launcher as specified by the stakeholders. It is measured by the power density of given systems.

System installation: For the installation of the wind energy system, the score is based on the Plug & Play attribute of the system (ease of user setup). This includes the ease of system deployment, considering the amount and difficulty of actions performed by astronauts and/or robots. Although an easily deployable system is preferred, this criteria is not the most driving for the trade-off, thus weighted as of moderate importance.

System operations: The system operations is split up in the following three aspects: operations risk, seasonal dependency, and operations complexity. Since the mission stands or falls with its performance, system operations is severely important. From the three aspects of system operations, operations risk is considered to be the most severe. Seasonal dependency is valued as significant, since power output depends heavily on the seasonal changes on Mars. Finally, the operations complexity, which includes control and stowability aspects, is considered to be of moderate importance for the system operations.

System maintenance: The system maintenance is of moderate importance to the design of the system. The system maintenance is divided in four aspects: the component critical failure likelihood, the maintainability cost, the ease of problem detection and the ease of component inspection. The component critical failure likelihood refers to a situation in which a component fails, disabling the system to operate, thus severe in importance. The maintainability cost is significant to the mission, due to logistical constraints of operating on Mars. The ease of problem detection and the ease of component inspection are considered of minor importance compared to the component critical failure likelihood and the maintainability costs.

System retirement: At end-of-life, the missions impact on the Martian environment should be minimised as per the key requirements of the project. Actions and effort to break down the system as well as the possibility to recycle or reuse certain parts on Mars is thus considered. This is an important part of the design, but is considered of minor importance due to the low possible impact of the system.

Sustainability aspect: The sustainability aspect of the design is weighted to be of significant importance due to the key requirement regarding impact on Mars. The sustainability aspect is divided in the three phases of the product: production, life-time and retirement. Retirement aspect is considered as the most severe for the sustainability of the system due to potentially high environmental impact. The impact on Earth during production is of moderate importance to the design decision. For the wind energy system, the difference in impact it can make during life-time is small compared to the other phases, thus considered to be of minor importance.

4.1.2. Scores for VAWT

Whilst it is labelled as VAWT-only in the trade-off, most VAWT concepts were actually discarded in the baseline design phase, except for the concept that used a spherical inflatable wind turbine. This particular VAWT was first described by James et al. [33], with little mention of the particulars of its operation and design, both warranting **research cost** and **design cost** marginal scores (3). As the main identified components of the VAWT concept (balloon, blades, ground station) are not concepts requiring novel manufacturing procedures, tooling or expensive materials, the **production cost** was rated at good (7). The models created to aid with the design of such a concept are not well researched, increasing the effort needed for **verification cost**, warranting a marginal score. Finally in the first category, if this type of system were to be tested for functionality on Earth, a sufficiently low (5) **validation cost** could most likely be achieved.

If precautions are taken during the design of such a system, it is expected to be good (7) with respect to the **power requirement compliance**. The blades for such a wind turbine and their interface around the balloon, whilst not seemingly too complex, are yet to be prototyped on Earth, providing a sufficient (5) **achievable manufacturability**. Due to the current lack of information on the Martian wind resource, precise evaluation of **design reliability** cannot be performed, and as no prominent strengths or weaknesses can be found, it is considered sufficient (5).

The **mass performance** of such a concept has to take into account large rigid wind turbine blades on top of having a ground station, and whilst a conceptual design encountered in James et al. [33] did come close to being compliant with the mass requirements, it only did so in a sufficient (5) manner. The need for the rigid wind turbine blades comes into play when evaluating **volume performance** as well. As a rigid structure would take up quite a lot of space compared to a flexible wing of an AWE system, a marginal (3) score is given.

Before operation, the **system installation** of such a concept would not take too much effort, as the system could probably be designed to require nothing more than the balloon inflation and blade turbine structure assembly, scoring sufficiently (5).

With respect to the **operations risk**, if such a structure suffers critical failure and falls out of the sky for example, the severity of impact on astronauts and structures could be quite high; yet, this scenario is preventable by planning the location of the system, thus scoring sufficiently (5). For the **seasonal dependency**, VAWT concepts are known to perform under low wind conditions in a sufficient (5) manner. In case of needing to stow the system away, or bringing it down for inspection and repairs, the **operations complexity** score was deemed to be sufficient (5), as the system would have to be pulled down or deflated to let it land, which is not ideal, yet also not such a large consideration.

The few components expected for such a system, e.g. balloons, turbine blades etc., are all critical to the nominal operation process of such a system. Hence, leading to a marginal (3) **component critical failure likelihood**. The same marginal score can be assigned to the system's **maintainability cost**, as performing maintenance on the blades or the balloon component (or even replacing them) could prove to be quite costly both in materials and effort required. The observation of sub-optimal performance, such as lower than expected balloon altitude and other considerations lead to a sufficient (5) potential of the **Ease of problem detection** aspect. Nevertheless, the fact that the (most likely composite) rigid blade components may have internal damage requiring special inspection tools and techniques, along with the fact that damage to the balloon would be also quite hard to find in a simple visual inspection, a score of marginal (3) is given to the **ease of component inspection**. Additionally, in order to complete full **system retirement**, the blades would hinder the ease of retirement as they would definitely need to be brought back to Earth for recycling, along with the balloon material itself, leading to a marginal (3) score.

In terms of sustainability, the **production** of such a system does not warrant a worse score than sufficient (5). This is mainly due to the environment-taxing process of creating the (most-likely) composite blades. For its **life-time** sustainability aspect, the material used for replacement could be minimised through good design, and the system itself would likely not affect the Martian surface much, warranting a sufficient (5) score. Finally, as mentioned before, the logistics of system requirement would require most of the components to be flown back to Earth for **Retirement**, so due to the consideration of the environmental impact of rocket fuel along with the difficulty of recycling composites, it is scored to be marginal (3).

4.1.3. Scores for AWE

The past decade has seen great improvements in research on the potential of using AWE to generate wind energy. However, as the technology is mainly in its prototype stage, it is deemed to be good (7) potential for **research costs** and sufficient (5) for the **design costs**. The knowledge about AWE harvesting is adequate and the techniques are achievable, warranting good (7) **production costs**. For both **verification and validation costs**, the AWE system scores sufficiently (5), as there are many models for the AWE system that could be used for the system verification, as well as many working prototypes.

Regarding the development risks of the AWE technology, it is evaluated to score good (7) on the **Power requirement compliance** aspect. Many considerations that affect the system power output are given in literature, and can be thus considered in the design procedure, ensuring the required power output. For the **Achievable manufacturability**, the AWE design option also scores good (7), since prototypes were already manufactured with seemingly no major complications. Once again, lack of knowledge about AWE on Mars leads to only a sufficient (5) **Design reliability**.

An AWE system enables the use of flexible textile kites to harvest wind resource from an area, the weight of which can be exceedingly low (in the magnitude of below 0.1 $\mathrm{kg\,m^{-2}}$ [9]), leading to great (10) **Mass performance**. The wing textile material can also be folded easily and elements that increase performance at marginal packing volume cost can be added to the design (e.g. leading-edge-inflatable tubes), giving a good (7) **volume performance**. With respect to all other wind energy systems, the AWE concept seems to be the greatest (10) when considering the ease of **system installation**, as it can be deployed on Mars and almost immediately activated without requiring much assembly.

Once again, a possible use of flexible kite strongly reduces the **operations risk** in terms of possible damage to astronauts and structures in the chance of a crash, warranting a good (7) score. Furthermore, the possible use of crosswind motion, enabling better power extraction even during lower wind conditions leads to a good (7) score on **seasonal dependency**. The active control required during flight, and the required launch and possible stowing away of the kite depending on the available wind resource do present possible issues regarding **operations complexity**, leading to a marginal (3) score for the system.

In addition, the majority of the components of an AWE system are critical and replacement of larger components (e.g. in the ground station) may not be accounted for by the mission, leading to a marginal (3) **component critical failure likelihood**. Over the operation period so far, the only system components that are expected to be replaced over its lifetime seem to be the wing or the kite and maybe the tether component, which can be designed to be replaced quickly, leading to a good (7) score for the **maintainability cost**. Sub-optimal power output of the system, along with easily noticeable deviations from nominal predicted flight path during the flying wing operation could be early signs of possible component failure or damage, warranting a good (7) **ease of problem detection** score. The ground station component can be designed to be easily accessible, and for flexible wing configurations visual inspection would most likely be sufficient, as damage to the wing surface would be quickly visible, thus a good (7) score is given to the AWE **ease of component inspection**.

Finally, since a recycled use for the wing and the ground station components was not identified at first, the fact that **system retirement** would most likely need to be transported back to Earth gives it a sufficient (5) logistical cost, being slightly better than that of a VAWT concept thanks to the possibility of taking up a low volume from a flexible wing design. Such a system, whilst using many composite materials, would likely have very little need for using environmentally unfriendly bonding agents, which would make it good (7) with respect to the **production** sustainability aspect. With regards to its **life-time** sustainability aspect, it is assumed that the wing would need more frequent replacements over its lifetime, yet the lower environmental impact of the materials and techniques used for its production do keep it at sufficient (5). Finally, the possibly used textile material could prove to be more recyclable than e.g. composite materials, leading to an overall smaller impact on the environment with its **retirement**, making it score good (7).

4.1.4. Results and Conclusion

The overview for the trade-off between the buoyant spherical VAWT and AWE concepts can be seen below in table 4.1. The respective scores that were discussed in sections 4.1.2 and 4.1.3 are shown in this table. Using the computational method shown in section 3.2.3, the weighted scores for both concepts were found. A score of 4.4 was calculated for the VAWT and a score of 6.3 for the AWE.

Table 4.1: Trade-off between Vertical Axis Wind Turbine (VAWT) and Airborne Wind Energy (AWE)

Category	Aspect	Weight	Score	
			VAWT	AWE
Development cost		**4**	**4.1**	**6.1**
	Research cost	3	3	7
	Design cost	3	3	5
	Production cost	5	7	7
	Verification cost	2	3	5
	Validation cost	1	5	5
Development risk		**4**	**5.7**	**6.3**
	Power requirement compliance	4	7	7
	Achievable manufacturability	3	5	7
	Design reliability	4	5	5
Mass performance	Specific energy [$\mathrm{W\,kg^{-1}}$]	**5**	**5**	**10**
Volume performance	Power density [$\mathrm{W\,m^{-3}}$]	**4**	**3**	**7**
System installation	Plug & Play factor	**3**	**5**	**10**
System operations		**5**	**5**	**6**
	Operations risk	5	5	7
	Seasonal dependency	4	5	7
	Operations complexity	3	5	3
System maintenance		**3**	**3.3**	**5.5**
	Component critical failure likelihood	5	3	3
	Maintainability cost	4	3	7
	Ease of problem detection	2	5	7
	Ease of component inspection	2	3	7
System retirement		**2**	**3**	**5**
Sustainability aspect		**4**	**4**	**6.6**
	Production	3	5	7
	Life-time	2	5	5
	Retirement	5	3	7
		Sum of category weights	**Weighted score**	
		34	**4.4**	**6.3**

A sensitivity analysis was performed on this trade-off according to the method in 3.2.4 of this report, which confirmed the result of the AWE scoring higher than the VAWT system on the criteria and aspects chosen as important for the given mission. Thus, it can be concluded that the spherical buoyant VAWT should be eliminated from the design process, leaving the AWE system as the one to be developed further.

4.2. Airborne Wind Energy Trade-Off

After the previous trade-off in which the AWE system was chosen, the next step is finding the possible options for AWE and making a trade-off between these to find the final concept. The subsystems up for consideration include the lift generation (flying) and power generation concepts, both of which will need to be decided upon. Both decisions are made based on a combination of quantitative and qualitative analysis of the remaining possibilities and the consequences of previous trade-offs.

4.2.1. Lift Generation

Lighter-than-air (aerostatic) AWE concepts can now be discarded, as these are too similar with regards to all of their design considerations to the VAWT buoyant type concept, eliminated in the preceding system-level trade-off. In the baseline report [15], it is explained why coupled rotor-generator (drone-like) concepts are not feasible either. Thus, the only feasible concepts for lift generation remain the use of a wing or a combined wing-aerostatic concept. Possible concepts include a rigid wing, a flexible wing (e.g. textile kite) and a semi-rigid wing (inflatable wing).

In the given mission, the AWE system must operate under Martian conditions, which gives rise to many challenges still untackled by the AWE industry due to the unique design considerations. The low atmospheric density on Mars is one of these factors. In order to operate and generate power, the wing must be airborne. Presented below is a simple analysis of the consideration with respect to the required launch conditions for a wing.

In AWE system models, the weight of the wing is often assumed small, and thus neglected in analysis - however, with rigid wings, this is no longer a feasible assumption, even on Earth [44]. In order to keep a wing statically airborne, assuming horizontal wind and disregarding the mass of the tether and the possible control unit, it is required that:

$$W < \frac{1}{2}\rho A V^2 C_L \tag{4.1}$$

Where gravitational acceleration $g = 3.711\,\mathrm{m\,s^{-2}}$, atmospheric density $\rho = 0.015\,\mathrm{kg\,m^{-3}}$ (surface-level), and a coefficient of lift of the wing $C_L = 1.5$ (agreeable maximum value for both a surf-kite and a rigid wing [27]). The area density of the wing (ρ_A) is assumed to be constant, such that the weight of the wing is equal to $W = A \cdot \rho_A$. Expanding W and rearranging equation 4.1, an inequality for the minimum speed that must be attained for the wing to take-off, as a function of ρ_A, is obtained:

$$V > \sqrt{\frac{2\rho_A g}{\rho C_L}} \tag{4.2}$$

On Mars this minimum velocity, as it is dependent on $\sqrt{\frac{g}{\rho}}$, becomes at least five times higher than on Earth for a similar wing. How this minimum velocity behaves as a function of ρ_A on Mars is shown below:

Table 4.2: Minimum wing velocity as a function of area density

Area Density ρ_A $\mathrm{kg\,m^{-2}}$	**Minimum Velocity** V $\mathrm{m\,s^{-1}}$
20	81.2
10	57.4
5	40.6
1	18.2
0.5	12.8
0.2	8.1
0.1	5.7
0.05	4.1

After consulting literature, average values for rigid wing area densities were found to be mostly in the range above 10 kg $\mathrm{m^{-2}}$ (often starting at 20) [19, 40, 44]. It should be noted however that area densities of 5 $\mathrm{kg\,m^{-2}}$ and above can be considered unfeasible according to this analysis, as flight speeds of more than 40 $\mathrm{m\,s^{-1}}$, would be required for just staying airborne. Higher weight would lead to lower tether forces, lowering power generation. The velocity given above would be higher without the simplifying assumptions made too.

As a consequence, rigid wings concepts are rendered unfeasible. Flexible and semi-rigid wings were found to have area density values mostly below 1 $\mathrm{kg\,m^{-2}}$ [27, 44], with the fabric materials themselves with area density values below 0.1 $\mathrm{kg\,m^{-2}}$ [9]. The stowability helps with the given volume requirements. They are more easily deployable [9], and safer – a flexible wing would deform on crashing, thus reducing the damage done to itself and possibly any astronaut or structure it could collide with [76]. Selection between flexible and semi-rigid concepts follows in section 4.2.3.

4.2.2. Power Generation Principle

AWE systems can be classified in two ways: power generation either occurring at the ground-station (lift-type) or on-board (drag-type) [19]. In this report, lift-type concepts are regarded to use aerodynamic forces on some kind of kite or wing to unwind a tether from a drum and in turn generate energy on the ground (also sometimes referred to as a "pumping" kite system). Drag-type concepts, on the other hand, are considered to utilise airborne wind turbines, rotors coupled with generators and other concepts to generate power, which is then transferred to the ground station through a conducting tether [67].

Drag-type concepts require more mechanisms in order to function, leading to a more complex design process and final system [13]. Having multiple wing turbines or coupled propeller-generator systems, on top of adding additional maintenance and operation issues, very highly increase the airborne mass of the wing.

On top of that added mass, all drag-type concepts either use rigid structures to ensure structural integrity around the power-generating components, or aerostatic principles [13]. The mass issue could be solved by using aerostatic variants of the drag-type concepts discussed previously, but this concept of using inflatable wind energy concepts has already been eliminated in section 4.1.

Leading from the analysis presented in the section above, in which aerostatic lift generation and rigid wing concepts are discarded, it follows that drag-type concepts are rendered unfeasible for the given mission as well.

4.2.3. Non-rigid Kites

For pumping-cycle power kites, the concept used to fulfil the given mission chosen in the trade-offs above, a few possible wing concepts remain: flexible surf kites, leading edge inflatable (LEI) kites, tensairity kites and ram-air kites.

Starting with ram-air kites: wind blows in through openings at the leading edge and the kite is inflated. This inflation helps the kite to reproduce an airfoil shape, increasing its aerodynamic performance [20]. The inflation of the kite is caused by an increase in dynamic pressure [56]. Commercially available ram-air kites show that big kites need a minimum inflow velocity of around 6 kts[1] (3.09 ms^{-1}) [22]. The dynamic pressure that causes this inflation can be calculated using $q = \frac{1}{2}\rho V^2$ and since the air density on Earth equals 1.225 kg m^{-3} and on Mars equals 0.015 kg m^{-3}, for the same kite a wind speed of approximately 28 m s^{-1} would be required. Wind speeds around 28 m s^{-1} are uncommon on Mars and therefore the ram-air kite should be eliminated from the trade-off process.

The wind inflation is not important for the remaining concepts. Surf kites are the most basic kite type and have no real stiffening elements. LEI kites use inflatable structures at the leading edge of the kite to add stiffness, increasing aerodynamic performance. Although scalability issues needs to be kept in mind [13]. Finally, tensairity kites use inflatable tubes both in the leading edge and in the spars of the kite to add even more flexural stiffness and again enhance aerodynamic performance. These two concepts are best based one their respective aerodynamic performances. To understand the differences in aerodynamic performance of the kites, assuming similar materials and thus similar mass, the reel-out and reel-in force factors F_{out} and F_{in} are analysed. These are calculated using the method shown in subsection 8.4.2. The force factors with their corresponding ratios are shown in table 4.3, for the surf kite, explicit values were found for the force factors in literature.

Table 4.3: Aerodynamic performance parameters of different kite concepts

Kite concept	C_L	C_D	F_{in}	F_{out}	$\frac{F_{out}}{F_{in}}$
Surf kite [27]	-	-	1.14	30	26.32
LEI kite [77]	0.69	0.1725	0.1725	8.55	64
Tensairity kite [9]	0.6	0.06	0.06	60	1000

The tensairity kite clearly has the highest force factor ratio, generating more power than its counterparts for the same area and thus is chosen to be the best concept for the mission. Similar scalability issues like in the LEI kite may be present, but no information has been found on this as of yet.

4.2.4. Tether Configuration and Control Unit

The kite is connected to the ground station by a tether, which should both handle the forces on the kite without failing during the entire mission lifetime and be able to control the kite motion.

The tension force on the tether is higher in the reel-out phase than during reel-in, so reel-out force is considered for design purposes. The strength and resilience of the tether depends on three different aspects: size, material, and the tether construction.

Considering the tether material in general high-modulus polyethylene (HMPE) fibres are used in AWE systems. The material has a very high strength-to-weight ratio compared to all other fibres [8]. It is a very durable material considering weathering factors and also is more flexible compared to the other fibres, which helps withstand the long term repetitive bending that is present in pumping kite systems[8]. A particular HMPE fibre called DM20, created by DSM Dyneema, was chosen for this mission. This specific HMPE fibre has very high creep resistance which helps prevent creep failure, an important consideration given the 10 (Earth) year length of the mission [8].

[1]https://www.f-one.world/product/halo-2/ [Cited 19 May 2020]

With regards to the tether construction, there are several ways to construct the tether from the HMPE fibres, the most commonly used being braided and laid construction. Braided makes the tether torque neutral, so that it does not untwist when loaded in tension. Laid construction on the other hand, would untwist when loaded and is therefore deemed unfeasible for this mission [8]. Braiding pitch (the length between each time a strand completes a full circle in the braiding) is another important variable, and its optimum equals seven times the tether diameter [70].

Finally, a trade-off needs to be done for the kite control unit. The motion of the kite is controlled by pulling or releasing the tethers, two configurations are available for this. Firstly, the control unit could be on the ground, where tethers lead from the ground unit to both the leading and trailing edge of the kite, which in turn can be controlled. Another option is to have an airborne kite control unit (KCU), where one big tether goes from the ground station to the airborne KCU where a bridle system deforms and thus controls the kite. This is left as a consideration for further analysis.

4.3. Primary Energy System Results

Following the trade-offs in previous sections, a final conceptual design for the primary energy system is determined. A lift-type AWE system will be developed, generating power in the ground-station, using a tensairity kite. For the tether, HMPE DM20 fibres will be used, braided using 12 strands (6 clockwise, 6 anti-clockwise).

During the future design phase, decisions still need to be made on kite control, whether this will take place on ground or airborne, along with a more detailed ground station design. The preliminary design steps taken are discussed in chapter 8.

5
Secondary Energy Trade-Offs

This chapter discusses the trade-off regarding the secondary energy system supplying the Mars habitat. First, a trade-off deciding whether geothermal or solar energy will be harvested is presented in the following section 5.1. Afterwards, the specific technology trade-offs related to the selected solution are described.

5.1. Geothermal vs. Solar

This section introduces the trade-off regarding the secondary energy unit, utilised for the purposes of a Martian mission. Moreover, the weights and scores of relevant aspect and categories along with the final outcomes are summarised in table 5.1.

5.1.1. Weights of Categories and Aspects

For the secondary energy system trade-off, the assigned weights for the categories and their corresponding aspects are discussed below. In addition, the category description is as documented in subsection 3.2.2 and the weights are distributed with accordance to table 3.1. The final weights can be found in table 5.1.

Development cost: The total development cost is relevant to the stakeholders of this project. Nevertheless, it is not among the most significant constraints driving this design trade-off. Hence, development cost is considered to be of moderate importance. As for the aspects, the most significant one is found to be the production cost followed closely by the validation cost. The research and verification costs are estimated to be of minor importance for the overall performance of this category while the design cost is considered almost negligible compared to the other aspects.

Development risk: The development risk for the mission is of significant importance as high risk could lead to devastating results. Furthermore, achievable manufacturability is of severe importance to the mission execution and the compliance with the power requirements and the design reliability are both estimated to be slightly less relevant.

Mass performance: The overall mass performance of the two systems is deemed critical to the mission completion, as there are stakeholders requirements on the maximum transported payload per launch. Therefore, a severe weight is assigned to this category.

Volume performance: The volume performance of the systems is of significant importance to the mission due to the launcher transport restrictions formulated in the stakeholders requirements. The aspects of this category are the total system volume and its power density. The overall volume is severely important while the power density of an energy source is moderately relevant.

System installation: The system installation specifics of geothermal and solar energy farms could result in a lot of additional costs and necessary logistics. Nevertheless, this mission aspect is not critically restraining to the design space, so it is estimated to be of moderate importance. Then for the aspects: since support infrastructures could be sourced from Mars, this aspect is of minor importance to the category. However, sourcing materials and infrastructure installation require a considerable amount of additional equipment and machinery, and thus it is of significant importance. Finally, the installation risks for either one of the energy sources to the astronauts, the system components, and the surroundings is judged to have significant relevance for this category.

System operations: The system operations have significant importance to the design trade-off, as its aspects are quite influential for the design solution. The most important of its aspects is the operational risk; next is the under-performance likelihood which is of moderate relevance. Finally the seasonal dependency is judged to be of minor importance as it does not critically limit the design option space.

System maintenance: The system maintenance category for this trade-off is of moderate relevance to the selected design solution. Its first aspect refers to the scenarios where a failure has occurred due to any circumstance, and hereafter the system is no longer operational. As it captures such extreme situations, this aspect is of severe importance. The cost for this category are considered of minor importance, while the importance of achievable maintainability is considered as significant.

System retirement: System retirement logistics and costs must be considered in this design trade-off as there is a top-level requirement to minimise the impact on Mars. Therefore, in order to comply with this requirement, certain capital must be reserved for the disassembly and the disposal of the secondary energy system. As retirement procedures would be executed for any type of system, it is weighted as moderate in the trade-off.

Sustainability aspect: As there are top-level requirements to minimise impact both on Earth and Mars, the sustainability category is weighed to be of significant importance. In addition, the sustainability performance of the production phase is of moderate relevance, while the sustainability of the operational aspect is judged to be of significant importance due to the lengthy operational period. Furthermore, as improper retirement procedures could result in critical amounts of environmental impact, this aspect is evaluated to be of severe relevance to the system design.

5.1.2. Scores for Geothermal Energy

In order to evaluate the performance potential of a geothermal power plant to be utilised as secondary energy source for a Mars habitat, the following characteristics of this technology must be considered.

Firstly, geothermal energy is heavily dependent on the site location, due to the required heat and fluid resources. As there is little research done regarding this on Mars, there would be added **research cost** associated with this, thus scoring marginal (3). This lack of knowledge also affects the **verification and validation cost** due to the complicated processes and additional costs, therefore also scoring a marginal (3). Even though the system is complicated to produce on Mars, geothermal power plants are commonly used on Earth and can be used as reference to evaluate the potential. The **design and production cost** can thus be judged to be sufficient (5).

Secondly, conventional geothermal power plants supply power in the magnitude of 10^1 MW [1]. For the mission however, the **power requirement** is considerable smaller then average, by a factor of around 10^3 – 10^4. Therefore, due to the general scale of geothermal energy sources, the power requirement scores poorly (1). In addition, it is unknown whether it is plausible to scale down the plant. Moreover, the borehole construction depends on heavy duty drills that require drilling mud [2], which would need to be adapted for the Martian environment. Hence the **achievable manufacturability** has a marginal (3) potential. For the same reasons as mentioned previously the **design reliability** scores a marginal (3).

Moreover, it is evident that geothermal energy is a viable solution its scale is large enough. However, the relation between size and efficiency is not linear. Hence, a scaled power plant would still have considerable mass and volume. Accordingly, the overall system **volume and mass performance** potential are evaluated to be poor (1). Nevertheless, geothermal energy could be an extremely **power dense** energy source given the right conditions [82] and is therefore considered good (7). Furthermore, as previously mentioned, geothermal energy requires wells and aquifers which need heavy equipment for construction and support. Thus the **installation equipment** and **support infrastructure** required perform poorly (1) and marginally (3) respectively. For the same reason, the **installation risk** also scores marginally(3).

An important characteristic of geothermal energy is the potential for a continuous energy source, not influenced by the Martian seasons. Thus it scores great (10) on **seasonal dependency**. HOwever, **Operational risk** and **likelihood of system under-performing** do not perform as well. The prior is considered sufficient (5) as there are no major risk factors, however there is no safety guarantee at this stage in the design. The latter is scored marginally (3) due to the aforementioned reasons on the unknowns of the design.

Furthermore, the aspects in the system maintenance category also do not score that greatly. The **component critical failure likelihood** and **maintainability cost** both score sufficiently (5), as all components are expected to have a long life-time. However most components are critical to the system operation, since if any of them fail, the system will need to be retired. **Achievable manufacturability** on the other hand, is scored as marginal (3) by reason of underground maintenance procedures that would be hard to perform and cannot be guaranteed to be feasible.

System retirement logistics performs sufficiently (5) as the components do need to be brought back to Earth, but have a relatively simple recycling process. By the same reasoning, the **retirement** aspect of sustainability for the components is very good. However the wells cannot be fully deconstructed, leaving metal and PVC on Mars. Thus this aspect totally scores a marginal (3). During the **life-time** much less pollution is left on Mars than during retirement, thus this scores a good (7) [48]. Lastly, the **production** is evaluated to have sufficient (5) performance as the needed components are commonly produced and do not require rare materials or complicated production procedures.

[1] https://www.open.edu/openlearn/nature-environment/environmental-studies/understanding-deep-geothermal-energy/content-section-5#:~:text=A%20typical%20geothermal%20power%20plant,geothermal%20operating%20costs%20are%20low. [Cited 13 May 2020]

[2] http://directdrill.com.au/water-well-drilling-methods/ [Cited 13 May 2020]

5.1.3. Scores for Solar Energy

Since plenty of research has already been done regarding the performance and optimisation of solar panels for space applications, solar energy scores good (7) in the **research, design and verification cost**. However, the **production cost** will be more higher, as rare materials need to be resourced to produce the solar panels[3]. Thus solar scores marginal (3) on this aspect. Also, **validation** will be challenging, as the Martian atmosphere will influence the performance as well, resulting in a sufficient score (5).

This knowledge on solar panels directly extends to the development risk as well, as more knowledge also leads to less risks. Therefore the aspects **power requirement compliance and achievable manufacturability** score good (7) in this category. Nevertheless, due to the Martian influence on the performance being not completely conclusive, the design can not be expected to behave perfectly as expected, influencing the **design reliability**, but it will perform sufficiently (5).

As solar panels continue to get an increasingly high **mass performance**[4], there will be enough power gained from an array that is manageable in size and will comply with the mass requirements. This aspect therefore scores good (7). Not only a high mass performance can be obtained nowadays, but also a sufficient (5) **power density**[71]. There is still room for improvement, since a larger surface area is needed to generate more power. Thus the **system volume** scores marginal (3).

The system installation of the solar panels will be relatively straightforward. There will be little need for **installation equipment required** and the **installation risk** is very low, as the panels can be assembled per cell, both resulting in good (7) scoring. There is some **infrastructure required** to support the panels, however, reducing its respective score to sufficient (5).

Since the panels are at risk of dust adhesion and micrometeriod impact, there is a **operational risk** and a **likelihood of the system under-performing**. However, since this can be largely accounted for, solar scores a good (7) on this. The **seasonal dependency** cannot be fully accounted for, therefore scoring sufficiently (5).

As solar arrays exist in a variety of cells and panels that do not fully depend on one another[71], there is a very small likelihood of the system **critically failing**. The same goes for **achievable maintainability**, as the panels allow for relatively accessible maintenance. Both aspects hence score good (7). The **cost of maintenance** will perform sufficiently (5) however, due to the tilt mechanism and possible malfunctioning cells.

System retirement of the panels is a more complex procedure, as the panels and cells cannot be fully deconstructed on Mars and thus need to be brought back to Earth. Therefore, the solar system performs marginally (3) in this aspect. The sustainability **retirement** is scored with similar considerations, as the recycling procedure of a solar panel is very complex[80], however it is doable and thus scoring sufficient (5). The **production** however, requires rare metals and is not fully sustainable and is therefore marginal (3). As panels have no emissions during their **life-time**, they are a great (10) option for this aspect.

5.1.4. Results and Trade-Off Selection

In the following section the design outcome resulting from the trade-off is discussed. Additionally, the sensitivity analysis of the secondary energy unit trade-off is incorporated in the discussion below.

Once the weights and scores of the categories and aspect are assigned, the final scores for both design options are computed through the steps listed in section 3.2. The overall geothermal energy performance rates with 3.4 points at slightly better than marginal potential. While the solar energy final result amounts to 5.7 points; hence having a good to great performance capability to meet the mission's needs. Those values are presented on the bottom row of table 5.1. Although the final result difference of 2.3 points clearly indicates a trade-off winner, a sensitivity analysis is performed to investigate possible uncertainties and misjudgements.

In order to make sure that trade-off is conclusive, the table was filled by two members engaging in a discussion on various strengths and weaknesses of both design solutions. Additionally, the scoring and argumentation has been checked by a third member and their feedback is incorporated. Additionally, small changes have been imposed on the weights and score in order to examine the outcome's behaviour. Nevertheless, only if an unreasonable amount of alternations are made in contradiction with the prior argumentation, geothermal energy would result as the winner. Furthermore, if a couple of parameters are excluded from the trade-off, the design result does not change. Also, if the score for some parameters introduces a level of uncertainty, the given scores of one option are compared with respect to the other one. As none of those changes, alone or together, could change the outcome of the trade-off, solar energy is chosen to be the secondary energy supply system. Therefore, further investigation and trade-offs for photo-voltaic technologies must be performed in order to finalise the preliminary design of the secondary energy system. This is presented in the upcoming sections.

[3] https://www.euci.com/researchers-increase-solar-cell-efficiency-by-more-than-50-percent-cost-is-the-big-hurdle/ [Cited 13 May 2020]
[4] http://www.azurspace.com/images/products/0003422-02-02_DB_3G30C.pdf [Cited 13 May 2020]

Table 5.1: Trade-off between geothermal and solar as secondary energy source

Category	Aspect	Weight	Score	
			Geothermal	Solar
Development cost		**3**	**3**	**3.4**
	Research cost	2	3	7
	Design cost	1	5	7
	Production cost	5	5	3
	Verification cost	2	3	7
	Validation cost	4	3	5
Development risk		**4**	**4**	**6.4**
	Power requirement compliance	4	1	7
	Achievable manufacturability	5	3	7
	Design reliability	4	3	5
Mass performance		**5**	**1**	**7**
Volume performance		**4**	**3.3**	**3.8**
	Power density	3	7	5
	System volume	5	1	3
System installation		**3**	**2.2**	**6.6**
	Installation equipment required	4	1	7
	Support infrastructure required	2	3	5
	Installation risk	4	3	7
System operations		**4**	**5.4**	**6.1**
	Operational risk	4	5	7
	Likelihood system under-performing	3	3	7
	Seasonal dependency	2	10	3
System maintenance		**3**	**4.3**	**6.6**
	Component critical failure likelihood	5	5	7
	Maintainability cost	2	5	5
	Achievable maintainability	4	3	7
System retirement		**3**	**5**	**3**
Sustainability aspect		**4**	**4.8**	**6.2**
	Production	3	5	3
	Life-time	4	7	10
	Retirement	5	3	5
		Sum of category weights	**Weighted score**	
		32	**3.4**	**5.6**

5.2. Solar Energy Trade-offs

The solar energy system contains multiple aspects, which each need to be traded off to find a fitting design. There are four main aspects that need to be decided on. First, the tilt and orientation mechanism of the panel are analysed in section 5.2.1, where the rotation axis and the pointing programming method are chosen. Then the dust handling mechanism is traded-off in section 5.2.2, followed by the cell technology trade-off in section 5.2.3. The combined results of each trade-off will discussed and concluded upon in section 5.3.

5.2.1. Tilt & Orientation

Table 5.2 shows the trade-off performed to decide between 1 or 2 axis rotation capabilities of the solar panel. Only a few of the previously used categories were implemented for this trade-off as the others scored too similarly for both options, making them irrelevant for the trade-off. In general, it is a decision between making the system more complex, thus less reliable, but more efficient. Systems operations was deemed most important, thus got the highest weight. Power requirement compliance and system volume are equally important, but somewhat less compared to the systems operations category. Single axis rotation wins over dual axis rotation in the volume department only, as it would likely take less space. In the systems operations category, 2 axis rotation is slightly higher than the 1 axis rotation. One could consider these pretty much equal. Finally, the 2 axis rotation scores higher for power requirement compliance, since orienting the panel in two planes will make it more efficient in gathering sun-rays, thus complying more with the power requirement.

The conclusion of the trade-off shows that the dual axis system wins. This might be unexpected, as the system is more complex and could thus result in more points of failure. However, the risk of both rotation directions failing can be mitigated if both rotations run independent of each other. This gives another reason for which the 2 axis rotation can be seen as a better option.

Table 5.2: Trade-off for number of rotation axes

Category	Aspect	Weight	Score	
			1 axis rotation	2 axis rotation
Development risk	Power requirement compliance	**3**	**7**	**10**
Volume performance	System volume	**3**	**3**	**1**
System operations		**4**	**4.4**	**4.8**
	System complexity	5	5	3
	Operational risk	4	3	5
	Likelihood system under-performing	4	5	7
		Sum of category weights	**Weighted score**	
		10	**4.8**	**5.2**

Table 5.3 focuses on which method will be used to ensure the pointing of the solar panels. This can be done either by implementing a sun tracking sensor or the sun's position will be simulated and the program will direct the panel's pointing. The two main categories considered for this trade-off are the development risk and the operations of the system. In both categories, the sun simulation wins and thus it also wins the trade-off. This makes sense as a simulation is a lot easier to produce, and the design ends up being a lot more reliable. If a sun tracker is implemented, there is a risk that it could get covered in dust or the reflection of dust particles could make the sun tracker measure the sun's position erroneously. These could lead to serious consequences in energy harvesting. To conclude, a sun simulation is simply the less complex and a more reliable option.

Table 5.3: Trade-off for orientation programming

Category	Aspect	Weight	Score	
			Sun tracking	Sun Simulation
Development risk		**4**	**4.5**	**6.3**
	Power requirement compliance	4	7	5
	Achievable manufacturability	3	3	7
	Design reliability	4	3	7
System operations		**4**	**4.5**	**6.1**
	System complexity	5	5	7
	Operational risk	4	3	5
	Likelihood system under-performing	3	3	7
	Seasonal dependency	3	7	5
		Sum of category weights	**Weighted score**	
		8	**4.5**	**6.2**

Finally, the solar panels will have a 2 axis rotational device which allows the panel to adjust its position more accurately, and this will be commanded by a programmed sun simulation.

5.2.2. Dust Handling

Next, the dust handling mechanism needs to be investigated. The options left over from the design options tree are the following: hydrophobic coating (Hyd.), electrostatic (Ele.), removable cover (Cov.), removable cover (Cov.). The trade-off can be seen in table 5.4.

Table 5.4: Trade-off for Dust Handling

Category	Aspect	Weight	Score			
			Hyd.	Ele.	Cov.	Rob.
Development cost		**2**	**4.1**	**6.1**	**7**	**7.1**
	Research cost	3	3	5	7	10
	Design cost	2	5	7	7	7
	Production cost	2	5	7	7	3
Development risk	Design reliability	**4**	**5**	**3**	**7**	**7**
Mass performance	System mass	**3**	**10**	**5**	**3**	**3**
Volume performance	System volume	**3**	**10**	**7**	**5**	**5**
System installation		**2**	**8.8**	**7**	**5**	**7**
	Installation equipment required	3	10	7	5	7
	Support infrastructure required	2	7	7	5	7
System operations		**5**	**5.9**	**3**	**3**	**7**
	Operations risk	4	7	3	3	7
	Likelihood system under-performing	5	5	3	3	7
System maintenance		**3**	**2**	**5**	**7**	**4**
	Maintainability cost	3	3	5	7	3
	Achievable maintainability	3	1	5	7	5
Dust removal efficiency		**5**	**7**	**5**	**1**	**7**
		Sum of category weights	**Weighted score**			
		27	**6.5**	**4.8**	**4.3**	**6.0**

It is easy to tell that the electrostatic and solar panel cover options are not winning this trade-off and from a logical point of view, they are the weakest options. The design options that are left, are hydrophobic coatings and robotic arm dust removal. Both these options are very viable options and they are equally efficient in removing dust. Coatings still require a lot more research and testing to be done to see whether they would work as intended on Mars, however they are passive and only nanometers thick[84]. Furthermore, although the robotic arm needs less research, it will be a more complex design and thus there are more points of failure. Following from table 5.4, hydrophobic coatings win and will be applied to the solar panels to ensure dust removal.

5.2.3. Cell Technology and Module Level Design

Here the cell technology that will be used for the solar panels will be decided upon. The options that are up for consideration are III-V technology and Crystalline Silicon (c-Si). The trade-off can be seen in table 5.5.

Table 5.5: Trade-off between III-V and c-Si cell technology

Category	Aspect	Weight	Score	
			III-V	c-Si
Development cost		**2**	**4.0**	**7.8**
	Research cost	2	5	10
	Design cost	2	5	7
	Production cost	4	3	7
Mass	System Mass	**4**	**7**	**5**

Continued on next page

Table 5.5: *Continued from previous page*

Category	Aspect	Weight	Score	
			III-V	c-Si
Volume	Power density	**3**	**5**	**3**
Conversion efficiency	Efficiency	**4**	**10**	**5**
System operations		**5**	**6.6**	**5.4**
	Operational risk	1	5	7
	Seasonal dependency	4	7	5
Sustainability	Production	**3**	**3**	**7**
		Sum of category weights	**Weighted score**	
		21	**6.3**	**5.4**

From this trade-off it is clear that the III-V cell technology wins over the c-Si. The c-Si is a first generation technology which makes it very reliable as much is known about its applications and the performance in space. The III-V is a newer technology, therefore there is still room for further research and there are some uncertainties in its technology. However the efficiencies of III-V are much higher and these cells have also been widely used in space already [71]. Furthermore, physical properties of III-V semiconductors allow the customisation of the cells to fit the specific spectrum of the martian environment, further increasing its efficiency and applicability to this mission. Therefore III-V is the winner of this trade-off. It should be noted that the aspects “Likelihood of system under performing”, “Degradation of cell efficiency” and the “Retirement” aspect of the sustainability were considered in the trade-off. However both cells scored the same, as equal performance was expected. As part of the sensitivity analysis, these aspects were thus removed.

In the baseline report, multi-junction cells were also discussed. “In multi-junction cells, several cell materials with different bandgaps are combined in order to maximise the amount of the sunlight that can be converted into electricity. To realise this, two or more cells are stacked onto each other.” [71]. By creating a multi-junction of multiple III-V semiconductor materials, high efficiencies can be reached. The technology has already proven itself as primary energy source for several Mars Exploration Rovers[5] [41]. As this technology can be applied to any cell technology, it was left from the trade-off as it could be used regardless of the winner.

As for the module, which is the assembly of different cells, three possible options were selected in the Baseline Report. However, the choice for III-V cell technology has led to a reconsideration of which concepts to select for the trade-off. This is because producing III-V cells and modules are two distinct steps that cannot be separated from each other. And because the layers of III-V semiconductor materials required for generating photoelectric current are already extremely thin, it can be considered to be a thin-film module. As a result, it would be better to consider a trade-off between a planar module and concentrator photovoltaics (which are either curved or need lenses).

From the trade-off, which is presented in table 5.6, it can be concluded that a planar module is preferred over concentrator photovoltaics (CPV). On the one hand, the efficiency from CPV is higher because of the increased irradiance. On the other hand, CPV relies on direct irradiance for power generation[71], and performs bad under diffused irradiance conditions, which is the case when the optical depth of the atmosphere is reduced (e.g. due to presence of dust). Therefore seasonal changes reduce the reliability in terms of power output for CPV. The planar module is also less complex, both for the development phase as the system installation phase. In conclusion, the planar module is the chosen option.

Table 5.6: Trade-off between planar and concentrator modules

Category	Aspect	Weight	Score	
			Planar	Concentrator
Development cost		**2**	**7.1**	**4.4**
	Research cost	2	10	7
	Design cost	4	7	3
	Production cost	2	5	3

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[5]https://janes.ihs.com/Space/Display/JSD_A080-JSD_ [Cited 13 May 2020]

Table 5.6: ***Continued from previous page***

Category	Aspect	Weight	Score	
			Planar	Concentrator
	Verification cost	3	7	5
	Validation cost	3	7	5
Development risk		**3**	**5.9**	**6.1**
	Power requirement compliance	5	5	7
	Achievable manufacturability	4	7	5
Mass	System mass	**4**	**5**	**7**
Volume	System volume	**4**	**7**	**5**
System installation		**3**	**7.0**	**3.8**
	Installation equipment required	2	7	5
	Installation risk	3	7	3
Structural rigidity	Ability to withstand loads	**2**	**7**	**5**
System operations		**5**	**5.8**	**3.8**
	Likelihood system under-performing	3	7	5
	Seasonal dependency	5	5	3
		Sum of category weights	**Weighted score**	
		23	**6.2**	**5.0**

5.3. Secondary Energy System Results

From the trade-offs that were discussed in the previous sections, a final conceptual design for the solar energy unit is determined. The system will be based on multi-junction cells from III-V semiconductor materials, that are structured into a planar module. These modules will receive a hydrophobic coating to prevent dust adhesion. Furthermore the panels that are made up of the III-V modules, will be supported on a 2-axis system. This will allow the panels to move accurately, using a pointing system based on a sun simulation to maximise the power output. With this concept decided, the preliminary design of the solar energy unit can follow. The preliminary sizing can be found in chapter 8.

6
Power Management and Storage Solutions Trade-Offs

In this chapter the trade-off for the power management will be performed. Starting with the trade-off between DC and AC currents and following the final conclusion will be elaborated upon. Secondly, the trade-off to determine the energy storage solution will be done. First to determine the seasonal storage, and afterwards the day-to-day storage will be decided upon.

6.1. Power Management Trade-off

In this section, a comparative analysis of AC and DC microgrids is performed. First, the pros and cons of DC and AC with respect to the Mars concept are summarised in table 6.1 [5, 37]. Following, a trade-off is performed between the two options. The chosen concept will be the one implemented in the Renewable Energy System.

Table 6.1: Advantages and disadvantages of AC versus DC for grid bus

	DC (Direct Current)	**AC** (Alternating Current)
Advantages	• Less power converters required, increasing overall system efficiency and lower total system mass. • Better controllability. • Only voltage drops needs to be monitored and can be immediately and locally detected. • No skin effect in cables (allows the current to flow through the entire cable and not just the outer edges, reducing losses and providing possibility to use smaller cables) • DC systems are likely to become cheaper in the future because of increased research and economy of scale	• AC voltages can be readily transformed to higher or lower voltage levels, more difficult with DC voltages. • AC infrastructure is well-developed and widely-used on Earth with scale. • Typically carries higher voltages with lower power loss
Disadvantages	• Protection is more difficult as there is no natural zero crossing of the current • Implementation of DC grids is currently very limited on Earth and on small scale • DC infrastructure typically experiences higher grounding and corrosion issues	• Need for continuous synchronisation (phase, frequency) of distributed energy resources. • Need for additional reactive power control units: capacitors, inductors etc. • AC transformers are typically made from copper and steel, which are heavier than power electronic converters (difference in the order of 10) • Both voltage and frequency needs to be monitored

6.1.1. Weights of Categories and Aspects

Development cost: The development cost of the microgrid is not considered the most critical category. This is because the process of designing a renewable energy system for a Mars habitat is an ambitious mission with significant risks, categories like effectiveness, operation and maintenance are considerably more important. Research is detailed on Earth-based power management systems and architectures. Hence, there is little-to-low financial costs for research and development of such systems. The only development costs associated with the system would be adapting the materials (such as insulating casing) to the Martian atmosphere and radiation conditions. In short, the development cost is only of minor importance in evaluating between the main grid bus channel options.

Within the development cost, five different aspects are distinguished. Because the effects of the hostile and unfamiliar Martian atmosphere on the hardware must be investigated, research and verification are assigned a moderate weight. Production and validation cost are of minor importance and finally the design cost is negligible.

Mass, Volume and Efficiency: The effectiveness of the microgrid is considered as the degree to which it is capable of transmitting power with minimum losses for a certain mass or volume. The mass is of severe importance because of launcher mass budgeting constraints. The volume is less relevant compared to the mass, as cabling is material-dense, which thus has a moderate weight together with volume. Finally, the efficiency is of severe relevance. This is because if the efficiency of overall power distribution system is low, the energy resources need to supply more energy to be able to meet the same power demand, which in turn leads to a higher energy supply system mass, volume, cost, etc.

System installation: Although this aspect requires future research and design, it is likely at this point that the system needs to be deployed semi-autonomously. This is because the robots, which manufacture the Mars habitat, also need energy from the renewable energy system. Therefore, the system installation is moderately important.

System operation: System operation is a severe concern in the design of a microgrid, because a non-optimal operation of the distribution system potentially leads to a total black-out. Within system operation, three aspects are considered. The potential operational risk to the astronauts and the project is of minor importance, because of the low probability. The operational complexity is of significant importance. A power system is a complex system which comprises many interrelated components that all function together. Any effort to reduce the complexity facilitates operation. Finally, the controllability is the most severe aspect of operations.

System maintenance: System maintenance is equally important, and also weighted severe. This category comprises four different aspects. The first one, reliability, is the most important. The system reliability should be maximum, as low reliability increases the chance of failure, whether it is component or system failure. Possible failure poses a great risk to the mission, and is unacceptable. Next, replacement cost & effort is also a significant concern. In fact, a faulty component must be able to be replaced by astronauts or robots. Therefore the effort should be minimum. Problems in power systems are usually detected by computers, as component inspection is not always easy. Ease of problem detection is of significant importance, however, and component inspection is of minor concern.

Sustainability: As sustainability in energy systems is mostly achieved in the power-generating or power storing systems, it is of minor importance for the microgrid. As the electronic hardware is readily available on Earth, production is considered less important than retirement in terms of environmental impact. The retirement on Mars is a significant concern and it should be well designed for.

6.1.2. Scores for AC Microgrid

The **research** associated with realising an AC grid on Mars is considerable. In table 6.1, it is explained that AC grids are well-developed and widely used on Earth. However, the impact of the Martian environment on the system should be researched. Both arguments combined lead to a sufficient score for AC on this aspect. As electrical power engineering is a rather complex discipline, the cost associated to **design** is considerable and therefore the AC grid scores marginally. Similarly, the **production cost** also receives a marginal score. Even though the AC microgrid requires extensive **verification** and **validation**, the available software to perform this is well developed. Therefore, a good score and a sufficient score is given to verification and validation, respectively. Overall, in terms of development cost, the AC microgrid receives a weighted score of 5.

AC microgrids require many power electronic devices and transformers to be able to facilitate the connection of various distributed energy resources. Evidently, these components all add **mass** and **volume** to the system. Furthermore, every power converter increases the power loss slightly, reducing the overall system **efficiency**. Hence the AC microgrid deserves a marginal score for mass and volume, and a sufficient score for efficiency.

As explained before, many power converters are needed for a successful implementation of the AC microgrid. Every component reduces the **plug & play factor**. Accordingly, the AC microgrid receives a marginal score. The weighted score for system installation is 3.0.

Concerning system operation, the operational risk increases with increasing mechanical parts, complexity, and controllability. **Operational risk** can be associated with a component malfunctioning and therefore putting the astronauts or the project in danger. For AC, due to its hazardous nature, and the microgrid being composed of more components compared to DC, the operational risk is more pronounced than for DC. Therefore it is given a marginal score. The **operational complexity** is also quite high. Not only does an AC microgrid require more power converters, but it also requires inductors and capacitor banks for reactive power control. AC is given a sufficient score on this point. Lastly, as explained in table 6.1, AC requires more parameters to control in comparison to DC. Although recent research and development increased the **controllability** of AC microgrids, it is not as simple as for DC microgrids. Therefore AC was given a good score for controllability. After processing the different aspect scores, the category score is 5.5.

Closely tied to the previous category is the system maintenance. As explained before, the **reliability** of the microgrid decreases when more components are added to the system. As an AC microgrid requires many power electronic devices just for synchronisation, the reliability is lower for AC in comparison with DC microgrids. Therefore AC scores marginally on this aspect. Replacement of parts or components should preferably not happen, as the cost and effort is high. The score associated to **replacement cost & effort** is poor. AC microgrids are monitored on the system level. The **ease of problem detection** is good, however it is not as good as for DC microgrids. This is because for the latter, only voltage drops are monitored and can be locally detected, instead of at the system level. Finally, **component inspection** remains a challenging aspect for both AC and DC microgrids. With AC being composed of many power converters, it receives only a sufficient score. The weighted average of all the scores results in a 3.8 for AC system maintenance.

Finally, the sustainability aspect of **production** and **retirement** of microgrids is not very straightforward. The primary focus of this project is on the design of the wind energy system. For the microgrid, the individual components are not designed, but instead off-the-shelf components are chosen. In terms of both production and retirement, they are not always very sustainable. Therefore, the AC microgrid scores marginally on both production and retirement. Overall, the AC microgrid receives a 3.0 in terms of sustainability.

6.1.3. Scores for the DC Microgrid

Overall, the total development cost of a DC microgrid is very similar to that of an AC microgrid. One main difference is in the **research cost**. This is because DC microgrids are not widely applied on Earth yet, so there is still quite a lot of research and development to perform. Here also, the effects of the Martian atmosphere should be investigated. Therefore the DC microgrid receives a marginal score. There is no difference in **design cost** compared to an AC microgrid, as off-the-shelf components are selected instead of designing all the individual components. Furthermore, the design process is similar. This results in a marginal score for DC. The **production cost** is also different compared to AC, because less power converters are required. Therefore less components need to be manufactured, evidently decreasing the cost. In terms of production cost, DC is rewarded a sufficient score. For **verification** and **validation**, similar to the reasons explained in the previous subsection, a good and a sufficient score is given respectively. All together, the DC microgrid receives a weighted score of 4.8 with respect to development cost, which is a slightly lower score than for the AC grid.

In terms of effectiveness, however, the DC microgrid clearly outperforms the AC microgrid. This has to do with the fact that the DC microgrid comprises less power converters, because e.g. no frequency or phase adjustments need to be done before connecting the distributed energy resources to the DC bus. Consequently, the **mass** and the **volume** are reduced. Another consequence of using less power electronic devices is an increased overall system **efficiency**. In conclusion, the scores for mass, volume and efficiency respectively are good, sufficient and good respectively.

Another consequence of the DC microgrid having less system components is the system installation. The **plug & play factor** is better compared to the traditional AC grid, and receives a sufficient score. The weighted score for system installation is 5.0.

The following category is system operation. Some considerations for **operational risk** have already been mentioned in the previous subsection. It must be noted that DC microgrids may suffer from grounding issues. However, with sufficient research these problems may be overcome and it will not be a risk to astronauts or other equipment anymore. Also noteworthy is the fact that DC is less hazardous than AC. Overall, the DC microgrid is rewarded a sufficient score with respect to operational risk. The **complexity**, in its turn, is reduced in comparison to AC, because of the fewer components. Therefore the DC receives a good score on this point. Finally, the **controllability** is enhanced because e.g. voltage drops can be detected and solved locally, as suggested in table 6.1. Hence the score for controllability is great. In conclusion, DC receives a 8.0 in terms of system operation.

In addition to operation, system maintenance is heavily influenced by the number of components that constitute the microgrid. While the DC microgrid comprises less power converters, it has a higher **reliability** than the AC microgrid. Therefore the score for reliability is good. Concerning the **replacement cost & effort**, this aspect is still a problem for the DC microgrid. However because of the fewer components, it is slightly better than for AC microgrids and therefore receives a marginal score. The **ease of problem detection**, however, is great. Voltage drops can be immediately and locally detected. The **ease of component inspection** is slightly better for DC microgrids, because fewer components need to be inspected. Therefore the score for DC on this aspect is good. In conclusion, the category of system maintenance deserves a score of 6.7 for DC.

Finally, the sustainability aspect is taken into account. As the considerations for DC and AC are pretty much similar, they receive the same score. A marginal score is given to the DC microgrid on both the **production** and **retirement** aspects. Therefore, the DC microgrid receives a 3.0 for sustainability.

6.1.4. Results of AC/DC trade-off

Once the scoring and weighting of all the categories and aspects is done, the conclusiveness of the final results is examined. First, it is noticed that both design options perform equivalently with respect to sustainability, so this category is removed and not included in the following table 6.2. Additionally, the behaviour of the trade-off was examined through the suggested steps in the sensitivity analysis method in chapter 3. Finally, it was evident that the DC has more advantages compared to an AC grid, and no reasonable alternations of the weights and the scores, would make AC the winning technology. Therefore, a DC migrogrid will be implemented in the design of the hybrid renewable energy system for the Martian habitat.

Table 6.2: Trade-off between Alternating-Current microgrid (AC) and Direct-Current microgrid (DC)

Category	**Aspect**	**Weight**	**Score**	
			AC	**DC**
Development cost		**2**	**5.0**	**4.8**
	Research cost	3	5	3
	Design cost	1	3	3
	Production cost	2	3	5
	Verification cost	3	7	7
	Validation cost	2	5	5
Mass	Total system mass	**5**	**3**	**7**
Volume	Total system volume	**3**	**3**	**5**
Efficiency	Power losses	**5**	**5**	**7**
System installation	Plug & Play factor	**3**	**3**	**5**
System operation		**4**	**5.5**	**8.0**
	Operational risk	2	3	5
	Operational complexity	4	5	7
	Controllability	5	7	10
System maintenance		**5**	**3.8**	**6.7**
	Reliability	5	3	7
	Replacement cost & effort	4	1	3
	Ease of problem detection	4	7	10
	Ease of component inspection	2	5	7
		Sum of category weights	**Weighted score**	
		27	**5.5**	**8.8**

6.1.5. Cable Infrastructure

In the following paragraphs, a qualitative trade-off is carried out to decide on the final cable infrastructure, which will be further developed for the preliminary design of the microgrid. Initially, three options were considered, namely: underground, on ground and overhead cables. Before entering the trade-off, the ”on ground” cable infrastructure can already be ruled out. This is because high voltage cables on the ground are hazardous and would be too high of a risk to astronauts and possibly other equipment. Thus the two concepts left to be evaluated are underground and overhead distribution cables.

On Earth, the most common infrastructure for transmission lines is overhead. Even though this is mostly for financial reasons [53], there are a few more advantages of using overhead lines. The air surrounding the cables is a natural insulator, and a cooling medium for the conducting cables that heat up do to their resistance. The latter argument would nevertheless be irrelevant for the Martian environment, because temperatures are already low. Air as the surrounding medium has some disadvantages as well though, namely the occurring of corona [66]. Finally, installation of overhead cables is cheap compared to the digging required for laying underground cables.

The Martian environment, however, provides new perspectives in terms of cable infrastructure. By placing the cables underground, they are not vulnerable to damage from dust storms, which pose a significant risk to overhead cables. From a safety point of view, underground cables is also the best option, as they are less of a risk to astronauts and other equipment. The complication of underground cables mentioned in the previous paragraph about the required digging is not of a big concern because of the availability of the robots that build the Mars habitat. Furthermore, an overhead cable infrastructure on Mars requires support structures, adding mass to the system. It is not feasible to bring this from Earth to Mars, and utilising in-situ resources is challenging. Lastly, it must be noted that inspection and maintenance is difficult for underground cables.

To conclude the trade-off, it is decided to go with underground cables. They are by far the safest option, and less challenging to install. In order to prevent maintenance issues, extra care should be taken during the preliminary design stage to maximise reliability of the distribution cables.

6.2. Storage Solutions Trade-offs

In the following section the engineering trade-offs regarding the storage solutions required, are discussed. As evident from the DOT presented in chapter 3, there are fours design options that could be implemented for day-to-day or seasonal energy storage; it already had been decided that phase change materials and super-capacitors will be implemented in the detail system design for the purposes of thermal isolation and power distribution management, respectively . Hence, the remaining trade-off options are the following: compressed air (CAES), gravitational storage (Grav.s.), secondary batteries (Sec.Batt.), and regenerative fuel cells (RFC).

In order to scale the option's performance and fill in the trade-off tables, the following procedure is implemented. First, quick calculations regarding the general size required for the storage solutions, are performed. Secondly, the strengths and weaknesses of the options along with their compliance potential with the storage requirements, are evaluated. Finally, the sensitivity of the trade-off results is analysed and a final solution is found. Due to the great size of seasonal storage solutions, there are more design limitations present and the sizing of the seasonal system would account for the day-to-day storage capacity by the same token. Hence, design options to find a suitable seasonal solution are qualitatively evaluated first, followed by a trade-off analysis for the day-to-day solution.

6.2.1. Seasonal Storage Solution

To determine which storage solutions would be applicable to the seasonal storage, a primary estimation was made to determine if the storage solutions would hold the energy required while being of reasonable size. The first step was to determine the approximate storage required for a day of energy, as seasonal storage would require the capacity for multiple days of energy. For this computation a safety factor of 1.5 was considered, as there are many uncertainties at this stage. Moreover, the technologies described still require more development before they are fully conform with the system requirements and have sufficient design reliability.

The preliminary estimation was done by a simple calculation where the 10 kW was multiplied by the amount of hours in the Martian day (24.6 h) and the safety factor of 1.5 as discussed above. This means 369 kWh of required storage per day. When estimating the weight and height for the gravitational storage however, the mass necessary would be outrageously high for the mission. In the scale of 10^6kg. Additionally the secondary battery and RFC solutions, would require very large facilities[1] to create enough capacity for seasonal energy storage. This would not be possible to realise within the mission requirements considering the mass and volume that would need to be transported. Therefore, it was decided to discard this options and select the compressed air energy storage as the seasonal storage solution.

A large benefit of the CAES, is that for the storage of the compressed air there is the possibility of using one of the underground compartments that already exist within the structure of the Rhizome habitat. As they are lined with an airtight material[6], there will be no leakage of the air into the surrounding structure. If more storage is needed, another compartment can be dug to increase the volume. Furthermore, this would also negate the need for a storage tank to be brought up from Earth, making CAES even more compliant with the mission. To further adapt to the Martian atmosphere and minimize transport costs, carbon dioxide (roughly 95% of atmosphere) [28] can be utilised as the main gas element of the CAES system.

6.2.2. Day-to-day Storage Solution

Once, the seasonal storage solution design option has been decided upon, the day-to-day storage could be determined. As gravitational storage was excluded as it is not competitive with respect to weight, performance or sustainability to any of the other three design options. Therefore, only compressed air energy storage, secondary batteries and regenerative fuel cells are considered. At this stage, it is paramount to note that those 3 technologies are most likely going to be already present in the system as CAES is used for seasonal energy storage, rechargeable battery modules will surely be used in the space launcher and a hydrogen fuel

[1] https://www.hydrogenics.com/wp-content/uploads/Kolon-MW-Power-Plant2.jpg [Cited: 15 May 2020]

cell will be implemented for oxygen production for the habitat [6]. Nevertheless, a trade-off is necessary to evaluate which of those technologies are most suitable for the needs of a day-to-day storage solutions.

Therefore, the same relevant categories as described in chapter 3 are used for the following trade-off, including an extra one which evaluates the regained energy efficiency. Additionally, this category along with the mass and operational performance of the design options, are of biggest relevance to the trade-off; thus they have been weighted by 5 as they can have severe impact. Moreover, development costs and risk, volume performance, system installation and maintenance are of significant importance for this subsystem; lastly, the retirement and sustainability are of moderate relevance and have been weighted by a 3.

Furthermore, for three of the general aspects, namely, the maintainability cost, achievable manufacturability and the life-time sustainability emissions, it is evaluated that the design option perform equally with respect to one another and have been removed from the table. Following, it is noticed that in the development risk category, the two remaining aspects namely, storage requirement compliance and design reliability have been evaluated with the same scores for each design option. Therefore, the aspects are removed and a single score is assigned to the category. This is also fully applicable to the sustainability category where the production and retirement aspect are evaluated with the same performance score for the design option. Hence, a single sustainability category is kept. All the categories and aspect and their respective weights are as recorded in the following table 6.3.

Compressed air storage could be suitable as a solution for the required day-to-day storage as it is already utilised as a seasonal solution and has high cycle life. Furthermore, the characteristic of this technology allows for indefinite capacity as it is depended solely on the available site storage volume and gas. On the other hand, for secondary batteries, their storage capacity is directly related to their total weight which should be transported from Earth to Mars, and back. Furthermore, regenerative fuel cells are an intermediate design option as you do have to transport some of the storage volume (the hydrogen tank), while water could be sourced on Mars and oxygen could be stored in a similar manner as the compressed air solution. In addition, secondary batteries and fuel cell are hardly maintainable once brought to Mars which is quite unfavourable considering the mission duration of almost ten years. Moreover, the production method of the last two technologies are quite unsustainable which also results in hardly recyclable or disposable components.

In addition, due to the hazardous nature of hydrogen, the operational risk of regenerative fuel cell storage system would be quite high. This technology specification also would require some logistical distance between the hydrogen tank, the oxygen storage facility and the habitat. Hence, this would result in increased response time of the system and would require a great deal of piping. Furthermore, hydrogen has quite low specific capacity if not pressurised. Therefore, such a system demands either storage tank of great volume or a pressurising devices along other necessary temperature regulators. Hence, the resulting total regained energy efficiency can not compete with CAES and battery technology.

Table 6.3: Trade-off between CAES, secondary batteries and RFC for day-to-day energy storage

Category	Aspect	Weight	Score		
			CAES	S.Bat.	RFC
Development cost		**4**	**5.3**	**5.7**	**3.7**
	Research cost	3	7	5	3
	Design cost	3	7	7	5
	Production cost	2	5	5	3
	Verification cost	2	5	7	5
	Validation cost	4	3	5	3
Development risk		**4**	**7**	**7**	**5**
Mass performance		**5**	**5.8**	**3.8**	**3.0**
	System mass	5	5	3	3
	Specific capacity	3	7	5	3
Volume performance	System volume	**4**	**5**	**5**	**1**
System installation		**4**	**5.8**	**8.2**	**4.2**
	Installation equipment required	4	5	10	5
	Support infrastructure required	2	5	7	5
	Installation risk	4	7	7	3
System Operations		**5**	**6.1**	**7.6**	**4.5**
	Operations risk	4	7	10	3

Continued on next page

Table 6.3: ***Continued from previous page***

Category	Aspect	Weight	Score		
			Planar	**Concentrator**	
	Response time	3	5	10	5
	Cycle life	5	7	5	3
	Energy dissipation	5	5	7	7
System maintainance		**4**	**7**	**5**	**5**
	Component critical failure	5	7	5	5
	Achievable maintainability	4	5	3	3
System retirement		**3**	**7**	**7**	**5**
Sustainability		**3**	**5**	**3**	**3**
Regained energy		**5**	**5**	**10**	**3**
		Sum category weights	Weighted Score		
		41	**5.8**	**6.3**	**3.6**

The weights and scores in the above table have been filled in by two team members presenting argumentation in the lines of the text above. Furthermore, it has been discussed with a third party and it was established that the assigned points are reasonable. Once the table was completed, the overall lack of advantages of implementing regenerative fuel cells for the purposes of a day-to-day storage solution, became evident. Hence, it was excluded as a design option. Hereafter, compressed air storage is with a losing score compared to secondary batteries. Nevertheless, the sensitivity of the trade-off analysis of the last two options had to be examined.

Therefore, the relationship of the final result to the inputs is further investigated. The trade off table is re-examined with only the compressed air storage and batteries. Furthermore, and all aspects with the same score are given a weight of 0 in order to increase the trade-off sensitivity. The score for secondary batteries remains the same at 6.3, while the score difference increases as the performance score of CAES has lowers to 5.4. Furthermore, the sensitivity of the analysis was examined through altering the weights and scores for different categories and aspects. It was evident that no amount of changes within reason would result in the CAES technology as a winner. Additionally, battery technology would be necessary during space travel and at the beginning of the on site operations as the CAES installation would require energy and time. Thus, secondary batteries have been selected for the purpose of providing day-to-day energy supply to the habitat.

7
Site Selection and Energy Resource

This chapter delves into the site selection for the habitat and the energy system on Mars. This is a crucial aspect for the mission as the wind, solar and other natural resource are not uniformly distributed on the planet. Hence, in order to ensure that the mission is performed successfully, a trade-off and selection for the location on Mars have to be performed so that the user's and operative requirements are fulfilled.

7.1. Site Selection

It is important to understand that the main characteristics driving the selection for the appropriate site on Mars are based on the necessities of a Martian habitat along with the necessary energy resource for a fully operative and effective power generation grid. Therefore, a good starting point to find possible location candidates is to pay special attention to the areas that can at least fulfil the most basic of requirements for a manned mission: the availability of water. Furthermore, as specified by the CEDL Design Team at NASA, the maximum allowed elevation for landing is -1000 m Mars Orbiter Laser Altimeter (MOLA)[1].

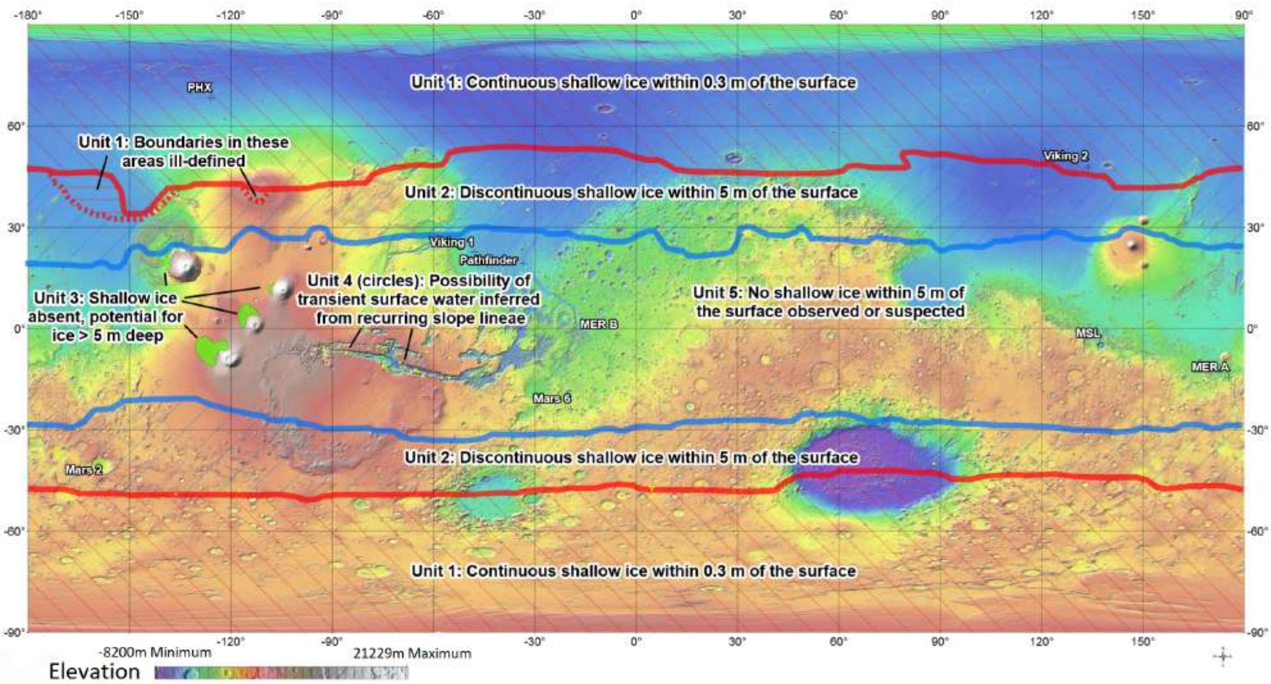

Figure 7.1: Map of presence of water on Mars [64]

Figure 7.1 serves as a good starting point to understand the potential of Mars as a place that can harbour life and provide useful resource for an Earth-independent, sustainable human settlement on Mars. Based on the landing site selection workshops conducted by NASA for its Mars 2020 mission, as well as other available information on future Mars colonisation missions, a list of plausible locations for which there is enough available information can be compiled. These are individually discussed in the following subsection and are also visualised on the map in figure 7.2 below:

[1] https://marsnext.jpl.nasa.gov/workshops/2014_05/05_LSW1_EDL_Eng_Constraints_v6.pdf [Cited 11 May 2020]

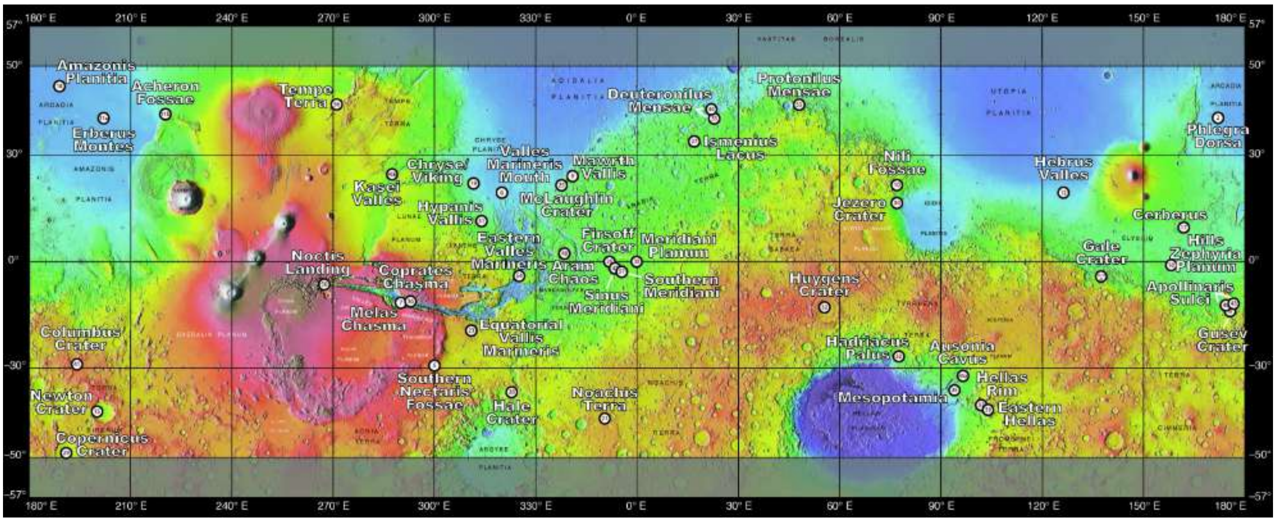

Figure 7.2: Map of all site candidates for the NASA Mars 2020 mission[2]

7.1.1. Site Candidates

The following section provides a brief introduction of the seven sites on Mars chosen as a result of the first round of selection based on the NASA landing site selection workshops[3] and from the known SpaceX landing site candidates for its upcoming Mars Starship mission[4]. From this, a detailed trade-off is conducted to determine the site where all subsequent subsystem designs will be based on. The candidates are as following.

Eberswalde: Eberswalde Crater is located on the southern hemisphere relatively close to the equator. Although this means that it is located in the area where it is suspected that there is no shallow ice below the surface within a six metre distance, it is known as the "longest and possibly the deepest drainage system on Mars"[5]. Furthermore, the likelihood of finding microbial life in this area is relatively high. The site is located at -1400 m, so it does not pose any problem for entry, descent, and landing (EDL), and the dust exposure is relatively low. Nevertheless, even if this site offers promising characteristics from a scientific point of view, it is deemed unsuitable for the habitat due to the high uncertainty of the availability of water and is not included in the trade-off.

Jezero: The Jezero Crater is located north of the Isidis Planatia, in northeastern Mars. The crater is rich in natural resource, which makes it a perfect choice for ISRU for additive construction processes. Furthermore, it is very relevant for its scientific potential as it is a site where organic matter could possibly be found[6]. These are the main reasons why this site was chosen as the landing site for the Mars 2020 rover mission[7]. Nevertheless, no proof has been found that would suggest a habitat establishment possibility, as there is no evidence of ice close to the surface. Hence, this site is also deemed an unsuitable location for the Mars habitat and is not considered in the following trade-off.

NE Syrtis: The Northeast Syrtis is an exploration zone (EZ) located 30 km from the Jezero Crater also on the edge of Isidis Planatia. This area is easily mappable from orbit, thus making the local navigation simple. In addition, the site has gone through several aqueous and volcanic phases implying it has high research potential. Furthermore, an extreme lack of dust characterises this region, which is beneficial for the generation of solar energy. While the site is ideal to study, it is located below the discontinuous water line and there are only traces of water from the past. Thus, this option has also turned out to be unsuitable.

Melas Chasma: Melas Chasma is a canyon located close to the equator. It is known that the local winds are the strongest here compared to any other place on Mars. Its elevation ranges between -0.7 and -5 km, which makes it the lowest elevation point close to the equator[8]. The ground is rich in raw materials, which can be used for ISRU. Moreover, this site is composed of both calm and windy areas, which are located fairly close to each other. This allows to have the habitat and the energy generation system at separate places close to each other, such that the needs of both are fulfilled. All these characteristics make this location a

[2] https://www.nasa.gov/sites/default/files/thumbnails/image/map-of-proposed-exploration-zones.jpg [Cited 11 May 2020]
[3] https://mars.nasa.gov/mars2020/mission/science/for-scientists/landing-site-selection/ [Cited 11 May 2020]
[4] https://behindtheblack.com/behind-the-black/essays-and-commentaries/spacex-begins-hunt-for-starship-landing-sites-on-mars/ [Cited 11 May 2020]
[5] https://www.nasa.gov/sites/default/files/atoms/files/post_hls2_workshop_polling_and_feedback_compendium.pdf [Cited 11 May 2020]
[6] https://www.nasa.gov/sites/default/files/atoms/files/mustard_human_landing_october-2015.pdf [Cited 11 May 2020]
[7] https://www.nasa.gov/press-release/nasa-announces-landing-site-for-mars-2020-rover [Cited 11 May 2020]
[8] https://www.nasa.gov/sites/default/files/atoms/files/e-melas-ez.pdf [Cited 11 May 2020]

good candidate for the final site trade-off.

Erebus Montes and Acheron Fossae: Erebus Montes and Acheron Fossae are exploration zones in the north-western mid-latitudes of Mars between the Arcadia and Amazonis Planitiae. These regions are considered as two of the most interesting options for a possible location for a Mars habitat, since they are located at relatively low latitudes, at which there is abundant subsurface ice within the uppermost few metres of regolith[9]. According to Viola et al. [79], both of these regions have a low elevation (between -3.98 and -3.15 km) and a relatively flat terrain, which make them ideal to facilitate EDL[8]. These are, however, regions that are moderately dusty, which could potentially pose additional problems for the solar energy subsystem, as well as the exploration aspect of future missions. For this reason, these EZ can be evaluated as suitable candidates for the final trade-off to select the location of the Mars habitat. For simplicity, these two EZ will be considered as "single" EZ as they are located relatively close to each other and have most of their key characteristics in common.

Phlegra Dorsa: Phlegra Dorsa is an EZ in the vicinity of the Phlegra Montes mountain range in Arcadia Planitia. According to Barker et al. [4], it is a candidate location that has a very substantial amount of shallow ice content with a relatively low dust content[8]. It is a zone with little rock and boulder presence, and has a low elevation, which is ideal to maximise atmospheric braking performance for entry, descent, and landing. Moreover, evidence has shown that this zone has potential for finding useful materials for ISRU processes and constructions, as well as several points of high scientific interest for exploratory purposes. Hence, this EZ is deemed a suitable candidate for the final trade-off to select the location of the Mars habitat.

Deuteronilus Mensae: Deuteronilus Mensae is an EZ in the north of Arabia Terra presumed to be the remains of a northern low-lands ocean. It is located at an elevation of -4 km and it is surrounded by cliffs and ridges at higher elevations. According to Head et al. [29], it is also speculated that these rocky formations might have been shaped due to wind erosion, which can be a valuable resource for the wind energy generation system[8]. Moreover, this EZ is optimal for the EDL operations due to its low elevation, and is also a very interesting option for its scientific potential. Furthermore, it is a region where shallow, high quality ice (i.e. high grade and high concentration) is available for extraction. Additionally, this EZ shows high potential of usable materials availability for ISRU and in-space manufacturing (ISM). For this reason, this EZ is considered a suitable candidate for the final trade-off to select the location of the Mars habitat.

7.1.2. Final Site Selection

The five sites that were identified as feasible can be seen in the second row of table 7.1. As already mentioned, Erebus Montes and Acheron Fossae were considered together as these are relatively close, thus their characteristics are similar. The others are spread out all over the planet, hence the characteristics are different.

The first criteria considers water resource. This is not strictly related to energy generation, but it was considered to be of top priority as the habitat will eventually need water when astronauts arrive. Civil engineering aspects were added to guarantee that a habitat can be built in the area and that it is easily accessible. Available resource also have been taken into account to be able to provide materials for ISRU. The primary energy system is powered by wind, thus wind is an important aspect of the mission. In order to reduce thermal stresses, high thermal inertia and low variation in extreme temperatures is desired. During dust storms, particles greatly increase optical depth, which reduces solar radiation, so a low maximum value is desired. Low elevation makes EDL easier, while high dust index means that more sun light hits the ground and more solar energy can be generated.

Part of the criteria and the scores were taken from the NASA site selection workshop[10] and part of it was formulated based on requirements. The weights and scores both ranges from 1 to 5, 5 being the most important or best performing and 1 the least.

[9] https://www.nasa.gov/sites/default/files/atoms/files/mars-c-abstracts_in_order_of_presentation10242015_0.pdf [Cited 11 May 2020]
[10] https://www.nasa.gov/journeytomars/mars-exploration-zones [Cited 14 May 2020]

Table 7.1: Final site selection trade-off

		Score			
Criteria	**Weight**	**Melas Chasma**	**Erebus Montes & Acheron Fossae**	**Phlegra Dorsa**	**Deuteronilus Mensae**
Water resource					
Potential for ice or water	5	2	5	5	5
Located no more than 3 metres below the surface	4	5	4	5	2
Civil engineering					
50 km^2 of flat terrain with sparse rock distribution	2	2	1	3	4
1-10 km length scale: <10°	2	2	3	4	4
Construction resource					
Potential for metal/silicon	4	4	2	5	5
Located no more than 3 metres below the surface	4	4	4	4	5
Wind					
Average wind speed	4	4	2	3	3
Peak wind speed	4	4	1	2	3
Temperature					
High thermal inertia	2	5	1	3	4
Extreme temperatures (ground)	3	4	3	3	3
Solar					
Low optical depth	3	1	4	4	4
Operations					
Low elevation	4	5	4	4	4
High dust index	3	4	1	3	2
		3.6	**2.7**	**3.2**	**4.1**

As one can observe from the table above Deuteronilus Mensae is the final choice for the landing and habitat location. This site is especially good in the top-rated criteria like water and construction resource and is decent in every other aspects. Nevertheless, in order to guarantee the reliability of the results, it is handy to conduct a sensitivity analysis. As the trade-off above is qualitative and not done quantitatively, the analysis is not done in the traditional way by altering the numbers. Rather, proof was given, showing that the scores actually represent reality.

Additionally, all the data to compile the trade-off table can be found in the footnote sources. To make the comparison meaningful, points were given based on the same source. For example, to evaluate wind at each location the same map was used to determine their relations. It is important to note that these maps usually are not accurate quantitatively, but are very useful to study the differences. The same method was used to evaluate all other criteria. Furthermore, one can observe that the winner of the trade-off is well above the other candidates. Thus, it can be deduced that it cannot be the influence of one faulty score, but rather is the result of distinctly different characteristics compared to the other sites.

7.2. Energy Resource

This section goes into detail about the wind and solar resource at the habitat location on Mars and it first discusses the Martian season definition. This information is later used to make a first estimation on the power mix values for solar and wind energy as presented in the first section of the following chapter.

7.2.1. Martian Seasons and Operating Conditions

Mars, just like Earth, has four seasons, which are defined by its location with respect to the Sun. The solar longitude L_s describes the locations of the planet, and ranges between 0 and 360 degrees. L_s = 0°is the northern hemisphere spring equinox - this is the point in time when the Martian year starts. Aphelion is when the planet is furthest away from the Sun, which occurs L_s = 71°. Summer on the northern hemisphere starts at 90°. The dust storm season begins at (northern hemisphere) autumn equinox at solar longitude of 180°. Mars is closest to the Sun at L_s = 215°. Winter spans from 270°until the end of the year (360°), which also means the end of the dust storm season[11].

7.2.2. Wind resource

In order to understand the availability of wind resource in the selected landing site, a more detailed analysis of the qualitative sources of information was necessary. Based on probabilistic analysis, it is possible to model wind variations using a Weibull distribution. For this, two important parameters - mean velocity v_m and shape parameter k - need to be obtained as input for the probability density function (PDF). This can be done by fitting the mean wind speed on site to the parameters found from Viking 2 lander measurements [43]. The measurements were taken at a height of 1.6 m, the location of the Viking II measurement unit. A wind profile at altitudes the kite is going to be operated at still needs to be determined.

Based on available information found by Fenton and Richardson [25], a qualitative analysis can be performed in order to estimate the mean wind speed in the selected landing site to fit it to the Weibull. Based on existing Mars general circulation model (GCM) simulations[12], it was found that the average wind speeds range approximately from 6 to 8 m/s, depending on the season. This way the Weibull distribution of wind on location can be determined for different conditions like quiescent, windy or dust storm.

Autumn and spring seasons were assumed to have the same parameters, resulting in k and v_m values of (1.7, 1.5, 1.3) and (3.5, 9, 5) for summer, winter and spring/autumn, respectively. The shape parameter k was not changed as it is still desired to have the same pattern. On the other hand, the mean wind velocities were slightly increased as it was observed that at the chosen site it was larger then at Viking 2's location.

7.2.3. Solar Resource

For solar energy two main aspects need to be taken into account. These are the varying solar irradiation over the course of a year on Mars, and the optical depth values determined by the amount of dust particles present in the atmosphere. The results come down to autumn having the lowest solar irradiation which is about 2/3 of the maximum possible solar irradiation present during spring. Of course, it should also be noted that autumn marks the beginning of dust storm season, which lasts until the end of winter. This means that during months 7-12, solar energy is a lot less reliable as the dust storms will block a large amount of the sun rays.

Furthermore, during the dust storm free months (1-6), the irradiance starts at its highest and gradually diminishes to its lowest value from spring until the end of summer. This means that even when there are no dust storms, the amount of solar power that can be harvested can vary quite strongly.

Finally, it is safe to assume that during the dust storm season, solar energy production will be highly unreliable, and the energy production will rely heavily on wind energy during this season. Additionally, the change in optical depth per season per year varies a lot. The worst recorded solar conditions per season will be used in the following design process.

[11] http://www-mars.lmd.jussieu.fr/mars/time/solar_longitude.html [Cited 14 May 2020]
[12] https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000JE001407 [Cited 14 May 2020]

8
Preliminary Design and Analysis

Once the sub-systems' trade-offs were finalised, the site had been selected and the available energy resource was evaluated, an overall system performance analysis is doen and documented in the first section of this chapter. Secondly, the system's architecture is presented along with the interface definition. Moreover, the preliminary design of the wind farm, solar farm, power management and storage sub-systems is presented in sections 8.3 to 8.6. Finally, the maintainability and safety aspect of the system are discussed.

8.1. System Performance Analysis

The performance analysis regarding a renewable hybrid energy system discusses the power generation required and actual potential of the wind and solar sources. Additionally, following the analysis, the required nominal generated power of the farms and the required seasonal storage capacities are evaluated.

First, a preliminary estimation of the monthly system required power output is performed. Due to the lengthy duration of the Martian months, the evaluation was done based on half-month periods for a whole year. As explained above in the previous chapter, it is considered that the wind and solar resources are quite limited through a Martian year. The Weibull distribution defining the summer wind characteristics has resulted to be far under the operational range for the airborne wind system. Additionally, the solar resource available in winter at the site location (quite north), has been evaluated to be unreliable for this season.

Furthermore, the beginning of spring is assumed to have available wind resources, while the end of this season is rich in solar resources. Moreover,the second month of the spring season is considered the transitional period from windy to not, it is speculated that for half the month wind energy will be able to be harvested for the day-time requirements. Nevertheless, for the first iteration of the system performance analysis, it is assumed that solar energy is still unreliable for the second month of spring, hence, the seasonal storage facility provides energy for that period. Analogically, the same statement is made from autumn, hence, the first month has reliable solar energy for day-time demand, the second month has no reliable solar energy and insufficient (but some) wind resources.

Secondly, an estimation of the necessary energy generation by each source in the time-frame of half a month is obtained. This is achieved through multiplying the total day duration times the required 10 kW and the sols in half a month. Furthermore, even if it is known that the day-time duration changes as the seasons do, for now, an equal yearly average of 12.3h is assumed for the day-time and night-time duration. Next to this, it is assumed that solar and wind energy are available only during day-time as explained in section 8.4. However, the implementations of those assumptions will be further examined through iterations in the detailed design stage. In addition, as the design team is interested in the required nominal power generation per month for the two farms in order to size the subsystems, the expected energy transmission and conversion efficiencies of the storage solutions are required. The secondary battery has an assumed total storage efficiency of 0.88% at the end-of-life due to consideration as later presented below in section 8.6. Similarly, the evaluated round-trip efficiency of the compressed gas storage facility is equal to 0.4% as further explained below in the section regarding storage preliminary design.

Therefore, in order to obtain the nominal monthly power, the following steps are performed. First, the required half-monthly energy demand is evaluated and it is decided from which sub-systems it is delivered(wind/ solar/ battery/ CAES). Then, if a monthly demand is met by the battery, the values are divided by the respective efficiency of the technology. While the microgrid efficiencies are considered in the preliminary sub-system design, as following in the section below, they are not included in the system performance analysis because no preliminary microgrid electrical paths were available at the start of the analysis; they will be considered in the next iteration step. Furthermore, it is reasoned that for the secondary battery supply to the habitat, the power generated is supplied by the then available daily energy source. For example, if the battery efficiency is neglected and no extra energy for seasonal storage is needed in a month, the nominal power required would then be 20 kW, as to provide for a full Martian sol(direct supply during the day and through the battery at night) while generating during half of it. Thus, for months 1 to 12, the total energy from the wind or solar farms for either direct or through battery supply, are evaluated and recorded in the following table 8.1.

Hereafter, in order to evaluate the required extra energy generation by the two farms for filing the seasonal storage, first the total CAES energy supply trough autumn and spring is evaluated and is then divided by the respective round-trip efficiency of 0.4%. Additionally, it is known that the autumn supply should be generated in summer by the solar farm while the spring supply is generated during winter by the wind farm. Hence, the total energy generation by either farms should be occurring over the course of about three Martian months on top of the already generated power for day and night habitat needs. Therefore, the total required generated power for filling in the storage for one season is distributed over the respective generation period through considering a weighted fractions. For example, in the second month of winter, $5/24$ of the total energy is generated for each half-month, while that value becomes $4/24$ for the periods around the second month, and $3/24$ for the beginning and the end of winter. Same reasoning is applied to the summer generation, however the fractions have a denominator equal to 19 as there are only five generation half-month periods. As those fractions are a preliminary estimation that considers the difference in energy availability and are not based on Martian data, they should be re-iterated in the detailed design phase. From those calculation, the preliminary required storage capacity of the CAES facility (not considering microgrid efficiencies) is evaluated to be 27MWh. Moreover, n the following table 8.1 the charge and discharge cycles of the seasonal facility are noted, where 'S/W:+' indicates charging by a certain source while '-' means discharging. Thus, the nominal power is calculated through dividing the total generated power by operational time of half a day (12.3h) and the given generation period (half or a full month).

Table 8.1: Monthly required energy generation by the wind(W) and solar(S) farms for direct usage or storage purposes

	Sols	Direct energy for habitat [kWh]		Energy for day-to-day storage [kWh]		Energy for seasonal storage [kWh]		Generated energy [MWh]	Nominal power [kW]
		Start	End	Start	End	Start	End		
1	61.2	W:3766	W:3766	W:4280	0	0	-3766	W:11.8	W:15.7
2	65.4	W:4025	0	0	0	-4025	-8049	W:4.0	W:10.0
3	66.7	S:4105	S:4105	0	S:4664	-4105	0	S:12.9	S:15.7
4	64.5	S:3969	S:3969	S:4511	S:4511	S:+6970	S:+9293	S:33.2	S:41.9
5	59.7	S:3674	S:3674	S:4175	S:4175	S:+11616	S:+9293	S:36.6	S:49.9
6	54.4	S:3348	S:3348	S:3804	S:3804	S:+6970	0	S:21.3	S:31.8
7	49.7	S:3059	S:3059	0	0	-3059	-3059	S:6.1	S:10.0
8	46.9	0	W:2886	0	0	-5772	-2886	W:2.9	W:10.0
9	46.1	W:2837	W:2837	0	W:3338	-2837	0	W:8.9	W:15.7
10	47.4	W:2917	W:2917	W:3315	W:3315	W:+6248	W:+8331	W:27.0	W:46.4
11	50.9	W:3132	W:3132	W:3560	W:3560	W:+10414	W:+10414	W:34.2	W:54.6
12	55.7	W:3428	W:3428	W:3895	W:3895	W:+8331	W:+6248	W:29.2	W:42.7

Finally, from the results above, the yearly power mix values for supply and generation, are evaluated for the fours seasons and for a full year. As seen in table 8.2 below, 24% and 22% of the total supplied energy is delivered directly through the wind and solar farms, respectively. Moreover, 31% is supplied through the battery and 23% through the CAES sub-system. Furthermore, it is evaluated that 52% of the total yearly energy generation is from the wind farm and the rest is from the solar one. The yearly supplied total wind and solar energy, also have the same ratio. Once, those values are obtained along with the maximal nominal power generation in table above, the preliminary sub-system sizing can be started as explained in the following sections. Nevertheless, first an overall system architecture is presented along with the interface definition of the sub-systems.

Table 8.2: Seasonal and yearly energy supply and generation power mix fraction values

	Method	L_s=0°	L_s=90°	L_s=180°	L_s=270°	Yearly
Supplied energy	Directly through wind	0.24	0	0.24	0.50	0.24
	Directly through solar	0.17	0.50	0.17	0	0.22
	Through battery	0.17	0.50	0.08	0.50	0.31
	Through CAES	0.42	0	0.50	0	0.23
Generated energy	Wind	0.55	0	0.66	1.00	0.52
	Solar	0.45	1.00	0.34	0	0.48

8.2. System Architecture and Interface Definition

This section specifically documents how the subsystems interact with each other. To make the connections clear, two visual diagrams have been produced.

The first diagram displays the subsystems and their boundaries in figure 8.1. This schematic illustrates the system's architecture up to the subsystem level. The interfaces between the components within a subsystem are shown, as well as the interfaces between the subsystems themselves. Additionally, three different connections have been determined: the energy flow, the command flow and the transport and operations. More specifically, the command flow denotes the flow of information or electronic inputs between elements, the energy flow denotes the path on which energy travels from its source until its destination (i.e the users), and the transport and operations arrow denotes the handling or movement of resources or equipment between elements.

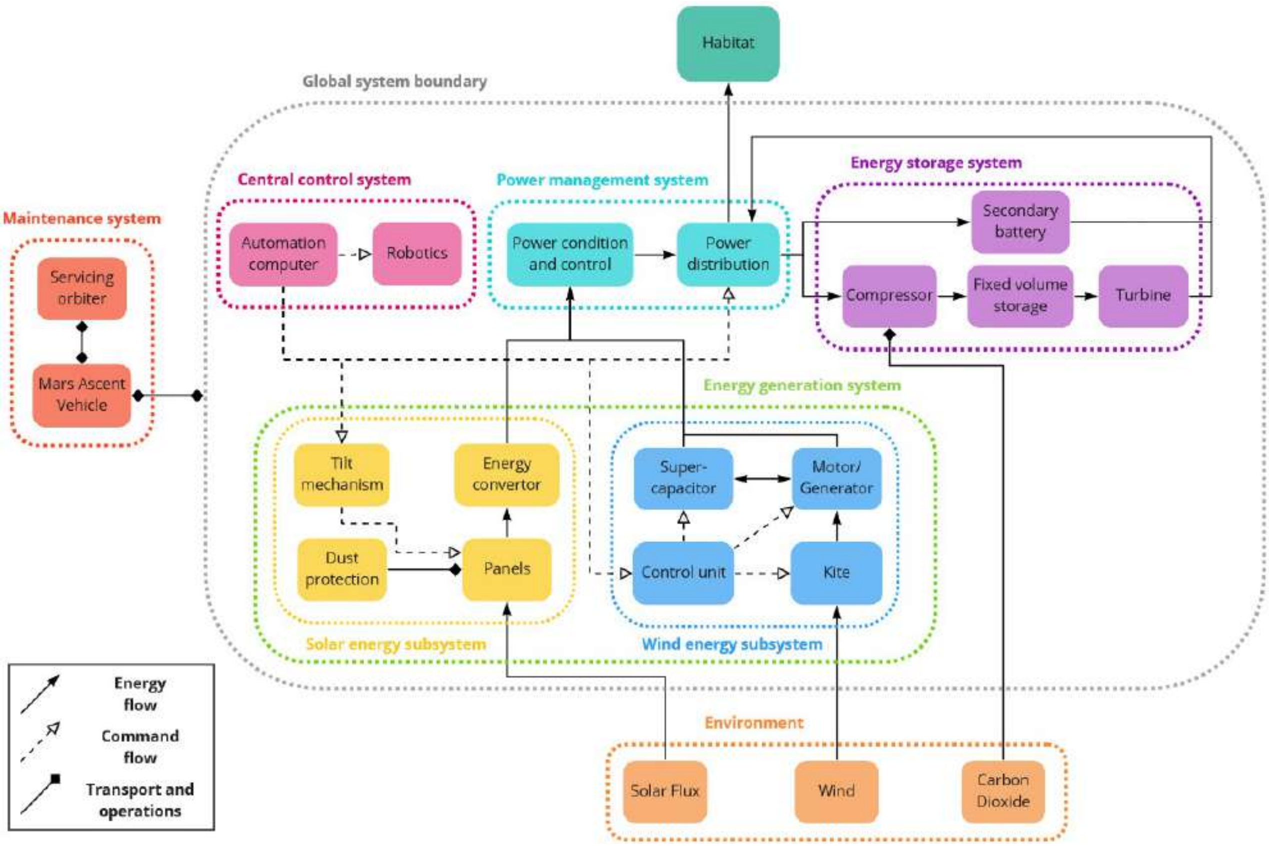

Figure 8.1: System architecture

In addition, the second diagram, the N2 chart gives a different view of the systems interrelations. The horizontal rows have the outputs of an orange block while the vertical columns contain the inputs for each orange block. This diagram is considered to be quite self explanatory, however just for some clarification about the central computer, it is worth mentioning that this would be the command centre for the system. Nevertheless, each subsystem has their own unit controller which ensures executions of the commands given by the central computer.

Environment	Solar flux	Wind	Windspeed		Martian Atmosphere	
	Solar Panels		Power generation feedback	Solar energy	Excess energy	
		Kite	Power generation feedback	Wind energy	Excess energy	
	Orientation of solar panels	Kite deployement	**Central computer**			
				Microgrid		Needed Energy
			capacity level feedback		**Energy storage**	
			Power request			**Habitat**

Figure 8.2: N2 chart interfaces

8.3. Power Management and Distribution Design

Once, the first iteration of the system performance analysis is done and the system's interfaces are defined, the preliminary design of the subsytems is started. First, the microgrid performance is evaluated as the electrical paths and their respective efficiencies are relevant for the sizing of the wind, solar farms and the energy storage solutions.

In the Baseline report, a basic structure for the power management system was proposed [15]. Moreover, in chapter 6, it was concluded that a DC microgrid was the most suitable concept for managing power in the Renewable Energy System. In this section, the preliminary design of the DC microgrid is elaborated.

The basic structure of the power management system is depicted in figure 8.3. The diagram shows how each subsystem (e.g. AWE, PV, storage, etc.) is integrated in the energy distribution system, and through which power electronic converters they are connected to the microgrid. Furthermore, the diagram shows the communication links between the centralised controller and the habitat, and between the centralised controller and the local controllers.

Each grid component has its own efficiency in terms of power loss. If energy is stored for buffering diurnal or seasonal fluctuations, the round-trip efficiency of these storage methods needs to be accounted for as well. All efficiencies are displayed in figure 8.3, and their values are tabulated in table 8.3. It is noteworthy that for the design of the distributed energy resources, it is imperative to know the efficiencies of the electrical paths that connect them to the demand. These need to be taken into account when sizing the energy supply systems. The path efficiencies are obtained by considering all possibilities of power flow from the supply to the load. That is either directly from e.g. the kite to the load, or from the kite to the load via a storage mechanism. Then, the product of the efficiencies of all components on the particular paths is taken. For the sake of simplicity, in this calculation, η_{dist} is only accounted for once. The resulting path efficiencies are documented in table 8.4. It must be pointed out that the round-trip efficiency of the battery and the CAES is not included in the computation of the electrical path efficiency. Furthermore, power losses from components that belong to individual subsystems, e.g. the generator efficiency for the AWE system, are not taken into account. Having determined all necessary efficiencies, the preliminary design of the other subsystems can start.

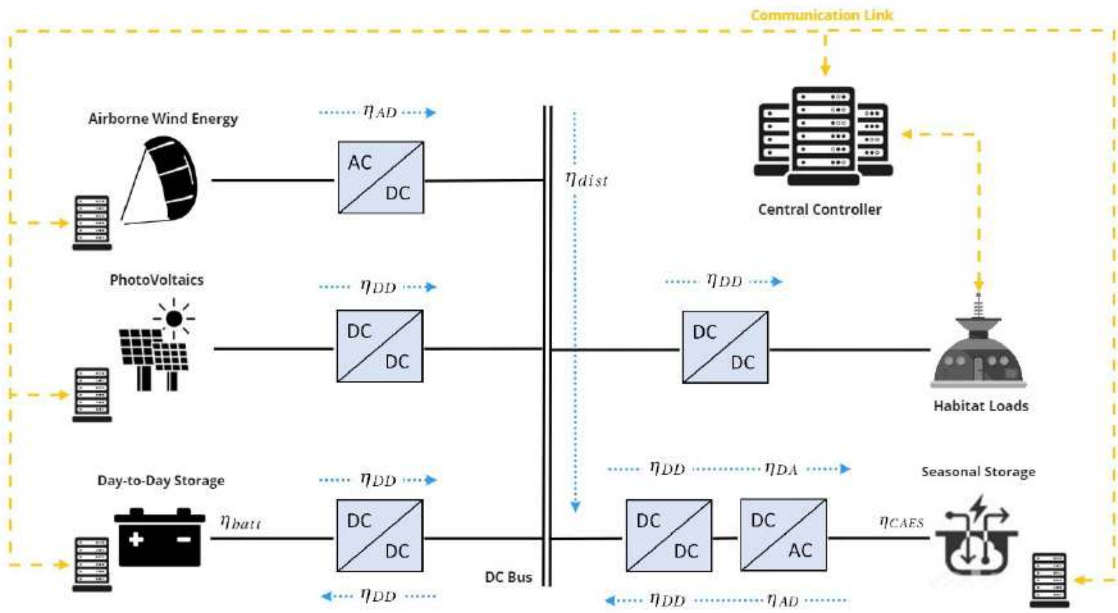

Figure 8.3: Diagram of the DC Microgrid and its relevant components and efficiencies

Table 8.3: Microgrid component and storage efficiencies

Component	Symbol	Value [-]	
DC/DC converter	η_{DD}	0.980	[23] [52]
AC/DC converter	η_{AD}	0.990	[54]
DC/AC converter	η_{DA}	0.990	[54]
Distribution (e.g. cables)	η_{dist}	0.980	
Battery (round-trip)	η_{batt}	0.880	[75] [69]
CAES (round-trip)	η_{CAES}	0.399	[42]

Table 8.4: Efficiencies of all possible electrical paths from supply to demand

Electrical Path Efficiency	
Kite - Load	95.1 %
Kite - Battery - Load	91.3 %
Kite - CAES - Load	89.5 %
PV - Load	94.1 %
PV - Battery - Load	90.4 %
PV - CAES - Load	88.6 %

8.4. Primary Energy System Design

In the primary energy trade-off in chapter 4, an AWE system was chosen for the mission. A preliminary design of the system is performed, discussed in this section. First, a brief description of the systems architecture is given, followed by a description of the model used for its preliminary sizing. Then, the system parameters resulting from the preliminary sizing are given.

8.4.1. Airborne Wind Energy System Architecture

The preceding trade-offs in subsection 4.2.2 have resulted in the AWE concept used being a pumping kite power system. In figure 8.4, a simplified overview of the systems architecture is given. The system is controlled by the central computer, which will have sensors measuring the wind speeds on Mars and prescribing the current operation phase. The kite is controlled by the control system during flight. It is connected to the kite and tether by the control unit, which controls the motion of the kite by pulling or releasing the tethers. The traction force generated by the lift of the kite, is transported trough the tether to the ground station, where the turning motion of the drum is converted to electrical power by the motor/generator. A motor/generator was chosen instead of two separate devices, due to the strict mass requirements stemming from transport to Mars and the sustainability aspect of saving on material costs [81]. The energy produced by the motor/generator is distributed to the Mars habitat and main storage, or to the supercapacitor used for internal energy storage by the power management module. The internal energy storage provides the energy for the motor in the recovery phase of the AWE and for the spindle motor, which makes sure the tether is spread over the drum evenly.

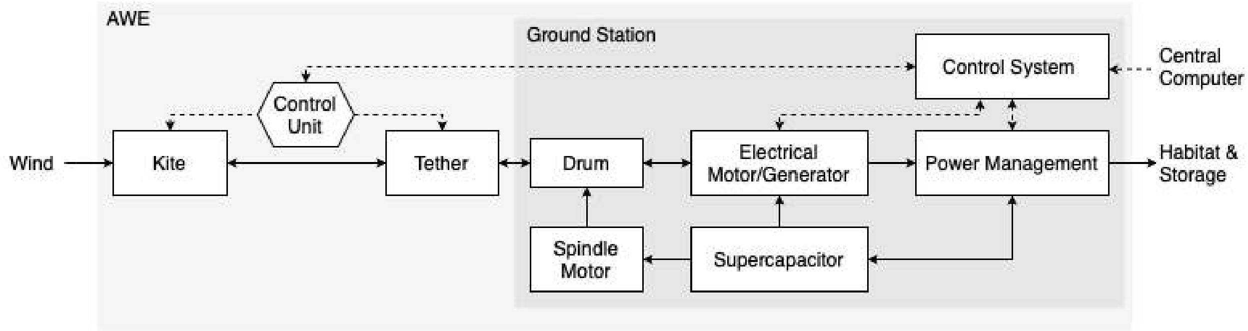

Figure 8.4: AWE system architecture. Solid lines stand for energy flows and dotted lines for communication flows.

8.4.2. Airborne Wind Energy System Model

In order to perform a preliminary sizing of the AWE system, a physical AWE system model from Luchsinger [44], giving the average power P_{av} over a certain time period, was implemented in code:

$$P_{av} = \int_{v_{cut_{in}}}^{v_{cut_{out}}} P_w A F_{out} f_c g_W(v_w)\, dv_w \tag{8.1}$$

Where $v_{cut_{in}}$ and $v_{cut_{out}}$ are the system cut-in and cut-out speeds respectively, v_w is the wind velocity, and P_w the wind power density;

$$P_w = \frac{1}{2}\rho v_w^3 \tag{8.2}$$

With F_{out} and F_{in} as the dimensionless reel-out and reel-in force factors;

$$F_{out} = \frac{C_L^3}{C_D^2}, \quad F_{in} = C_D \tag{8.3}$$

The normalised power factor f_c is given by;

$$f_c = \max_{\gamma_{in},\gamma_{out}} \left\{ \left((1-\gamma_{out})^2 - \frac{F_{in}}{F_{out}}(1+\gamma_{in})^2 \right) \left(\frac{\gamma_{out}\gamma_{in}}{\gamma_{out}+\gamma_{in}} \right) \right\} \tag{8.4}$$

In which γ_{out} and γ_{in} are the dimensionless (numerically optimised) reel-out and reel-in velocities respectively, and $g_W(v_w)$ the Weibull probability density of the wind speed;

$$g_W(v_w) = \frac{k}{v_m} \cdot (\frac{v_w}{v_m})^{k-1} \cdot e^{-(\frac{v_w}{v_m})^k} \tag{8.5}$$

The control model in Luchsinger [44], accounting for constraining power output and tether force, was left to be implemented in a more detailed design stage. A tether sizing model from Bosman et al. [8] was implemented, which was used to choose a preliminary cut-out wind velocity of 25 m s^{-1}, and thus provide a simplistic tether force constraint to the model. Based on discussion present in 4.2.1, a preliminary minimum cut-in wind velocity value of 5 m s^{-1} was chosen. The model for the preliminary sizing of the tether is integrated in the AWE system code. The first step of Bosman et al. of sizing the tether is calculating the reel-out force T_{out}, as this is the most critical load case for the tether, the equation for which is given by;

$$T_{out} = 0.5\rho v_w^2 A (1-\gamma_{out})^2 F_{out} \tag{8.6}$$

Now the Maximum Breaking Load (MBL) of the tether can be calculated by multiplying T_{out} by a design factor, the chosen factor being only 1.2 since DM20 has a very high creep resistance. The material used for the tether is HMPE DM20, of which the properties are known. From tables found on the DM20 tether mass per 100 meters m_t [kg (100m)$^{-1}$] and diameter d [m] against the MBL[1], the tether size can be interpolated.

After the tether has been sized, some safety checks need to be done to make sure it will not fail during its lifetime. Two checks are done, the first one ensuring that the tether will not fail because of creep. First the tension σ_t in the tether is calculated using;

$$\sigma_t = \frac{100\ T_{out}\ \rho_l}{(1 - cc) m_t} \tag{8.7}$$

Where ρ_l is the linear density which equals 970 kg m^{-3} for DM20 and cc is the coating content which commonly equals 0.1 [8]. Several factors also need to be calculated. The first being a load factor F_L which takes into account the fact that the critical force is encountered only during reel-out and not during reel-in, $F_L = \frac{t_{out}}{t_{out}+t_{in}}$ where t is the reel cycle time [s]. These cycle times can be calculated by dividing the operational tether length by the reel-out and reel-in speeds. Afterwards, two factors are calculated that account for the daily and seasonal fluctuation in temperature, both of which equal approximately 2 due to the low temperatures on Mars. Finally, the Safe Working Life (SWL) can be interpolated from the plot in Bosman et al. [8], multiplying SWL by all three factors described previously results in the Safe Service Life (SSL) of the tether considering creep. This SSL needs to be higher than the mission lifetime of 5 Martian (≈10 Earth) years.

The second tether safety check considers bending fatigue of the tether, since it is winded on the ground station drum. As at this stage of design, almost no values on the ground station/drum size are known, this check can not be performed as of yet. Later stages will include the lifetime check for bending fatigue. Furthermore, to account for the elevation angle θ of the tether, a correction shown in the equation 8.8 below is used for all final sizing calculations, with a set angle θ = 30 °, as per Luchsinger [44].

$$P_{av_c} = P_{av} cos^3(\theta) \tag{8.8}$$

This value was further multiplied by an assumed mechanical-to-electric power conversion efficiency of the ground-station, η_{gs} = 0.8 [10], to give a final value for the power produced. To comply with the system performance analysis, the model outlined above was expanded to account for seasonal resource and power requirements variations. A four-season (twelve-month) wind resource model was used based on a Weibull distribution, outlined in subsection 7.2.2. For preliminary design purposes, as a wind altitude model was not implemented yet, a factor of 1.35 was applied to the v_m values shown in this subsection, slightly increasing the mean wind speeds simulated in the design. To show how the model reacts to extreme inputs, a factor of 2.6 was tried and the outputs are shown in table 8.5, it can be seen that the AWE system size and mass decreased. Research has also shown that through months 3-7 (approximated by solar longitudes of 60-210°), the wind resource is found to be highly unreliable due to various atmospheric interactions (for which the wind generation is thus set to zero), and further it is considered that there tends to be about a 50% chance of wind wind not being present in the 2nd & 8th months, accounted for by halving the power output for those months by the wind system (given in section 8.1). Complex atmospheric interactions also results in significantly lower wind-speeds at night, resulting in the assumption that in working seasons, the AWE system produces power only at daytime (half a sol) [2].

Based on the seasonal power requirements for the wind system given in section 8.1 and the model given above, a value for the airborne mass (kite and tether) was calculated. This was done for the kite mass by $m_{kite} = A \cdot \rho_A$ and for the tether through the implementation of the model in Bosman et al. [8]. Moreover, the tether length was set to vary between 400 m and 200 m during operation, which is a value obtained from literature on an experimental utilisation of an Earth AWE system [76]. In further design steps, the tether length will be optimised for parameters like mass and performance. Furthermore, due to the mission being set on Mars, mass of the whole system - not just the airborne mass - is a new consideration of its own, often overlooked or unmentioned by AWE system research performed on Earth. Thus, ground station sizing has been found to be quite challenging, and for preliminary system sizing, a mass of 100 kg was assumed based on information found on some commercially available components [3].

8.4.3. Airborne Wind Energy System Sizing

For the seasonal power requirement generated in the 8.1, the model and the design steps presented above, following system values were obtained:

[1] https://www.moremarine.nl/pdf/dyneema_dm20_specs.pdf [Cited 19 May 2020]
[2] http://www-k12.atmos.washington.edu/k12/mars/data/vl1/part2.html [Cited 19 May 2020]
[3] www.solectro.se, www.hydrotechnik.co.uk, www.alxion.com [Cited 19 May 2020]

Table 8.5: AWE Preliminary System Parameters

Parameter	Parameter symbol	Value #1	Value #2 (extreme)	Unit
v_M multiplication factor	c	1.35	2.6	[-]
Kite area	A	900	700	[m^2]
Kite lift coefficient	C_L	0.6	0.6	[-]
Kite drag coefficient	C_D	0.06	0.06	[-]
Kite area density	ρ_A	0.1	0.1	[kg m^{-2}]
Cut-in speed	$v_{cut_{in}}$	5	5	[m s^{-1}]
Cut-out speed	$v_{cut_{out}}$	25	25	[m s^{-1}]
Kite mass	m_{kite}	90	70	[kg]
Tether length	l	400	400	[m]
Tether mass per 100 m	m_t	19.7	15.3	[kg 100 m^{-1}]
Tether mass	m_{tether}	78.9	61.3	[kg]
Tether diameter	d	1.65	1.45	[cm]
Tether SSL creep	SSL	29	29	[yrs]
Ground Station (GS) mass	m_{gs}	100	100	[kg]
GS conversion efficiency	η_{gs}	0.8	0.8	[-]

This results in the primary energy system providing 52% of the annual energy capacity, with a mass of 268.9 kg, and a [TBD] volume.

8.5. Secondary Energy System

From the trade-off in section 5.1 it has been decided that the secondary energy system will be using solar panels. To check if the subsystem is still compliant with its requirements and to estimate the whole system performance, a preliminary design must be made. If any problems arise, they can be accounted for in the later stages of the design. For the solar panels, the preliminary design entails the sizing of the array by means of data from literature to get an initial estimation of the system mass and volume necessary. The sizing of the array was done using the following formula[12]:

$$P_{sa} = S_{in} \cdot A \cdot \eta \cdot I_d \cdot L_d \cdot \cos(\Theta) \tag{8.9}$$

Where P_{sa} is the solar array power output, S_{in} is the solar flux, A is the surface area of the array, η is the efficiency of the cells, I_d is the inherent degradation factor which accounts for e.g. malfunctioning of specific cells in the panels, L_d which is the life degradation of the cells and panels and lastly Θ is the incidence angle at which the solar radiation hits the panel.

By means of the system performance analysis that was discussed previously in this chapter, it was determined that peak nominal power required from the solar array will be 49.9 kW. With this, equation 8.9 was used to determine the surface area A needed to produce the necessary power. However there will also be cable and storage losses, as are described in section 8.3. To determine the actual power that needs to be produced by the panels, to ensure the required power is left after the losses, a distribution of the 49.9 kW was made. The required peak power was split according to the percentage of power that would be used directly (20%), stored in the batteries (23%) or stored in the CAES (57%). Using their respective efficiencies as mentioned in tables 8.3 and 8.4, it can be determined that the actual power that needs to be generated is 57.1 kW. The other values needed in the equation were taken from literature and were estimated based on expected system performance.

For the S_{in} experimental data from the Viking 1 and Viking 2 landers were considered [2][39]. This lead to a solar irradiance of 300 W m^{-2} during the summer ($L_s = 90° - 180°$), in which the solar system is used, for the specific latitude corresponding to the site selection discussed in chapter 7. For the PV cell no definite decision beyond III-V multi-junction cells has been made. Therefore to obtain a realistic value for η, an estimation for an efficiency of 0.25 was made based on data from other III-V multi-junction PV cells [12]. For the inherent degradation factor (I_d) and the life degradation (L_d), again literature was consulted[12]. From this it was found for the prior that this usually ranges between 0.5 and 0.9 and is constant throughout the lifetime of the panel. For this preliminary design it was assumed to be 0.9, as e.g. a packing factor (deficit cells in the array) can be compensated for by thorough testing. The latter of the two requires a separate equation to determine the degradation;

$$L_d = (1 - \delta)^x \tag{8.10}$$

Where δ is the yearly power degradation, which for III-V is between 0.01-0.02 usually, and x is the amount of years the panel is in service. From this it follows that the life degradation L_d is 0.904 for the mission solar array after a lifetime of 10 years. Note, this equation was developed in relation to Earth years. As one Martian year is almost equal to 2 Earth years, x was taken equal to 10 years, which is a small overestimation however since this is still a rough preliminary design, 10 years is a detailed enough estimation. Lastly the incidence angle was taken to be 0, as the solar panels will have a 2-axis system which allows them to track the sun efficiently, and keep the incidence angle at around $\Theta = 0°$. Of course this is a slight idealisation. The energy efficiency has not been taken into account yet [18], as with the selection of the specific III-V PV technology and with design of the full panel, more consideration can be made to drastically improve the exergy efficiency by e.g. refrigerated panels. This will be done in the next phase of the design. From all this it follows that the area of the panels should be 934.8 m^2 to supply the habitat and its storage with up to 49.9 kW of power.

8.6. Energy Storage Systems

In this section, the considerations regarding the preliminary storage solutions design are outlined.

Seasonal Storage

As has become clear, the natural resources on Mars are not sufficient to fully support the habitat directly throughout the year. The size of the CAES system will therefore be dependent on the energy necessary to supplement these shortages in e.g. spring. Furthermore, there are less examples of CO_2 based CAES systems, compared to ones that use Earth air. However, there have been extensive studies done on the efficiencies and energy densities of such a system. From those, a primary estimate on the efficiencies can be made. Using what has already been found in Liu et al. [42] the following efficiencies were approximated:

The compressor efficiency will be estimated at 0.7, the expansion efficiency at 0.6 and the storage efficiency at 0.95. The storage efficiency is slightly higher than what has been found in literature, as the CAES storage that is designed to be implemented in the Martian system is expected to be lined with an airtight isolation layer. A preliminary estimation on the size of the storage cannot be made as of yet, as this would require more detailed information on the maximum allowable pressure of the habitat ”pods”. Also, a more through analysis on the thermal cycle of the CAES would be required to determine the energy density that would be obtainable for the system in the martian conditions. However, a preliminary estimation is made, yielding that the required storage volume would be in the magnitude of 10^2 m^3.

Day-to-Day Storage

Following from the trade-off in chapter 6, it was decided that batteries will be used for day-to-day energy storage. There are many possible battery technologies. Choosing one is a concern for future design activities. However, in order to get a first estimate on weight and round-trip efficiency, a short literature study was done on the implementation of secondary battery technology in current and future space missions. From this research, it was concluded that Li-ion is a promising battery technology, with a foreseeable energy efficiency of 88% and an energy density of 220 Wh kg^{-1} [34]. A preliminary estimation of battery size can be done. Taking into account the longest night[4] [26] for a latitude of 40°and a usable energy of 70%, the estimation yields an energy capacity of 240.83 kWh. Hence the required mass for storage is in the order of 10^3 kg.

8.7. Maintainability

Since the energy system will be fully operated on Mars, integrated with the Martian habitat, the physical maintenance will be carried out by the astronauts and robotic support on Mars. However, for certain major malfunctioning(s), such as issues within built-in computer unit, a series of management procedures can be communicated to the Martian station via long-range telecommunication systems from Earth if additional instructions need to be implemented that was unplanned and not part of astronaut training.

There are two main categories of the energy system that should be planned for maintenance is the software and the hardware:

- **Software Maintenance:** The software is a crucial backbone of the energy system as it dictates the power management based on energy availability and demand. A mismanagement will affect multiple components of the system at once, and can cause irreversible physical damage as well. Thus, the software architecture behind the system must robust, self-contained and to a large extent, self-healing[5]. This means that layers of redundancy are built into the back-end system so that there are no single points of failure. In the actual event of a software malfunction, patches, updates and recovery algorithms need to be implemented.

[4] http://ops-alaska.com/time/gangale_mst/daylight.htm#figureA3-4 [Cited 20 May 2020]
[5] https://ubiquity.acm.org/article.cfm?id=1241853 [Cited 14 May 2020]

- **Hardware Maintenance:** The hardware maintenance can be further categorised by the respective hardware. However, this section is a brief summary. The full procedures of their maintenance can be found in section 9.2.
  - Primary energy System: The lift-type kite concept is flexible and semi-rigid structures are used. Which means for an airborne wind energy concept, it has relatively high reliability and these structures can be easily replaced.
  - Secondary energy system: For the solar panel system, hydrophobic coatings are in place to ensure there is low-to-none dust accumulation, which means manual maintainability intervention from the astronaut is kept minimal.
  - Energy Storage: The batteries are largely managed internally by the software. However, their physical maintainability includes proper ventilation and serviceability of the batteries to avoid overheating and sudden overloading.
  - Microgrid: The cable infrastructure and intermediate components need to be frequently visually inspected by the astronauts. As well as through a regular electronic system check. In this way, any circuit error or power disruption that arises from grid components can be detected early.

8.8. Safety

Safety is a key requirement for production, implementation and operations of the energy system aboard Mars. It can be a determinant for life and death, especially for the astronauts, who have to depend on these life systems (habitation and energy) to protect themselves from harsh Martian conditions and provide the basic necessities to survive. Through the entire process, there are several safety considerations that are most critical to the success of the mission as well as to the life of astronauts.

Some key safety considerations include:

- **Production:** The health, safety and well-being of the team during design and production is explained in the Social Responsibility section of Project Plan [16].
- **Primary Energy System:** The lift-type system is a safe design choice. The softness and flexibility of the kite means that an impact with it would keep the damage to a minimum. Nonetheless, the kite control unit, wires and ground system all need to be regularly checked as they all pose their own inherent safety issues such as tangling and fire risks.
- **Microgrid:** Each component of the microgrid also poses their own safety concerns and appropriate procedures. The cable infrastructure need to incorporate a safe ground-gateway, before the system begins to overload risk a complete shutdown or physical damage (from fires etc.), which endangers the astronauts' lives.
- **Maintenance procedures:** While the astronauts are executing maintenance procedures and require to be outside of the habitation and inspecting, re-configuring or replacing parts of the airborne wind energy system and the other subsystems, proper safety gear is needed at all times. And safety training when interacting with the systems are provided pre-launch to the astronauts. The maintenance tools are designed to work with the systems and the safety gear in parallel.

8.9. Next Steps

The next steps regarding the system's and sub-systems' design are discussed in the following section, along with considerations and assumptions that have to be accounted for. First, the next iteration of the performance analysis is suggested. Secondly, the further investigation and sizing of the airborne wind system, solar farm, secondary battery, CAES, and microgrid are discussed.

System Performance Analysis: In the next design stage the system performance analysis will be iterated upon and considerations of the microgrid efficiencies, the day-time hourly variation through the year, the seasonal storage energy generation distribution over the summer and winter seasons, will be examined. In addition, the possible implementation of hybrid operation will be discussed.

Power Management and Distribution: Concerning the microgrid, further design activities include estimating the mass and volume of the system. Furthermore, the cable area and length need to be calculated. A more accurate estimation on the efficiency of power electronic converters is also one of the next steps. Finally, control methods for DC microgrids will be touched upon in the next design stage.

Primary Energy System: Airborne mass can prove to be a large consideration regarding to the kite's power performance, it will be further investigated in the following design phase [44]. If an airborne kite control unit (KCU) is chosen in favour of multiple ground tethers for kite control, its mass will need to be accounted for; as the actuators inside and their power requirements increase with increased kite size, so will the KCU and the tether which will have to bring power to the KCU (or airborne energy storage is used) [76]. Inflatable kites from textile materials seem to require an airborne pump in order to stay pressurised and thus rigid, which would add more airborne mass and power requirements. Tether drag should be accounted for in the more detailed model [3]. For stability concerns, even during the reel-in phase a minimum value for C_L can arise for stable flight operation concerns, decreasing the feasibility of the $F_{in} = C_D$ assumption [27].

The model used for the preliminary sizing optimised reel-in and reel-out speeds with no power constraints, which can be taken into account along with limiting tether force after a certain nominal wind velocity, increasing the range of wind speeds over which power can be generated [44]. A peak rated power of 55 kW (68 kW if accounting for η_{gs}) was identified from section 8.1, which can be used in future ground station component sizing. The motor/generator maximum reel-in and reel-out speeds will need to be taken into account then too, along with launch and landing systems and procedure [24]. This is also expected to lower the maximum T_out force, lightening the tether design [8]. In the ground station sub-system design, a better mechanical-to-electrical power conversion efficiency than $\eta_{gs} = 0.8$ could be realisable [10, 24]. The tether length variation of between 400 m and 200 m allowed van der Vlught et al. [76] to operate a pumping-cycle power kite on Earth, however operating in Martian conditions could have an impact on this range due to kite controllability. Wind speed variation with altitude will be accounted for in the next design phase.

Secondary Energy System: To continue with the design of the solar energy system, the next step is to determine the specific semiconductor materials for the III-V cell technology. This is a step that deserved extra consideration, as the right combination of materials could greatly improve the performance of the array in the martian spectrum and conditions. With this decided upon, a more accurate estimation on the array size can be made as the inherent degradation factor and the life degradation of the panels can determined. This also follows from a careful exergy efficiency analysis, which will be performed while considering low temperature, or refrigerated arrays. Furthermore the configuration of the two axis system needs to be determined. With this known and the surface area more precisely sized, the weight of the whole secondary energy unit can be estimated, which will lead to a more accurate material selection and mass budget for the mission operations. Also an approach for the operations and system integration can be established. All this will allow for the completion of a more detailed design for the whole system.

Secondary battery: For the secondary battery, different storage technologies will been examined and the winning concept will be further developed and precisely sized. The specifications and characteristics of the battery production, transportation, operation and retirement will be addressed in the detailed design stage.

Compressed gas storage: To improve the design for the CAES, a system needs to be developed to ensure a high thermal efficiency by means of e.g. a heat exchanger. This would drastically increase the overall efficiency of the CAES, reducing the volume needed to comply with the storage requirement. Furthermore, the allowable pressure to which the storage can be pressurised needs to be determined, as this directly relates to the energy density of the CO_2 and thus influences the volume required. Lastly an approach for the component transportation, installation and retirement needs to be developed.

With those next steps and considerations, the detailed design phase of the renewable hybrid energy system can be started and later documented in the Final Report.

9
Operations and Logistics

This chapter will provide details about the mission's operations and logistics. Section 9.1 will provide an overview of the initial mission configuration, and will delve into the first-order concept for the most important logistics and transportation procedures. Following this, section 9.2 includes a description of the system's main components and how these interrelate with each other to ensure a correct operation.

9.1. Mission Operations and Logistics

Figure 9.1 illustrates a first-order concept for the mission configuration. It is important to note that, as in any space mission, the mission configuration is a preliminary concept only and it is subject to modifications based on changes that may occur during the design iteration.

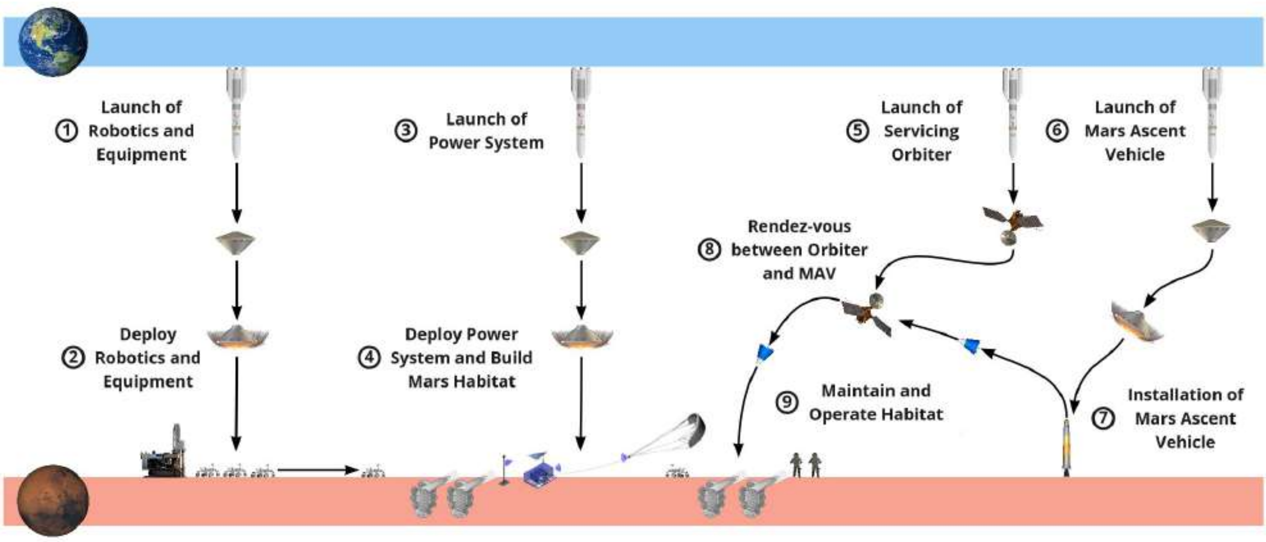

Figure 9.1: Simplified schematic of the mission configuration

From this figure, several important points must be noted: in order to guarantee a mission that can enable a sustained human presence on Mars, there must be a ready-for-crew landing site with an operational habitat ready for occupancy prior to any human travel. According to Moses and Bushnell [51], this not only improves safety and affordability, but it also ensures that nobody is put into unnecessary danger in trying to install and operate an on-surface station. Moreover, tele-operation is another aspect that adds a substantial layer of complexity to implementation of such a system, as there can be a 20 minute communication delay between Earth and Mars [51, p. 11]. Hence, a major aspect to consider is the necessity for a high levels of automation and Earth-independence to be adapted within the architecture of the mission and its commissioning [47].

Following these considerations, the mission will start by sending to Mars the necessary equipment to build the habitat as well as the autonomous robotics needed to install and operate the renewable energy system. Although, the current state-of-the-art technology would not provide sufficient reliability, literature shows that the usual 10 years of R&D required for space missions are sufficient to assume that the necessary robotics and machine intelligence technologies could all be available and usable by the time the mission design is finalised [51, p. 11].

Next, the payload of the Renewable Energy for Mars mission is brought to Mars for the automated robots to start setting up and get running. As soon as the power system is producing sufficient energy to power the ISRU equipment, the habitat can start to be constructed. These activities will continue in parallel. The finished renewable energy system should be able to continuously provide the expected 10 kW of power as specified by the user requirements.

It is natural to expect that the construction of a habitat system will lead to a considerable amount of maintenance and repairs. This is usually dealt with by adding redundancy within a system by, for example, including spares in the payload that will be sent to Mars. However, based on historical data only 5% of these spares will actually be used [59]. Due to the nature of the mission, it is impossible to predict the amount and nature of the spares that will be required to ensure a correct operation of a system of such complexity. For this reason, a system of on-demand production of spares and servicing must be set in place. This is explained in more detail in subsection 9.2.2.

The next step is to investigate and understand the nature of the conditions that the system will have to undergo throughout its operational lifetime. This will be further explained and illustrated in section 9.2.

9.2. System Operations

The system architecture and its external factors have been summarised in figure 9.2 to provide an overview of the interrelations. The scope of the design for the DSE team is shown in this figure by the dotted line. It must be noted that although the interrelations of the elements outside this boundary is something that must be investigated, the detailed description of the functioning of these external systems is outside the scope of this project.

The energy generation system is split in two, where both solar and wind energy are used. These two generation methods are heavily influenced by the environment. They need to work together to provide the needed power, hence when one is not able to provide enough, the other needs to make up the difference. The solar energy will be harvested with solar panels with a mechanism to ensure an optimum incidence angle. The wind energy mechanism is airborne and more specifically will be a kite, as explained in chapter 4. The energy produced, needs to be distributed and stored efficiently, hence a power management system is implemented. For this, an energy day-to-day and seasonal storage solutions are designed, as well as, a DC microgrid to process and distribute the power to be ready-for-use for the habitat.

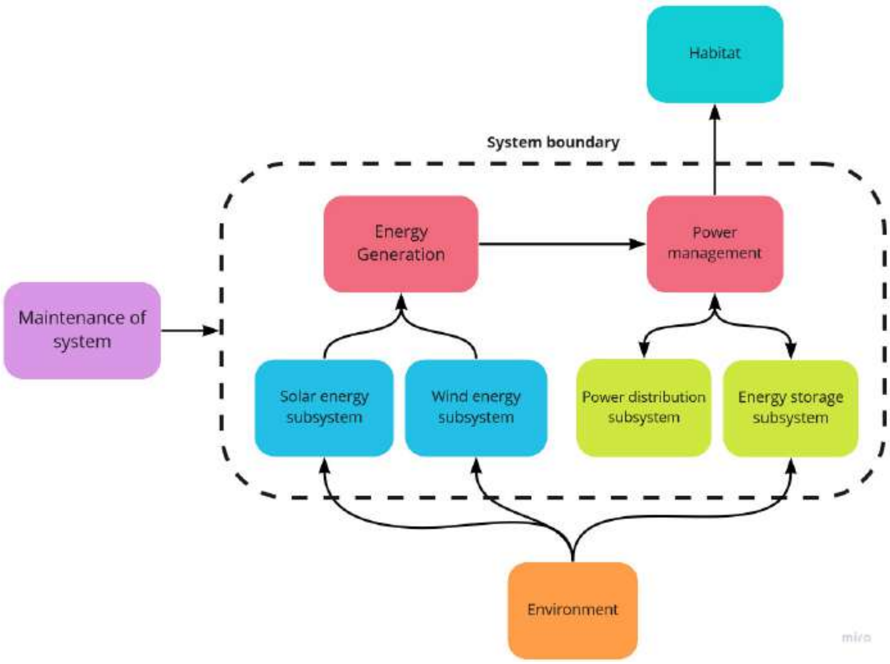

Figure 9.2: Simplified schematic of system architecture

The system operations must be designed such that there is a guaranteed energy supply even during the most undesired of conditions. Moreover, there must be a plan set in place to ensure that the system can be maintained, and once its end-of-life stage is reached, that it can be decommissioned following the design's guidelines for sustainable development. This is further explored in the upcoming subsections.

9.2.1. Plan for a Guaranteed Energy Supply

A plan needs to be devised in order to guarantee the continuous power production by the solar and wind energy subsystems. Unfortunately this is less straightforward than on Earth as the environment on Mars is less forgiving. To be able to plan for a guaranteed energy supply, the main operational conditions and situations have been defined:

- **Optimal conditions:** Those refer to situations where both wind and solar are able to produce a significant amount of energy. None of the two are impaired by dust storms of low winds.
- **Sub-optimal conditions:** Those are defined as a situation where only one of the two energy source can be operated. This would usually be during dust storm season where the solar panels performance suffers a lot. The wind energy would thus be nearly solely responsible for energy provisions.
- **Extreme conditions:** In extreme conditions, none of the two systems would be able to work. This would mean the habitat needs to keep running only on energy that has been stored which is only a finite amount. These situations are considered to be rare. For these to occur, first, the optical depth should be high, and second, the wind should be of insufficient speed, which is possible according to the research done on this topic.

All of these cases have been taken into account and the power mixes have been estimated in section 8.1. These will help to ensure that the subsystems are designed such that enough power is available for use at all times.

9.2.2. Plan for Maintenance and Retirement

The Martian environment can be very hostile and can potentially pose a major threat to the integrity of the mission. In order to ensure that the system will be able to comply with the life-span requirement of five Martian years (i.e. 9.41 years on Earth), a well-defined maintenance approach must be defined.

Two concepts play a major role in this approach: firstly, on-orbit servicing, assembly, and manufacturing (OSAM) processes can be adapted to this mission to manufacture, assemble, and perform maintenance on larger than payload structures [59]. As described by Moraguez [50], this augments the system redundancy as it introduces the capability of making components on demand, thus increasing the system's overall reliability. For this, a servicing orbiter can be launched to orbit at low Mars orbit (LMO) to alleviate the required constraints imposed on the manufacturing equipment sent to the Martian surface, (e.g. ability to withstand launch and EDL loads, resistance to radiation and corrosion, low required power, etc.). Furthermore, it introduces a framework to widen the recycling and re-usability spectrum of all materials after decommissioning, as this orbiter can serve as a gateway to send parts and components back to Earth [31]. Additional to this, the Rhizomatic habitat designed by Bier et al. [6] already considers the inclusion of the necessary equipment and infrastructure to enable manufacturing and servicing on the surface of Mars with the available resources.

In order for this concept to be operational, however, it is important to identify and explain the role of the Mars ascent vehicle (MAV) as the connecting link. The MAV is simply put a vehicle that enables the transportation of payloads of up to 20 metric tonnes from the Martian surface to the servicing orbiter and back [51]. This is a concept that is currently being investigated by several third parties [31, 32, 63], which moreover delve into the potential of ISRU for the manufacturing of propellants and heat-shields to power and protect the MAV [30, 38].

9.3. Next Steps

In the final report, this chapter will be extended to include more information regarding the mission configuration and the specification of the system operations. For this, a study on the complex interrelations between the elements that constitute this mission and its implementation must be performed. Moreover, the integration of all the “off-the-shelf” solutions must be simulated, verified, and validated.

10
Risk Assessment, Reliability and Availability

This chapter delves into technical risk assessment and its related aspects from the RAMS analysis. Section 10.1 elaborates on the failure modes of the subsystems described in chapters 4 to 6 and risks of site selection from chapter 7. First, the failure modes and risks are identified with their corresponding likelihood and impact. Then, the new risk matrix is presented with the mitigation measures. Reliability and availability from the RAMS analysis are described in sections 10.2 and 10.3, respectively.

10.1. Technical Risk Assessment

At this maturity of the design, the risks related to the different subsystems can already be introduced as the preliminary design has already been made. The organisational and top-level risks are described in the Project Plan [16] and the Baseline Report [15], respectively. Thus, these aspects are not discussed here. The risks are identified for every subsystem: wind energy unit (**WE**), solar energy unit (**SO**), Compressed Air Energy Storage (**CA**), secondary battery (**SB**) DC microgrid (**DC**) and site selection (**SS**). The risks defined here only involve the ones directly related to the trade-off conducted in the report.

As already introduced in the Baseline Report [15], Continuous Risk Management is going to be implemented. The risks are monitored constantly and changes are implemented in the risk assessment as soon as needed. Furthermore, a Failure Mode Analysis is conducted as the subsystems are already determined. The failure modes/risks are identified in table 10.2 with likelihood and impact scores defined in table 10.1.

Table 10.1: Points definition for likelihood and impact

Point	Likelihood	Impact
1	Rare	Negligible
2	Unlikely	Minor
3	Possible	Moderate
4	Likely	Significant
5	Certain	Severe

Table 10.2: Failure mode analysis and risk assessment

ID	Failure mode/risk	Likelihood	Impact
Wind energy [1][65]			
WE-01	Tether(s) brake	2	5
WE-02	Kite not steerable	2	4
WE-03	Airborne communication software (SW) failure	2	3
WE-04	Ground communication SW failure	2	3
WE-05	Airborne main data-link hardware (HW) failure	2	2
WE-06	Airborne backup data-link HW failure	2	5
WE-07	Ground main data-link HW failure	2	2
WE-08	Ground backup data-link HW failure	2	5
WE-09	Inertial measurement unit (IMU) HW failure	2	4
WE-10	IMU SW failure	2	3
WE-11	Global Positioning System (GPS) HW failure	2	2
WE-12	GPS SW failure	2	2
WE-13	Sensor box HW failure	2	4
WE-14	Sensor box SW problem	2	3

Continued on next page

[1]https://onlinelibrary.wiley.com/doi/abs/10.1002/we.2433 [Cited 20 May 2020]

Table 10.2: ***Continued from previous page***

ID	Failure	Likelihood	Impact
WE-15	Left motor HW failure	1	5
WE-16	Right motor HW failure	1	5
WE-17	Motor driver microcontroller unit (MCU) failure	1	5
WE-18	Motor driver MCU SW failure	1	4
WE-19	Flight SW problem	3	3
WE-20	Primary CPU HW problem	2	4
WE-21	System state controller SW problem	2	4
WE-22	Maximum power point tracker charger HW failure	2	3
WE-23	Battery pack HW failure	2	4
WE-24	Winch control SW problem	2	3
WE-25	Ground control HW problem	3	3
WE-26	Wind sensor HW failure	1	3
WE-27	Wind sensor SW failure	1	2
WE-28	Force sensor HW failure	1	4
WE-29	Force sensor SW failure	1	3
Solar energy[2]			
SO-01	Mechanical solar panel orienting system failure	2	4
SO-02	Orientation program malfunction	2	3
SO-03	Short-circuited cell	3	2
SO-04	Open-circuited cell	3	2
SO-05	Short-circuited module	3	3
SO-06	Open-circuited module	3	3
SO-07	Glass breakage	3	4
SO-08	Delamination of encapsulant and solar cell	2	3
SO-09	Hot-spot failure	2	2
SO-10	By-pass diode failure	2	2
SO-11	Encapsulant failure	2	3
Compressed Air Energy Storage [58]			
CA-01	Uplift failure	2	5
CA-02	Rock mass deformation	2	4
CA-03	Buckling failure of steel lining	2	5
CA-04	Fatigue failure of steel lining	2	5
CA-05	Concrete plug instability	2	4
Secondary battery [45]			
SB-01	Fracture in cathode	2	4
SB-02	Mechanical failure of anode	2	4
SB-03	Degradation of anode	3	3
SB-04	Dendrite formation	2	3
DC microgrid			
DC-01	Mismatch in supply and demand	2	4
DC-02	DC-DC converter failure	2	3
DC-03	Rectifier failure	2	3
DC-04	Inverter failure	2	3
DC-05	Transmission cable failure	2	3
Site selection			
SS-01	No water/ice on site	2	5
SS-02	Not enough water/ice	2	5
SS-03	Low mean wind speed	3	5
SS-04	High optical depth	2	4

Risk is defined in equation 10.1. Knowing the values for likelihood and impact, the risk matrix can be estab-

[2] https://www.pveducation.org/pvcdrom/modules-and-arrays/degradation-and-failure-modes [Cited 17 May 2020]

lished in order to determine the severity of the risks. The matrix can be seen in figure 10.1. One may observe that there is one extreme risk and numerous high risks. As this concerns the situation before mitigation, this is still acceptable.

$$Risk = Likelihood \cdot Impact \tag{10.1}$$

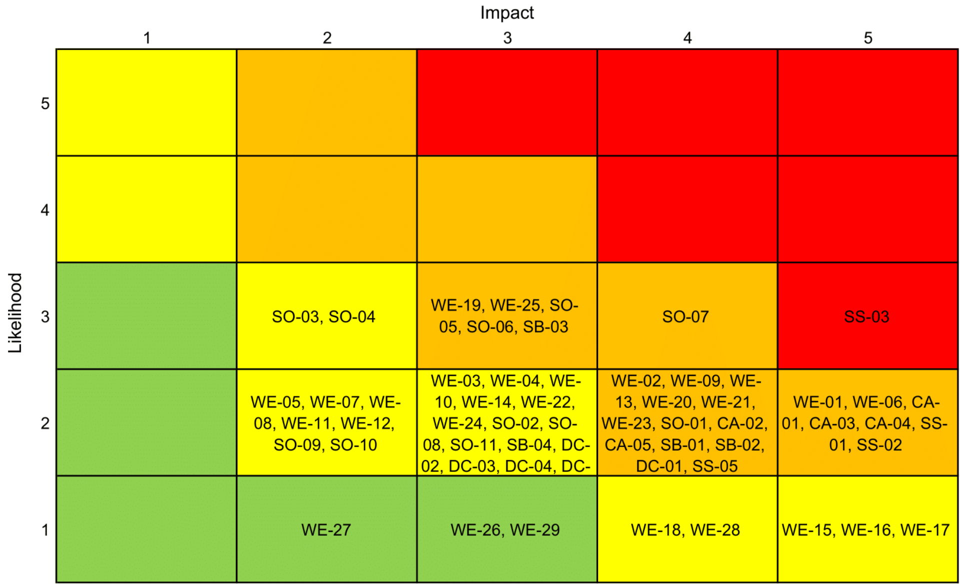

Figure 10.1: Risk matrix before mitigation (red: extreme risk, orange: high risk, yellow: moderate risk, green: low risk)

The mitigation measures and the new scores for likelihood and impact can be seen in table 10.3 and the new risk matrix can be seen in figure 10.2. There are only five extreme risks, while the majority is moderate. This result is considered acceptable from a risk management point of view.

Table 10.3: Risk mitigation measure and new points

ID	Measure	Likelihood	Impact	ID	Measure	Likelihood	Impact
WE-01	Mitigate	2	4	**SO-01**	Mitigate	2	3
WE-02	Mitigate	2	3	**SO-02**	Mitigate	2	2
WE-03	Mitigate	2	2	**SO-03**	Mitigate	3	1
WE-04	Mitigate	2	2	**SO-04**	Mitigate	3	1
WE-05	Mitigate	2	1	**SO-05**	Mitigate	3	2
WE-06	Mitigate	2	3	**SO-06**	Mitigate	3	2
WE-07	Mitigate	2	1	**SO-07**	Mitigate	3	3
WE-08	Mitigate	2	3	**SO-08**	Mitigate	2	2
WE-09	Mitigate	2	3	**SO-09**	Mitigate	2	1
WE-10	Mitigate	2	2	**SO-10**	Mitigate	2	1
WE-11	Mitigate	2	1	**SO-11**	Mitigate	2	2
WE-12	Mitigate	2	1	**CA-01**	Research	1	5
WE-13	Mitigate	2	3	**CA-02**	Research	1	4
WE-14	Mitigate	2	2	**CA-03**	Research	1	5
WE-15	Mitigate	1	4	**CA-04**	Research	1	5
WE-16	Mitigate	1	4	**CA-05**	Research	1	4
WE-17	Mitigate	1	3	**SB-01**	Mitigate	2	3
WE-18	Mitigate	1	2	**SB-02**	Mitigate	2	3
WE-19	Mitigate	3	2	**SB-03**	Research	2	3
WE-20	Mitigate	2	3	**SB-04**	Research	1	3
WE-21	Mitigate	2	3	**DC-01**	Mitigate	2	3
WE-22	Mitigate	2	2	**DC-02**	Mitigate	2	2

Continued on next page

Table 10.3: ***Continued from previous page***

ID	Measure	Likelihood	Impact	ID	Measure	Likelihood	Impact
WE-23	Mitigate	2	3	**DC-03**	Mitigate	2	2
WE-24	Mitigate	2	2	**DC-04**	Mitigate	2	2
WE-25	Mitigate	3	2	**DC-05**	Mitigate	2	2
WE-26	Mitigate	1	2	**SS-01**	Research	1	5
WE-27	Mitigate	1	2	**SS-02**	Research	1	5
WE-28	Mitigate	1	3	**SS-03**	Research	2	5
WE-29	Mitigate	1	2	**SS-04**	Research	1	4

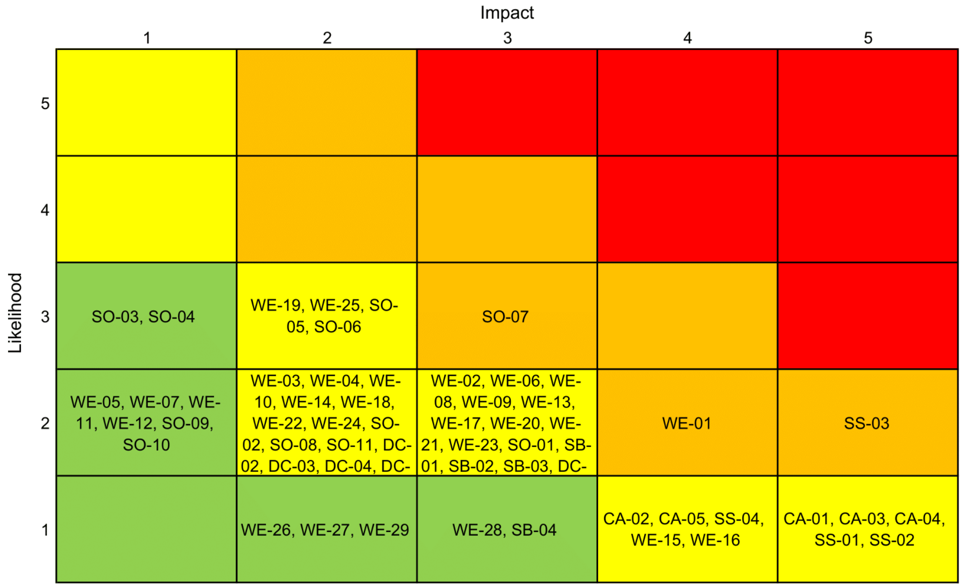

Figure 10.2: Risk matrix after mitigation (red: extreme risk, orange: high risk, yellow: moderate risk, green: low risk)

It is important to emphasise that the contingency plan is omitted on purpose. Although the subsystems are known, their exact layout are not. Thus, making a plan to handle risks and failures is only possible at the detailed design stage.

10.2. Reliability

Reliability is essential for any system to guarantee it can fulfil all mission requirements until end-of-life. In space environment, it is paramount as the system is barely accessible or not accessible at all. Reliability analysis goes hand in hand with risk assessment as risks define how a system can fail, which is the basis of this investigation.

In this section the methods are introduced to deal with reliability related issues, but as the final concept is not yet mature enough the analysis itself will not be conducted.

One of the methods is the Reliability Block Diagram (RBD). This consists of functional blocks of subsystems, components or parts depending on the level of detail needed. It is a success oriented logical layout, which described the essential elements for a functioning system. It can be made up of elements in series or parallel. For the former, if any one of the elements fail, their path fail. Whereas for the latter, if all elements fail except one, the system can still function through that path. A simple system can be built up of elements in series and parallel and the reliability of the system can be easily calculated.

The reliability of an element with a constant failure rate of λ is $R(t) = e^{-\lambda t}$. Knowing the failure rate for each system, and given the RBD, the reliability of the whole system can be calculated at any given time. For non-reliable elements, the Mean Time To Failure is an important indicator and is defined as the integral of $R(t)$ from 0 to ∞.[3]

[3]https://www.ntnu.edu/documents/624876/1277046207/SIS+book+-+chapter+05+-+Introduction+to+RBDs/61af88f9-b6d6-402a-94f7-902706c921c7 [Cited 13 May 2020]

The other method is called the Fault Tree Analysis (FTA). This is a systematic rundown of all elements connected by logic gates (AND, OR, etc.). Initiators or events are the starter points of every fault running up through the elements and their gates. The impact of an event can be evaluated by determining the probability that this single event will lead to a top failure. In case the probability of a single failure is not know, FTA can be used as a quantitative analysis.[4]

10.3. Availability

While reliability focuses on non-repairable parts, availability deals with repairable components. It is defined as the quotient of the downtime and the total time the component/part is to be used. More formally, it can be expressed as a function of Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR)[5]:

$$A = \frac{MTTR}{MTBF + MTTR}$$

This is by definition inherent availability, which is the case in an ideal support environment without any logistic or administrative delays. A way to increase reliability is maintenance prevention, which aims at reducing maintenance-related costs by designing for higher reliability. This way future maintenance as well as down time is reduced. This involves every aspect of the project and the team will investigate issues related to quality, operations, maintainability or productivity.

[4] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950012517.pdf [Cited 13 May 2020]
[5] http://web.utk.edu/~kkirby/IE591/ReliabEg_1.pdf [Cited 15 May 2020]

11
Verification and Validation

Verification and validation procedures are crucial in order to ensure that the design meets all requirements and the product fulfils its intended purpose. In this chapter, the verification and validation methods implemented during the mid-term phase of the design are explained. Furthermore, a strategy for verification and validation during the final design phase is suggested.

11.1. Verification of the Preliminary AWE Model

A preliminary sizing has been done of the AWE system at this stage of the design process. A physical model was implemented in Python to calculate weights and sizes for both the kite and its tether. For this, calculations on the wind distribution and the power generation needed to be done.

To ensure that the model works correctly, verification procedures were performed. Firstly, unit tests were done on the separate calculations in the Python code. Using the aerodynamic parameters found from research, several values could be calculated. Forces applied on the tether, average power generated and kite and tether sizes were all computed with the code. Comparing these values with the literature from which the aerodynamic parameters were taken, it could be verified that the separate units of the model work correctly. Sensitivity analysis was also performed to see how the model reacts to extreme input values. Throughout the creation of the model, the code was checked for syntax errors to make sure that it does what it is supposed to do and that no obvious mistakes have been made. Finally, a system test was performed to check if all the units together give the correct results. All of these verification tests and checks came out positive and therefore it can be said that the preliminary design model is verified.

It is important to mention that no validation procedures have been started as of yet, since this is just the preliminary stage of design. Validation procedures will be included in the final design for different aspects of this simulation. First, the aerodynamic inputs which are fed to the model and describe the kite performance should be validated as for now they are referenced from literature. This could be achieved through aerodynamic modelling software such as XFoil and XFLR5; nevertheless, as airborne technology is mostly in its experimental stage, software results are considered to be of insufficient credibility, hence, wind-tunnel testing is evaluated to be essential. However, even if the aerodynamic inputs are validated, if the model is not performing as expected, the outputs can be off. Therefore, to validate that the quasi-steady model, that will be used for the final design, still performs the way it should, a set of inputs with pre-known outputs [9] will be fed to the model. If the model produces the expected results for the Earth environment, it is expected that it would also produce credible outputs when the inputs are adjusted for Martian conditions. Nevertheless, the outputs of the model should also be validated through testing, either in facilities that simulate the Martian environment or on Mars.

11.2. Verification and Validation Strategy for Future Design Activities

As the design of a renewable energy system involves different systems (i.e. wind, solar, etc.) and their integration, verification and validation must be performed at different levels. On one hand, each individual system must prove its compliance with the requirements set in the baseline phase. On the other hand, all individual systems must prove that they can function together to fulfil the mission needs. The design of such systems in the hostile and little-known Martian environment requires a lot of simulation and modelling. It is of utmost importance that these models are well-verified. Therefore, the first section is dedicated to software verification. Furthermore, it must be proved that the system as final product complies with its requirements and fulfils the mission need. Hence, the second section is dedicated to verification and validation procedures to test compliance with requirements.

11.2.1. Software Verification

During the design of the Renewable Energy System for Mars Habitats, models are built to simulate the Martian environment. Not only for determining atmospheric properties, but also for estimating wind speeds, which are required for evaluating the energy yield of the wind system. These models must be verified to check whether they are well-engineered and without errors. This is done by applying software testing techniques at three different levels.

The lowest level is called unit testing. Individual units of the code are tested independently from other parts, to check whether every single part works correctly. It mainly includes debugging activities such as syntax error testing (where it is checked if there are no critical errors in the code).

On the second level, software performance is evaluated by integration testing. As the name suggests, individual units are combined and tested as a group to verify whether the interaction between the integrated units is error-free. For integration testing, sensitivity analyses can be performed (i.e. how does the code react to extreme values and is the output logical).

Finally, at the highest level, system testing will be performed. For these types of tests, all units composing the system are tested together to verify the behaviour of the complete system. System robustness can also be tested here with a sensitivity analysis.

Some examples of unit and system tests that will be executed in the next design stage of the project are itemised below.

- **Unit test 1: Martian conditions**
  As key input parameters for the sizing and design models, the specific conditions for Mars are required to simulate the actual conditions. Thus, the magnitude of these parameters should be first verified. This can be performed by an extensive simulation of literature research on Mars, as well as incorporating ongoing information from the data observed and provided by Space organisations while the design process is ongoing. This allows taking into account any anomalies that might occur on Mars, especially pertaining to the site selected.
- **Unit test 2: Battery sizing**
  An important element of the system is its storage capacity. This design process can be treated as an unit, in which known technical specifications from existing technologies are extracted. The battery sizing can be verified by an analytical model of the capacity or a brief demonstration of the validity of product specifications by the manufacturing source. The verified value can then be inserted into higher-level system design modules.
- **Unit test 3: Solar radiation model**
  Understanding the solar energy resource availability is also key in sizing the secondary energy system at a further stage. The solar radiation model can undergo a juxtaposition with Earth data, using known orbital periods and solar radiation availability at different times of the year, to verify these models.
- **Integration test 1: Computer calibration**
  The computer unit is the main driver of the operational functionality of the energy system, thus its software architecture and modules need to be integrated accordingly as well. This includes among other things units, dimensions and vector systems. Essentially, the disparate unit models have to communicate with one another without implementation errors. This adopts the use of sensitivity analysis, whereby ghost values can be substituted into the integrated module to demonstrate that there are no highlighted anomalies among each output with respect to the changing inputs.
- **System test 1: Wind energy**
  A big part of the design of the primary energy system is to simulate true-to-life wind resources on Mars to size kite parameters or to program the kite control unit. This model can first be tested using known empirical results with well-known Earth conditions, that can later on be transcribed to Mars conditions (density, pressure, composition, etc.), which are unit modules that have been verified by previous unit tests (see unit test 1).
- **System test 2: Solar energy**
  This system test is similar to the wind energy system test. To ensure the energy received from the secondary energy system meets the requirements and that of the power mix, a few components come into play. The first component is the solar radiation model, followed by the design specifications of the solar panel's III-V technology and the mechanisms used to tilt and maintain (dust handling) the system. This module can be verified holistically as a system.
- **System test 3: Microgrid design**
  As all subsystems of the system are integrated, the microgrid needs to perform as a functional closed circuit. This circuit shall have appropriate gateways for discharging to avoid physical damage. In addition, the specific amounts of energy need to be stored, transported and distributed within a margin of error to ensure that energy requirements are met at all times, taking into account seasonal and sub-optimal conditions. Hence, the multiple modules that allow to integrate and run the microgrid design are utilised in the same system test. It is at these junctures that there would be, by the same token, consolidated key results of the design as a whole. Which can be verified systematically to peer results.

11.2.2. Verification and Validation of Final Product

Several methods exist for verifying and validating compliance of the product with its requirements. Four different methods are distinguished: test, analysis, inspection and demonstration.

- **Test**: For this method, a realised component or end product is tested to obtain data to verify or validate its performance. It is done in dedicated test facilities. Specific to this project, the Aarhus Mars Simulation Wind Tunnel[1] [1] would be a valuable testing facility. This wind tunnel is capable of reproducing Martian pressures and temperatures. But more importantly, it has been specially designed to simulate dust storms by introducing particulates of sand and dust in the wind tunnel. In this way, it can be tested whether the equipment (e.g. solar arrays or the inflatable kite) will be damaged by dust particles and wind loads. Another facility of interest would be Spectrolab's testing facility for testing the equipment and particularly the solar arrays under Mars' solar conditions [21].
- **Analysis**: This method makes use of well-validated mathematical and physical models to predict the performance of a design. Based on the calculated data, the design is checked for compliance with its requirements. Of course, all existing energy systems are specifically designed for Earth. It may therefore be challenging to analyse the system for a Martian environment. Nevertheless, if mathematical or physical models are well-validated for the Earth environment, then it may be assumed, by changing atmospheric parameters, that the software is validated for the Martian environment as well. Thus they can be used for analysis.
- **Inspection**: By visual examination of a realised component or end product, physical design features can be verified. These can be length or volume of a product, but also the mass (weighing the product is considered inspection here).
- **Demonstration**: If none of the above methods are suitable, then a demonstration of the product is an option. It aims to establish compliance of the product with its requirements by operating it.

All requirements are listed in table 11.1. For each requirement, it is indicated which method is used to verify or validate compliance of the design. It must be noted that one of the requirements (REM-NRG-09) requires two methods. This is because testing allows to evaluate whether the system is able to withstand the impact by flying particles of dust storms for a short period, but not for four months. It would require further analysis using a computer model to evaluate the durability of the system.

Furthermore, there are a few requirements to which none of the aforementioned methods apply, e.g. requirement REM-NRG-07: "The location of the habitat and its energy system shall be jointly decided by the external Mars habitat project team and the DSE team". Compliance of these requirements are evaluated by "other" methods, as indicated in the table.

[1] https://www.esa.int/ESA_Multimedia/Images/2019/05/Aarhus_Mars_Simulation_Wind_Tunnel

Table 11.1: Different methods planned for verifying and validating the Renewable Energy System to ensure it meets the given requirements.

Requirement ID	Verification or Validation Method				
	Test	Analysis	Inspection	Demonstration	Other
REM-NRG-01		X			
REM-NRG-02				X	
REM-NRG-03		X			
REM-NRG-04		X			
REM-NRG-05				X	
REM-NRG-06				X	
REM-NRG-07					X
REM-NRG-08	X				
REM-NRG-09	X	X			
REM-Sys-N02-01			X		
REM-Sys-N02-02		X			
REM-Sys-N02-03		X			
REM-Sys-N05-01		X			
REM-Sys-N05-02		X			
REM-Sys-N05-03		X			
REM-Sys-N05-04			X		
REM-Sys-N05-05					
REM-Sys-N06-01		X			
REM-Sys-N06-02		X			
REM-Sys-N06-03		X			
REM-Sys-N06-04		X			
REM-Sys-N06-05			X		
REM-MENV-01				X	
REM-MENV-02					X
REM-Sys-M02-01				X	
REM-Sys-M02-02		X			
REM-EENV-01					X
REM-Sys-E01-01		X			
REM-LD-01			X		
REM-LD-02			X		
REM-LD-03				X	
REM-LD-04		X			
REM-COST-01		X			
REM-COST-02		X			
REM-Sys-C02-01		X			
REM-Sys-C02-02		X			
REM-Sys-C02-03		X			
REM-Sys-C02-04		X			
REM-LEG-01				X	
REM-LEG-02				X	
REM-LEG-03				X	
REM-IAS-01					X
REM-IAS-02		X			
REM-IAS-03				X	
REM-Sys-I01-01		X			

12
Sustainability

Sustainability can be divided into three aspects: environmental sustainability, social responsibility and economic sustainability. In order to consider a design sustainable, all of these aspects must be considered. In this chapter, the sustainability strategy for the renewable energy system on Mars is described. First, the applied sustainability considerations during trade-off are described. Next, the material discovery for the final design is presented in preparation for a further detailed life cycle analysis. Lastly, the sustainable engineering steps during the finalisation of the design is discussed.

12.1. Sustainability in the Trade-Off Process

During this phase of the project, sustainable engineering is introduced in the trade-offs and the design processes. As can be read in the trade-off method in chapter 3 and the trade-offs in chapters 4 and 5, for all trade-offs the sustainability aspect is considered on three different stages of the design: production, life-time and retirement. Depending on the subsystem, these stages are weighted heavier or lighter. For production, the possibilities of application of sustainable resources and processes during manufacturing are reviewed. Over the lifetime, the produced emissions and need for maintenance and repair are considered. For end-of-life, the possibility to reuse or recycle the products as well as the logistics of the retirement are watched.

12.2. Material Discovery

This section consolidates the materials and other activities with environmental impact, categorised by the individual subsystems, as well as the mission operation considerations. This is highlighted in table 12.1, and the references in which the material discovery are cited accordingly. Note that the materials presented are the bulk, which means the materials in each table account for at least 70% of the total subsystem material input. Small volume parts, such as special metals for bolts and lubrication for gearboxes are considered in 'others'. A deeper investigation in material discovery will be carried out in the final design report.

12.3. Next Steps

Regarding the material discovery and life cycle analysis, the minimisation of material costs, especially for scarce materials, during manufacturing, transport and waste handling needs to be further analysed. A resource budget sheet will be provided in the final design report, describing the breakdown on the resources and materials needed for production, installation and operation of the system. In order to facilitate a circular economy, documentation about the end-of-life of the system will also be provided. In this document, strategies to reuse or recycle will be considered for each subsystem. A plan for the minimisation of the impact on Mars after life and the logistics of the retirement of the system will also be presented. To ensure the production of the system will be as sustainable as possible after finalising the design, a production planning chart will be created. In the production planning chart, all activities for production are described and visualised in order to decrease waste and inefficiencies. This includes energy and emissions created by the manufacturing process.

Regarding the financial and social aspect of the project, the following things will be carefully considered. For the final design regular financial analysis will be performed to ensure financial sustainability. Within the team, the group's work ethics and values will be continued being improved and consolidated, among others by a weekly evaluation meeting involving the whole team. Regarding the project design, space legislation will be constantly monitored for the fulfilment of the mission. It is key to ensure the ethics of the design and production, as this would influence public opinion and thus potential financial support of the project.

Table 12.1: Material discovery and estimated waste production of energy system

Part	Nature	Pct. [%]
Primary Energy System		
Kite	Kevlar-29 [78]	4.1
	Kevlar Protector	0.7
	Spectra (Cords)	2.9
	Polyurethane [78]	6.1
Kite Control Unit	Electrical steel [7]	5.8
	Silicon [7]	0.5
	Copper	3.5
	Other steels	2.8
Tether	High-Modulus Polyethylene (HMPE-DM20) fiber [8]	7.6
Ground Station and Generator	Electrical steel [81]	23.1
	Cast iron [17]	11.0
	18CrNiMo7 (Gearbox) [73]	7.8
	Low-alloyed steel	9.2
	Copper [7]	6.3
	Lead (Radiation Coating) [62]	2.6
	Alkyd paint [36]	1.7
Other	Others	4.3
Waste Production	Scrap materials	75
	Disposal solvents	7.2
Secondary Batteries		
Cathode	Lithium [60]	31.6
	Lithium-metal oxides [60]	13.3
Anode	Graphite [60]	22.9
	Copper foil [60]	8.2
Electrolytes	Dissolved salts (polymer) [74]	6.3
Casing	Aluminium	5.8
	Copper	4.4
	Carbon [14]	2.5
Other	Others	5
CAES (compressed air)		
Tank	Steel (forging) [74]	17
	Iron (forging) [74]	6.3
Gas	Hydrogen [83]	4.5
Compressor	Rotor (Steels) [57]	5.8
	Stator (Laminated electrical Steel) [83]	7.4
	Hydraulics (Steels) [11]	22.7
Structures	Aluminium [68]	20.8
Other	Others	15.5

Part	Nature	Pct. [%]
Secondary Energy System		
PV Modules	GaAs substrate (III-V cells) [49]	0.5
	Dust protection film	0.5
	Galvanized Steel (Frame) [49]	25
	Optics PMMA (Optics) [72]	8
	Aluminium (Heat sink) [61]	9
Tilt mechanism	Concrete (Foundation)	9.5
	Hydraulics and actuators [55]	27
	Motor [17]	1
Electrical	Various Inverter	6
	Various (Transformer)	1
	Copper (Cables) [35]	6
	Controller	3
Other	Others	3.5
Waste	Scrap materials	60
	Disposal solvents	25.5
Microgrid		
Cables	Electrical Steel [46]	24.1
	Lead [74]	14.8
	Copper	11.3
	Jacketing Resin [46]	9.3
Convertors	Steel [68]	3.8
	Aluminium	4.7
	Copper [81]	2.3
Computer	Silicon [7]	5.1
	Aluminium	4.3
	Copper [55]	2.8
Other	Various (Transistors, Inductors, Capacitors, Connectors, Integrated Circuits)	17.5
Waste Production (microgrid)	Scrap Metals	67
	Disposal Solvents	32
Waste Production (batteries)	Scrap Metals	80
	Disposal Solvents	16

13 Conclusions and Recommendations

In order to provide a continuous renewable energy supply of 10 kiloWatts to a Mars habitat, a distributed energy system is designed which comprises four subsystems: a primary energy supply system, a secondary energy supply system, an energy storage system and a power management and distribution system.

Many design options were considered for each subsystem, of which the most feasible concepts were compared following the same systematic approach. The trade-off process for the primary energy unit yielded a pumping kite power system with a tensairity kite and a braided HMPE DM20 tether, for their high performance at low weight. For the secondary energy unit, the trade-off resulted in a photovoltaic system of III-V multi-junction cell technology on a planar module with hydrophobic coating and biaxial rotation. The best choice for the power management and distribution system was a DC microgrid with underground cable infrastructure. For the energy storage system, it was decided to have separate solutions for buffering seasonal and diurnal fluctuations. Following from the trade-off, the best seasonal storage concept was compressed air energy storage. For day-to-day storage, a secondary battery system was chosen.

The site location and its available resources are key inputs to the preliminary design of the system. After an extensive trade-off, Deuteronilus Mensae was selected as the preferable site for the habitat and energy system. Even though solar and wind resources are more scarce in the northern polar region than around the equator, it was concluded that presence of water and low elevation were key criteria for the habitat.

A preliminary study of the available resources, along with a system performance analysis showed that the seasonal and diurnal variations in wind and solar resources are a big concern for balancing supply and demand. This is an adverse consequence of the choice for the site location, and resulted in needing to over-design the energy supply units.

For a preliminary design, the kite area is estimated at 900 m^2, the kite and tether mass together are estimated at 170 kg, the solar array area is projected to be more than 900 m^2 and the battery system is predicted to be over 1000 kg. These preliminary sizing activities suggest that the design would not comply with the set requirements. Hence a couple of recommendations are formulated.

To ensure a correct analysis of the available resources and the system performance, it is recommended that a greater effort is put into investigating wind and solar irradiance data for the site location. With the aim of doing so, hourly variations of wind speed and variation of wind speed with altitude should be looked into, just to name a few. Only then, it can be said with confidence whether or not building a 100% renewable energy system on Mars is technologically feasible.

Another recommendation would be to investigate the integration of non-renewable energy sources, such as nuclear energy, for that matter. The rovers from the rhizomatic habitat project, that are powered by radioisotope thermoelectric generators, could be connected to the microgrid when they are not performing other activities. Multiple rovers together could power a base load, which would greatly influence the required size of the primary and secondary energy systems, and the size of the storage solutions.

Finally, it is recommended to reassess the requirement for a continuous 10 kW power supply. It is plausible to expect that during the night, less power will be required by the users of the habitat. For that reason, it would be interesting to investigate the load profile of the habitat, and see whether the power demand could vary between day and night, instead of it being constant.

These recommendations will be discussed with all stakeholders before entering the final stage of the design.

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